Chemical Enrichment of the ISM by Stellar Ejecta

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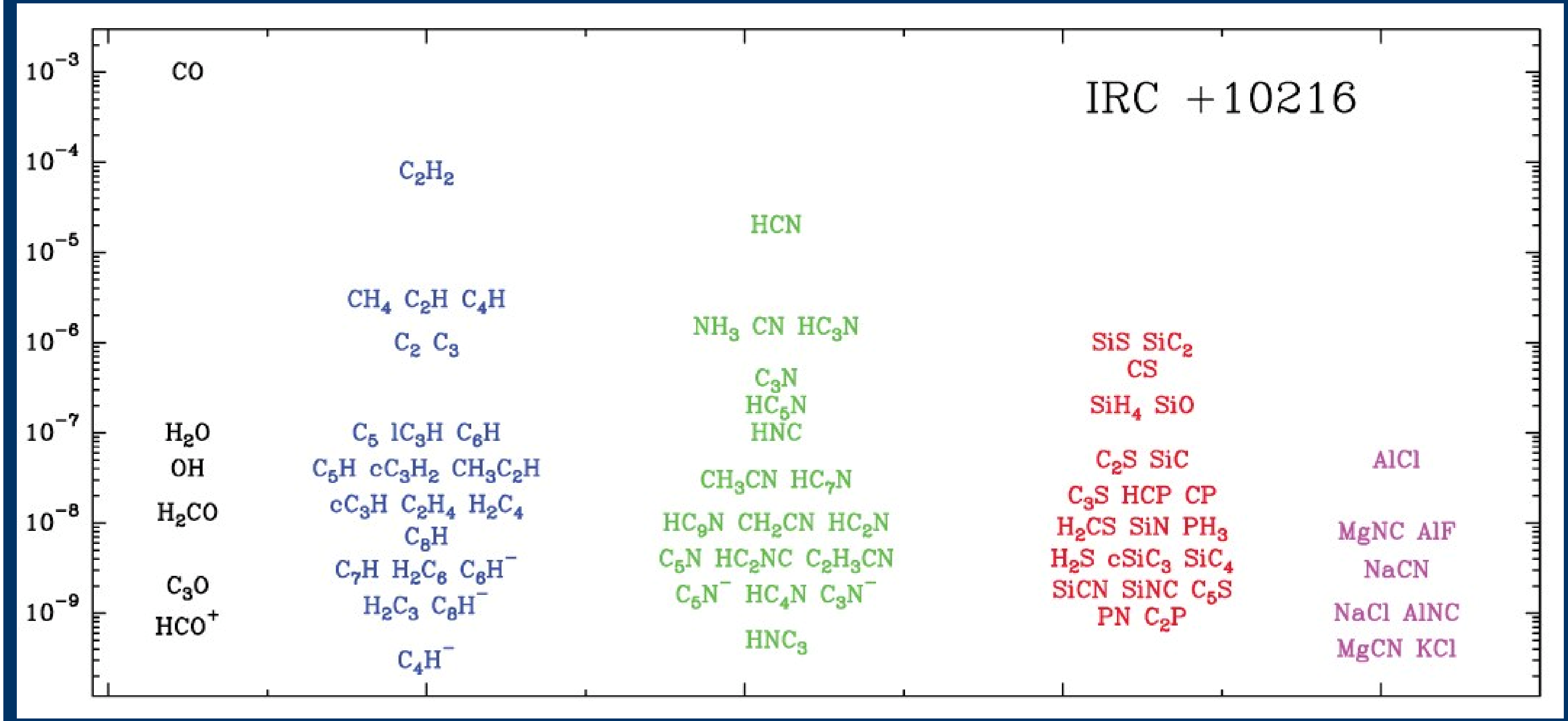
Molecular synthesis in the late stages of stellar evolution

- It has been known since the 1950s that the ISM is enriched by heavy elements synthesized in AGB stars and SNe.
- Over 70 molecules (inorganics, organics, radicals, molecular ions, rings, chains) are known to be synthesized in AGB stars and planetary nebulae

