Infrared Imaging and Spectroscopy for the Studies of the Late Stages of Evolution

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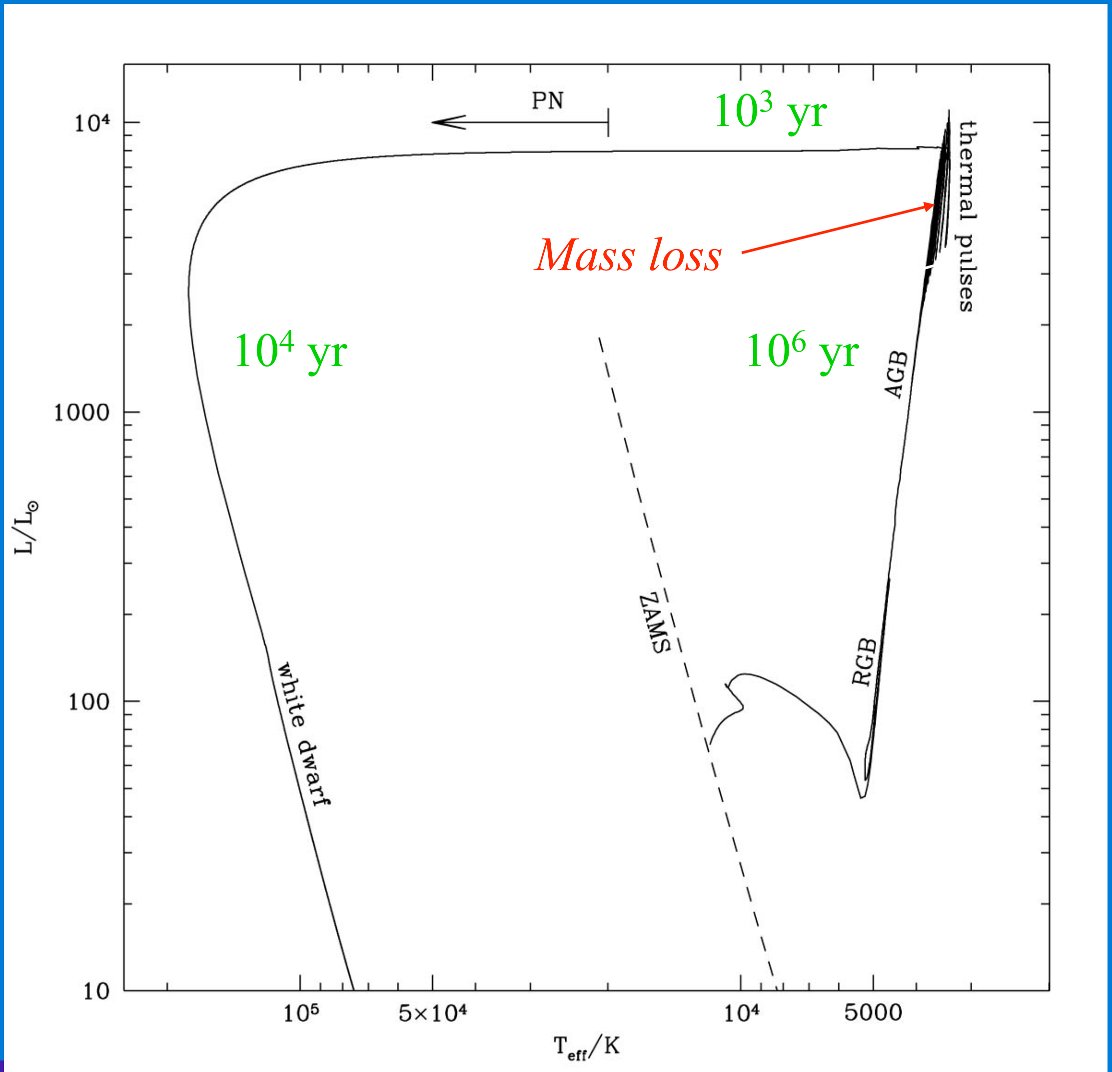
Asilomar, June 2010

What can far IR astronomy do for studies of the late stages of stellar evolution?

