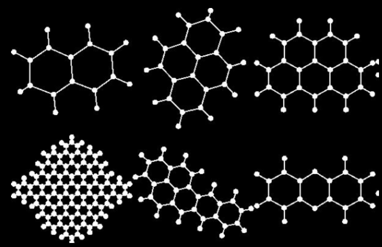
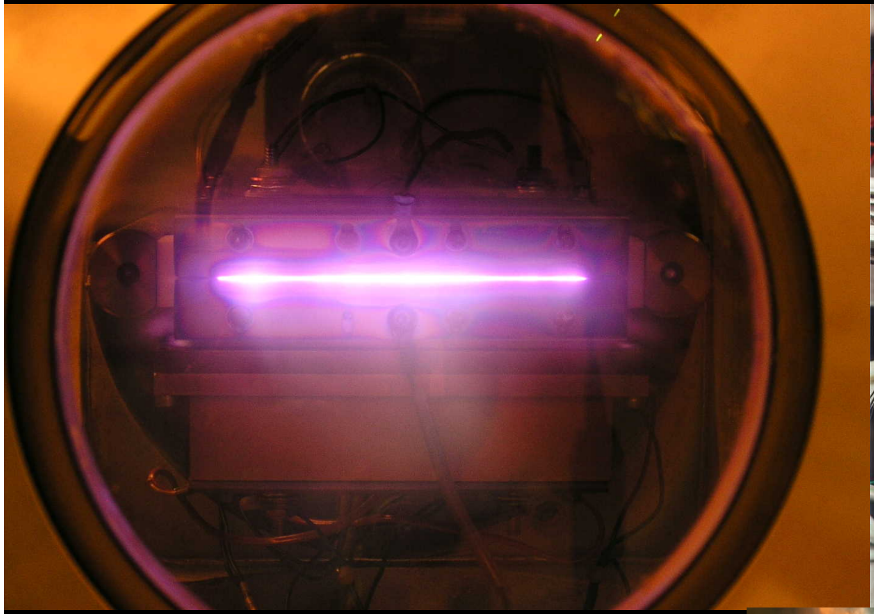
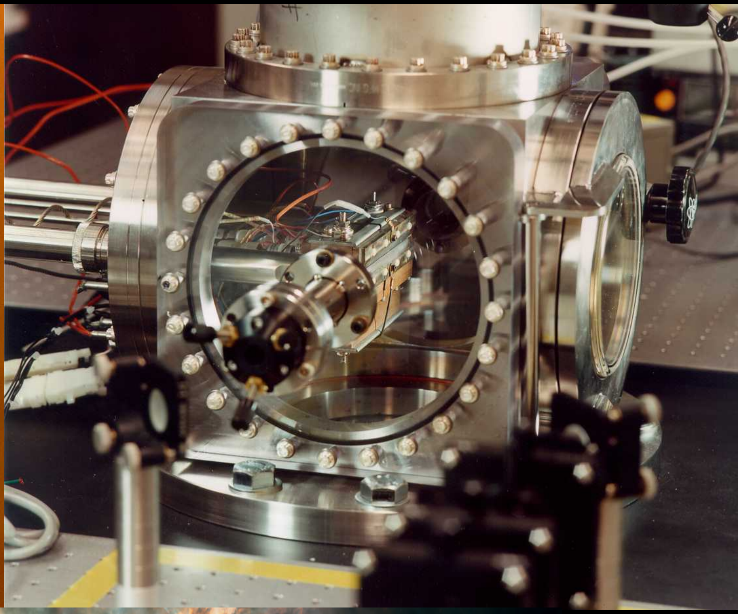
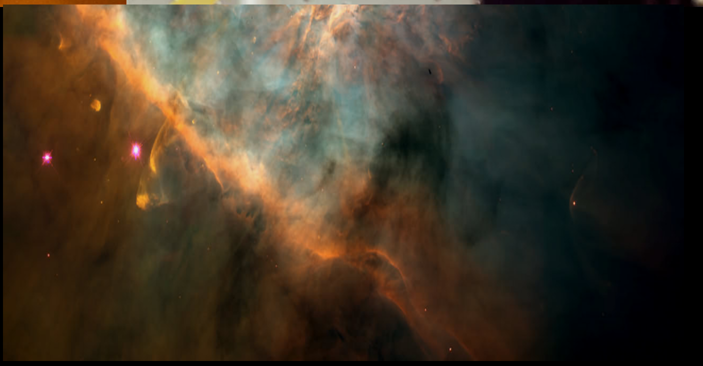
Interstellar Dust









Farid Salama

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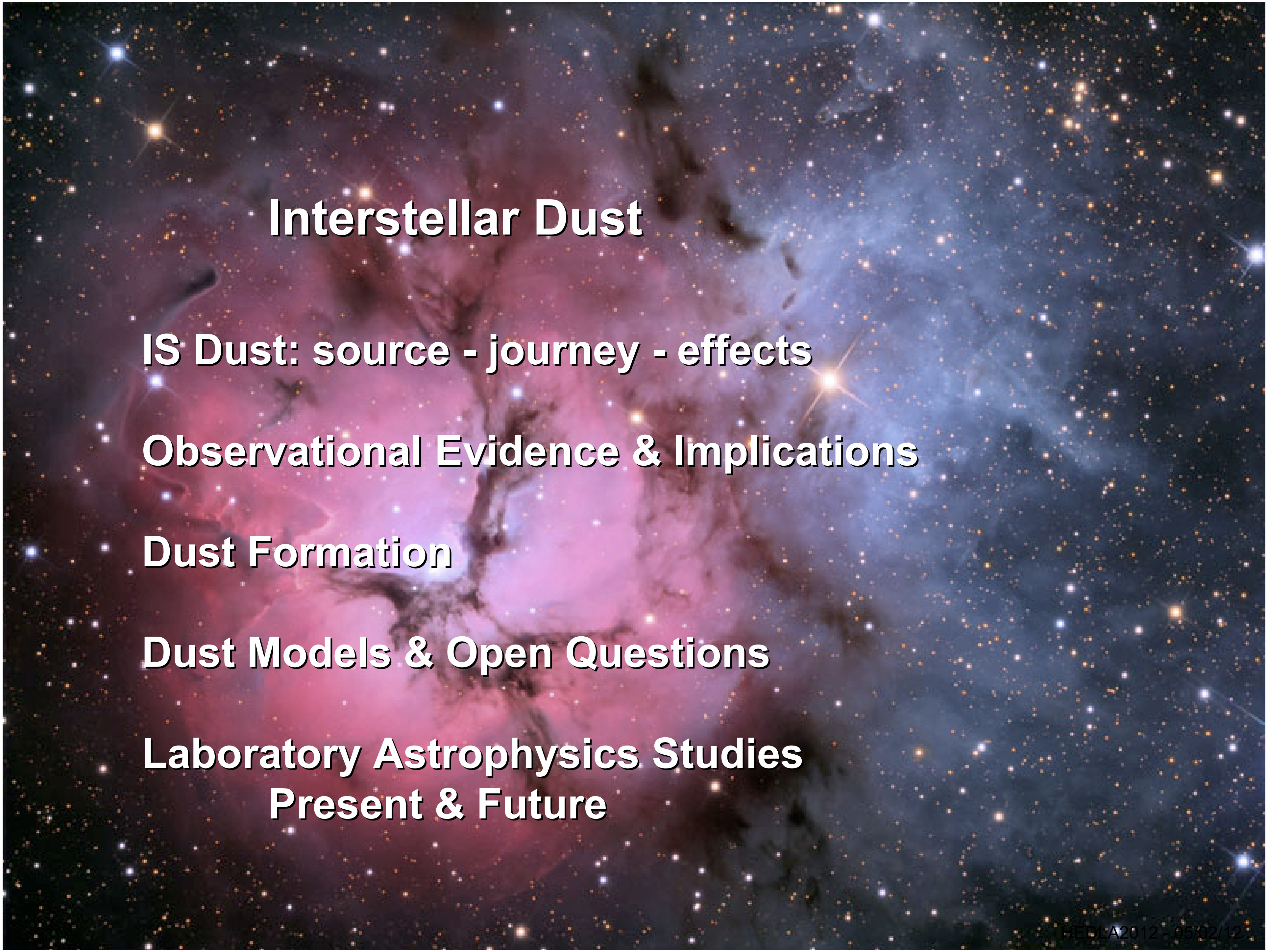
Space Science & Astrobiology Division

Ames Research Center



Interstellar Dust

IS Dust: source - journey - effects

Observational Evidence & Implications

Dust Formation

Dust Models & Open Questions

Laboratory Astrophysics Studies
Present & Future

BRIEF HISTORY…

Historically, interstellar dust was regarded by astronomers as an annoying interstellar "fog" which prevented an accurate measurement of distances to stars.

The first observational evidence of the existence of obscuring material in dense clouds that blocked light from the stars behind the clouds was the observation of dark lanes and patches in photographic surveys of the Milky Way in the 1800s

1930: R. Trumpler discusses the "Absorption of Light in the Galactic System" in PASP
1963: J. Mayo Greenberg: "The role of dust is that of observer and of catalyst."
1996: J. Mayo Greenberg: "dust plays a role not only as a tracer of what goes on in space, but also actively contributes to the chemical evolution of molecular clouds."

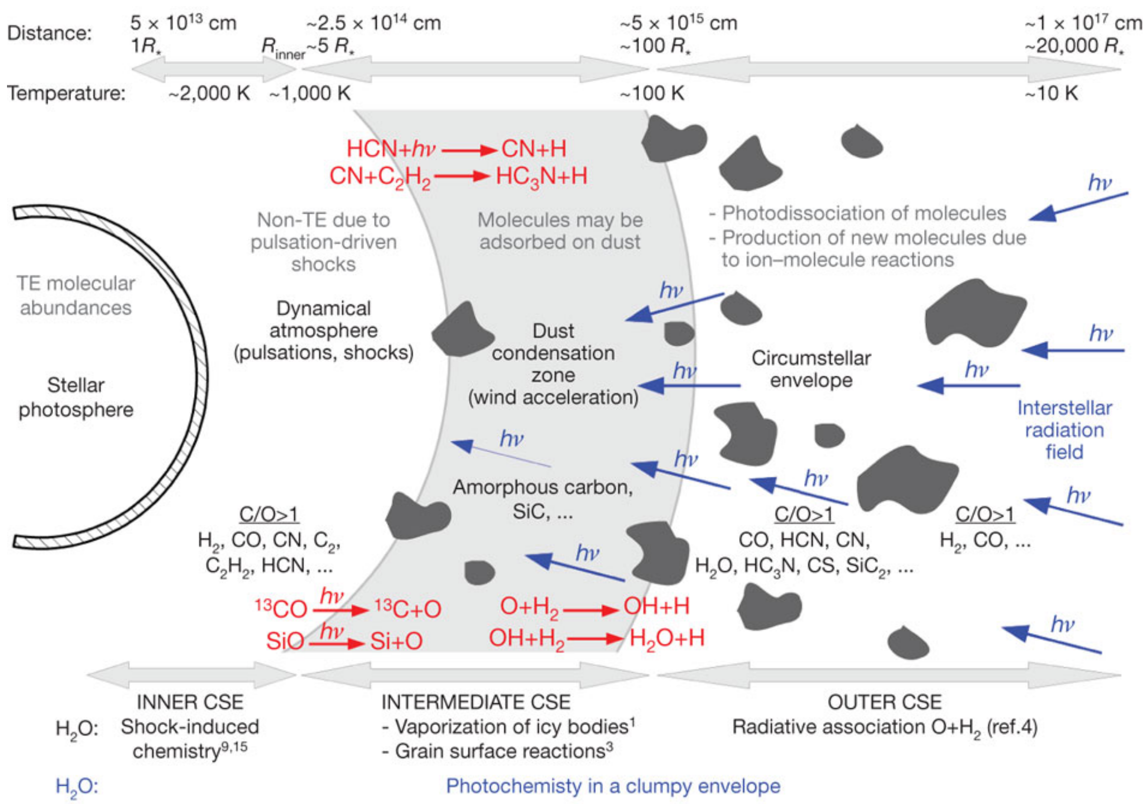
Today: the advances of IR-UV astronomy, laboratory astrophysics, and modeling have had a tremendous impact on our understanding of the physical and chemical nature, origin and evolution of interstellar grains and their significance in the evolution of galaxies, the formation of stars, planets, asteroids, and comets, and the synthesis of complex organic molecules.

Mass Budget for the ISM

Stellar Sources

- O-rich stars (O/C > 1) produce (mainly) silicate dust (C is in CO)
- C-rich stars (C/O > 1) produce (mainly) carbonaceous dust and SiC (O is in CO)

$M_{dust} \approx 0.005 M_{\odot}$/yr from stellar sources



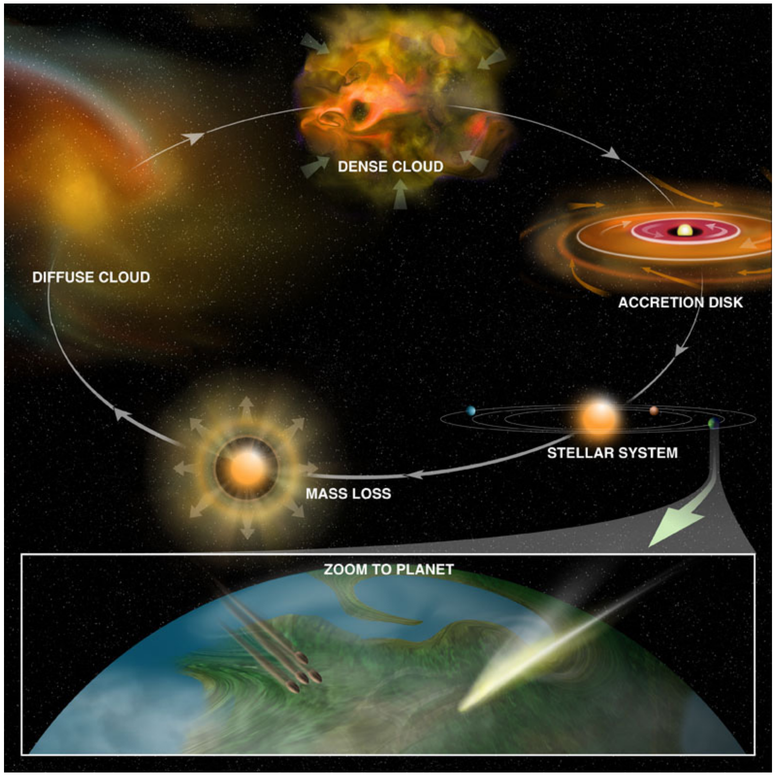
L Decin *et al. Nature* **467**, 64-67 (2010)

Journey through the ISM

Stardust grains will reside in ISM ~1.5 Gyr before being incorporated into protostar or protoplanetary disk

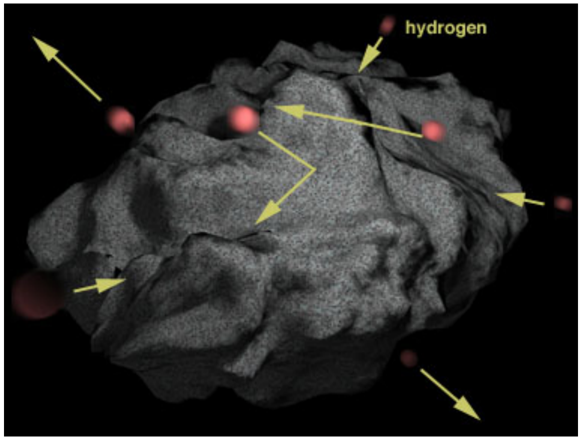
What happens to stardust grains as they journey through the ISM?

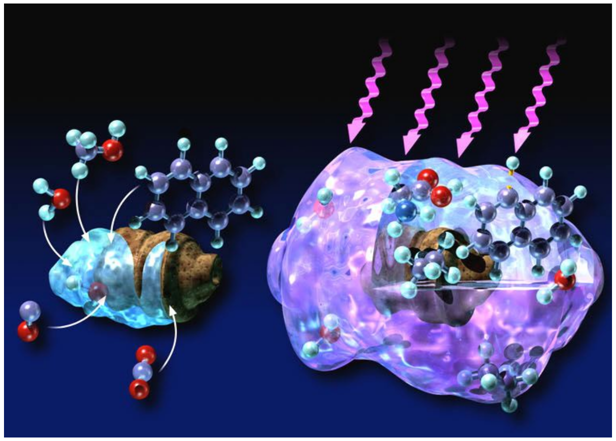
- chemical reaction with reactive species (H, O)
- UV photolysis (silicate immune?)
- CR damage (amorphization); CR flux is uncertain
- erosion by sputtering in hot gas
- erosion in shocked regions
- grain-grain collisions
    - ∗ coagulation at low velocity
    - ∗ shattering at intermediate velocity
    - ∗ vaporization at high velocity
    - ∗cratering of large grains by small grains



Effects of Dust on Interstellar Gas

- Photoelectric Heating
- H_2 Formation and Other Chemistry
- Grains as Sources of Complex Molecules
- Ion Recombination on Dust Grains
- Coupling Neutral Gas to Magnetic Fields





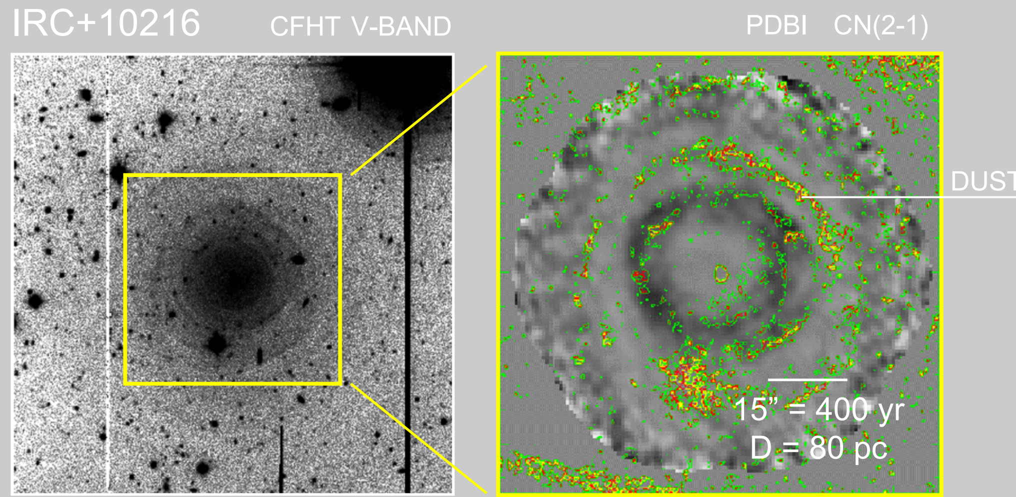
Evidence for IS dust?

Observational evidence:

Measured attenuation of starlight by interstellar dust (interstellar extinction)

Dust grains produce substantial scattering of star light at visual wavelengths

Polarization of starlight (continuous and spatially coherent)



Mauron & Huggins (1999) *Guélin et al. (2000)*

Physical properties?

Broad grain size distribution (R # 0.01 -- 0.1 μm); non-spherical, aligned grains

Composition of interstellar dust?

Spectroscopy of dust: Observed spectral features

Two Reflection Nebulae: Pleiades (M44) NGC 7023

- extinction curve (the 2175 Å feature)
- absorption features (Silicate bands, DIBs, 3.4 μm, Ice features…)
- emission features (PAH IR features, ERE, …)

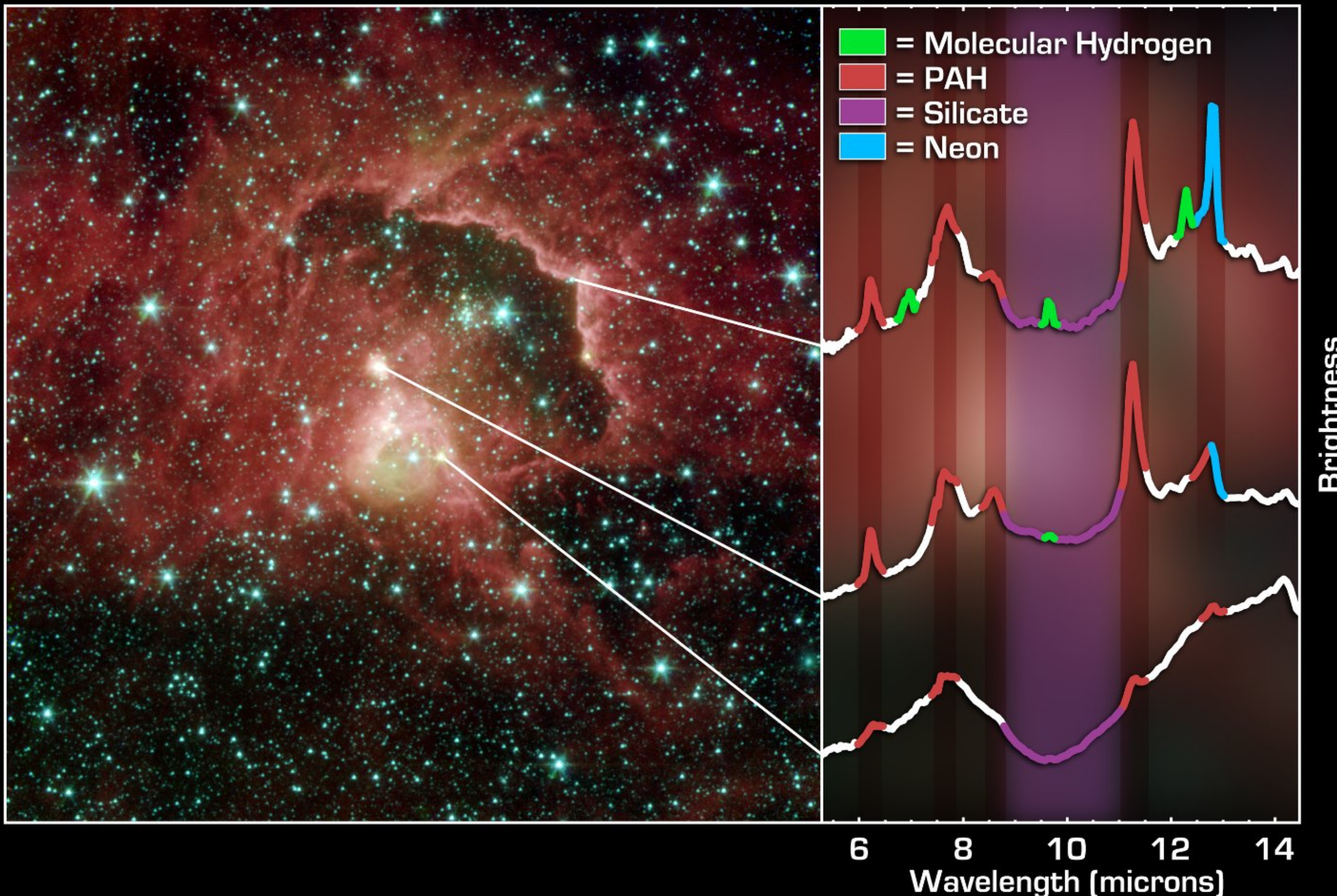
2 May 2012 — ESO Photo Release eso1219
Sifting through Dust near Orion's Belt

Cosmic dust clouds in Messier 78

This image of the region surrounding the reflection nebula Messier 78, just to the north of Orion’s belt, shows clouds of cosmic dust threaded through the nebula like a string of pearls.