Molecular synthesis in AGB stars

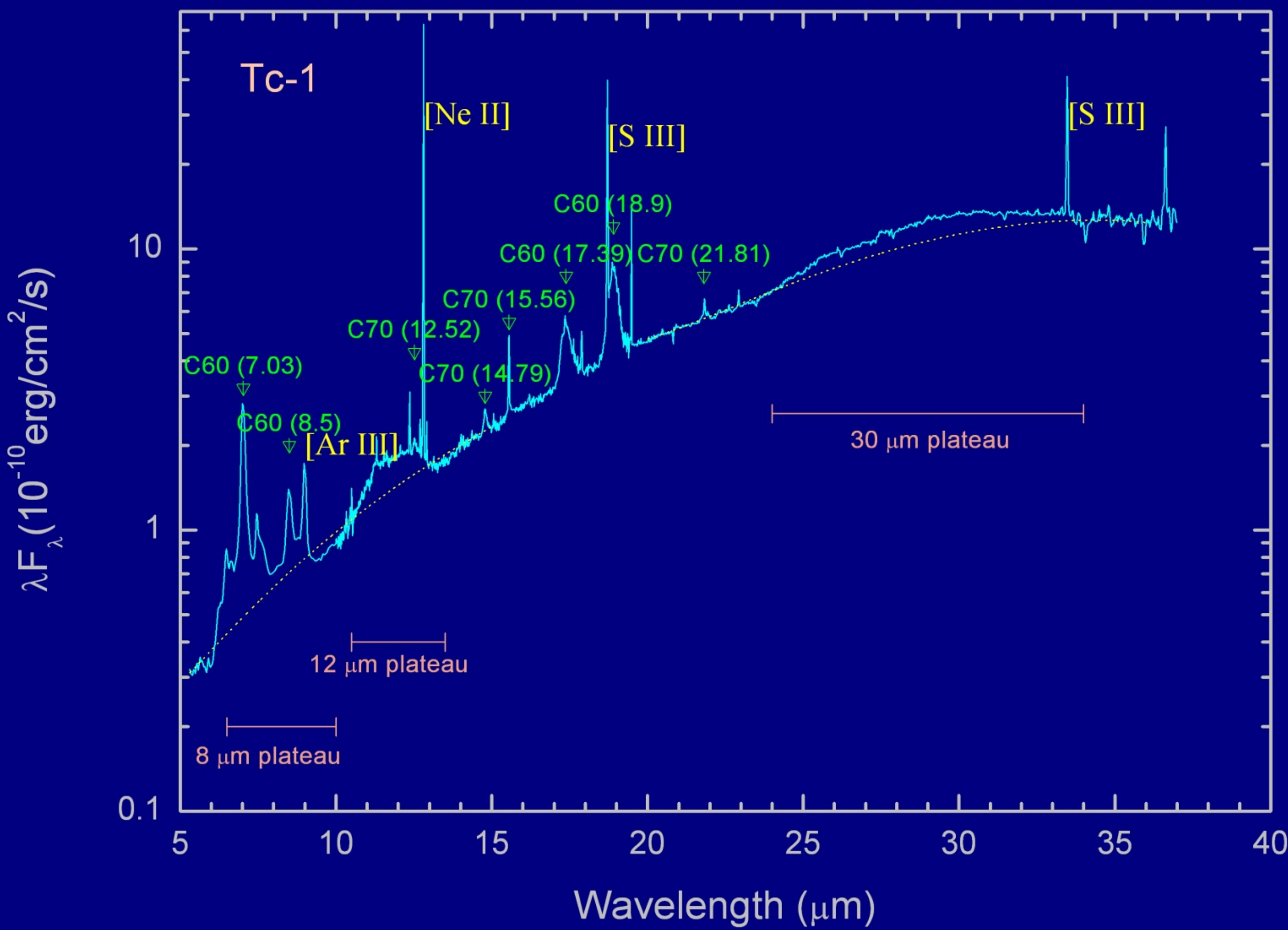


Cernicharo et al. 2011

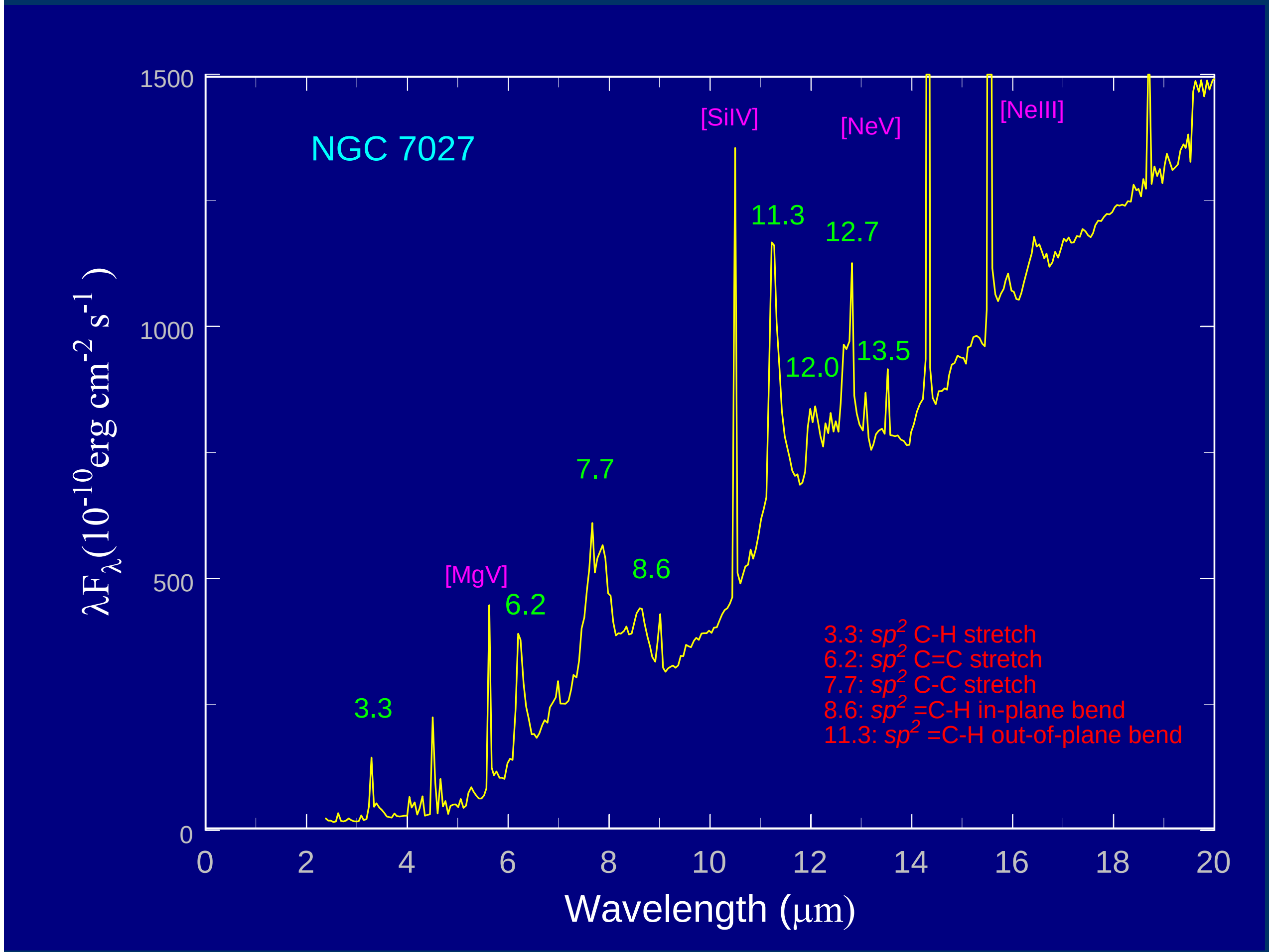
Circumstellar synthesis of solids

- Amorphous inorganics (silicates)
- Refractory oxides
- Silicon carbide
- fullerenes
- Complex organics (aromatic and aliphatic)

Fullerenes (C_{60}, C_{70})