- Imaging: morphology
- Spectroscopy: distribution of organic solids, circumstellar chemistry
- Imaging spectroscopy: kinematics

Evolution of intermediate mass (1-8 $M_\odot$) stars

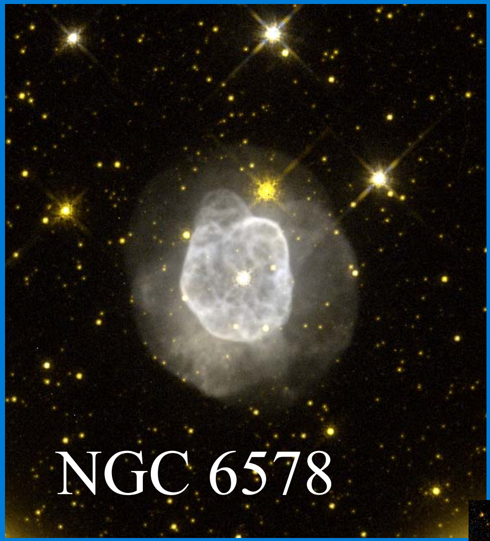
- Triple-α reaction (He→C)
- Slow neutron capture (s-process) (Y, Zr, Ba, La, Ce, Pr, Nd, Sm, Eu, etc)
- Thermal pulse and dredge up

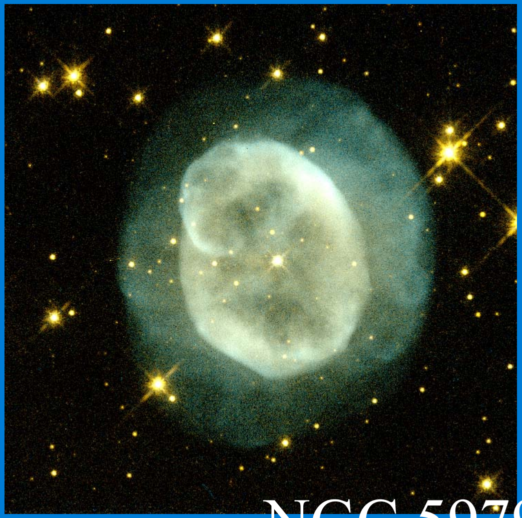


3 $M_\odot$ track

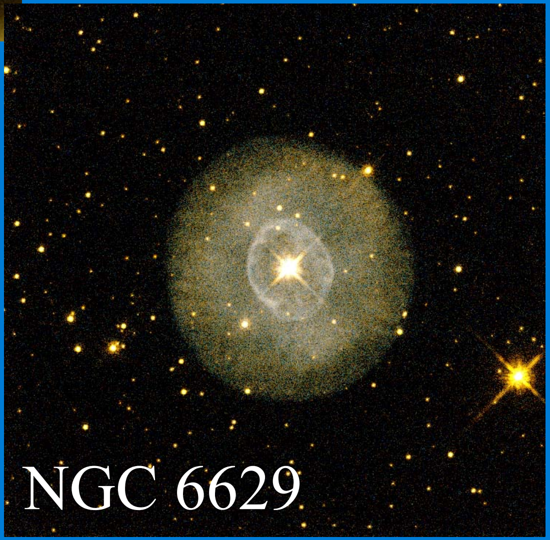
Origin of planetary nebulae

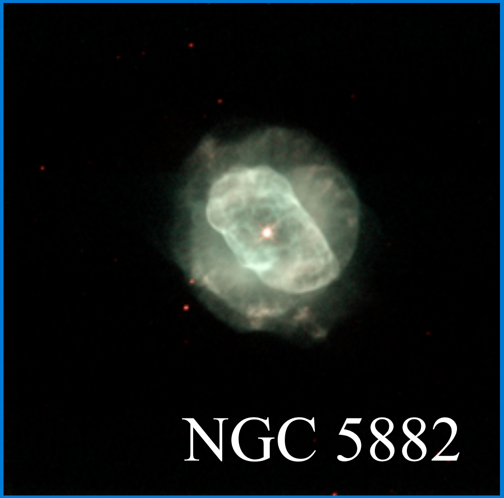
- PN are the result of dynamical interaction between the remnant of the AGB wind and a newly developed fast wind (Kwok, Purton, Fitzgerald 1978)
- The interacting winds model has successfully predicted (i) the optical halo; (ii) fast wind (by *IUE*); (iii) dust envelopes (*IRAS*); and the X-ray bubble (*ROSAT, Chandra*)