The submillimeter-wavelength observations, made with the Atacama Pathfinder Experiment (APEX) telescope and shown here in orange, use the heat glow of interstellar dust grains to show where new stars are being formed. They are overlaid on a view of the region in visible light.

Credit: ESO/APEX (MPIfR/ESO/OSO)/T. Stanke et al./Igor Chekalin/Digitized Sky Survey 2



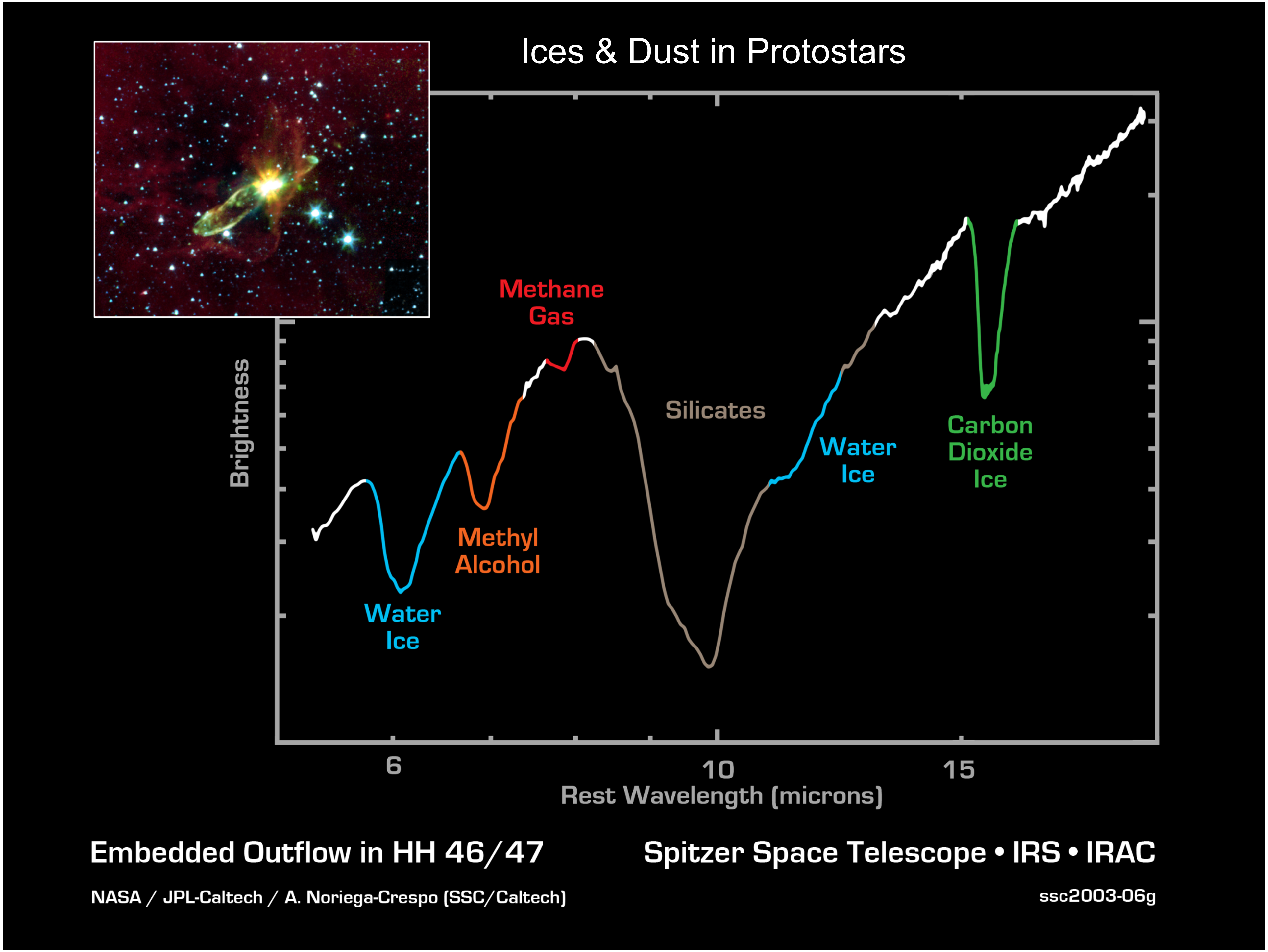
Star-Forming Cloud in Cepheus

Spitzer Space Telescope • IRS

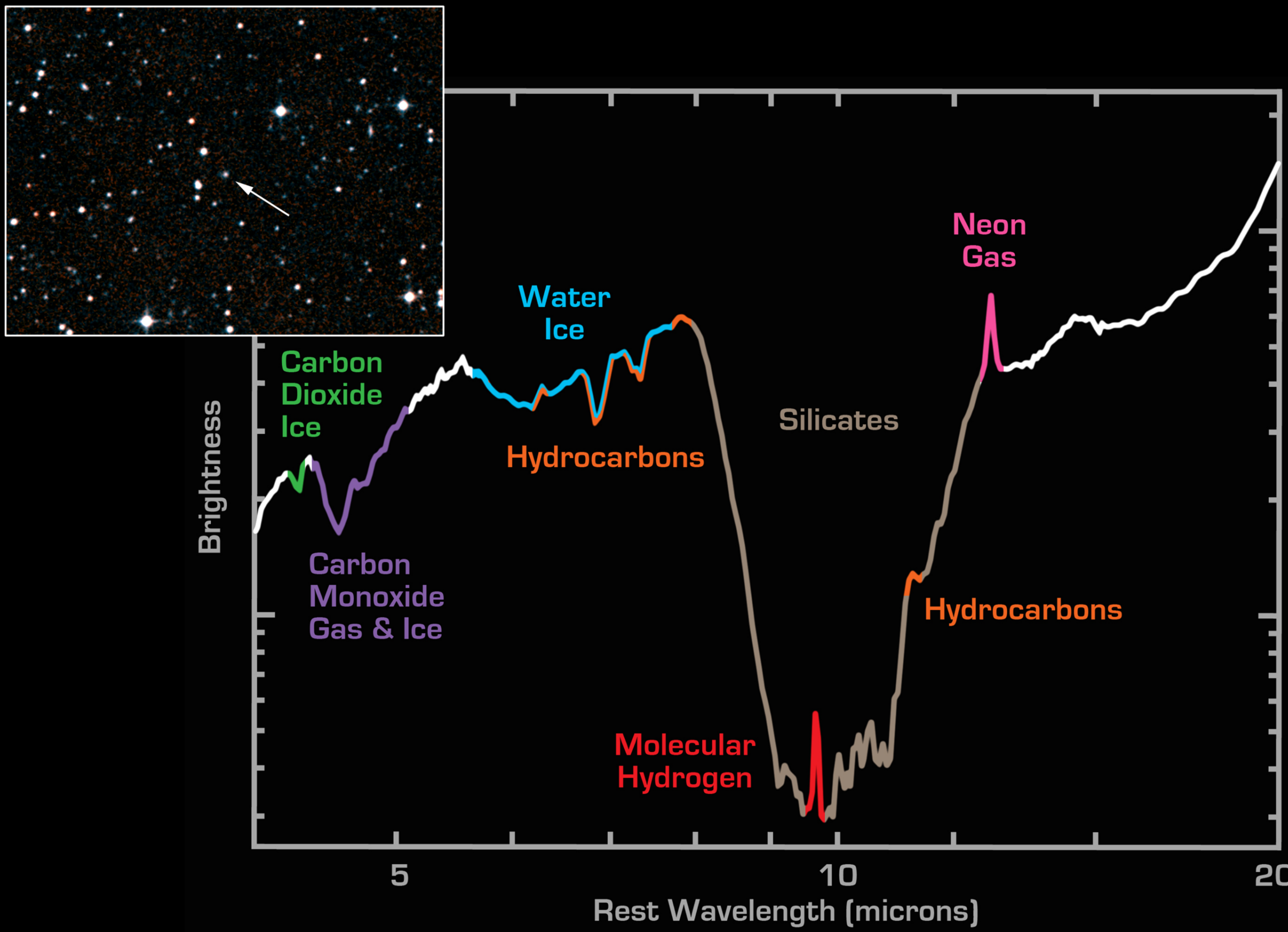
(Image: Spitzer Space Telescope • IRAC)

NASA / JPL-Caltech / J. Ingalls & S. Carey (Spitzer Science Center/Caltech)

sig06-021



Ices & Dust in Protostars
Brightness
Methane Gas
Methyl Alcohol
Water Ice
Silicates
Water Ice
Carbon Dioxide Ice
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



Galaxy IRAS F00183-7111

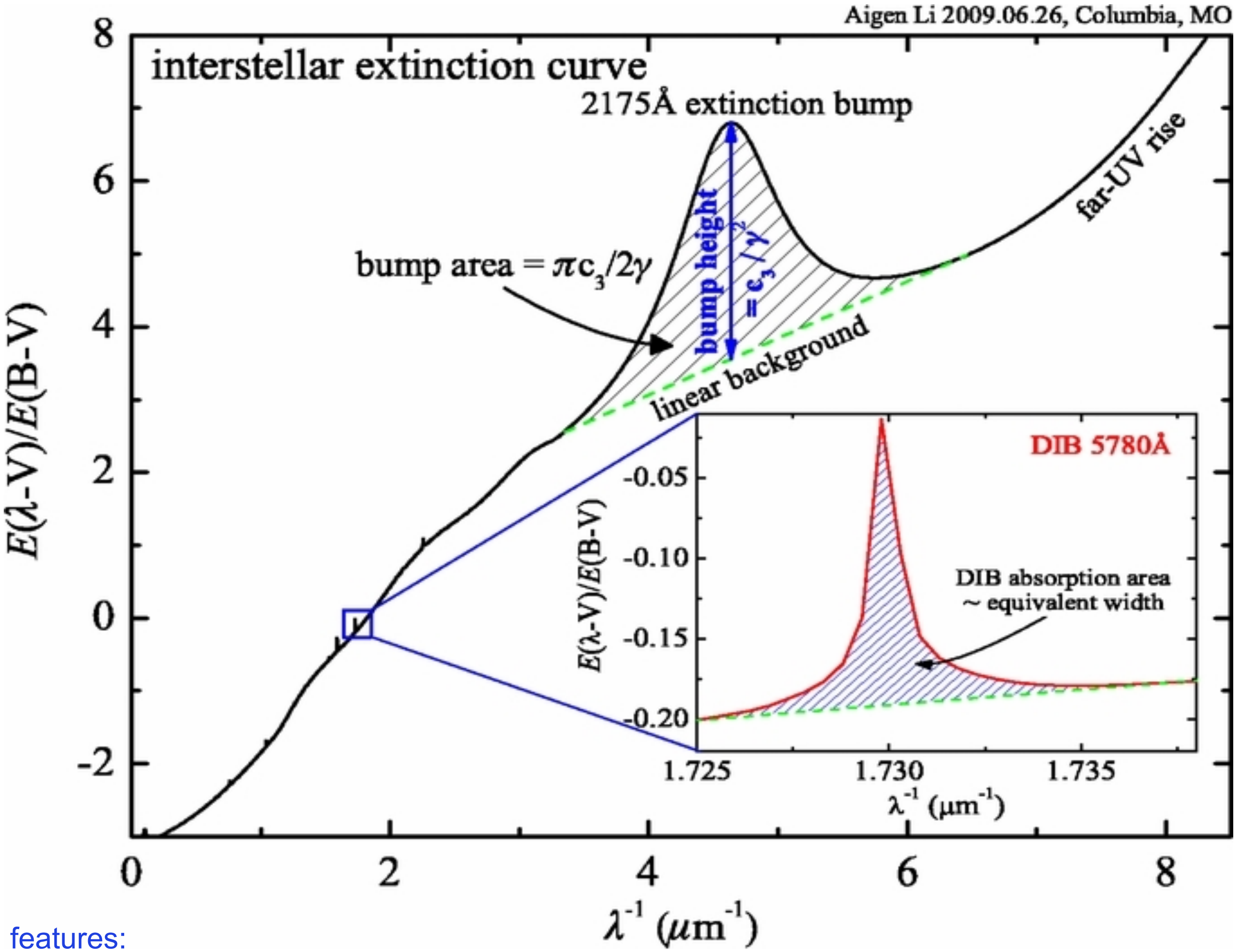
Spitzer Space Telescope • IRS

Inset: visible (DSS)

NASA / JPL-Caltech / L. Armus (SSC/Caltech)

ssc2003-06h

Composition of IS Dust: Observed Spectral Features



Principal features:

– General rise from IR to VUV (~ 0.1 μm)

– 18 μm and 10 μm: O-Si-O bend and Si-0 stretch in amorphous silicates

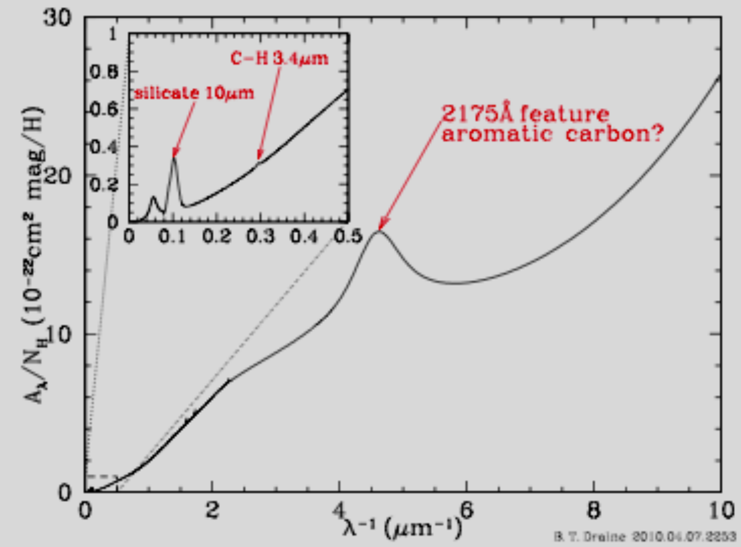
– 3.4 μm: C-H stretch in hydrocarbons

– 0.2175 μm: “2200 Å bump”. Probably $\pi \rightarrow \pi^*$ electronic transition in sp2-bonded carbon (e.g., graphite or PAH)

– > 500 weak features – the Diffuse Interstellar Bands – still unidentified.

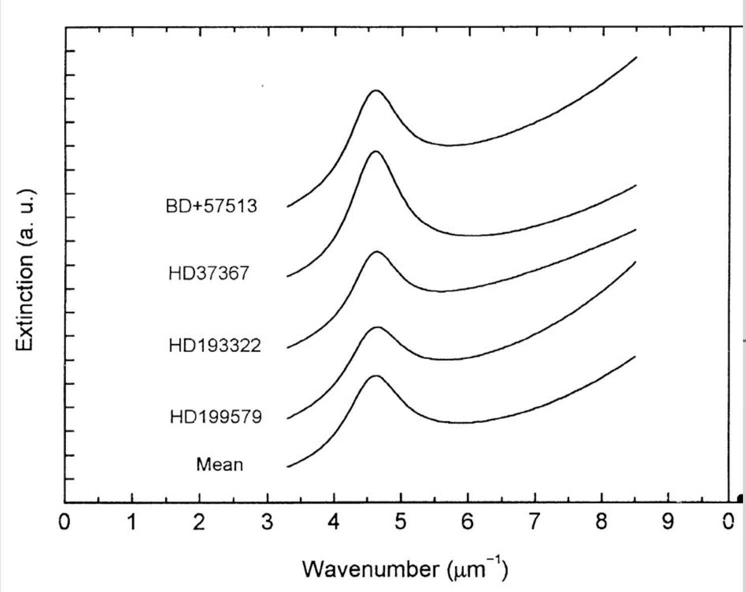
7. Composition of Interstellar Dust: Observed Spectral Features

7.1 The 2175Å Feature



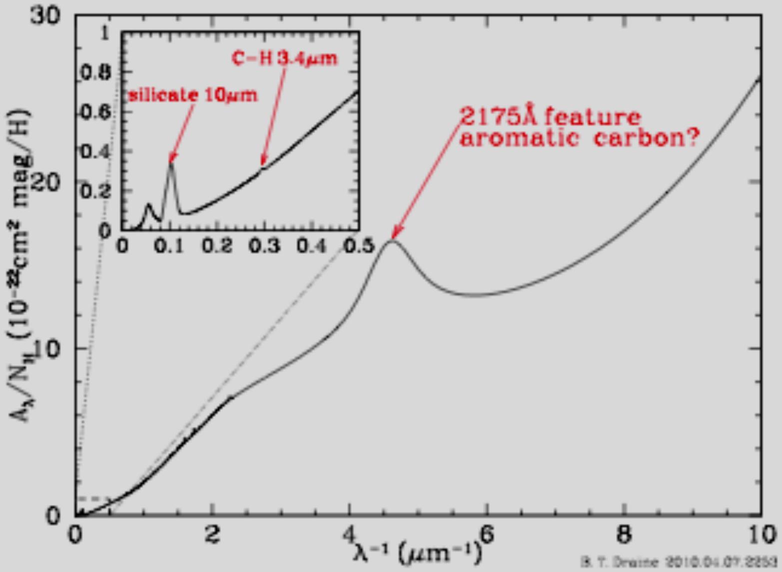
- Very strong: grain component must be abundant. Must come from compound of some subset of {C, O, Mg, Si, Fe} – other elements not abundant enough.
- In good agreement with calculations of absorption by randomly-oriented spheres of graphite: absorption comes from $\pi \rightarrow \pi^*$ excitations of π electrons in the graphite basal plane.
- Large PAH molecules have C in sheets of hexagons (sp^2-bonding) just as in graphite. Also have strong absorption in neighborhood of 2200Å
- Little or no polarization in 2200Å feature
- Current estimates of PAH abundance – (C in PAHs)/H ≈ 55ppm – suggest that **2200Å feature is probably due to C in PAHs**.
- Other carriers have been proposed (e.g., MgO).

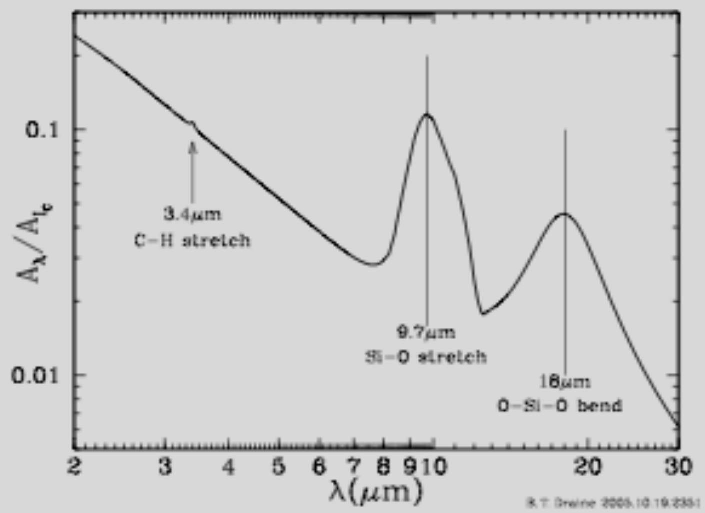
IS extinction curves toward different stars probing the diffuse ISM.