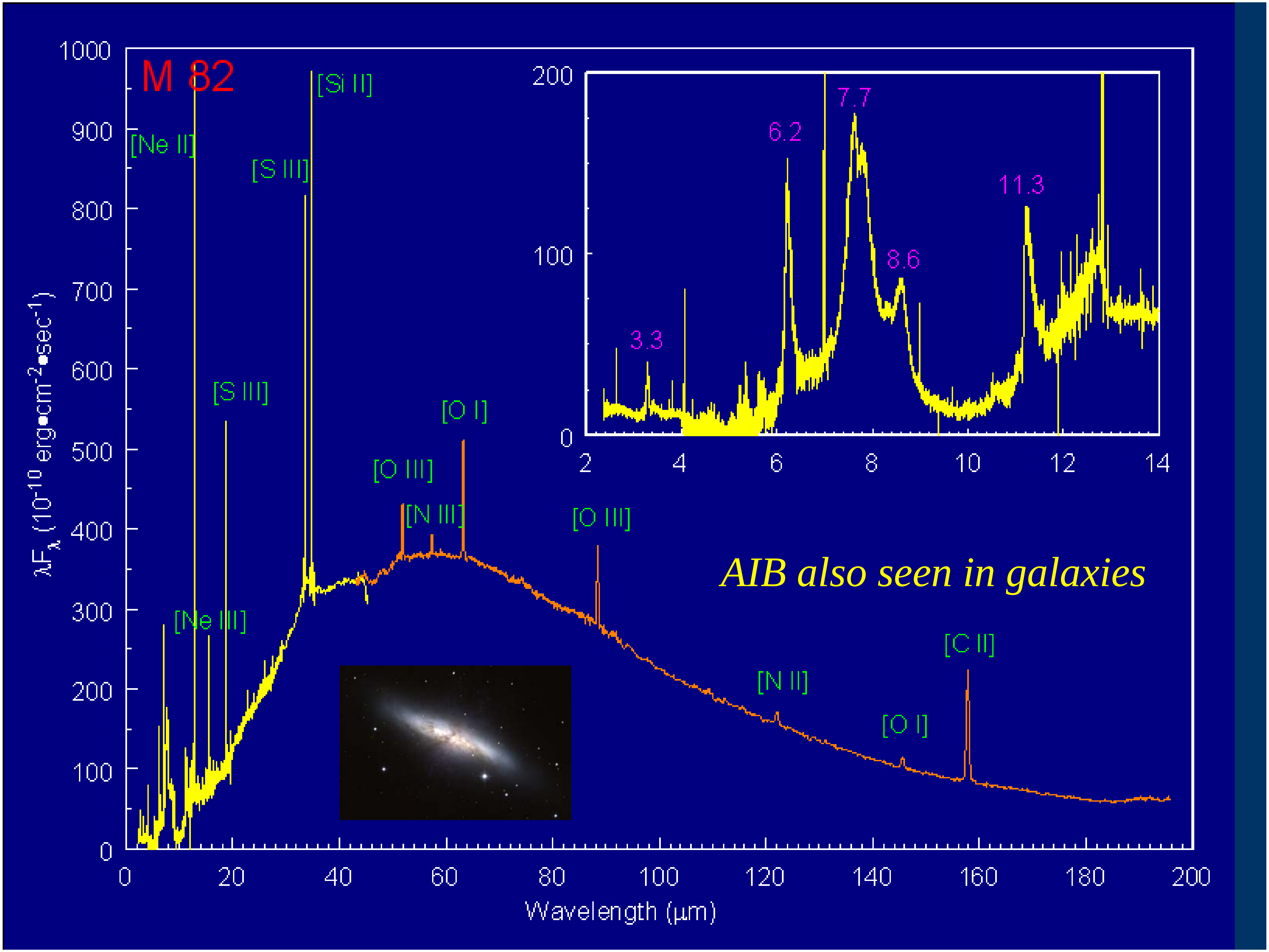


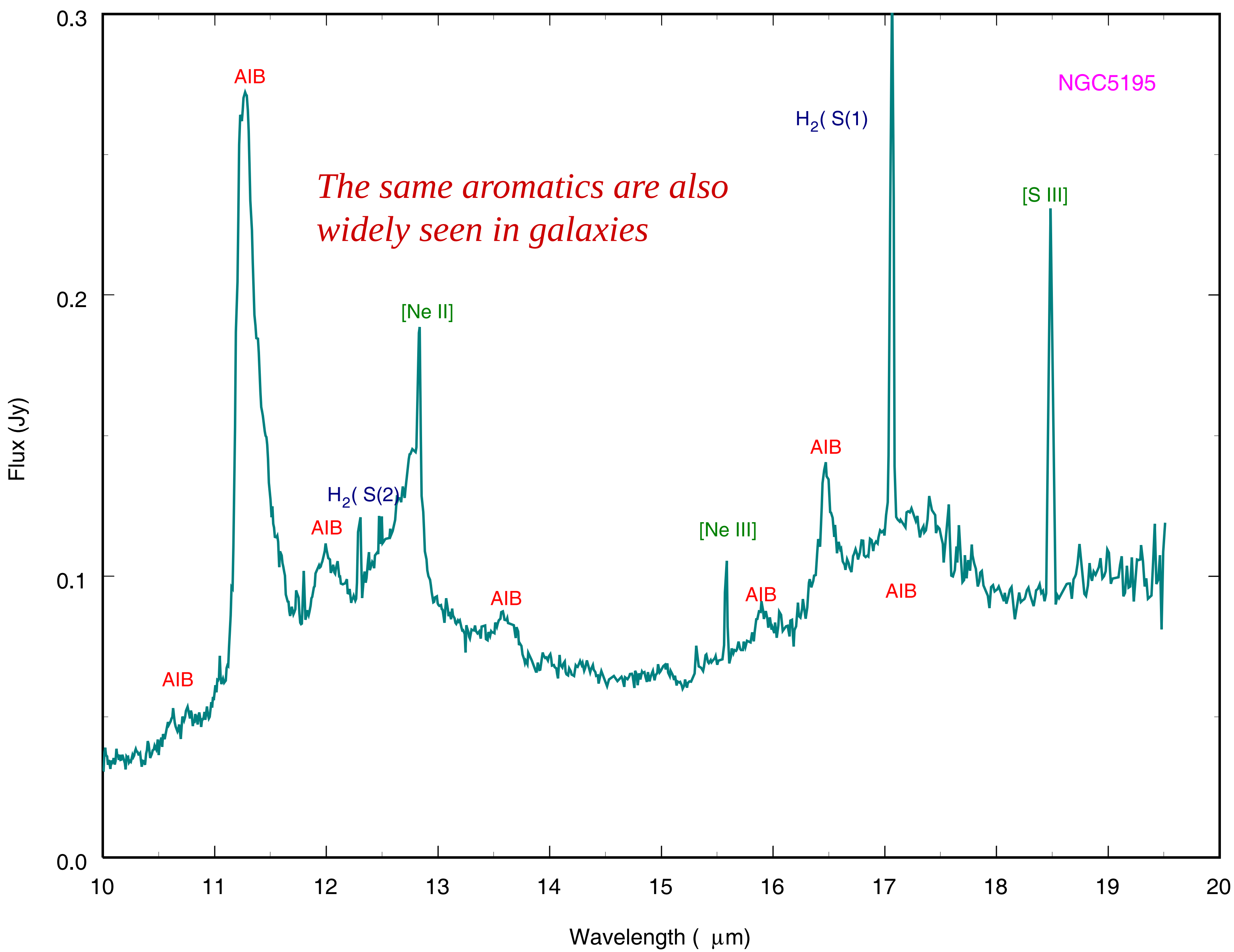
Unidentified infrared emission bands



Aromatic grains:
(Knacke 1977, Duley & Williams 1979, 1981; Puetter et al. 1979)

Stretching and bending modes of aromatic compounds


M 82
[Ne II]
[Si II]
[S III]
[S III]
[Ne III]
[O III]
[N III]
[O I]
[O III]
[N II]
[O I]
[C II]
3.3
6.2
7.7
8.6
11.3
AIB also seen in galaxies
λF_λ (10^-10 erg•cm^-2•sec^-1)
Wavelength (μm)