Shells,
Rims,
Crowns,
and Haloes





Multi-shell morphology can be explained by 1-D interacting winds dynamics (Schönberner)

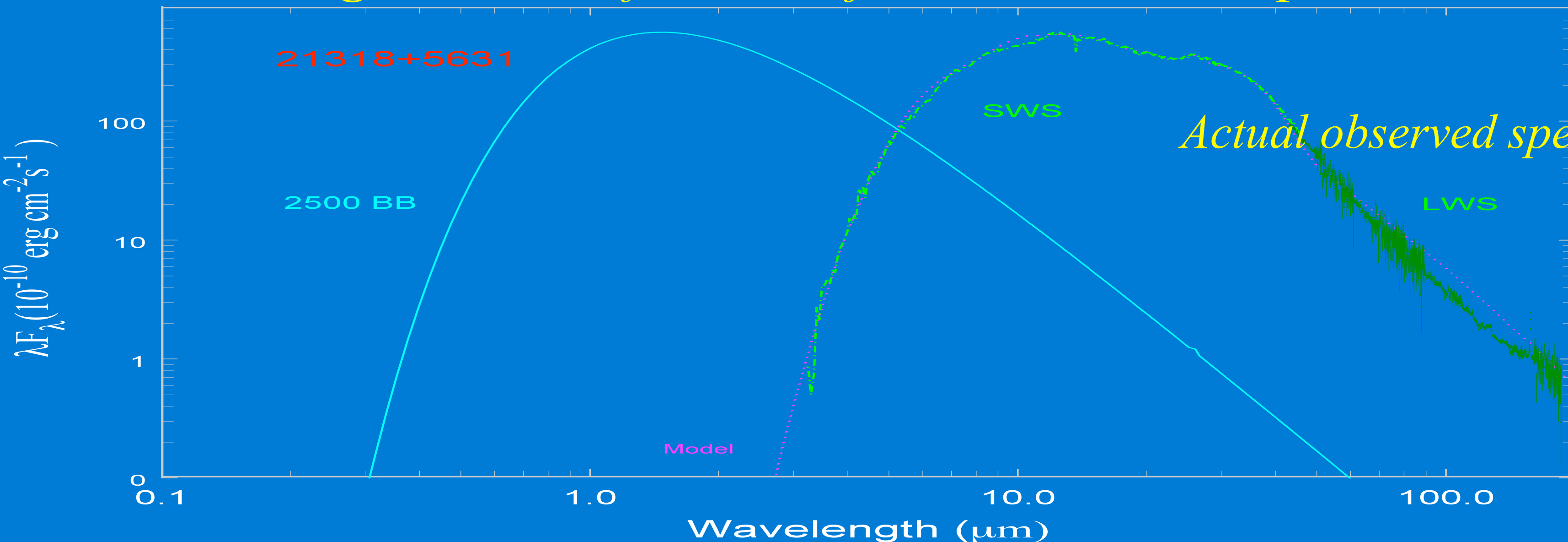
Including the Ring, the Helix, the Dumbbell….

But many PN are bipolar, where do they come from?

Our Traditional Concept of Planetary Nebulae is Dominated by their Optical Images

Although bright because of recombination lines of H and He and collisionally excited lines of metals, the ionized region in fact represents a very small fraction of the total mass of PN