T Henning, F Salama Science 1998; 282: 2204-2210

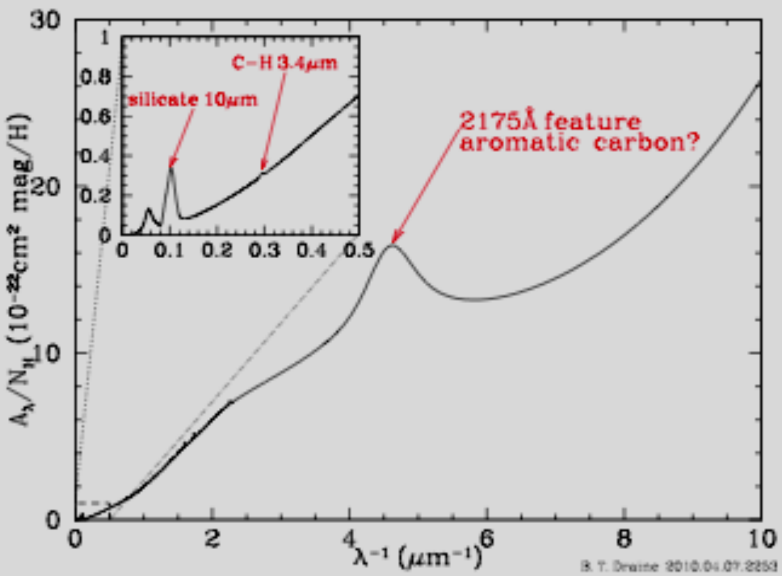
7.2 The Silicate Features

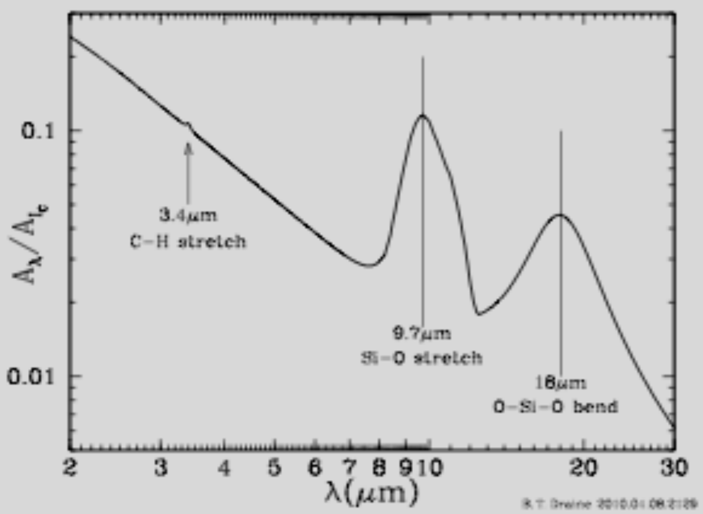




- Broad feature at $\sim$9.7 μm feature observed in absorption on sightlines with sufficient $N_{\rm H}$
- Profile consistent with Si-O stretching mode in **amorphous silicate**
- Also a weaker feature at 18 μm consistent with O-Si-O bending mode in amorphous silicates.
- Similar features seen in **emission** in winds from cool O-rich stars.
- Identification as amorphous silicate is secure
- Nearby ISM has $A_V/\Delta\tau_{9.7} \approx 18.5 \pm 2$
- Sightlines to sources near the GC have $A_V/\Delta\tau_{9.7} \approx 9 \pm 1$
- Strength of silicate profile: requires that majority of Mg, Si, and perhaps Fe be in amorphous silicates (possible composition $MgFeSiO_4$)
- Absence of sharp structure in profile: no more than **2%** of interstellar silicates are crystalline.
- Polarization in silicate feature is observed: silicate grains can be aligned in ISM

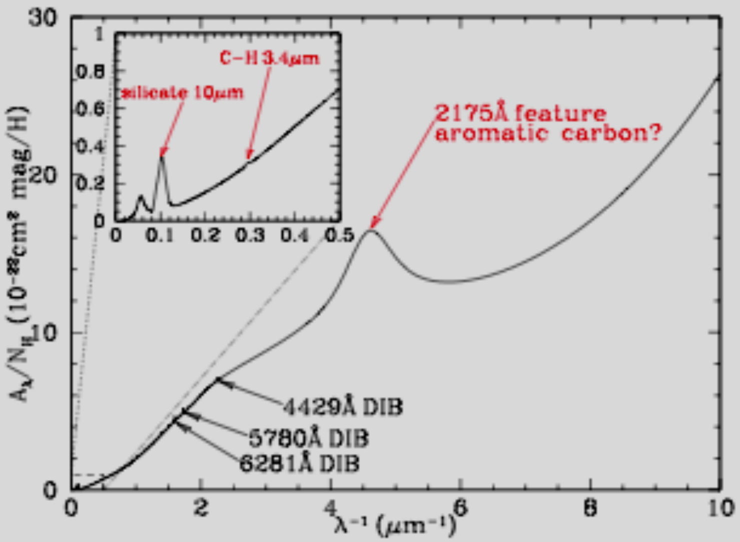
7.3 The 3.4 μm Feature

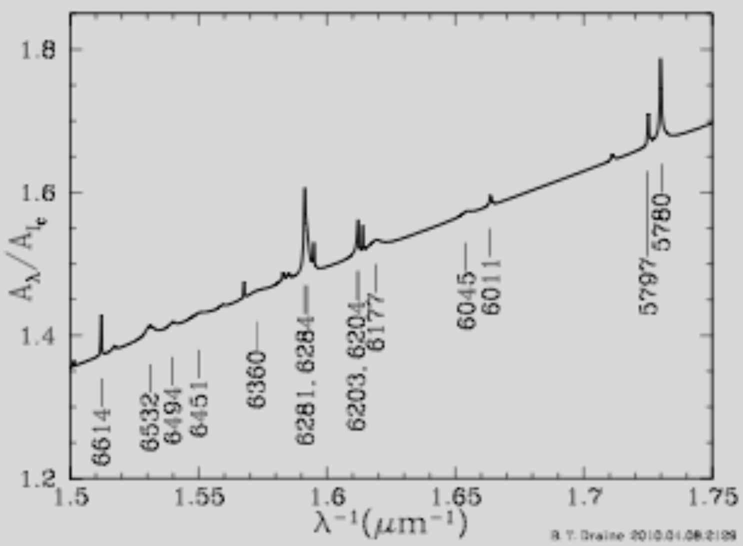




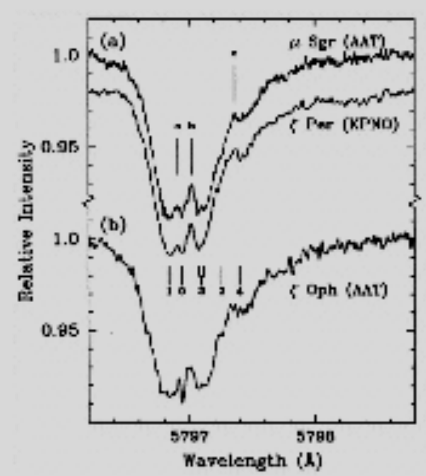
- Weak feature at ∼3.4 μm feature observed in absorption on sightlines with sufficient N_H
- Identified as C-H stretch in hydrocarbons
- Type (and amount) of hydrocarbon is **controversial**
  - Pendleton & Allamandola (2002): ∼85% aromatic, ∼15% aliphatic
  - Dartois et al. (2004): $< 15\%$ aromatic
- $\Delta\tau_{3.4\,\mu m}/A_V$ depends on environment: higher in HI clouds, lower in dark H_2 clouds (Shenoy et al. 2003).
  Mennella et al. (2003) suggest
  - Destruction of C-H bonds by CR in dark clouds?
  - regeneration of C-H by exposure to H in HI clouds?

7.4 Diffuse Interstellar Bands (DIBs)



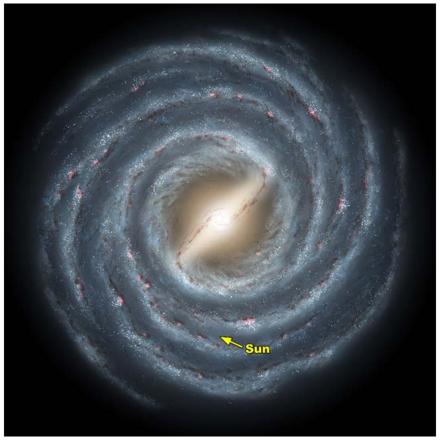


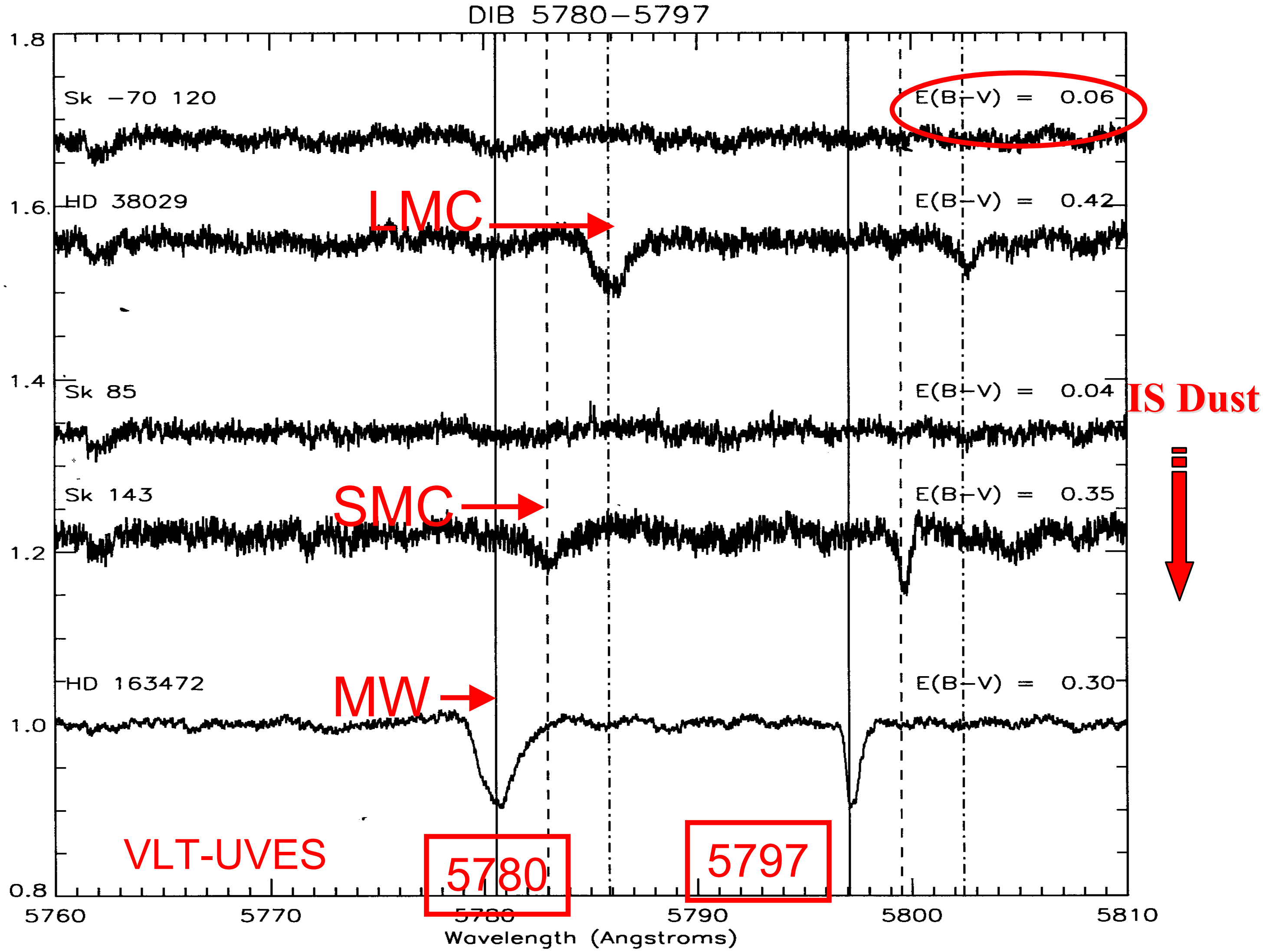
- weak but well-defined spectral features, too broad ($\Delta\lambda \sim 1$ Å) to be due to atoms, ions, or small molecules.
- First observed by Heger (1922). Recent surveys have tabulated **MANY:** **>400** between 3900 and 8100Å (Hobbs et al. 2009)
- **NONE** have been identified!
- Indications of structure (Kerr et al. 1998) consistent with molecular rotation...



- Hypothesis: DIBs = electronic transitions in PAHs.

Diffuse Interstellar Bands in the Magellanic Clouds

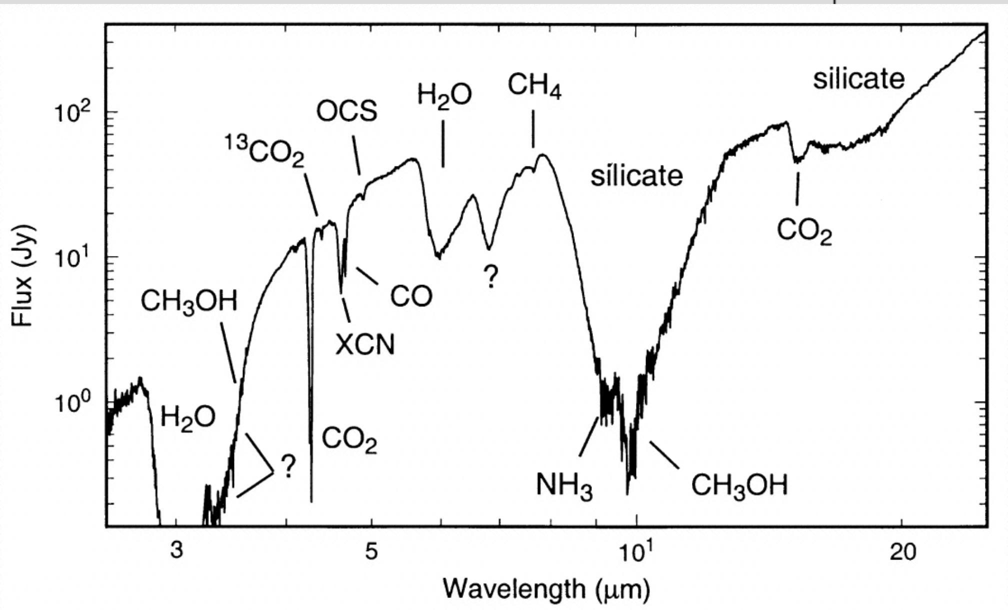




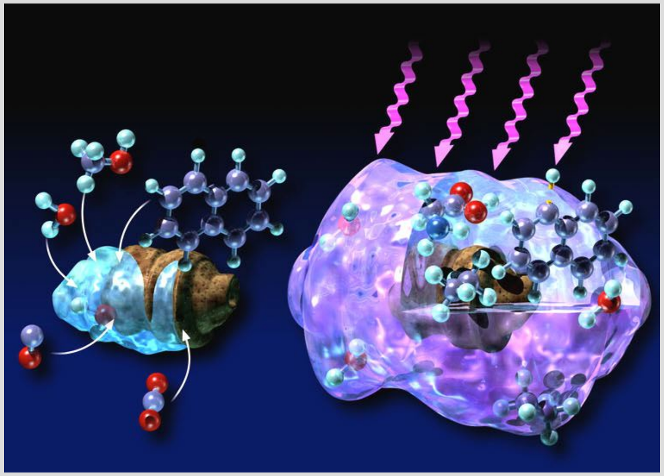
Ehrenfreund et al. ApJ 2002; Cox et al. A&A 2006, 2007

7.5 Ice Features in Dark Clouds

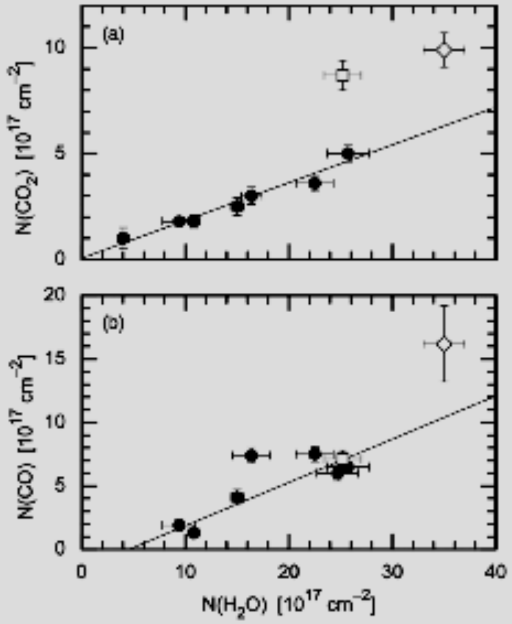
ISO spectra of the dust-embedded protostar W3 IRS5



Gibb et al. 2004



- **Predominantly H_2O** ice but also CO, CO_2, NH_3, CH_3OH, ...

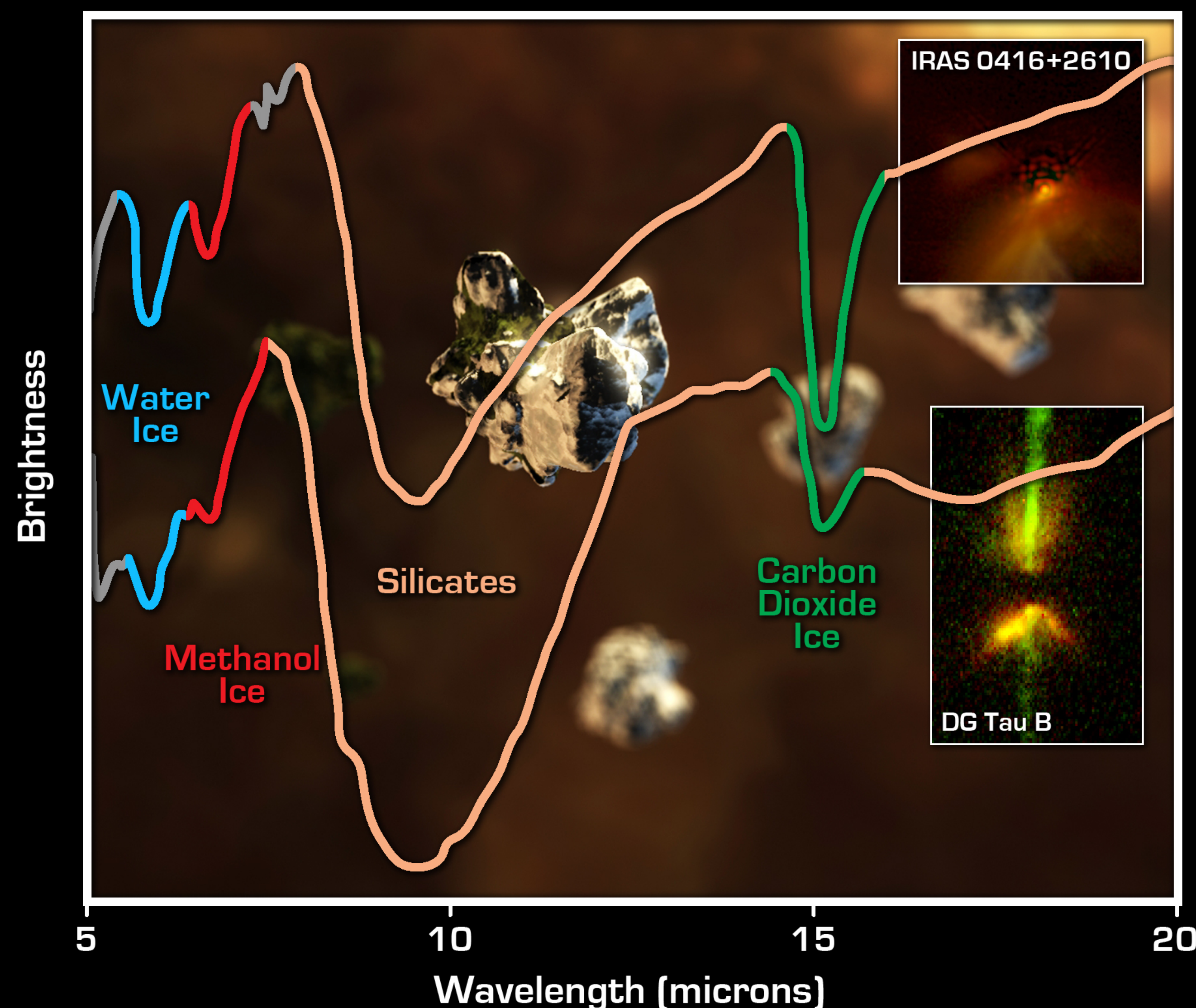


(From Whittet et al. 2009)

- Ice can increase total grain volume by factor of up to ~ 2.
- **ONLY** in **DARK** clouds with $A_V \gtrsim 3.3$ mag:

$$\Delta\tau_{3.1} \approx 0 \qquad \text{for } A_V < 3.3\,\text{mag}$$
$$\Delta\tau_{3.1} \approx 0.093[A_V - 3.3\,\text{mag}] \qquad \text{for } A_V > 3.3\,\text{mag}$$

- **Photodesorption by UV removes H_2O from dust in diffuse clouds.**



Ices in Protoplanetary Disks

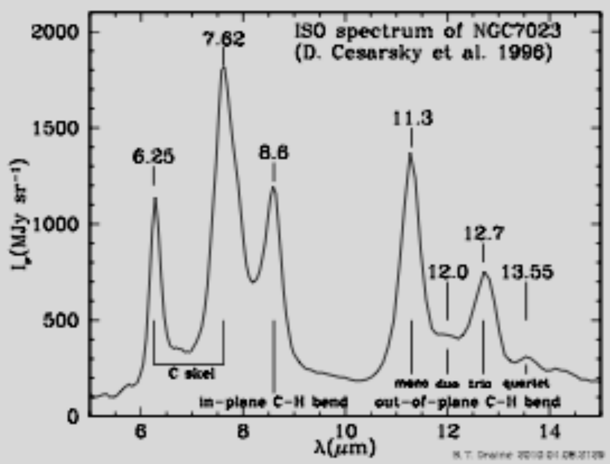
Spitzer Space Telescope • IRS

left insets: Hubble Space Telescope; backdrop: artist's depiction

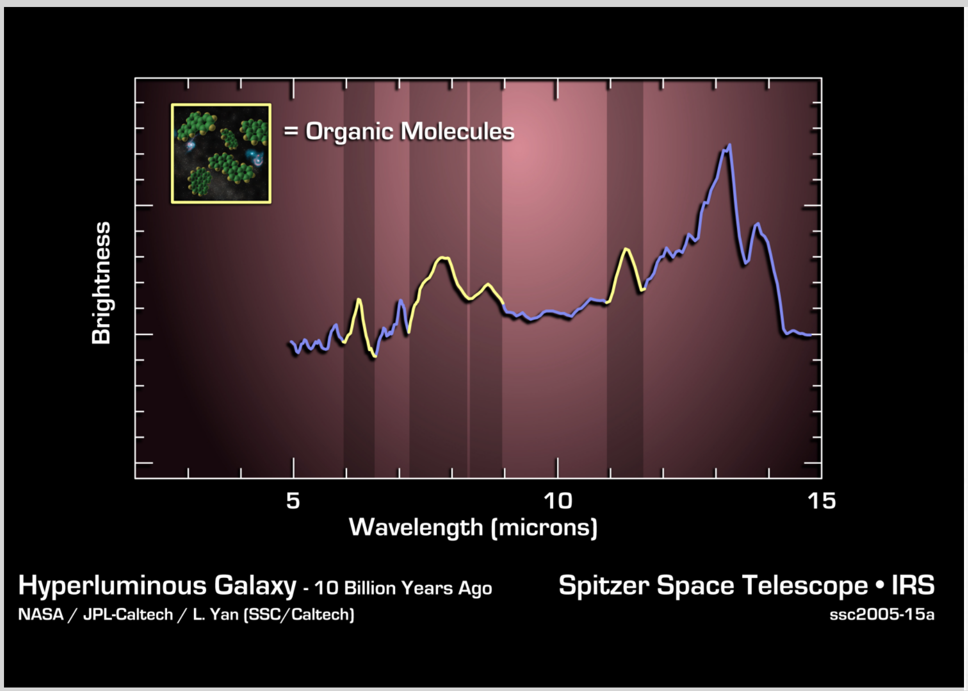
NASA / JPL-Caltech / D. Watson (University of Rochester)