AIB observed to z~2

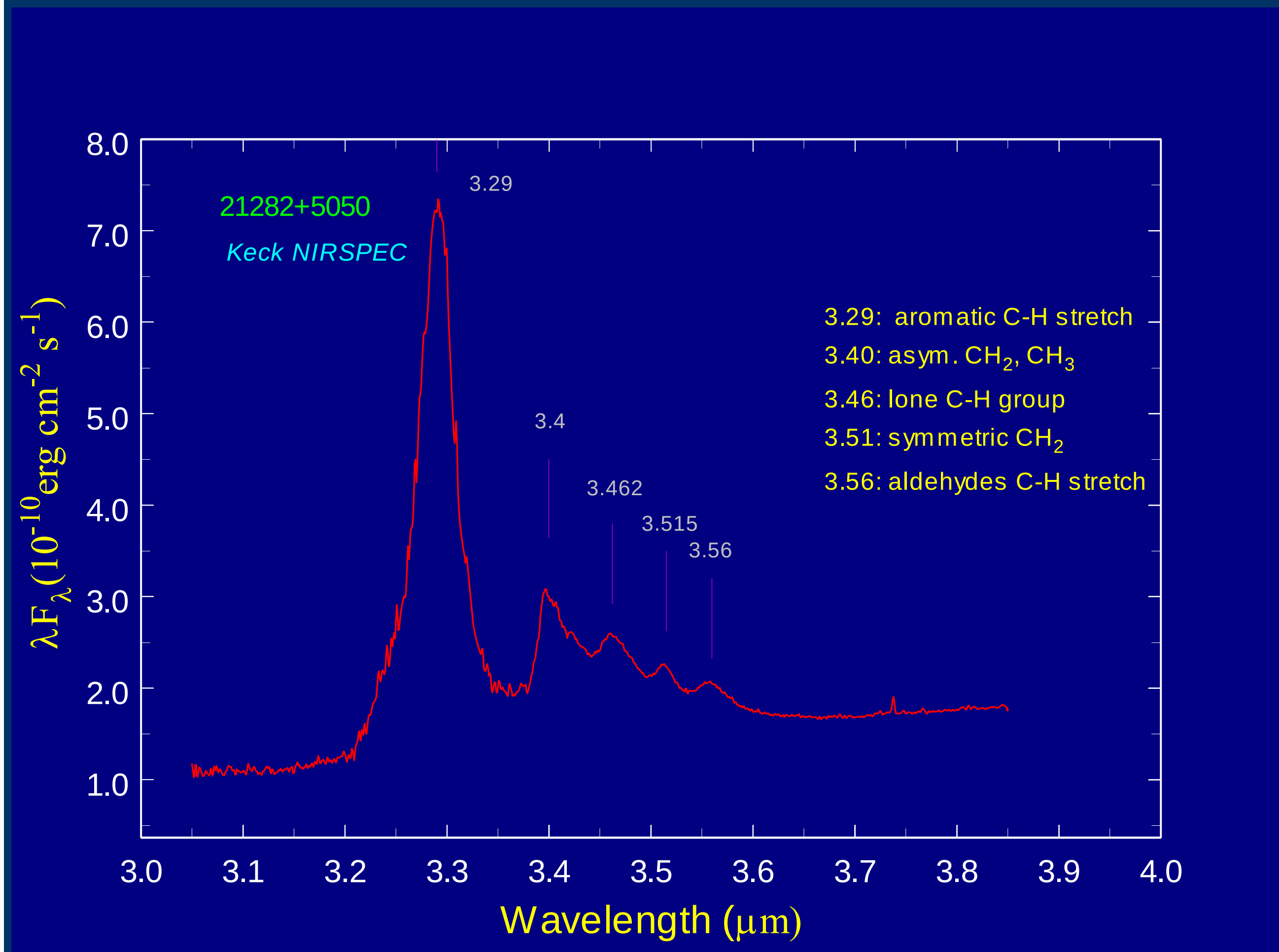
Smith et al. 2007

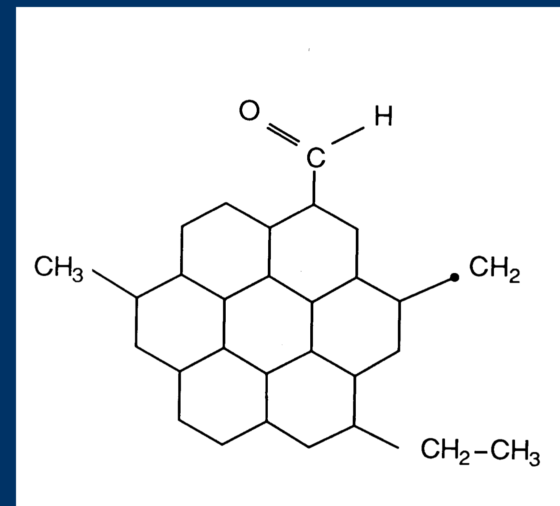
Characteristics of the UIR features

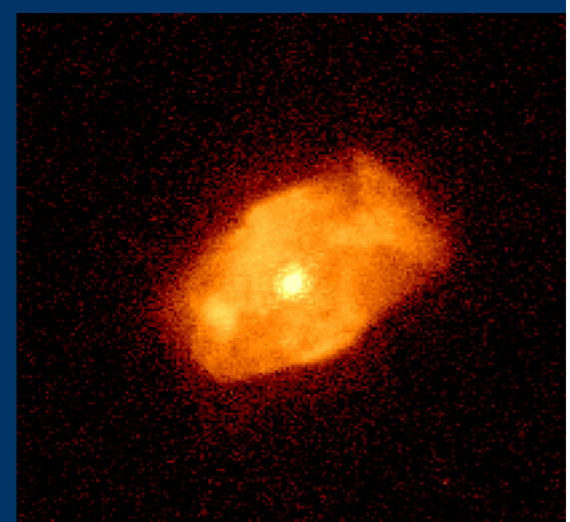
- Aromatic features: 3.3, 6.2, 7.7, 8.6, and 11.3 μm
- Aliphatic features: 3.4 and 6.9 μm
- Features at 15.8, 16.4, 17.4, 17.8, and 18.9 μm
- Broad plateau features at 8, 12, and 17 μm.

What is the chemical structure of the carrier?