A large amount of dust is ejected in the AGB phase

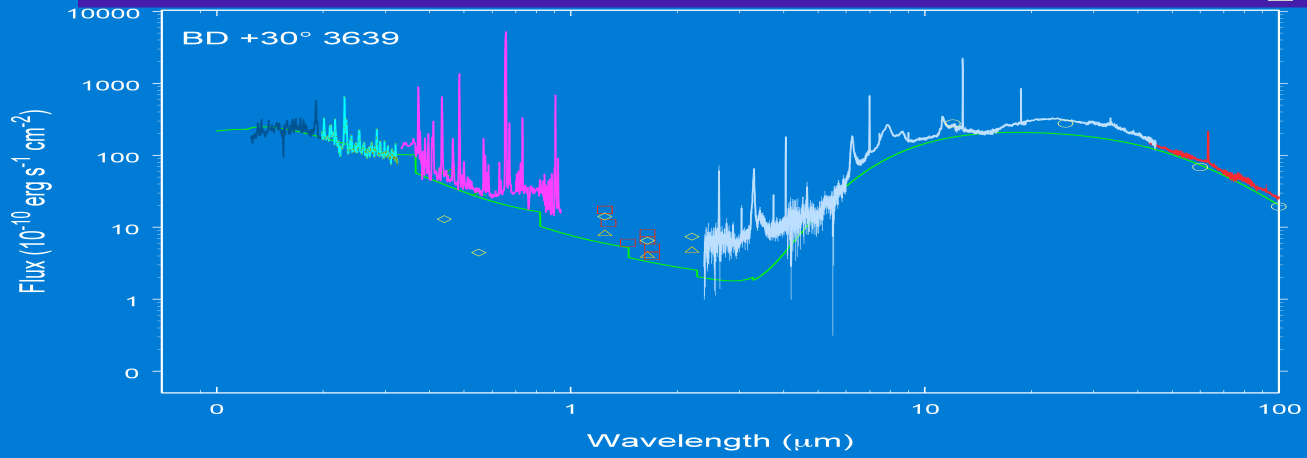


Actual observed spectrum

Hidden photosphere

Star completely obscured

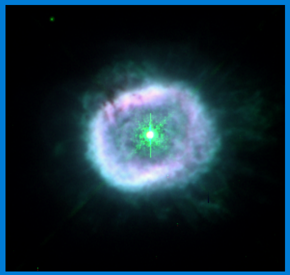
Remnant AGB dust envelope in PN



Ionized (10^4-10^6 K), molecular (10^1-10^2 K) and dust (10^2 K) components

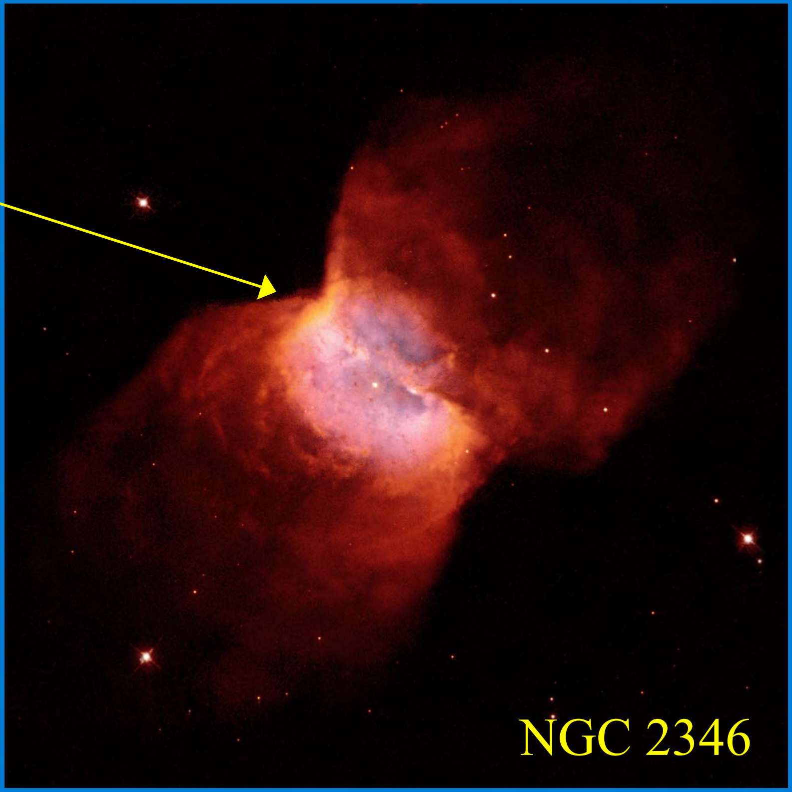
Dust continuum

b-f continuum

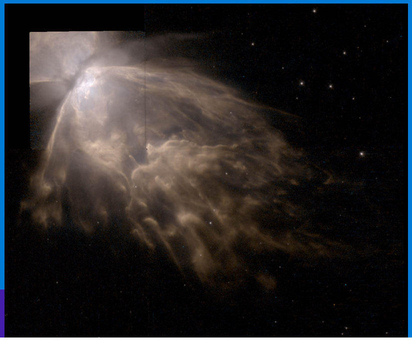


Indirect evidence for "dark matter"

Confined by dust torus?