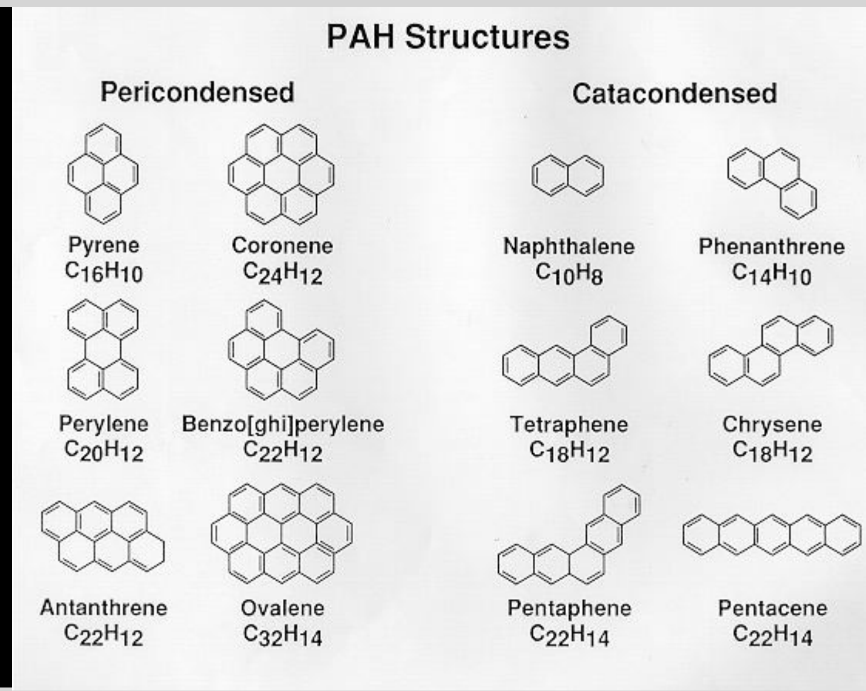
ssc2004-08b

7.6 Polycyclic Aromatic Hydrocarbons in Emission



- IR emission features at 3.3, 6.2, 7.6, 8.6, 11.3, 12.7 correspond to vibrational modes of **polycyclic aromatic hydrocarbons (PAHs)**.
- For normal star-forming galaxies, integrated emission in PAH features can be up to 20% of total IR emission.
- This requires that PAHs be abundant enough to account for up to 20% of the starlight absorption.
- Required PAH abundance: **at least ~5% of the total grain mass contributed by PAHs in the MW**.

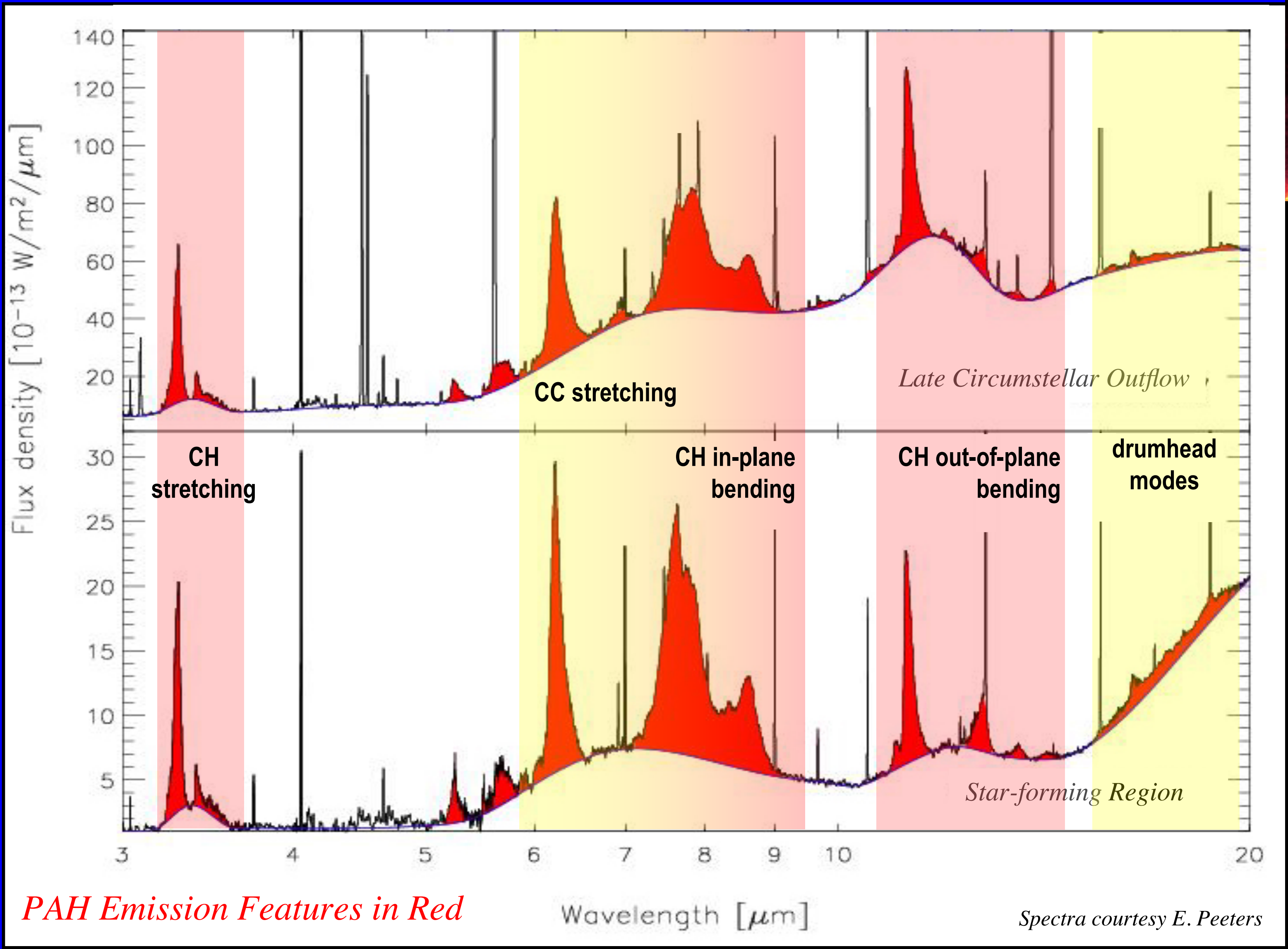


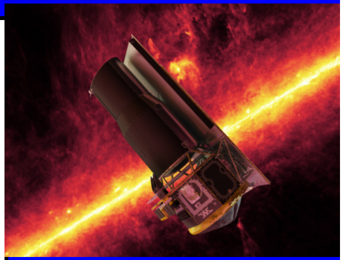


T Henning, F Salama Science 1998; 282: 2204-2210

PAHs as Probes of the Interstellar Medium

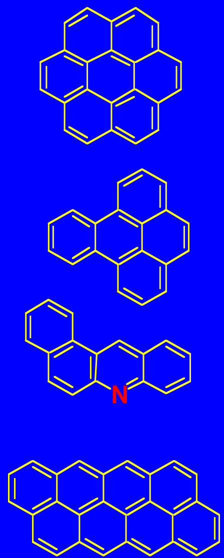
The interstellar emission spectra represent the composite emission of a complex mixture of aromatic compounds. The features are not resolvable, but show subtle variations.



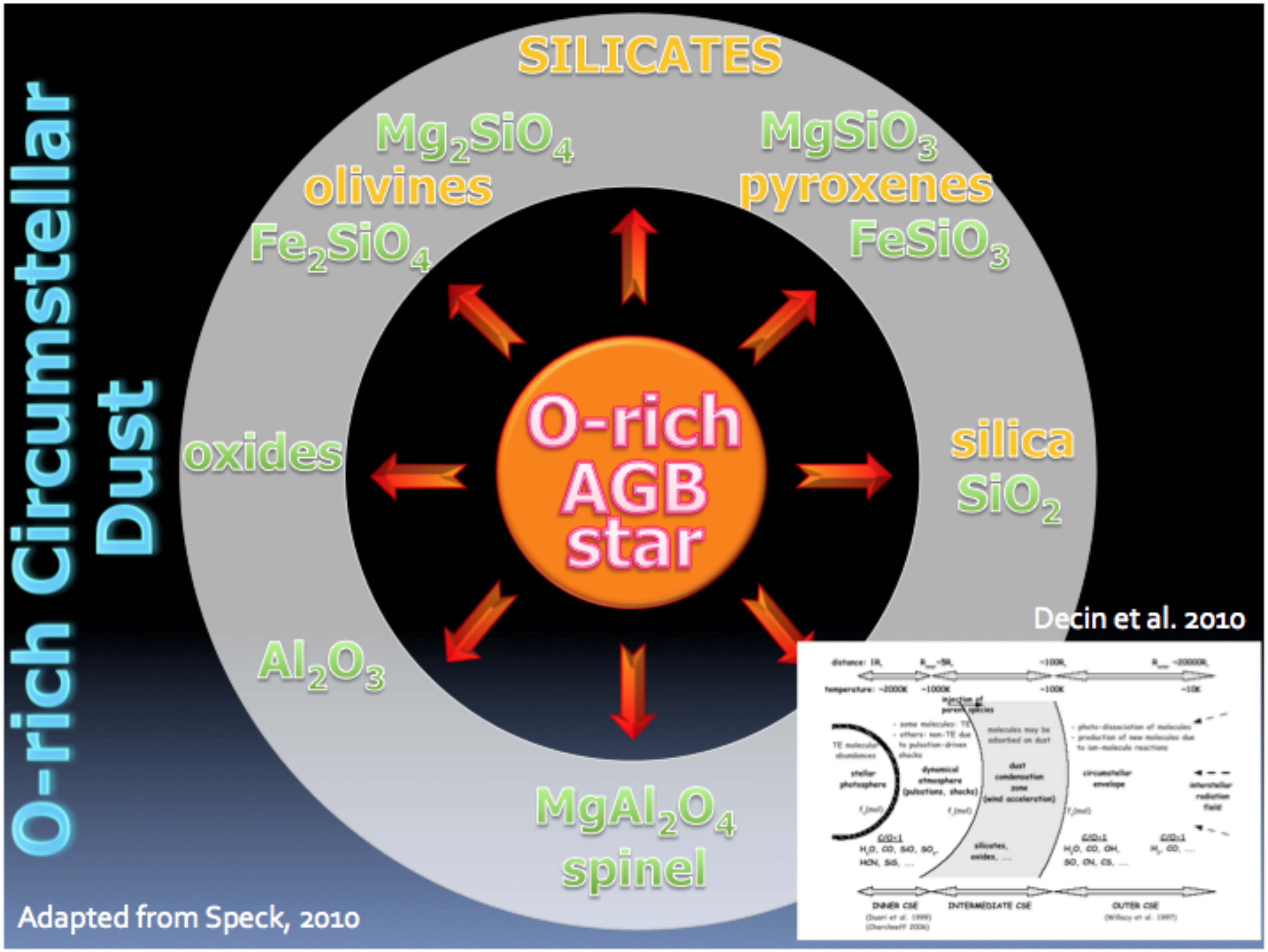


ISO, Spitzer, Herschel

PAHs Structures



Dust Formation: Silicates



Dust Condensation Sequence

	Abundance
O	2.09×10^7
C	1.00×10^7
N	2.63×10^6
Mg	1.02×10^6
Si	1.00×10^6
Fe	8.91×10^5
S	4.47×10^5
Al	8.51×10^4
Ca	6.36×10^4
Na	5.75×10^4
Ni	5.01×10^4
Cr	1.35×10^4
Mn	9.33×10^3
P	8.13×10^3
Cl	5.25×10^3
K	3.72×10^3
Ti	2.40×10^2

Lodders & Fegley (1999)

Al_2O_3 [1760-1300K]

↓

$Ca_2Al_2SiO_7$ [1625-1400K]

↓

$CaMgSi_2O_6$ [1450-1100K]

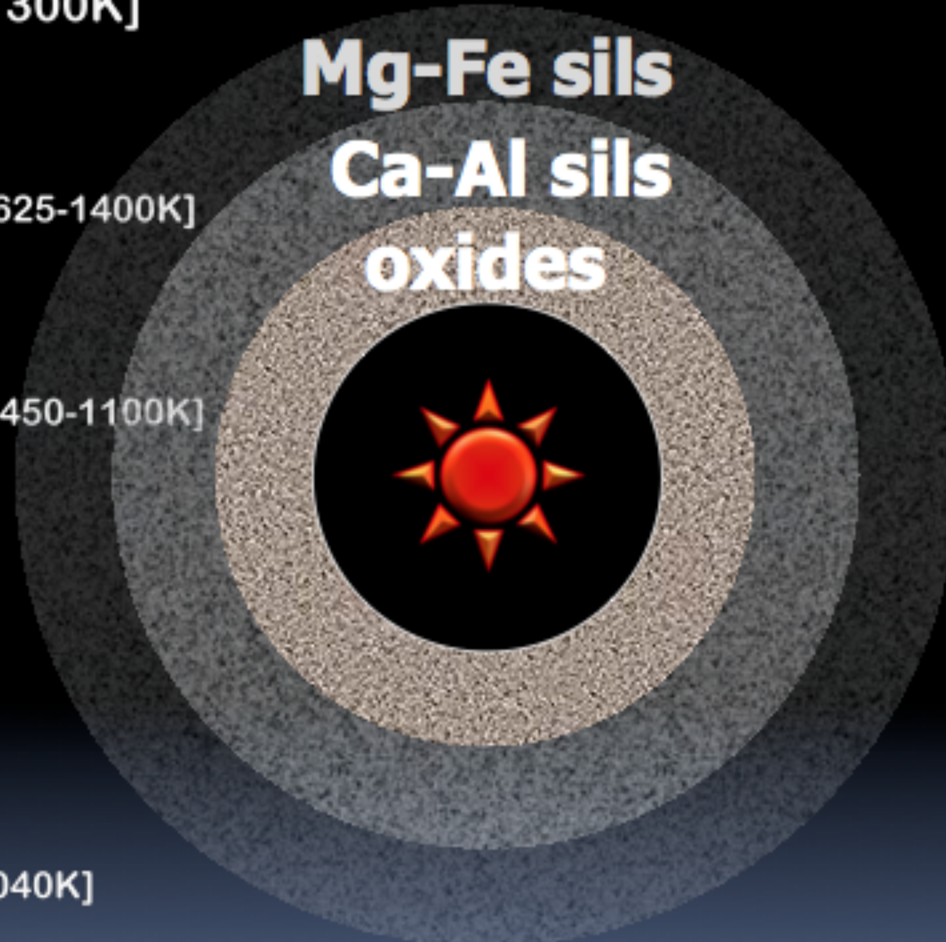
Mg_2SiO_4 [1440-1050K]

↓

$MgSiO_3$ [1350-1040K]

↓

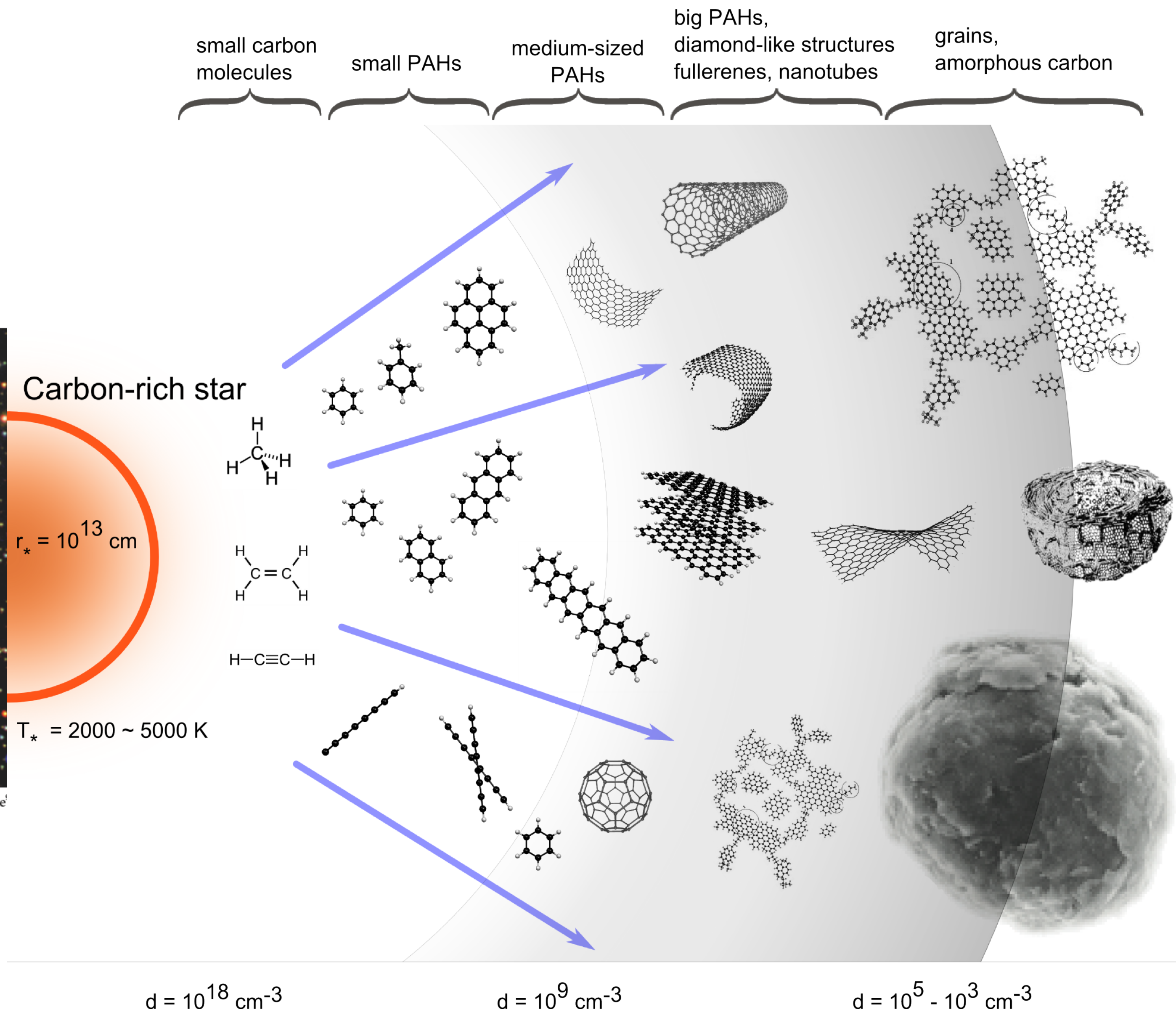
$(Mg,Fe)_2SiO_4$ [1100-950K]



Adapted from Speck, 2010

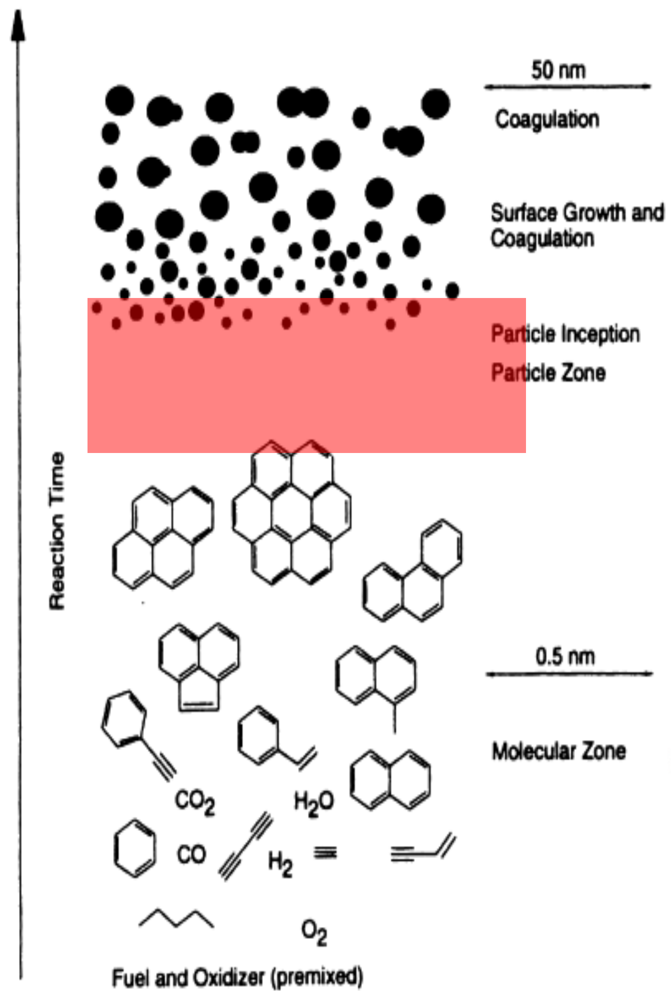
Dust Formation: Carbon Grain Formation

Figure 1 Carbon factories. This three-colour composite image of the constellation Auriga includes several red-giant stars, a primary site of carbon synthesis.