Aliphatic sidegroups



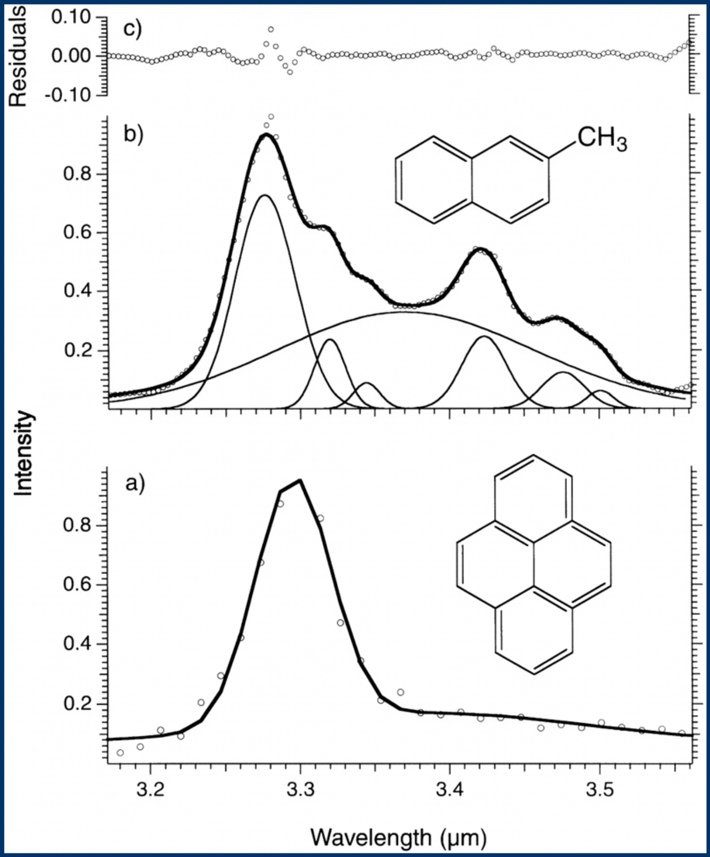




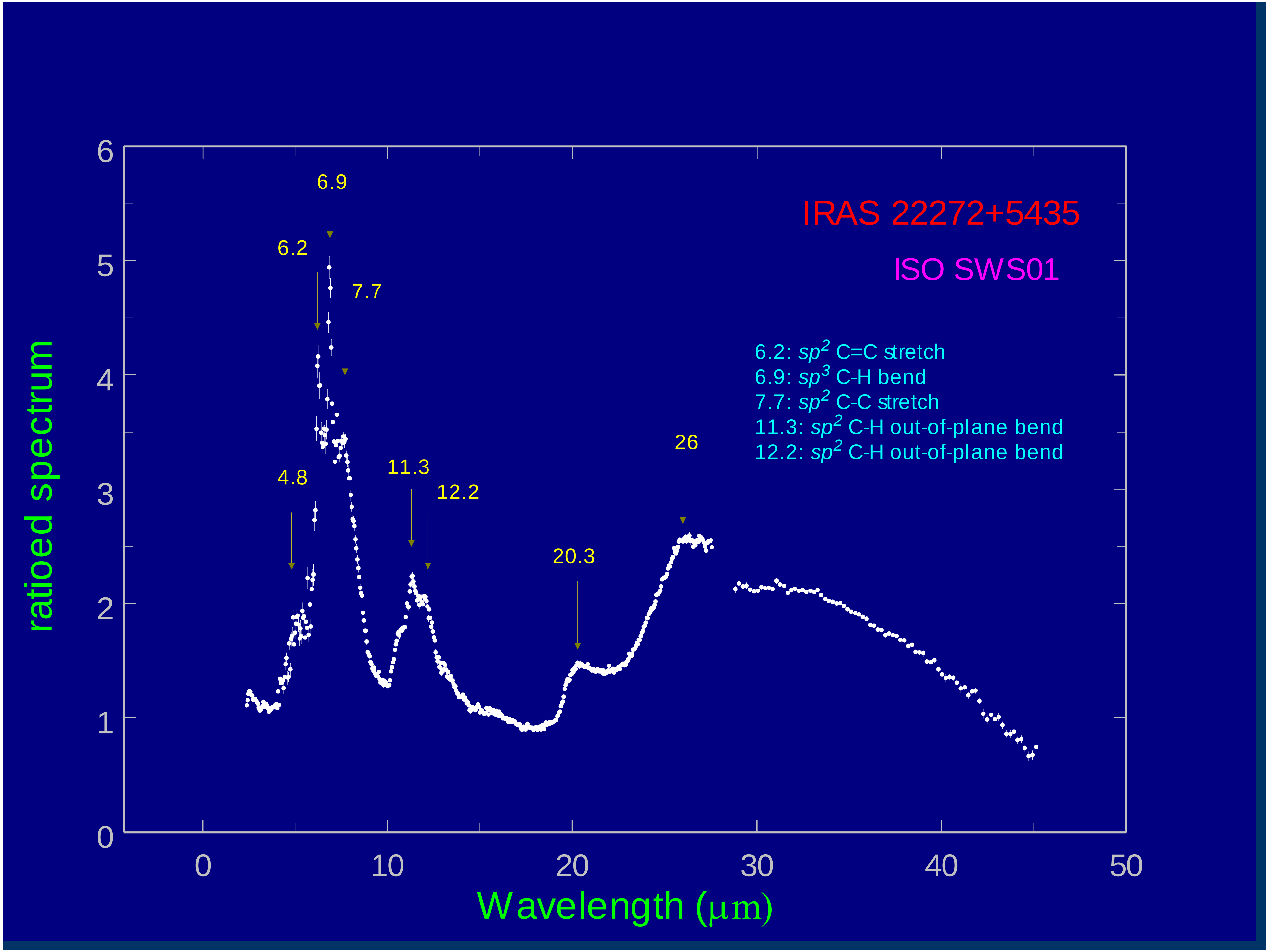
3.4 μm aliphatic C-H stretch

- 3.38 μm: asymmetric CH_3
- 3.42 μm: asymmetric CH_2
- 3.46 μm: lone C-H group
- 3.49 μm: symmetric CH_3
- 3.51 μm: asymmetric CH_2

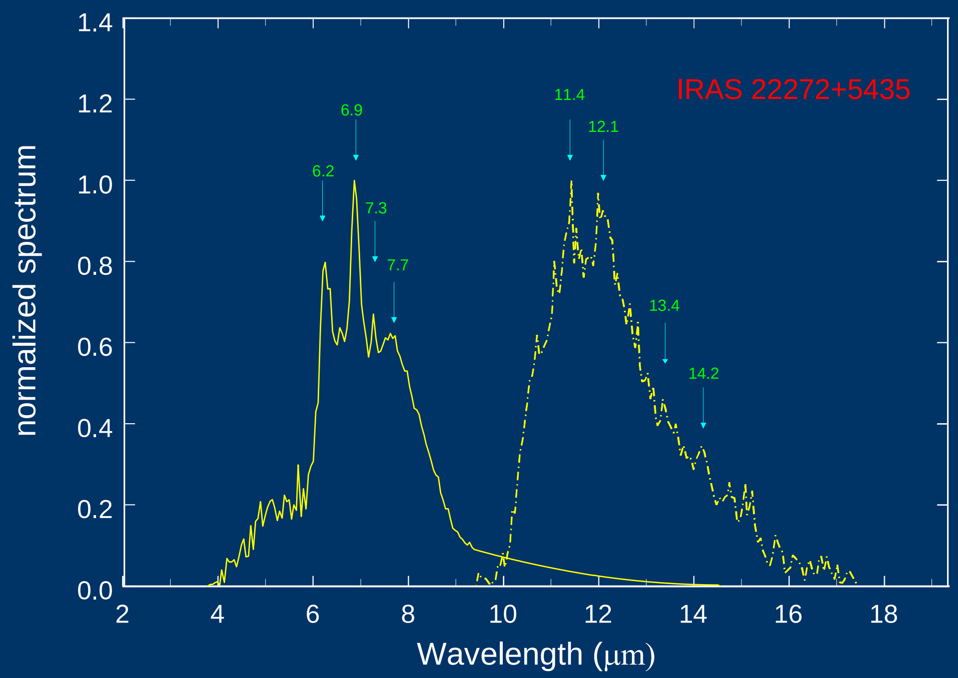
Joblin et al. 1996

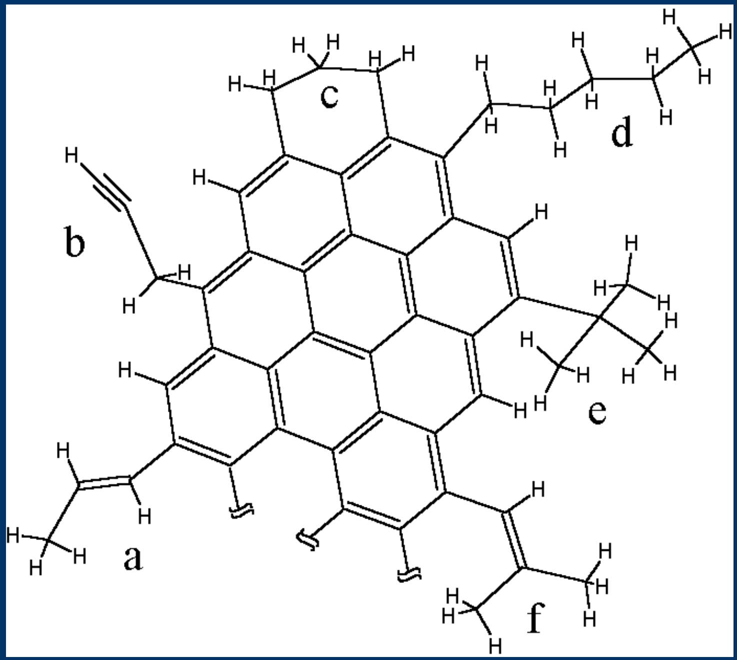


Wagner et al. 2000


IRAS 22272+5435
ISO SWS01
6.2: sp2 C=C stretch
6.9: sp3 C-H bend
7.7: sp2 C-C stretch
11.3: sp2 C-H out-of-plane bend
12.2: sp2 C-H out-of-plane bend
6.9
6.2
7.7
4.8
11.3
12.2
20.3
26
ratioed spectrum
Wavelength (μm)
0
1
2
3
4
5
6
0
10
20
30
40
50

Aliphatic bending modes





Kwok et al. 2001

- 8μm plateau: $-CH_3$ (7.25 μm), $-C(CH_3)_3$ (8.16 μm, “e”), $=(CH_3)_2$ (8.6 μm, “f”)
- 12 μm plateau: C-H out-of-plane bending modes of alkene (“a”, “b”), cyclic alkanes (9.5-11.5 μm, “c”), long chains of $-CH_2-$ groups (13.9 μm, “d”).