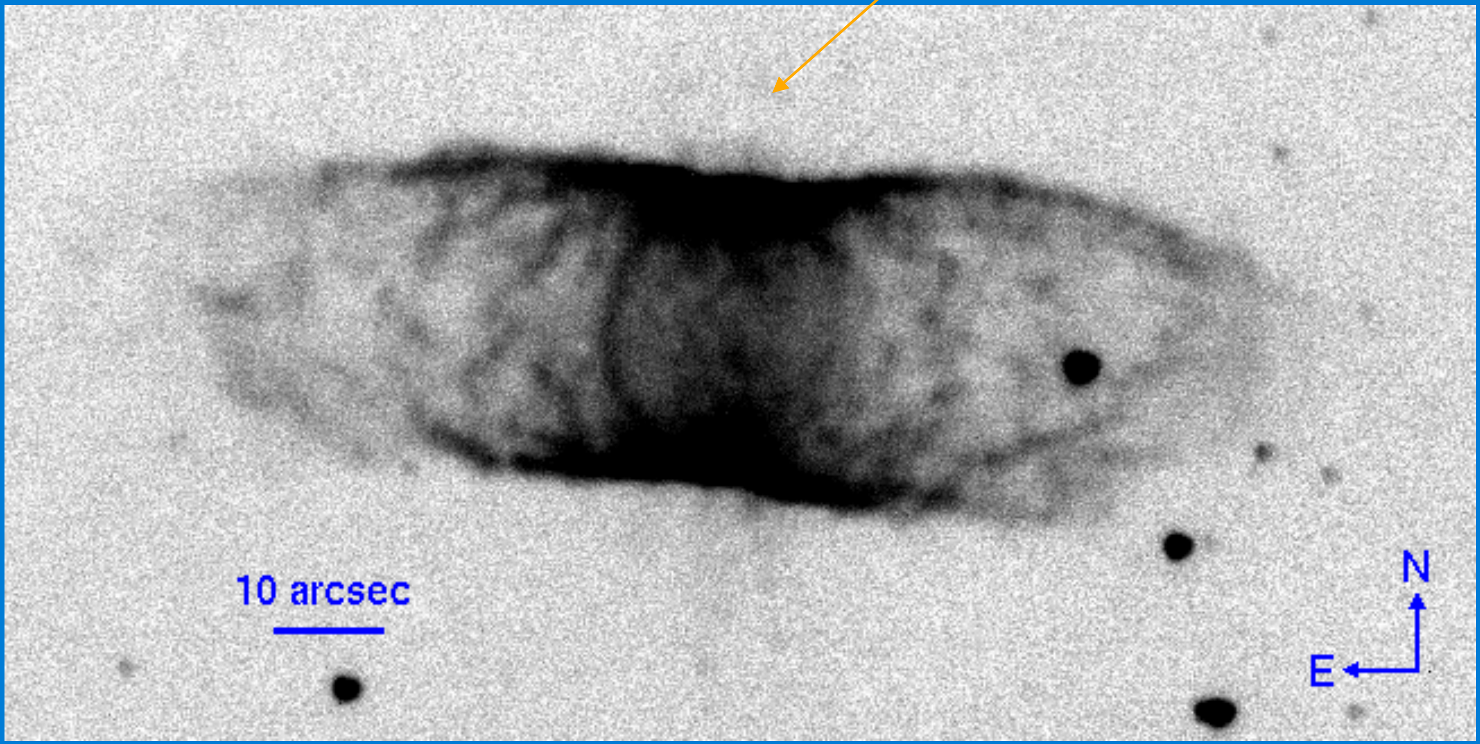
Eastern lobe



The sharp boundaries suggest that the optical lobes are confined by external medium