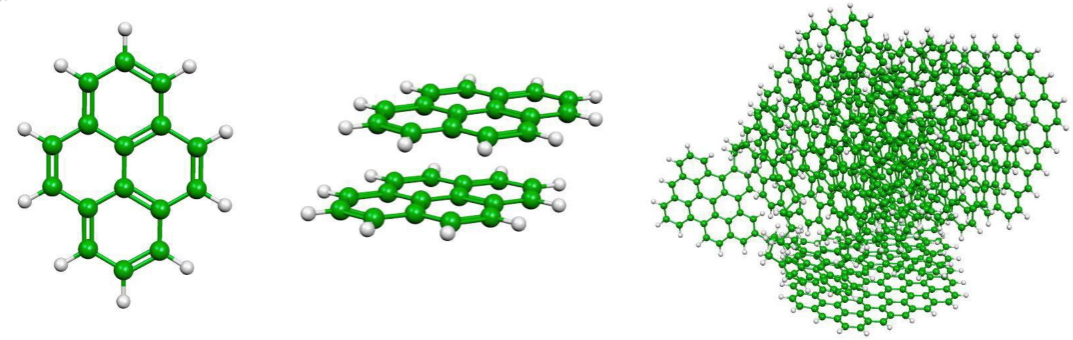


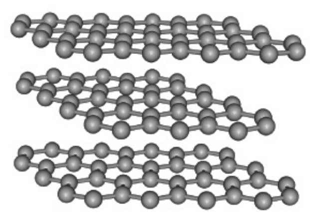
Nanoparticle growth processes ➲ Transition not well understood

H. Richter, J.B. Howard / Progress in Energy and Combustion Science 26 (2000) 565–608

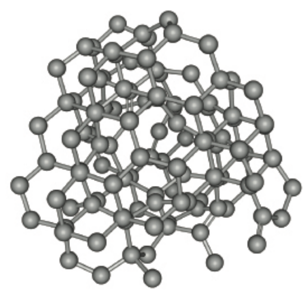


. A rough picture for soot formation in homogeneous mixtures (premixed flames) (Bockhorn [15]).

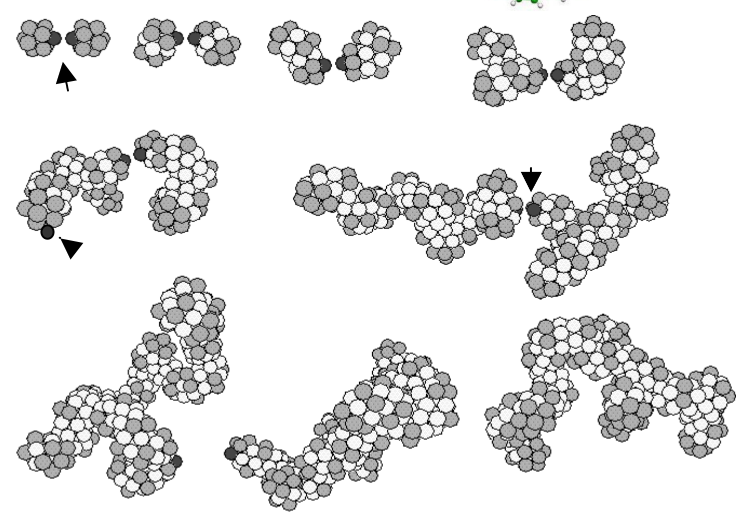




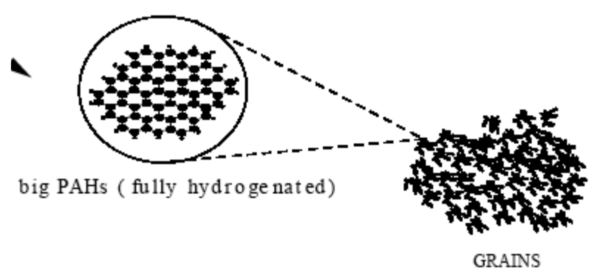
Graphite

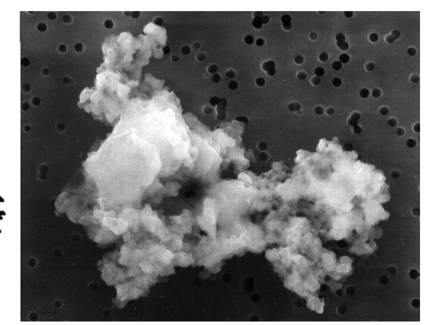


Amorphous carbon



Grain collision fractal model, E.L. Wright UCLA



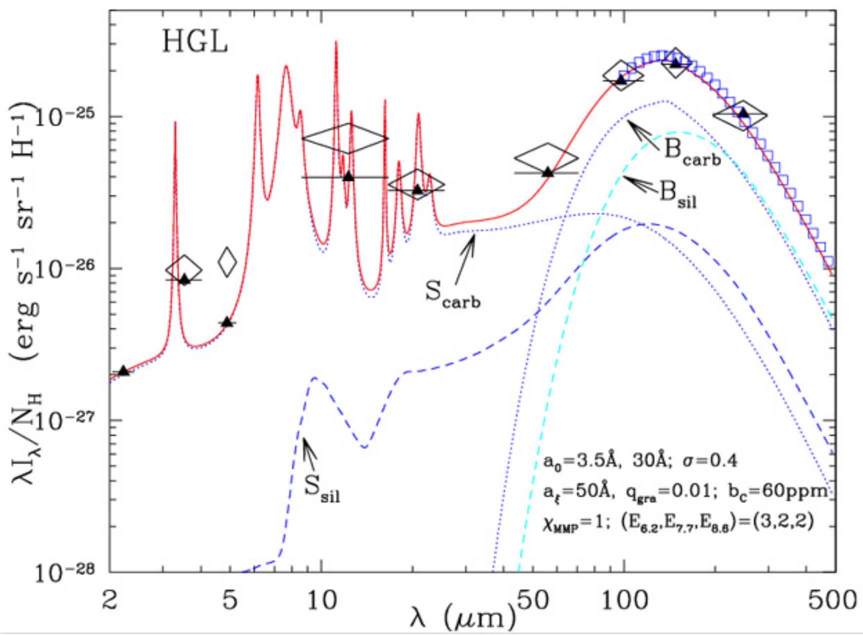


Dust = Gas + Solid; Dust = Molecules & Grains

Grain Models = consistent with observations

Constraints

1. the extinction, obscuration, reddening of star light.
2. abundances of different elements and their observed depletions
3. polarization and alignment properties of grains .
4. spectral absorption features
5. the continuum and line emission features
6. wavelength dependence of albedo and phase functions.

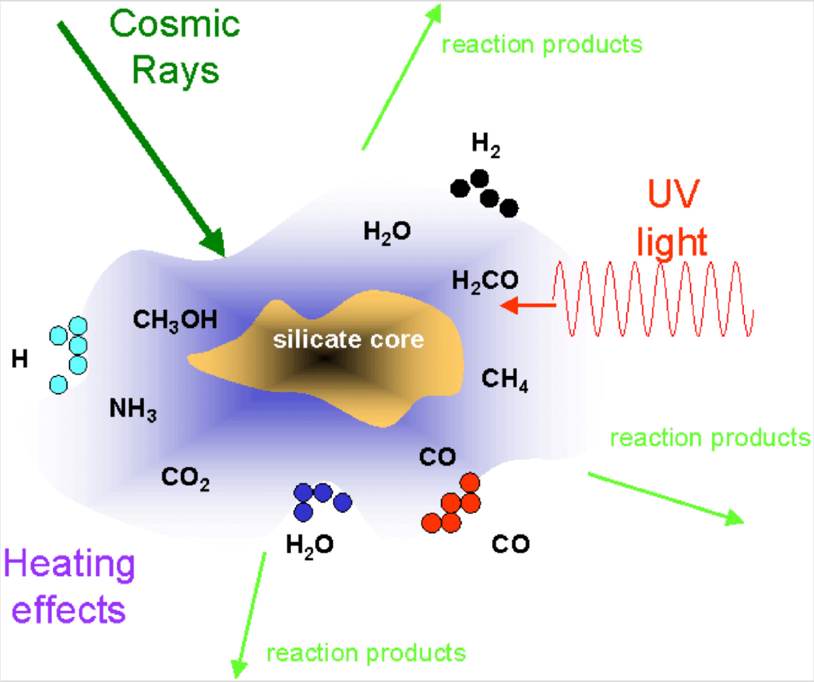


Comparison of the model to the observed emission from the diffuse ISM at high galactic latitudes. Curves show emission from "big" (a ≥ 250 Å) and "small'" (a < 250 Å) silicate and carbonaceous grains (including PAHs). Triangles show the model spectrum (solid curve) convolved with the DIRBE filters. Observational data are from DIRBE (diamonds) and FIRAS (squares).

Taken from Li & Draine (2001b).

Model consists of:

- Mixture of carbonaceous particles and silicate particles.
- Carbonaceous particles:
    - have the physical and optical properties of polycyclic aromatic hydrocarbon (PAH) molecules when they are small (a < 50 Å), or NC < 6 × 10^4 carbon atoms.
    - when they are larger, the carbonaceous grains are assumed to have the optical properties of randomly-oriented graphite spheres.
- The silicate grains:
    - assumed to be amorphous silicates.
    - constraints on behavior at λ = 9.6 - 9.7 μm, 18 μm and >20 μm
    - assumed grain shape = 2:1 oblate spheroids (randomly oriented)
    - based on olivine $(Mg, Fe)_2SiO_4$ data

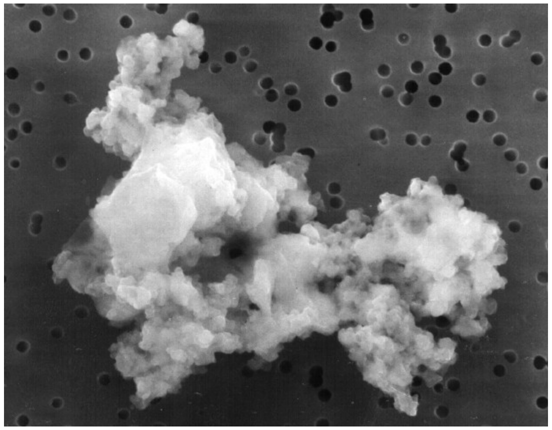


References: Draine 2003, ARAA 285, 42, 241

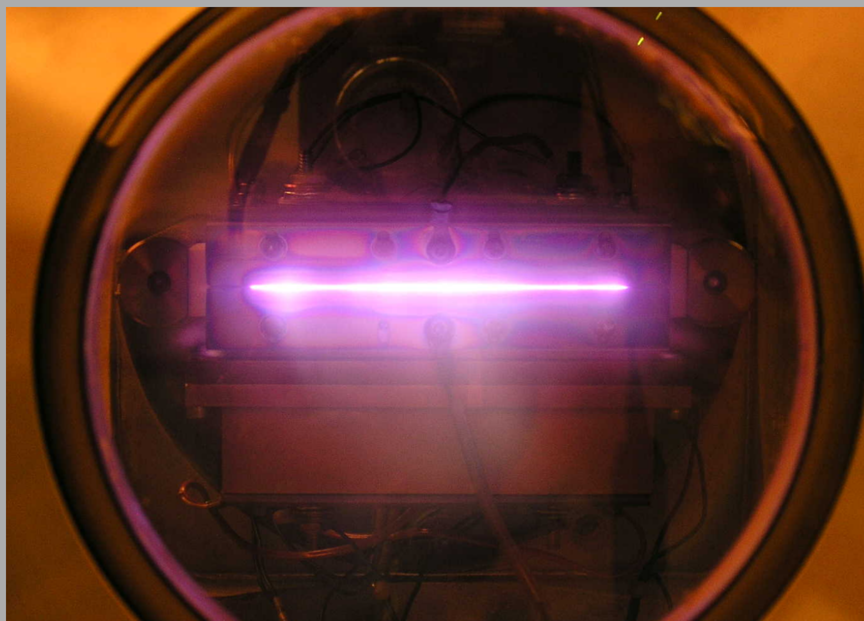
Unresolved issues:

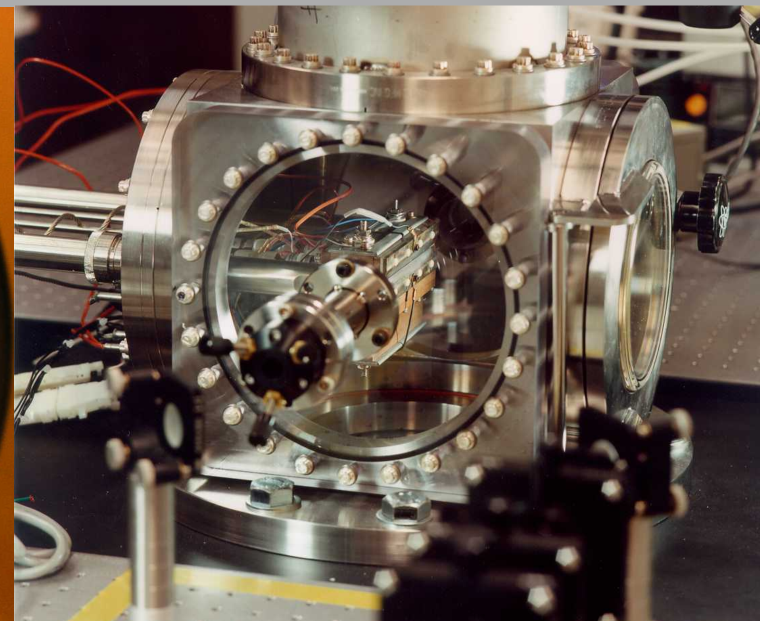
1. Efficiency of dust formation in various sources, especially in supernovae
2. The composition and survival of the newly formed dust
3. Efficiency of dust destruction
4. The reconstitution of dust particles by accretion and the resulting dust composition.
5. Dust evolution .

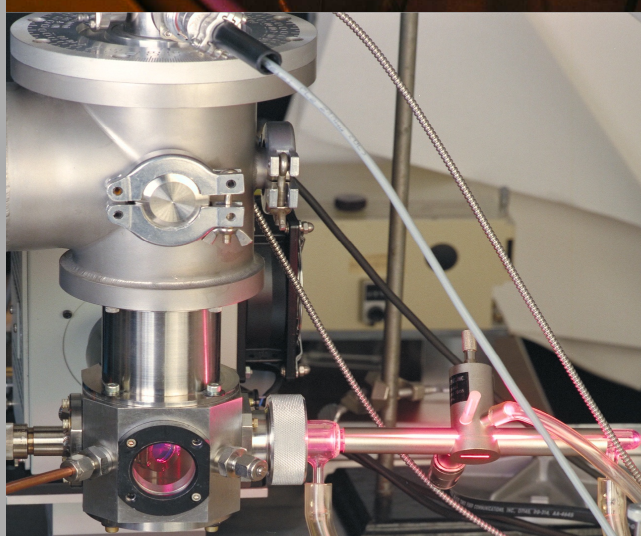
→ Dust Evolution: Formation, Processing, Destruction?

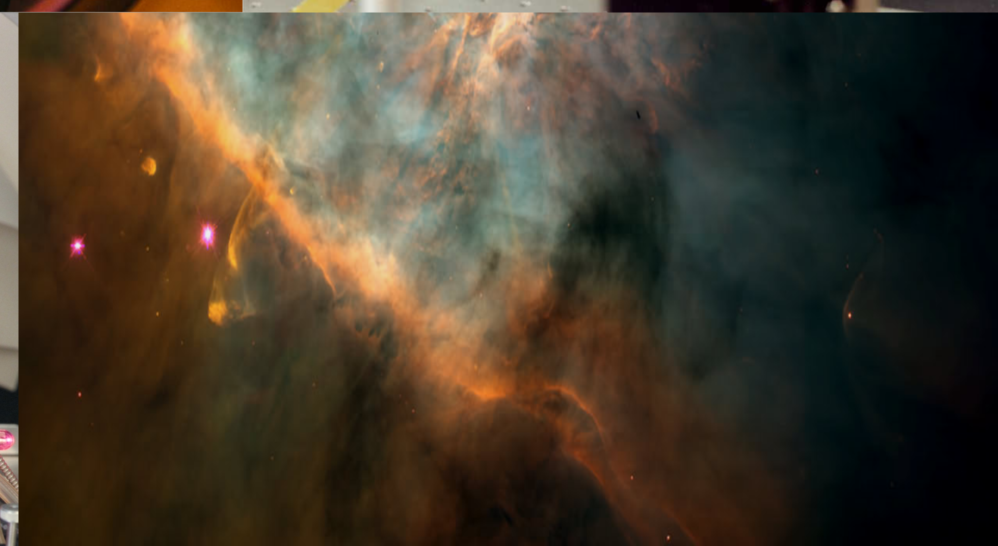


Laboratory Studies





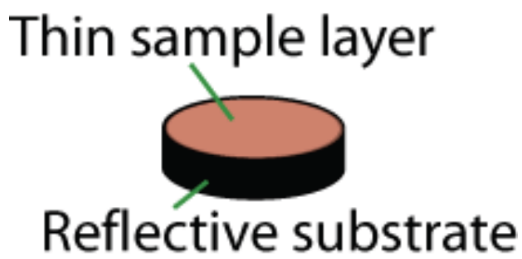




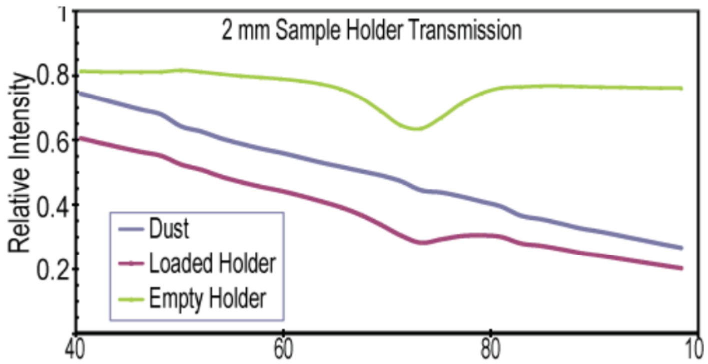
Methods I

In the past, two major methods:

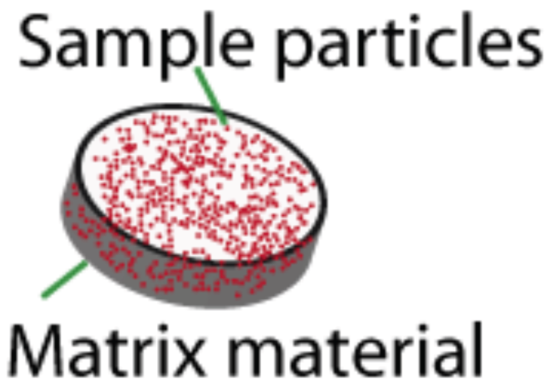
– Bulk

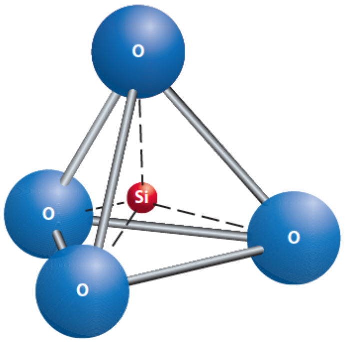


Sample holders



– Matrix





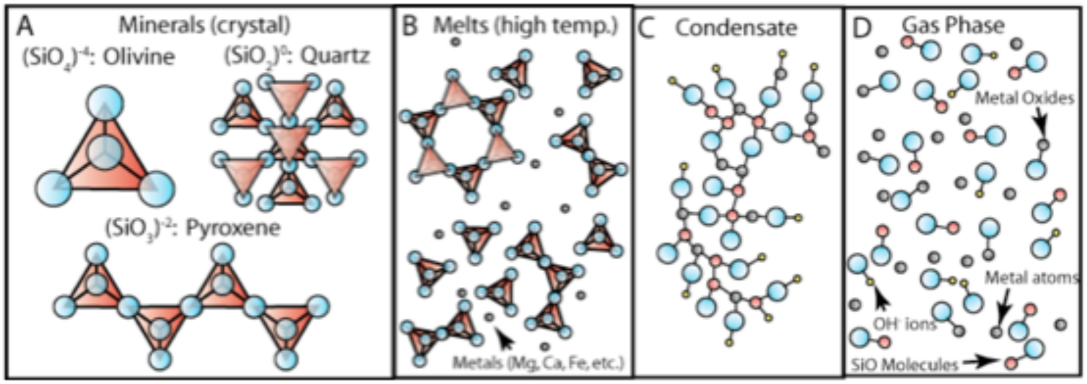
Materials (Silicates)