The PAH hypothesis

(Allamandola et al. 1989, Puget & Léger 1989)

- the UIE features are the result of infrared fluorescence from small (~50 C atoms) gas-phase PAH molecules being pumped by far-ultraviolet photons (Tielens 2008)
- The central argument for the PAH hypothesis is that single-photon excitation of PAH molecules can account for the 12 μm excess emission observed in cirrus clouds in the diffuse interstellar medium by *IRAS (*Sellgren 1984, 2001*)*.

Problems with the PAH model

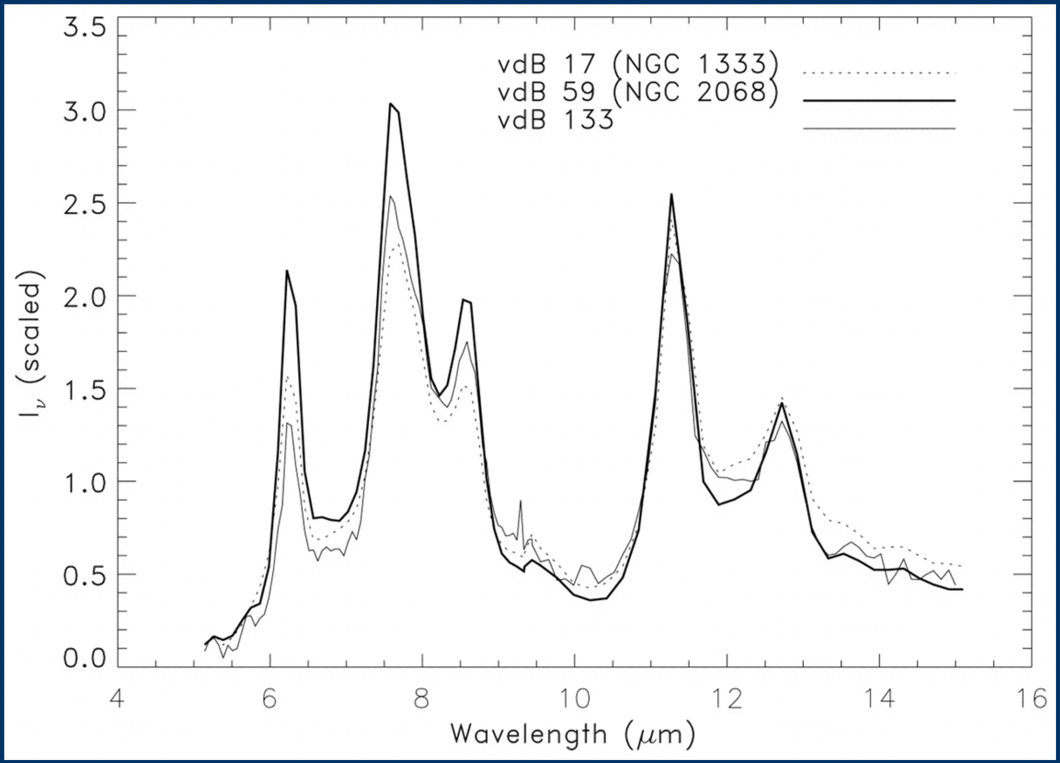
- PAH molecules have well-defined sharp features but the UIR features are broad
- PAHs primarily excited by UV, with little absorption in the visible
- UIR features seen in PPN and reflection nebulae with no UV radiation
- The strong and narrow predicted gas phase features in the UV are not seen in interstellar extinction curves
- No PAH molecules have been detected in spite of the fact that the vibrational and rotational frequencies are well known

Problems with the PAH model

- No PAH emission spectrum has been able to reproduce the UIR spectrum w.r.t. either band positions or relative intensities (Cook et al. 2008)
- The shapes and peak wavelengths of UIR features are independent of temperature of exciting star
- In order to fit the astronomical observations, the PAH model has to appeal to a mixture of PAH of different sizes, structures (compact, linear, branched) and ionization states, as well as artificial broad intrinsic line profiles.

Reflection nebulae

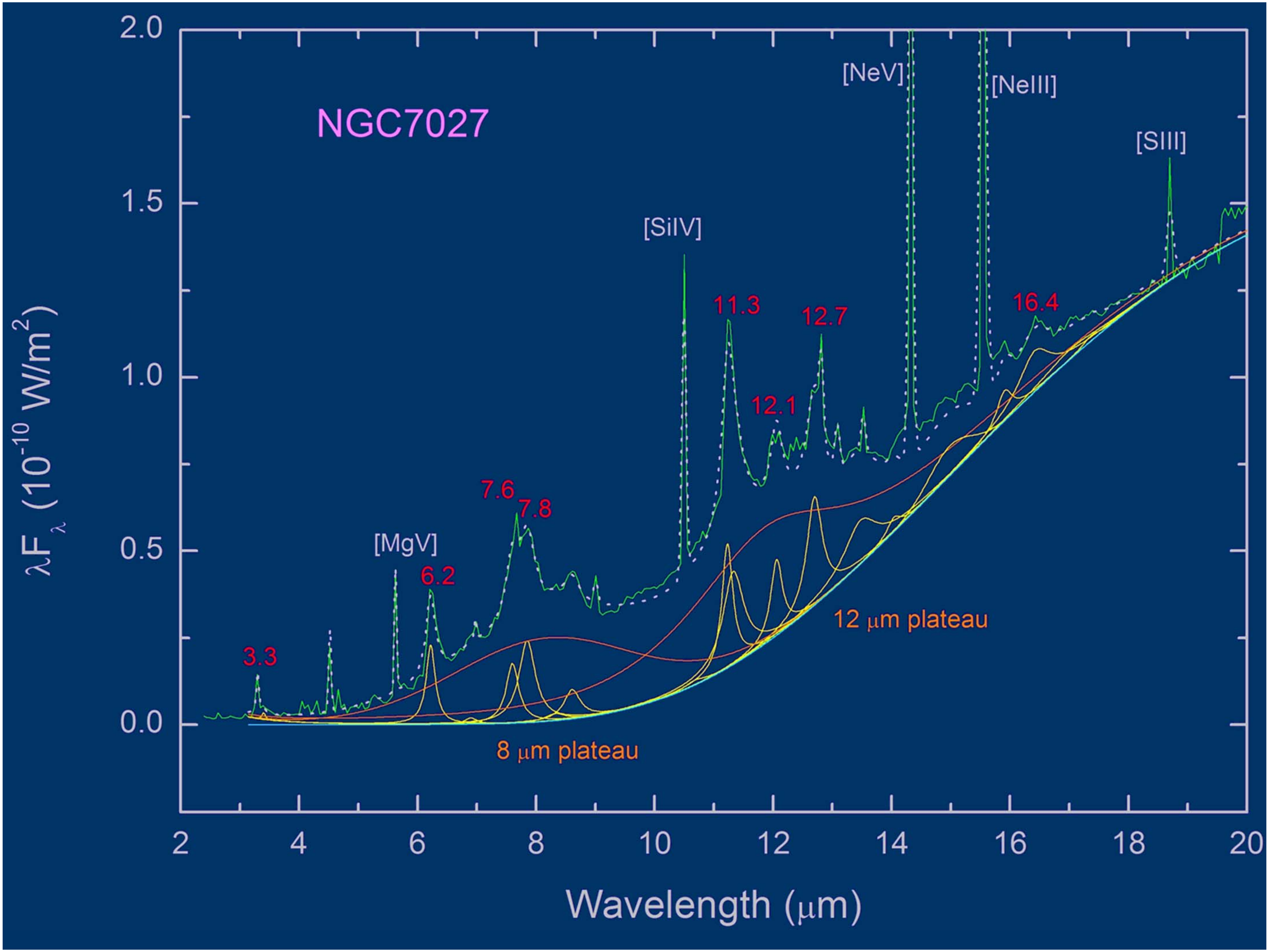
- The UIR features have consistent profiles and peak wavelengths in spite of the fact that the nebulae are heated by central stars of 11000, 19000 and 6800 K
- No UV background