Silicate Production

- Grinding
- Sol-Gel
- Melts
- Smokes

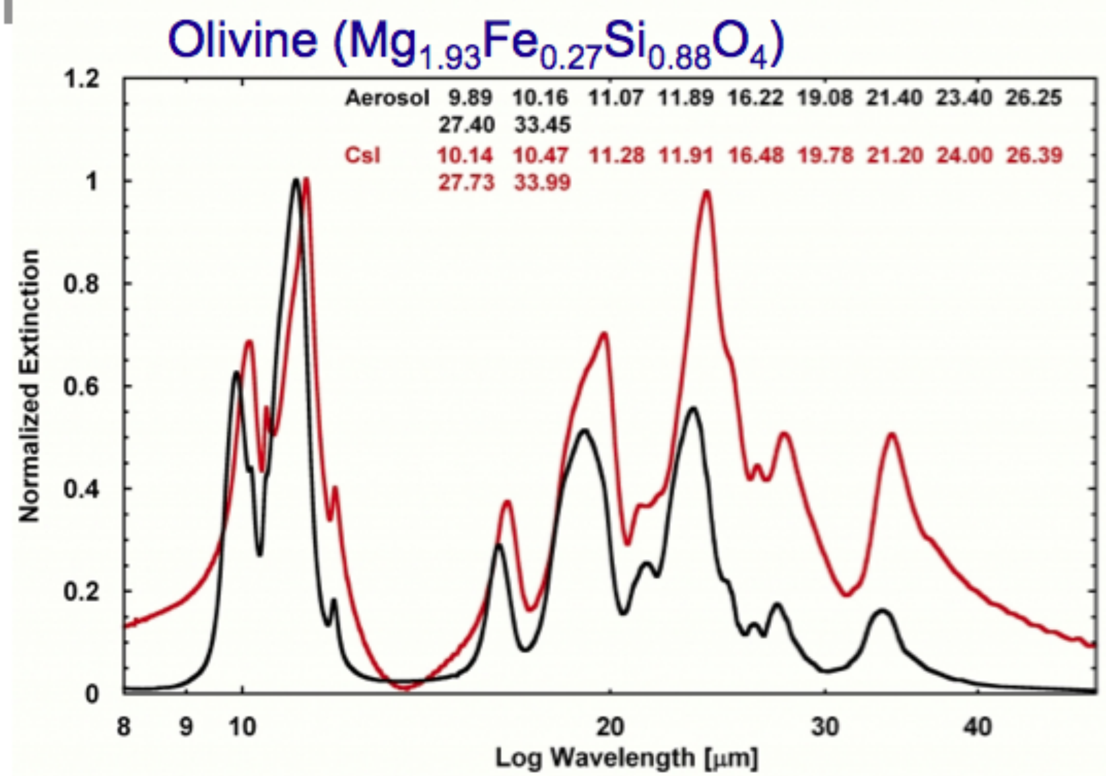
Issues:

- Annealing (Hallenbeck, et al. 2002)
- Irradiation



Rinehart, et al. 2008

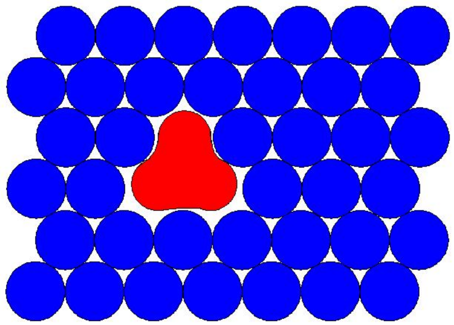
Aerosols



Jena database

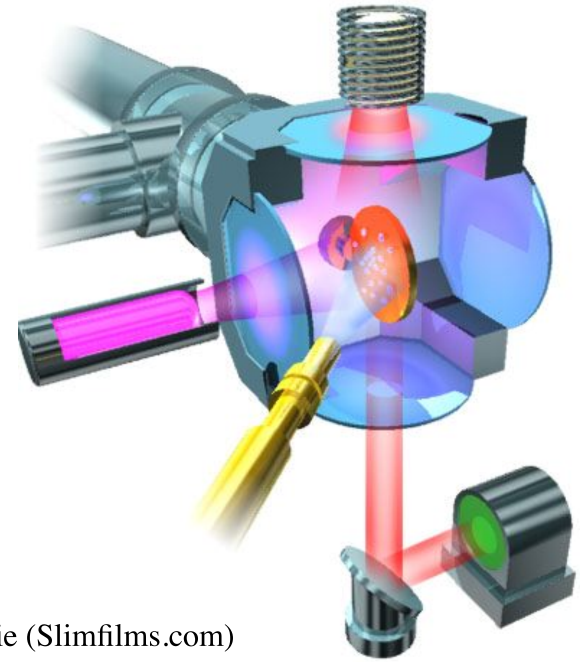
http://www.astro.uni-jena.de/Laboratory/OCDB/index.html

Requirements: Molecules & Ions: **1:** Free - **2:** Cold - **3:** Exposed to VUV photons



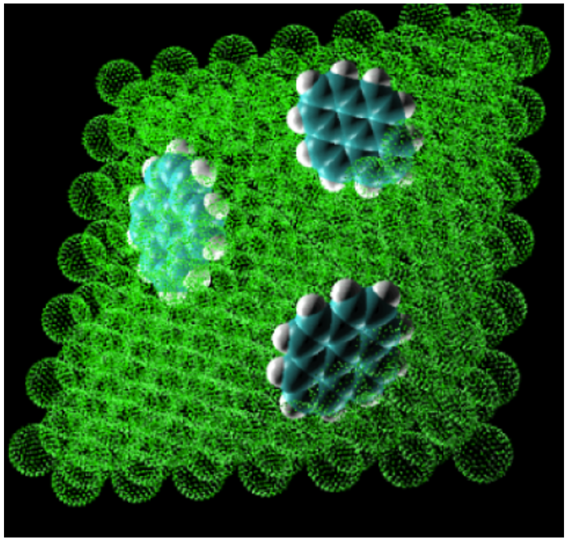
Matrix Isolation Spectroscopy (MIS) provides:

- Low temperature (5 K)
- Low density (molecule/ion fully isolated)
- High-energy photons (VUV)
- Solid phase



A. Christie (Slimfilms.com)
in Bernstein et al. 1999

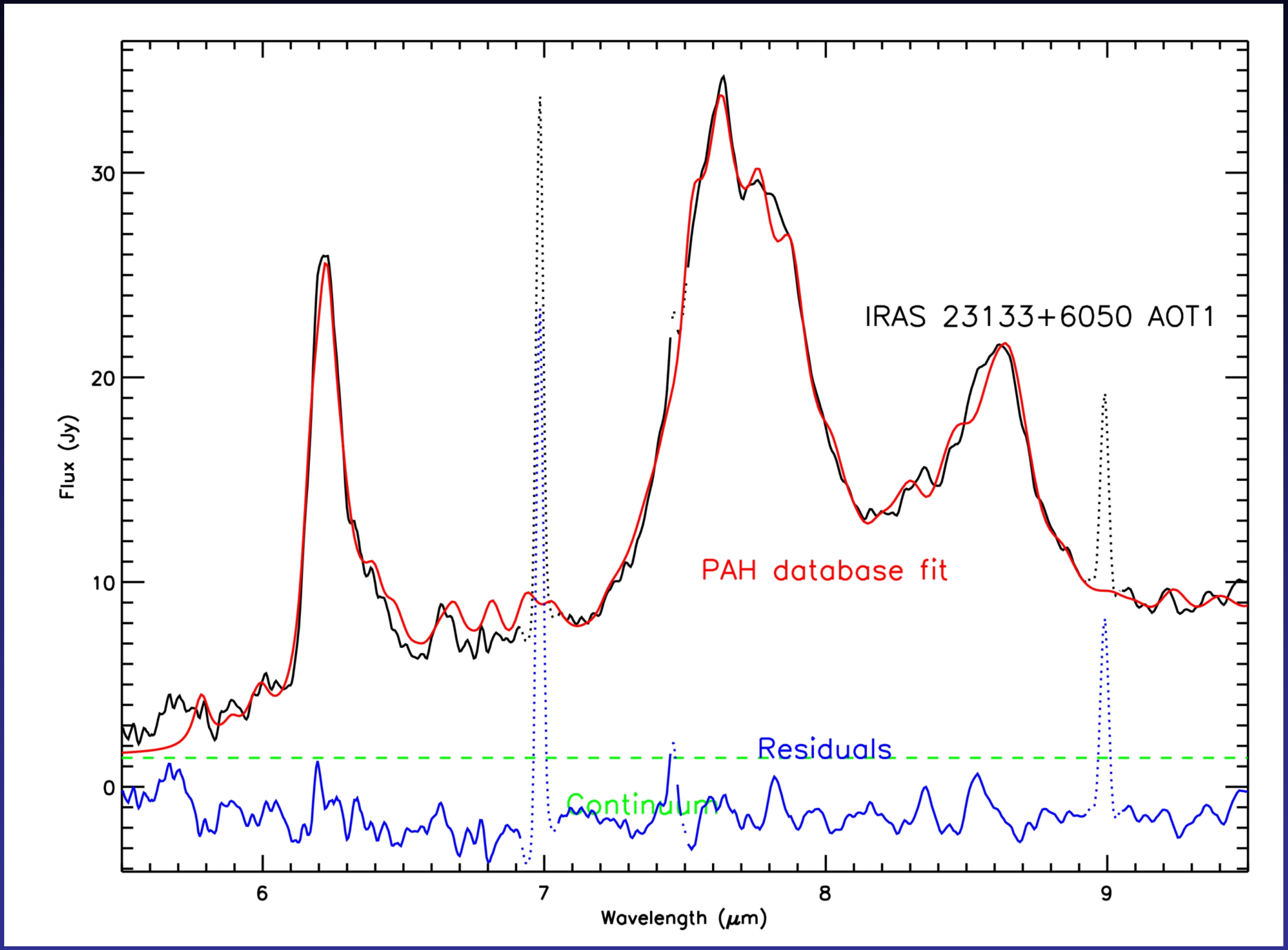
Ne Matrix-embedded molecules



Adapted from Huneycutt et al. 2003

Matrix Isolation Spectroscopy (MIS) Chamber

Least squares fit of the spectra in the database to the ISO SWS spectrum of the HII Region IRAS 23133

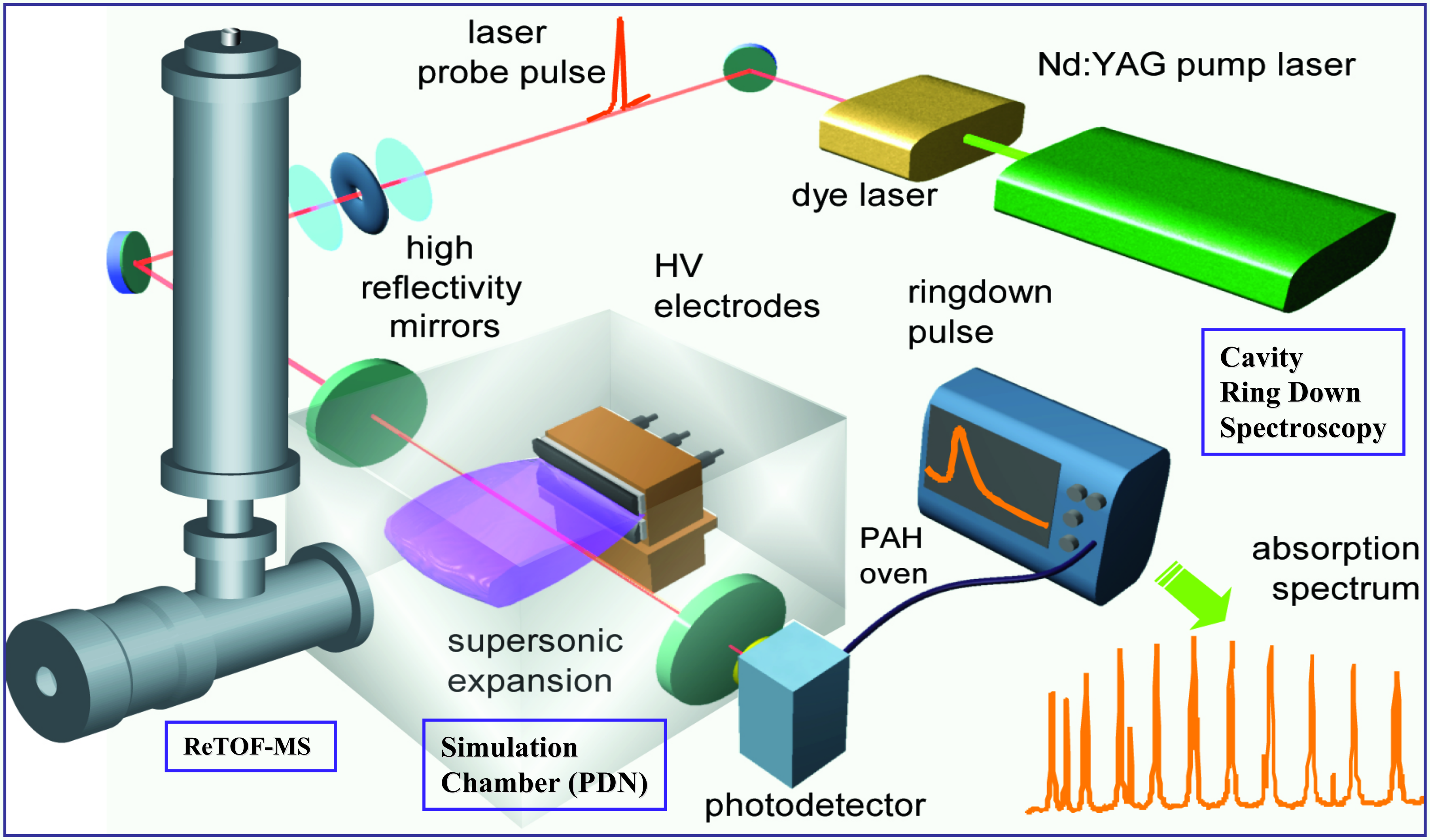


Cami et al. 2008

The NASA Ames PAH IR Spectroscopic Database: http://www.astrochem.org/pahdb/

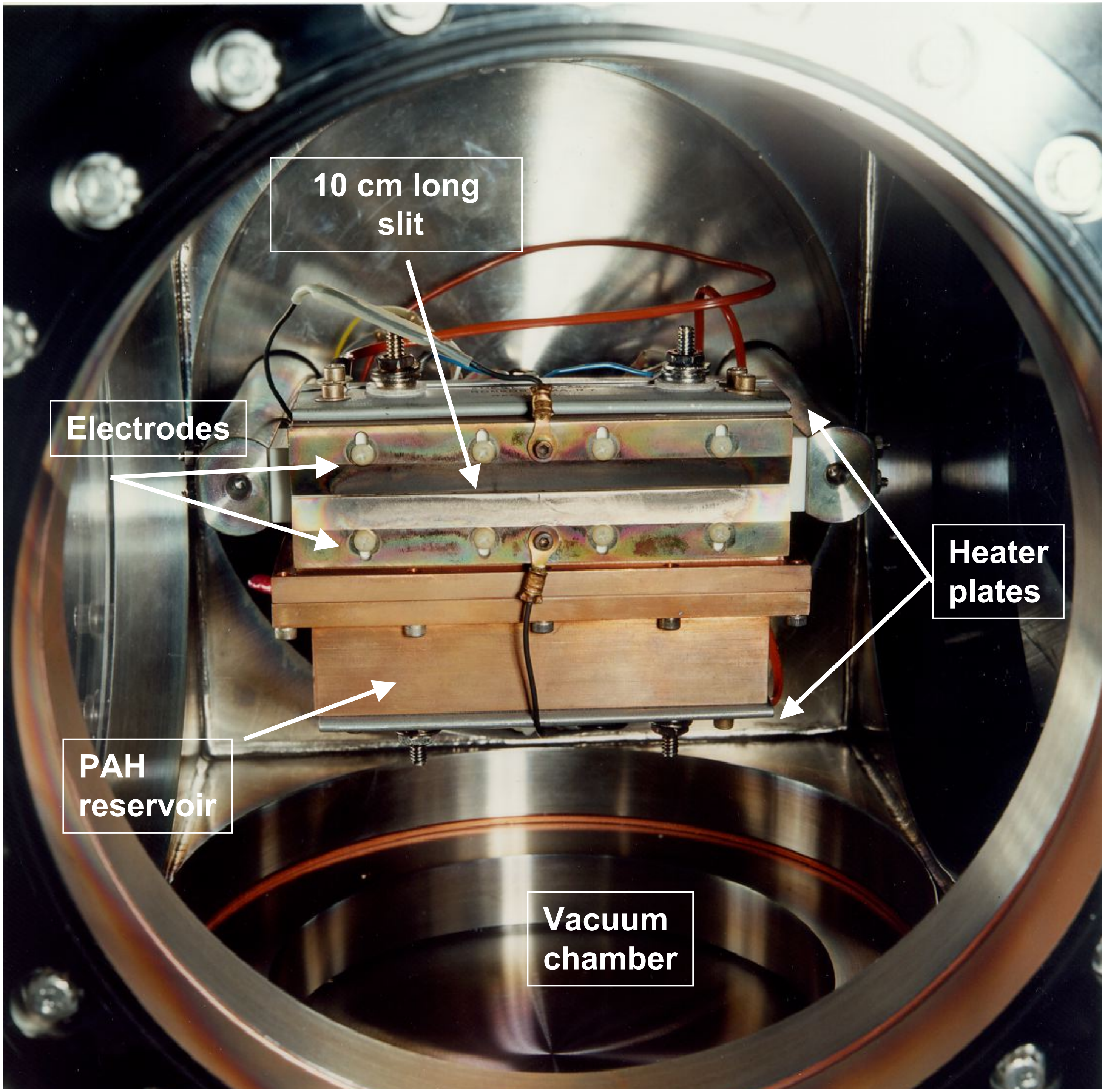
Bauschlicher et al. 2010. ApJSS 189, 341

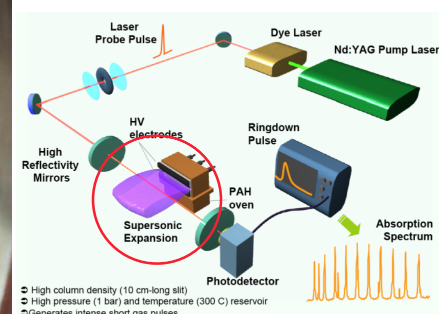
Tools in the Laboratory: Combine PDN + CRDS + o-ReTOF-MS



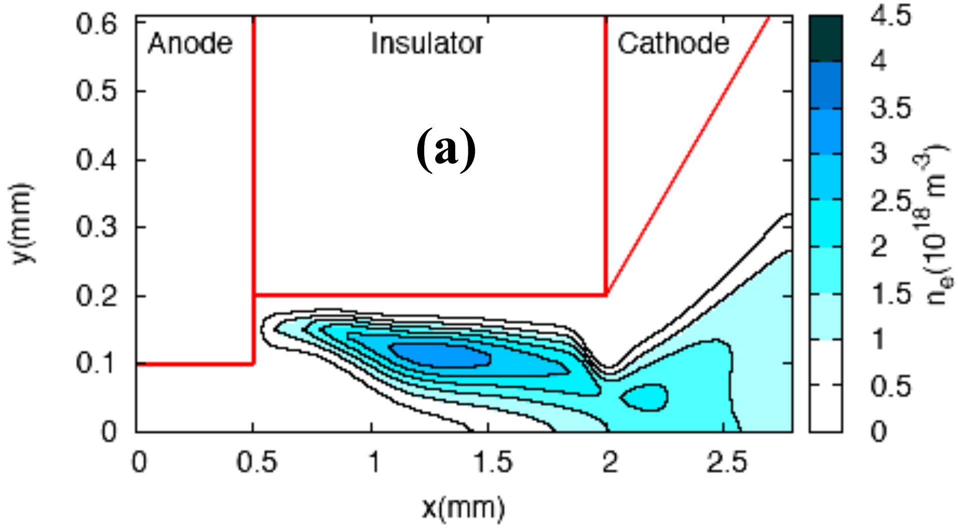
- High column density (10 cm-long slit)
- High pressure (1 bar) and temperature (300 C) reservoir
- Generates intense short gas pulses
- Generates (plasma) and stabilize (supersonic expansion) transient species