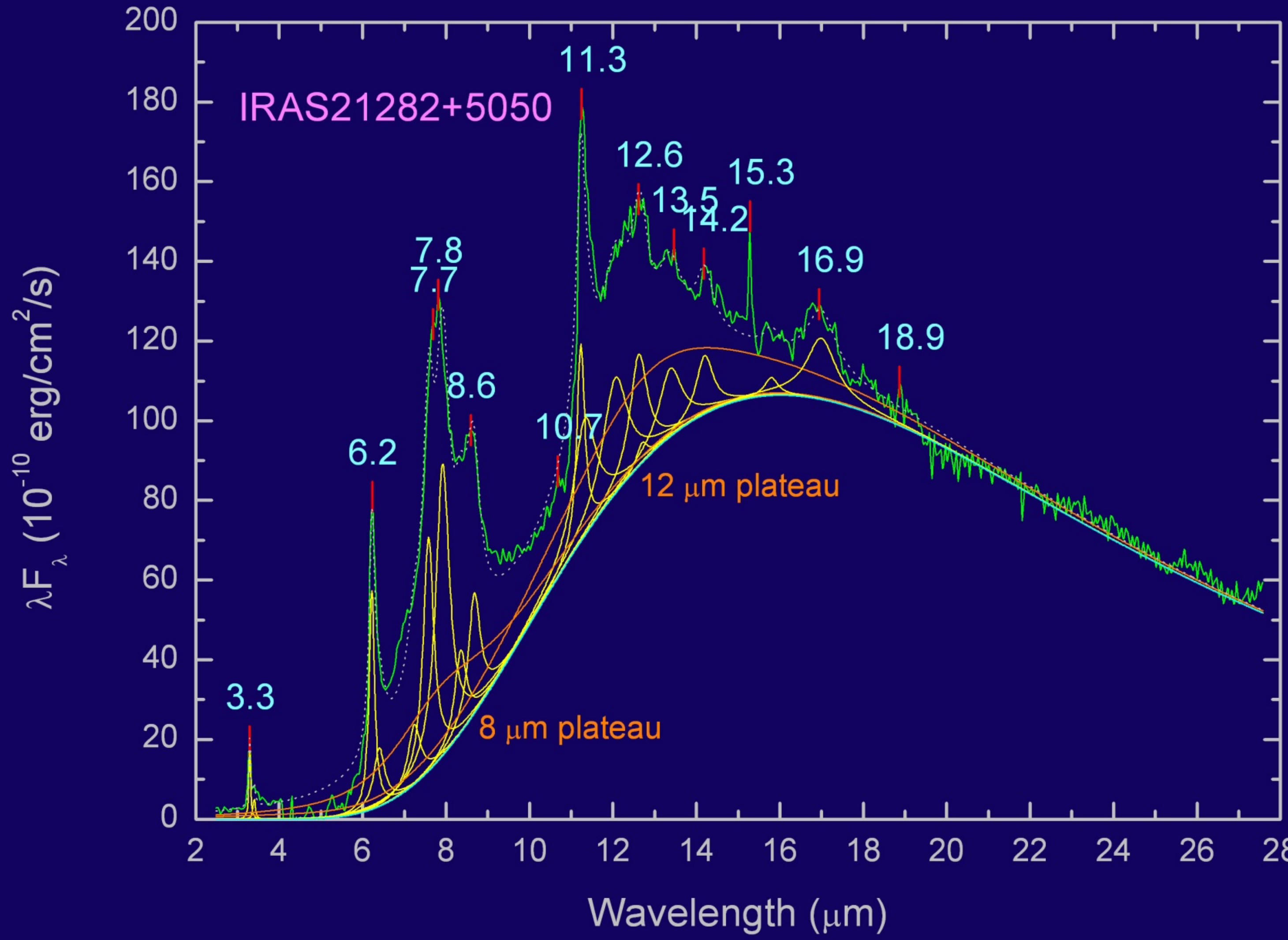


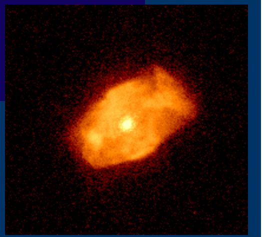
Uchida et al. (2000)

Excitation problem

- The 3.3 and 7.7 μm radiate at too short a wavelength for the grains to be in thermal equilibrium
- Stochastic heating by single photon
- Alternate explanation: sudden release of chemical energy as a source of transient heating (Duley and Williams 2011).

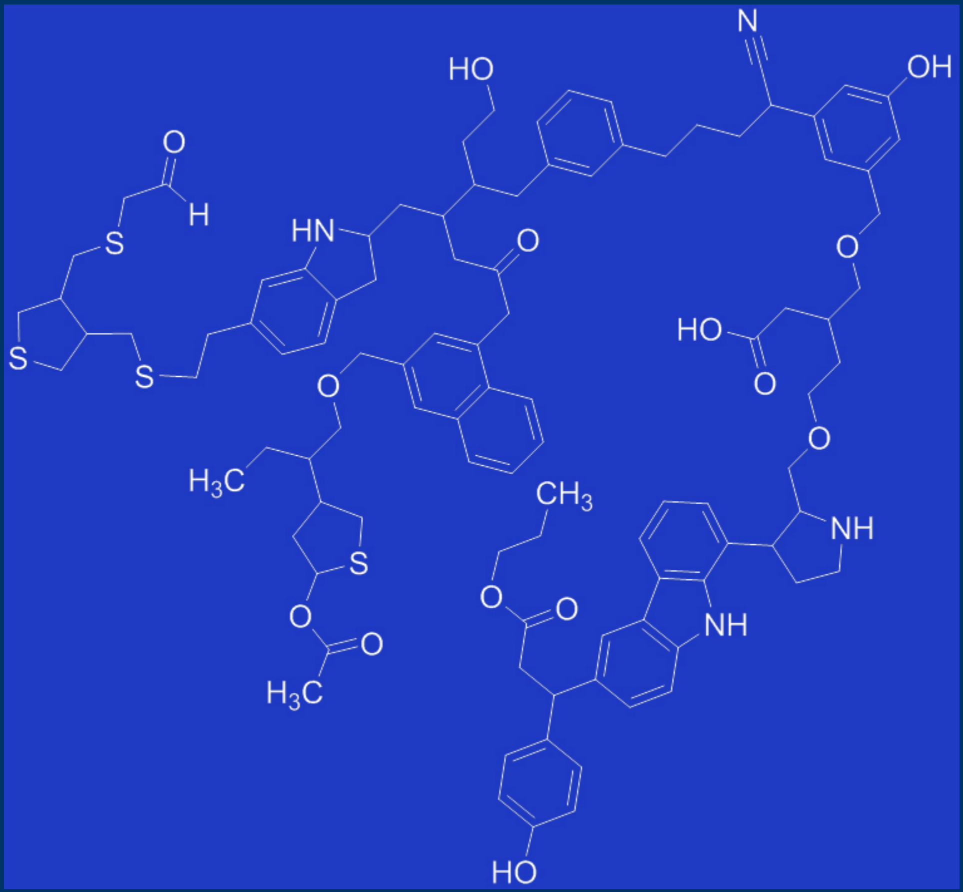

NGC7027
[MgV]
[SiIV]
[NeV]
[NeIII]
[SIII]
3.3
6.2
7.6
7.8
11.3
12.1
12.7
16.4
8 μm plateau
12 μm plateau
λFλ (10^-10 W/m^2)
Wavelength (μm)
2.0
1.5
1.0
0.5
0.0
2
4
6
8
10
12
14
16
18
20