Simulation Chamber

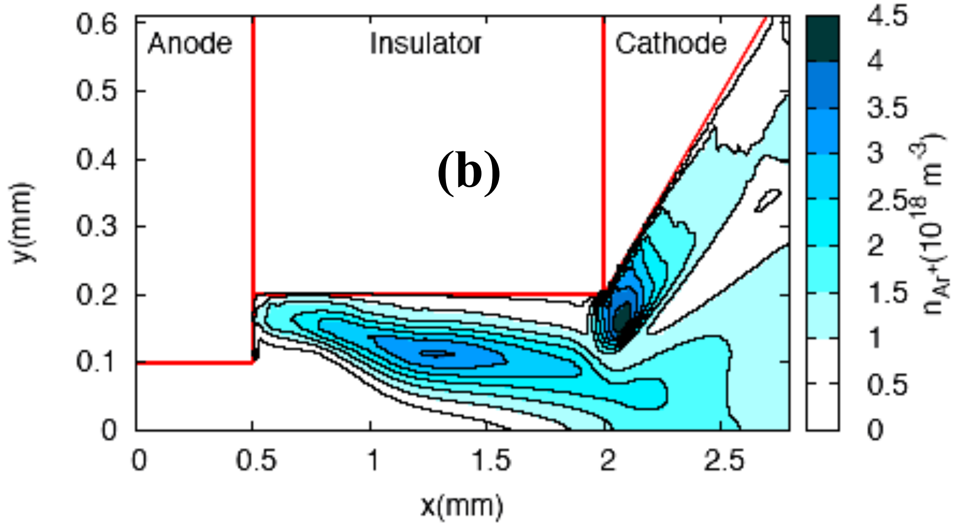


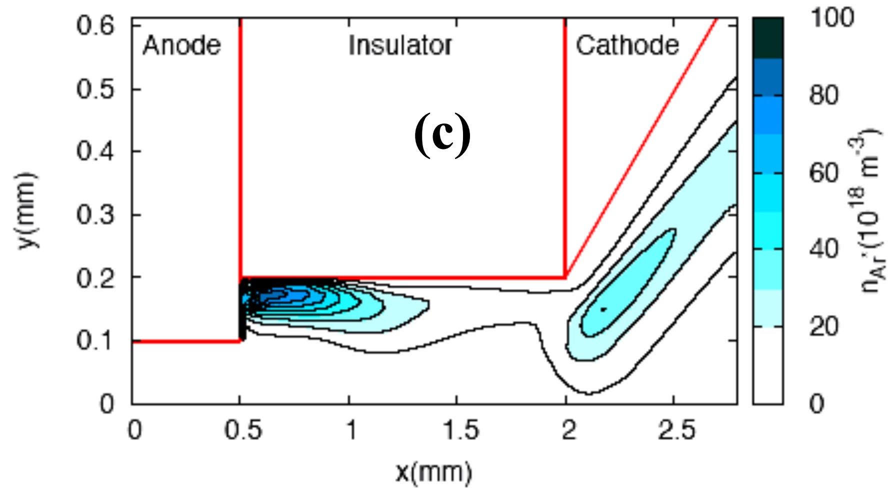


Results: Simulation of the Plasma ➜ Glow Discharge



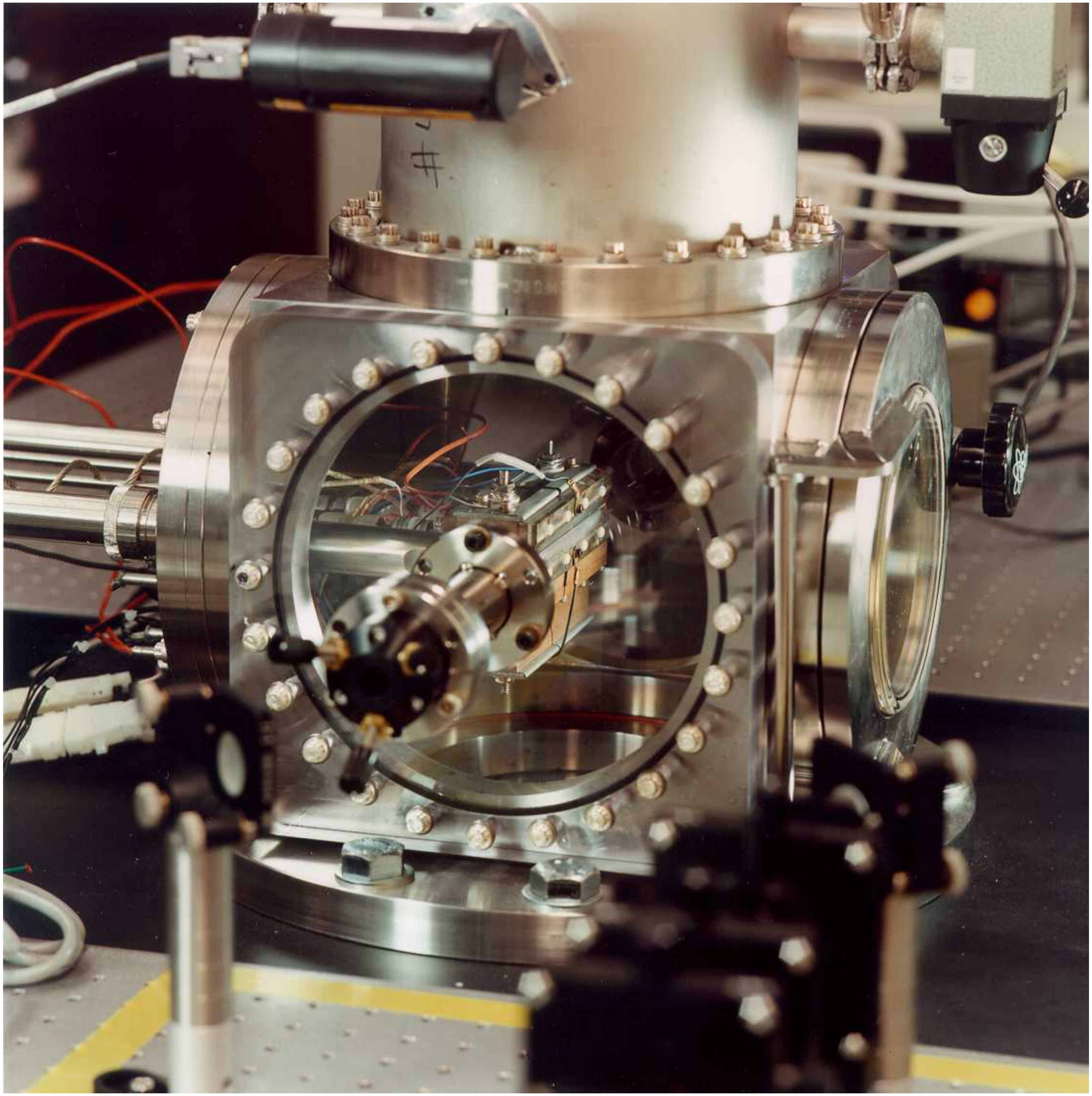
The (a) steady-state electron density, (b) Ar^+ density and (c) Ar* density of the pulsed discharge nozzle for a source voltage of -500 V.





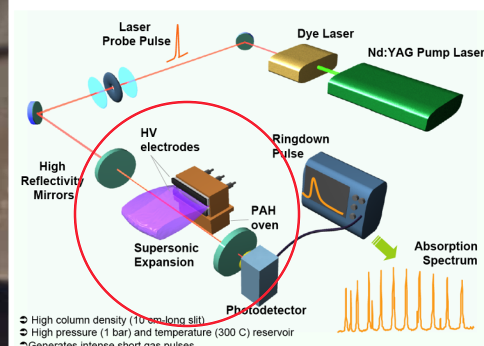
Ar* atoms in the expansion region >> electrons and ions. PAH ions are dominantly formed through Penning ionization of the neutral molecular precursors seeded in the supersonic expansion of Ar gas.

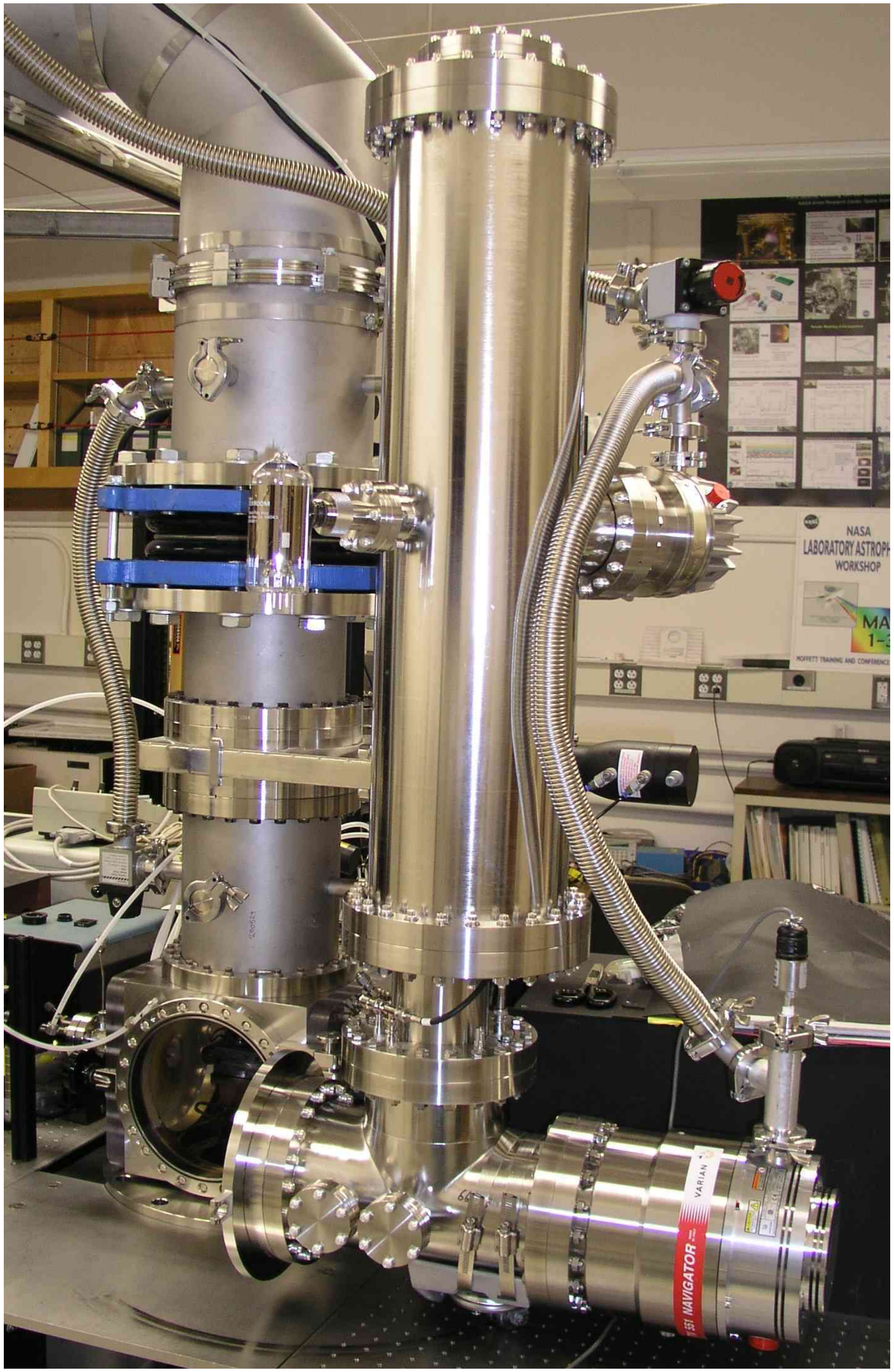
Remy, Biennier, Salama, IEEE 2005; Benidar, Biennier, Salama, Chem. Phys. 2006; Broks et al., Phys. Rev. E 2005; Broks et al. Spectrochim. Acta A 2005



TOOLS

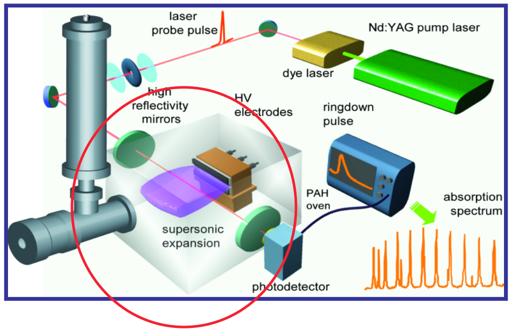
Simulation Chamber



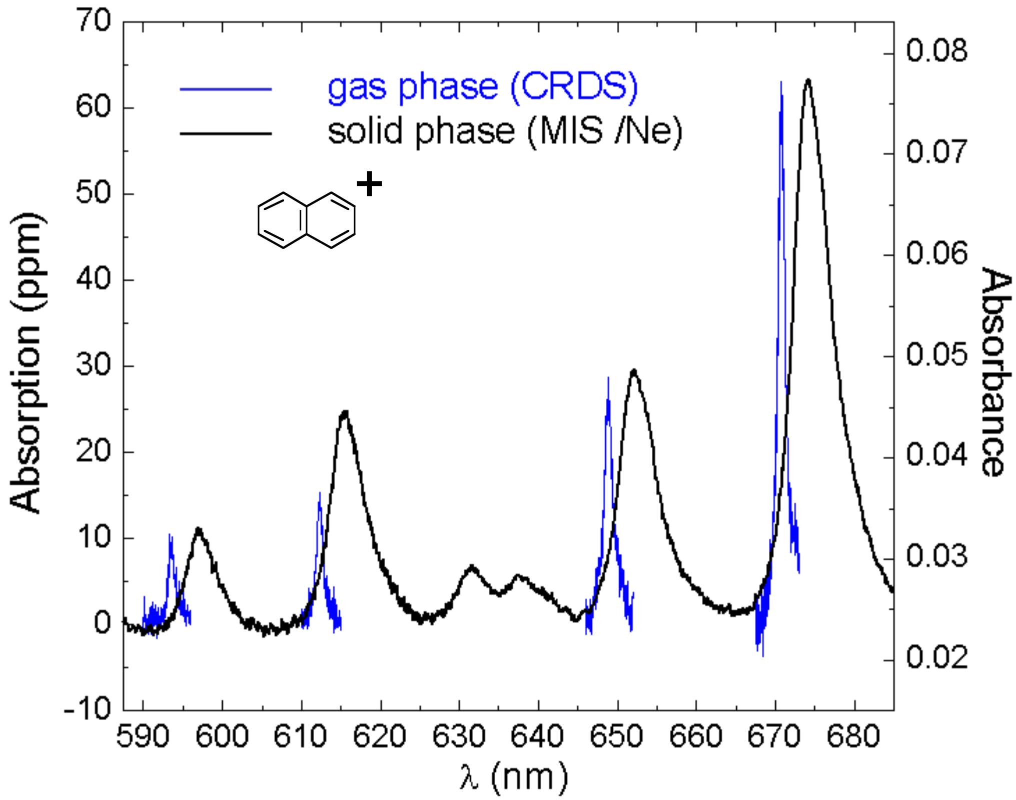


TOOLS

Simulation Chamber

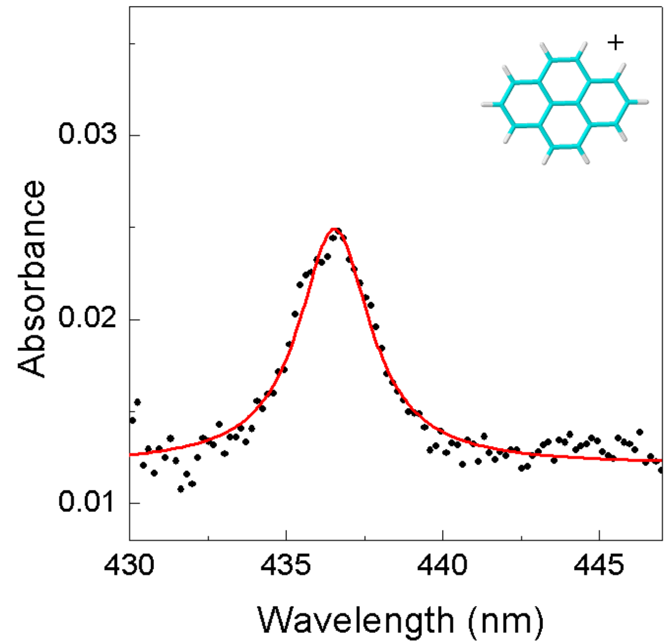


Cavity Ringdown Gas-Phase Spectra of the PAH Ions compared to MIS



Bandwidths: MIS: 120 cm^{-1}; Gas: 25 cm^{-1}

Biennier et al., JCP 2003



Pyrene ion ($C_{16}H_{10}^{+}$)

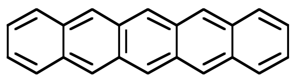
Bandwidth: $\Delta\nu$ = 145 cm^{-1}

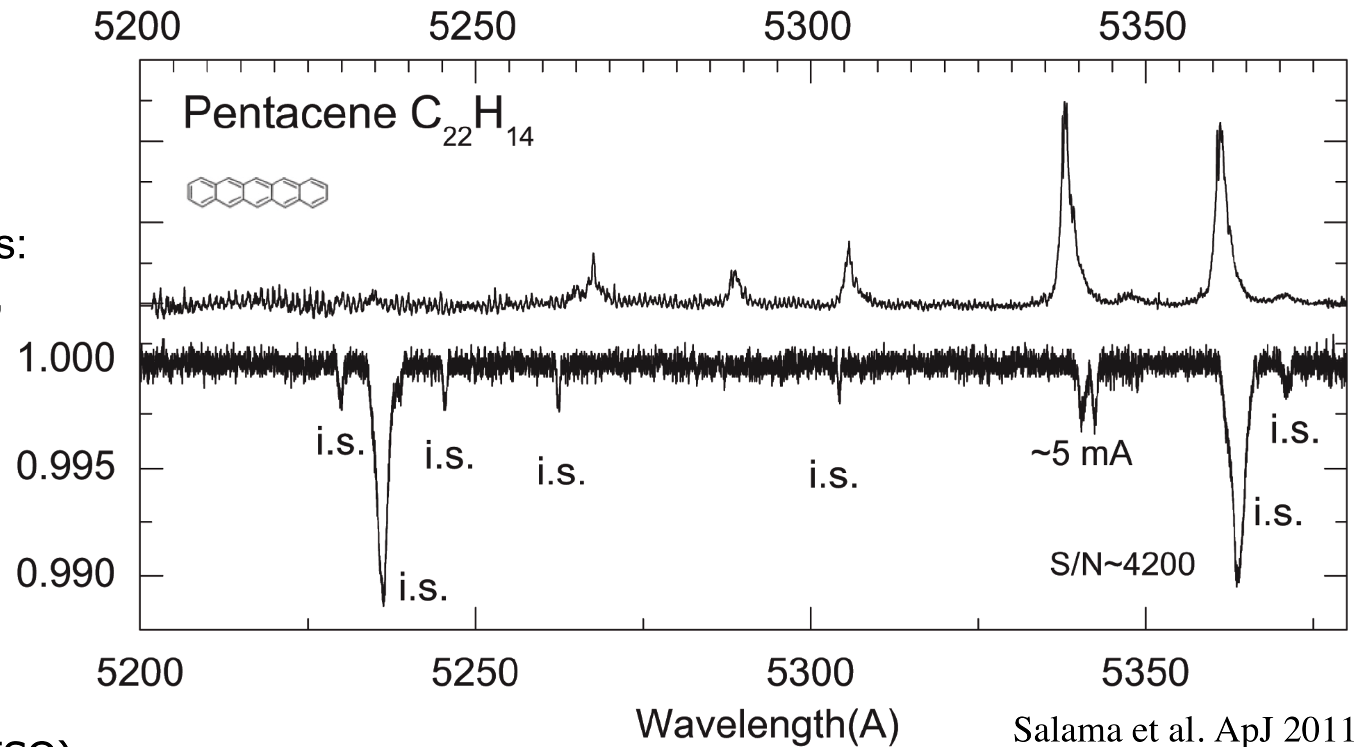
The vibronic bands of PAH ions are broad.

Intrinsic band profiles and peak positions can now be measured in the laboratory to search for <u>specific</u> PAHs (neutrals and/or ions) in interstellar and circumstellar spectra.

Comparison with Astronomical Data:

Comparing Band Profiles: The Case of PAHs (e.g., Pentacene)





Salama et al. ApJ 2011

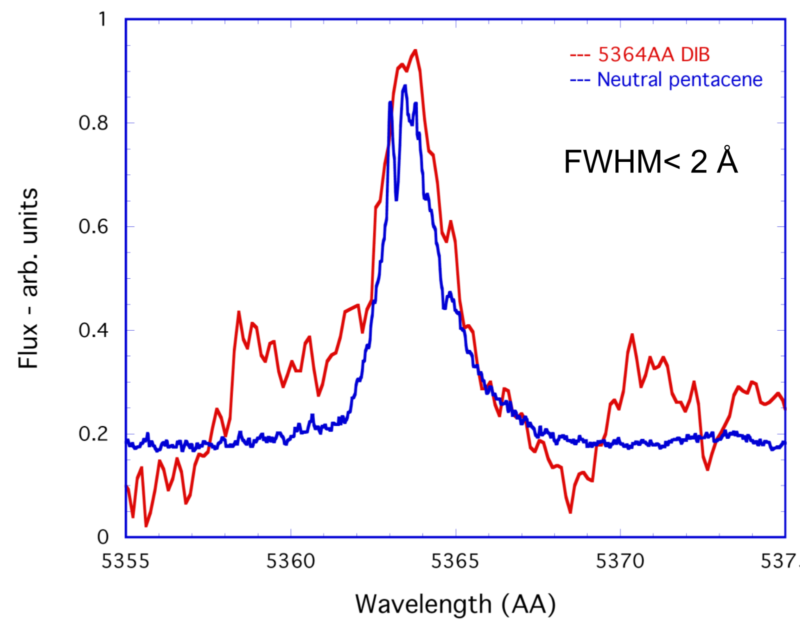
2010-2011 DIB Survey:

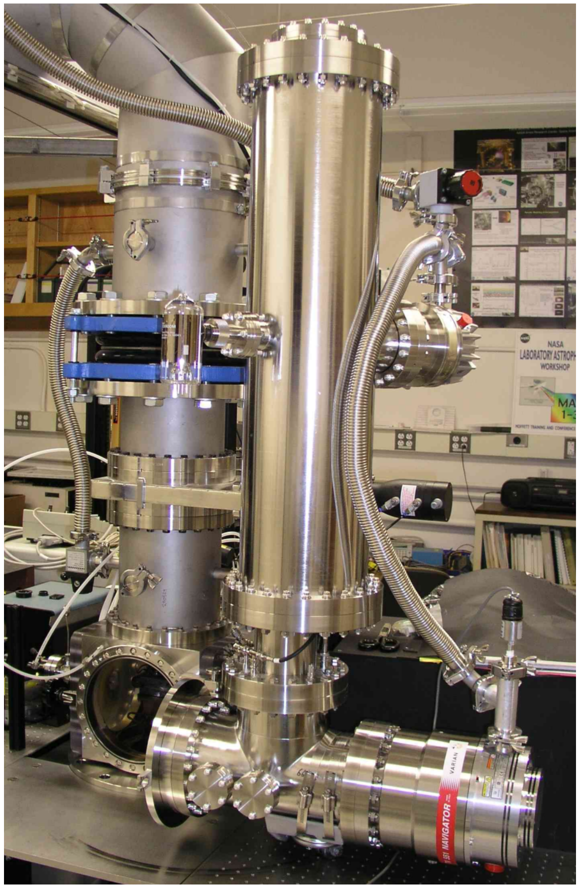
UVES (8-m telescope, ESO)