Flux (2.4-27.6 μm): continuum 65%, AIB: 13%, aliphatic 17%

Mixed aromatic/aliphatic organic nanoparticles (MAON) as a component of interstellar dust



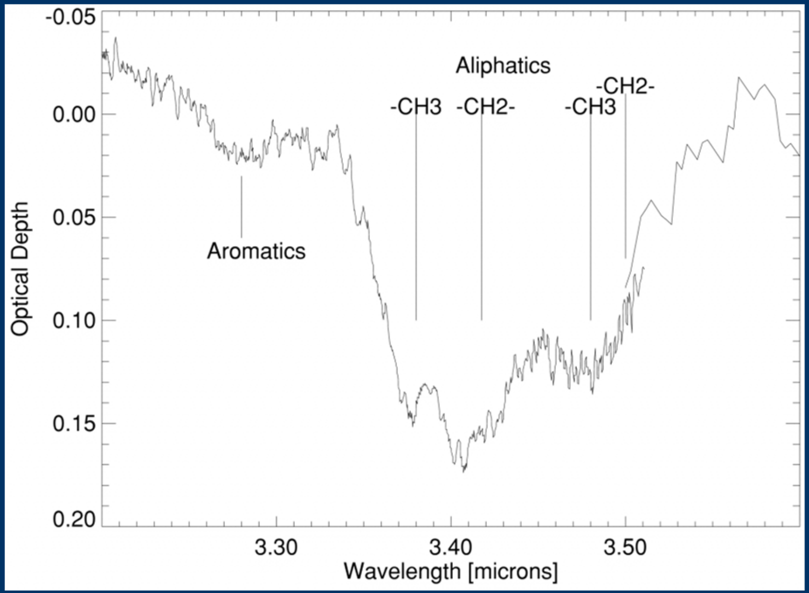
Complex organic solids with disorganized structures

- *Small units of aromatic rings linked by aliphatic chains*
- *Impurities of O, N, S*
- *A typical nanoparticle may contain multiple of this structures*

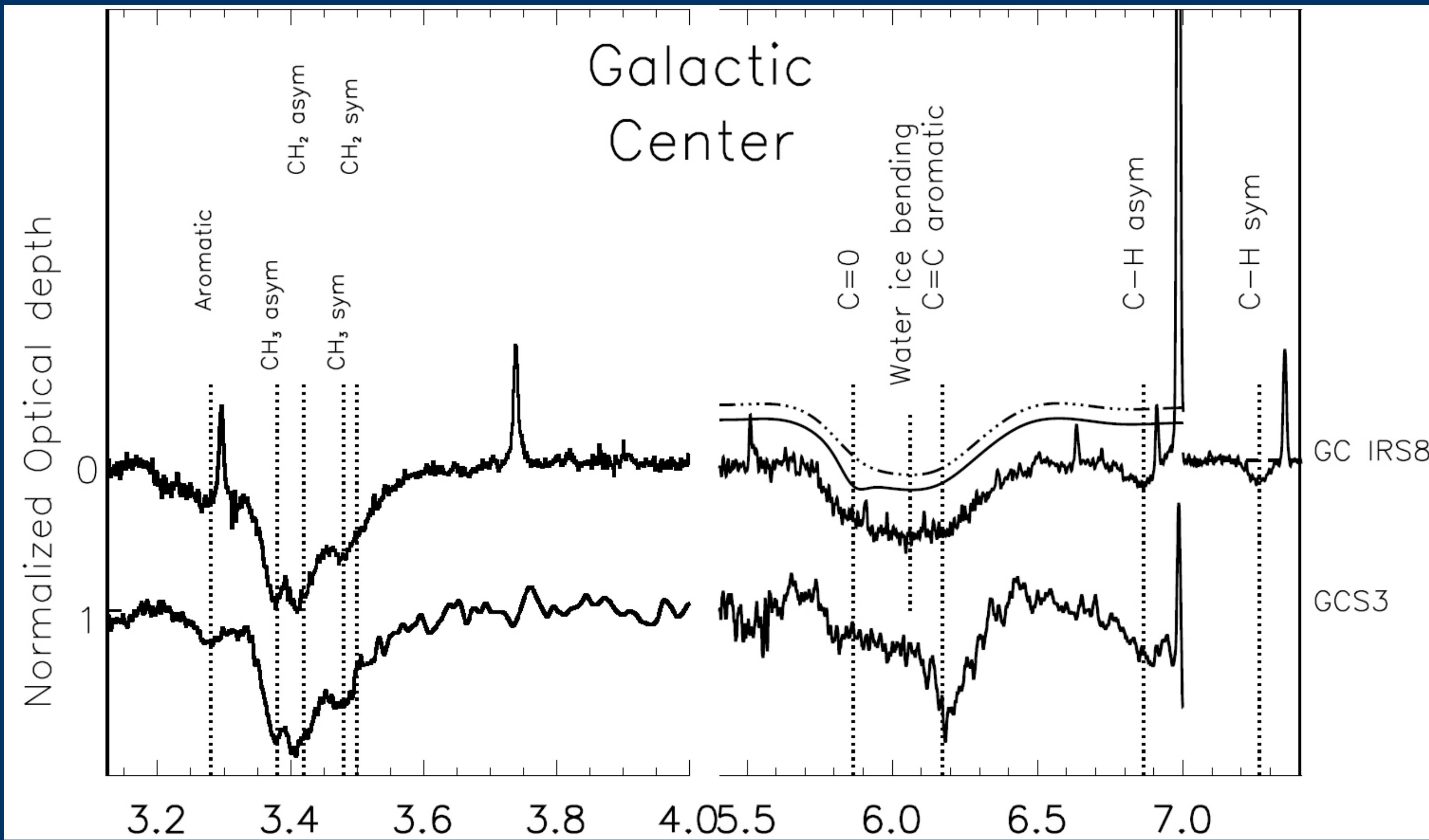
Kwok & Zhang 2011, *Nature*, **479**. 80

Organic grains in the diffuse ISM

- 3.4 μm C–H stretch observed along the line of sight to the GC (Wickramasinghe & Allen 1983)
- Other sources: Sandford et al. 1991, Pendleton et al. 1994, Chiar et al. 2000
- 3.4 and 6.9 μm features in external galaxies: Spoon et al. 2004, Dartois et al. 2007



Aliphatics in diffuse ISM



Dartois et al. 2004,
Chiar et al. 2002,
Dartois 2011

15% of C in sp^3 bonding

Summary

- Organic compounds are everywhere in the Universe (from solar system to ISM to galaxies)
- Hydrocarbons with linear, aromatic and aliphatic structures are detected in the circumstellar envelopes of evolved stars
- Chemical evolution leading to complex organic compounds can take place over only a few thousand years in the circumstellar environment

Summary (cont.)

- Aliphatic signatures are seen in absorption throughout the Galaxy and in external galaxies
- Ejection from evolved stars provides the most likely explanation to the wide presence of organics in the diffuse ISM

References

Kwok, S. 2004 The Synthesis of Organic and Inorganic Compounds in Evolved Stars, *Nature*, **430**, 985

Kwok, S. & Zhang, Y. 2011, Mixed aromatic/aliphatic organic nanoparticles as carriers of the unidentified infrared emission features, *Nature*, **479**, 80

Special session 16 at IAU GA 2012