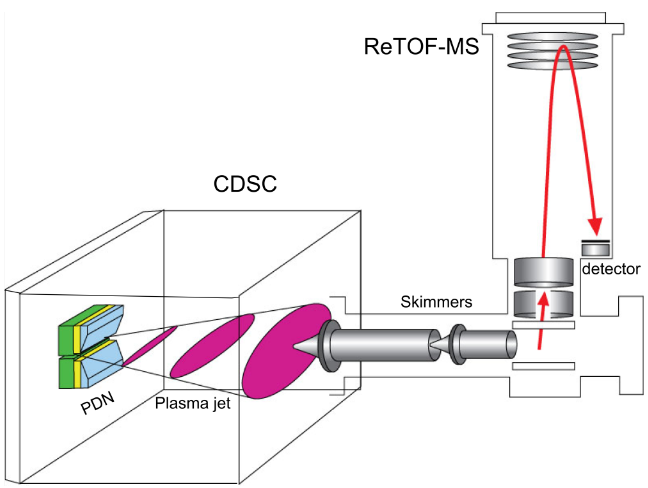
Spectra of 17 reddened O/B stars with E (B-V) ranging from 0.2 to 1.2

Wavelength range of neutral PAH bands (3090-5500 Å)

Set of 12 PAH molecules; N(PAH) ~ 10^{-12} - 10^{-11}

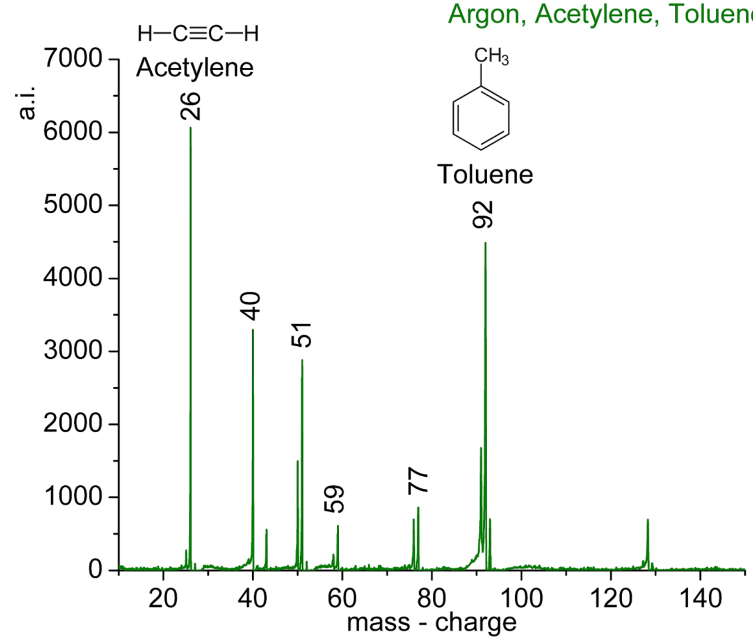




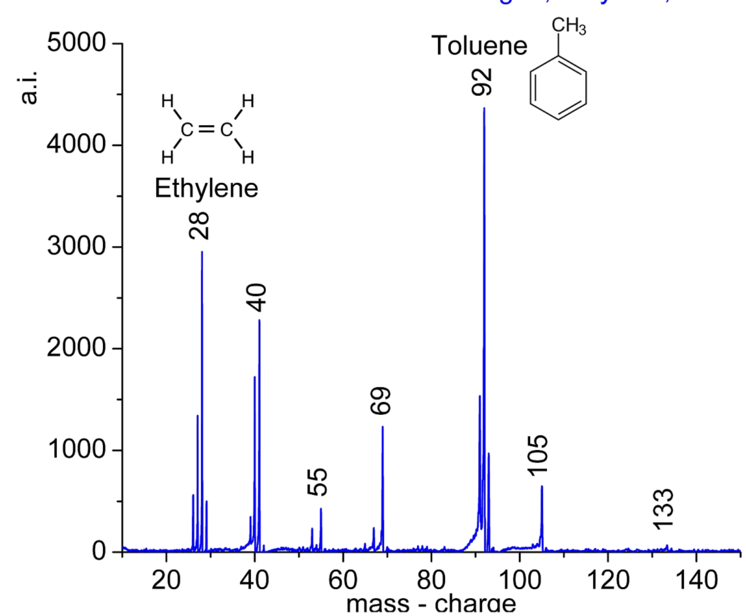


Aromatic - Hydrocarbon Mixtures

Argon, Acetylene, Toluene



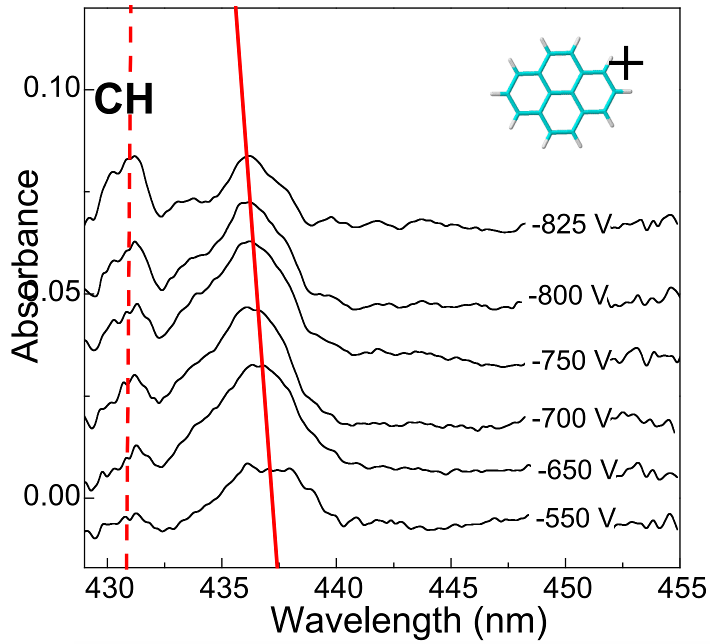
Argon, Ethylene, Toluene



Argon, Methane, Toluene

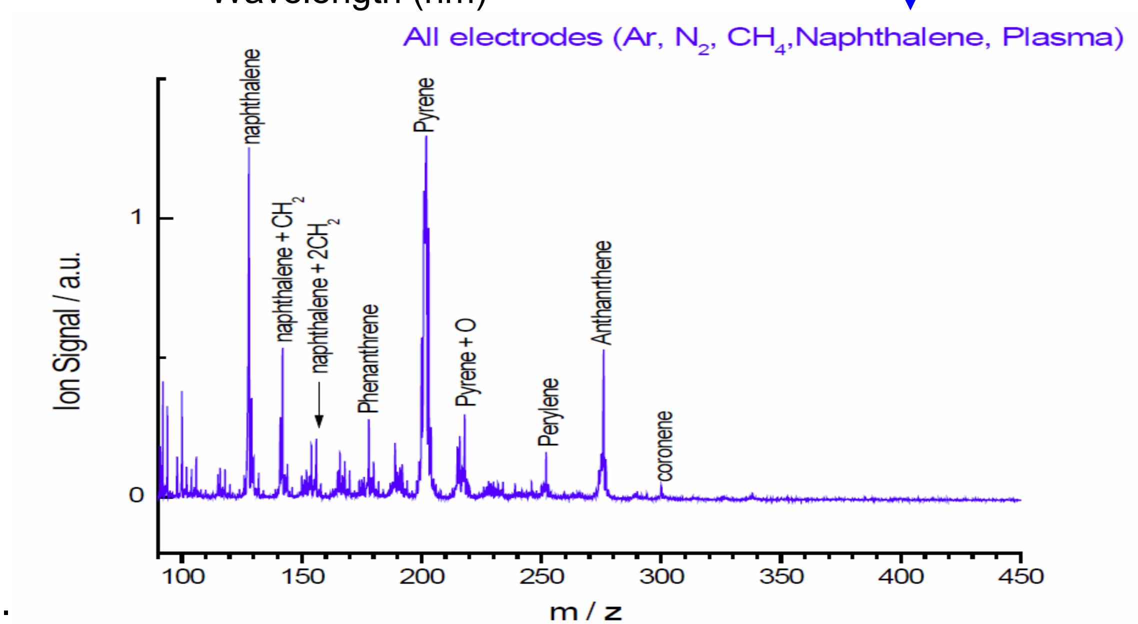
Monitoring fragment formation & detection of carbon particles

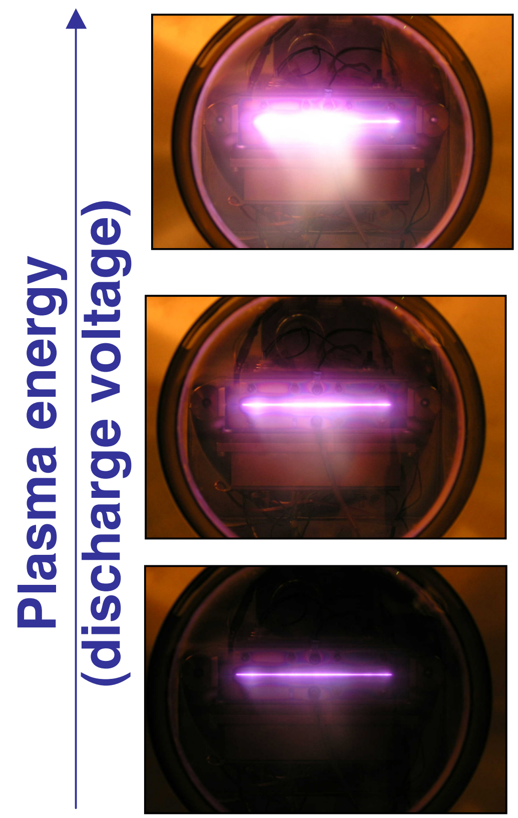
Spectrum of Pyrene ($C_{16}H_{10}$) seeded plasma versus discharge energy



Observation of soot on the electrodes

Mass Spectrometry studies confirm the formation of larger particles: LDMS of soot formed from $C_{10}H_8$ (128 amu) precursor.





Sabbah et al.

OUTLOOK -

Dust & Ices Formation and Evolution

New Directions: Simulating Astrochemistry: The Origins and Evolution of Interstellar Dust and Prebiotic Molecules

Current experimental structures do not allow one to study the entire process in one setting.

NIF offers a unique platform to generate and study dust from inception in a plasma to grain formation and further processing by shocks and radiation bursts.

new, highly multidisciplinary research

- diagnostic of dust inception in plasma to grain formation
- processing by shocks and radiation bursts
- ice processing and formation of prebiotic molecules

study grain formation from plasmas and the processing of grains and icy grain mantles by a wide range of x-rays at fluxes otherwise inaccessible in laboratory astrophysics.

OUTLOOK: Carbon Grain Formation and Evolution

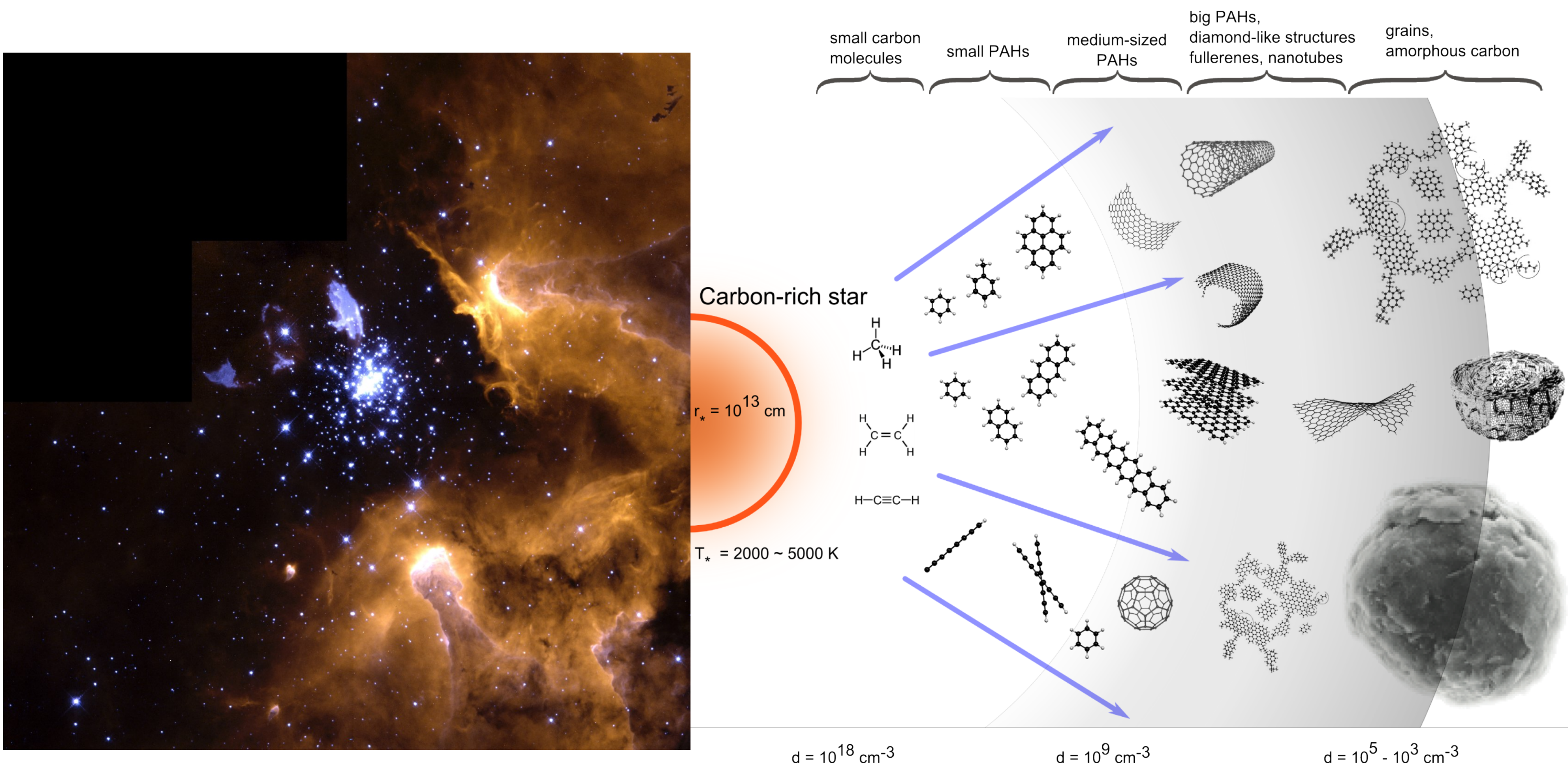


Fig. 1. Left: Life cycle of stars. True-color picture taken on March 5, 1999, with the Wide Field Planetary Camera 2 of the Hubble Space Telescope. Credit: NASA, Wolfgang Brandner, JPLIPAC, Eva K. Grebel, University of Heidelberg. Right: Cartoon depicting the model of formation and processing of cosmic carbon-dust grain formation. Source: Adapted from Pascoli and Polleux, Astron. Astrophys. 359, 799 (2000); Credit: Cesar Contreras (NASA ARC and NPP) and Farid Salama (NASA ARC).

Reference: NIF Report 2012

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NASA SBIR Program

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Jan Cami (NPP, UWO)
Ludovic Biennier (NPP, CNRS)
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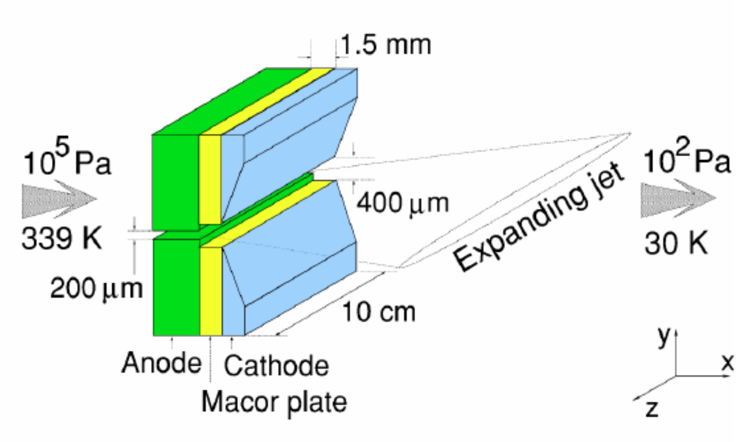
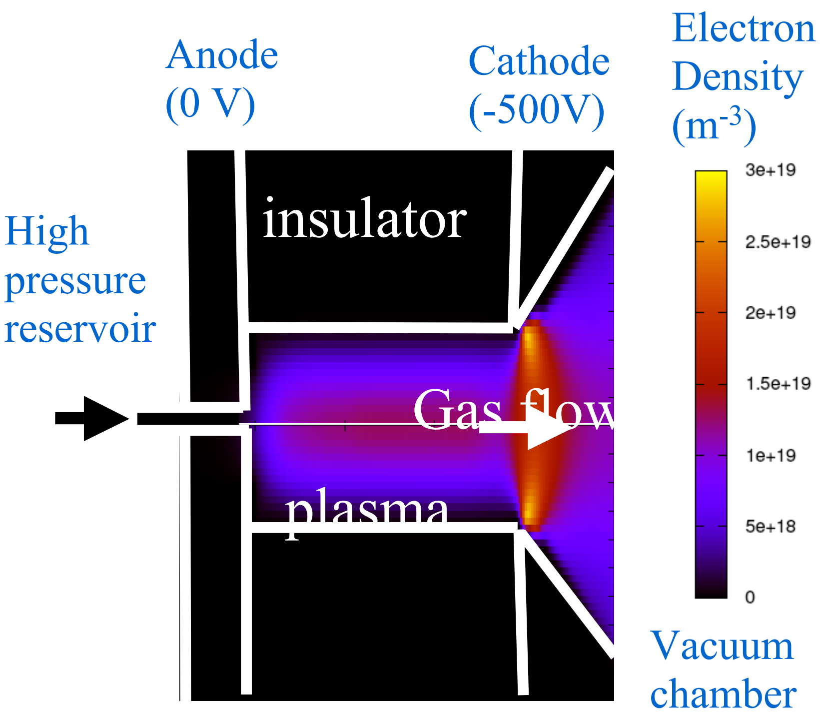
Univ. Leiden, NL (Observations): VLT consortium (N. Cox, M. Cordiner, P. Ehrenfreund...)
Univ. Torun, Poland & ESO, Chile (Observations): J. Krelowski; G. Galazutdinov
Tu/e Eindhoven, NL (Plasma simulation): B. Broks; W. Brok; J. v. der Mullen

BACK UP SLIDES

Methods - Pulsed Nozzle Discharge

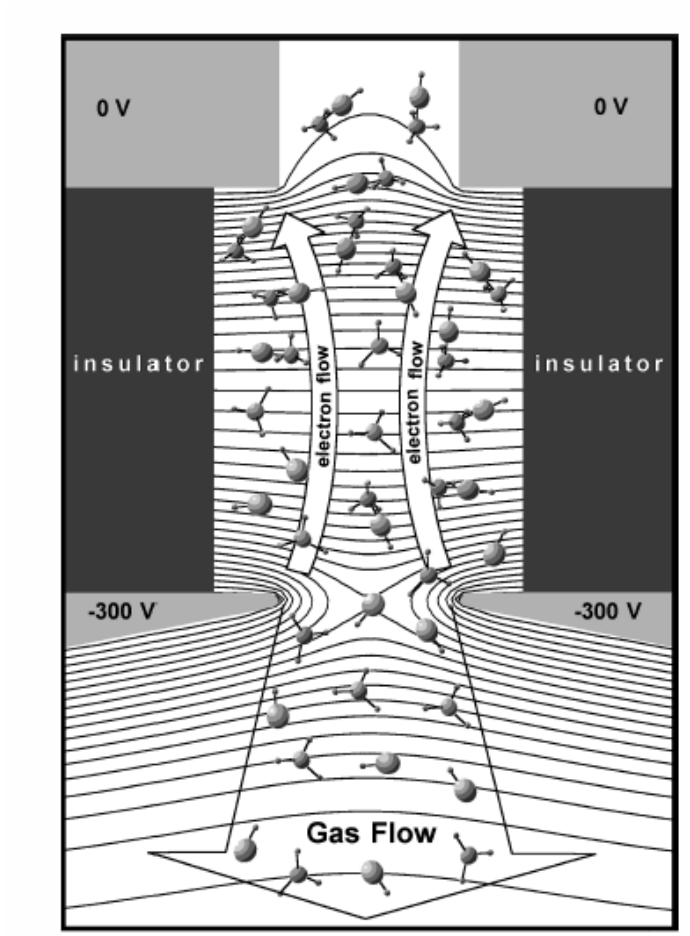
High energy discharge setup





B. Broks et al., Phys. Rev. E, (2005)

Simulation of the plasma



Davis et al., J. Chem. Phys. (1997)

Where Silicates Have Been ID'd

Dust Species / Feature	Astronomical Object	References
Crystalline Silicates λ~ 10 μm (Si-O stretch) λ~ 18 μm (O-Si-O bending)	AGB stars, PNe, YSOs, comets, ULIRG, O-rich stellar outflows, β-Pic, Herbig Ae/Be stars	Knacke et al. (1993); de Graauw et al. (1996); Waters et al. (1996); Waelkens et al. (1996); Crovisier et al. (1996); Sitko et al. (1999); Molster (2000); Meeus et al. (2001); Henning et al. (2005); Sloan et al. (2006); Spoon et al. (2006)
*Olivine $(Mg,Fe)_2SiO_4$	See above; meteorites, asteroids, comets	Zolensky et al. (2006); Lisse et al. (2007); Sunshine et al. (2007); Stroud et al. (2009)
*Pyroxene $XY(Si,Al)_2O_6$	See above; circumstellar outflows, micrometeorites	Tielens et al. (1990); Vollmer et al. (2009)
Silica (SiO_2) λ ~ 12.5-13 μm	YSOs, T Tauri, protoplanetary disks, cometary dust	Rietmeijer & McKay (1986); Mikouchi et al. (2007); Sargent et al. (2009)

* = Predicted in abundance models (Sofia & Meyer 2001; Lodders & Fegley 1999)