Sharp, well defined lobe boundaries

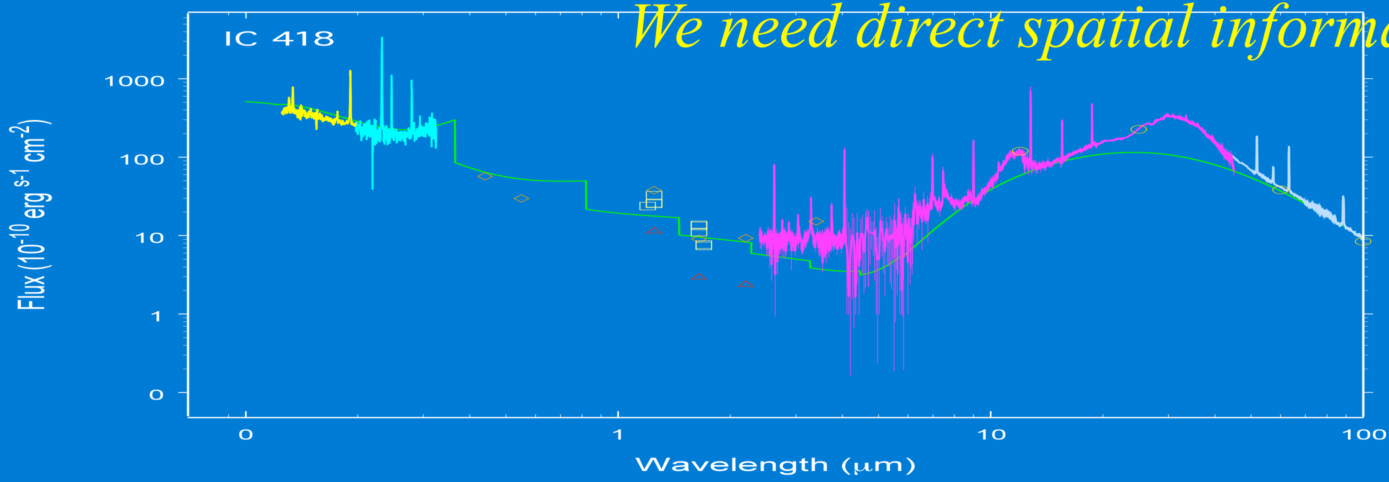
Unseen material



IC 4406 H_2

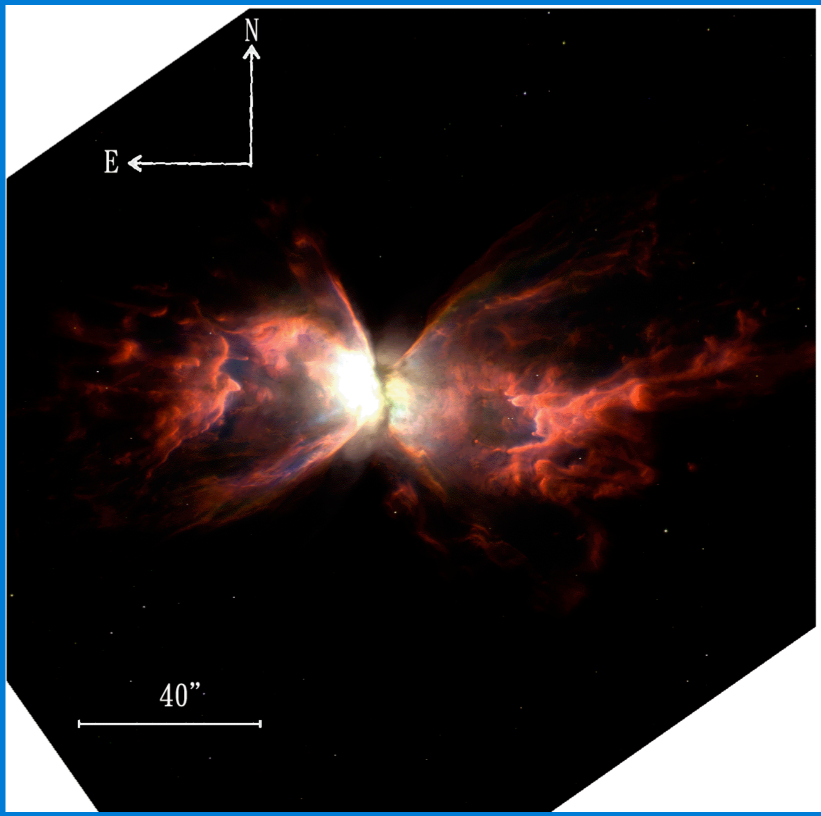
Where is the Dust?

We need direct spatial information



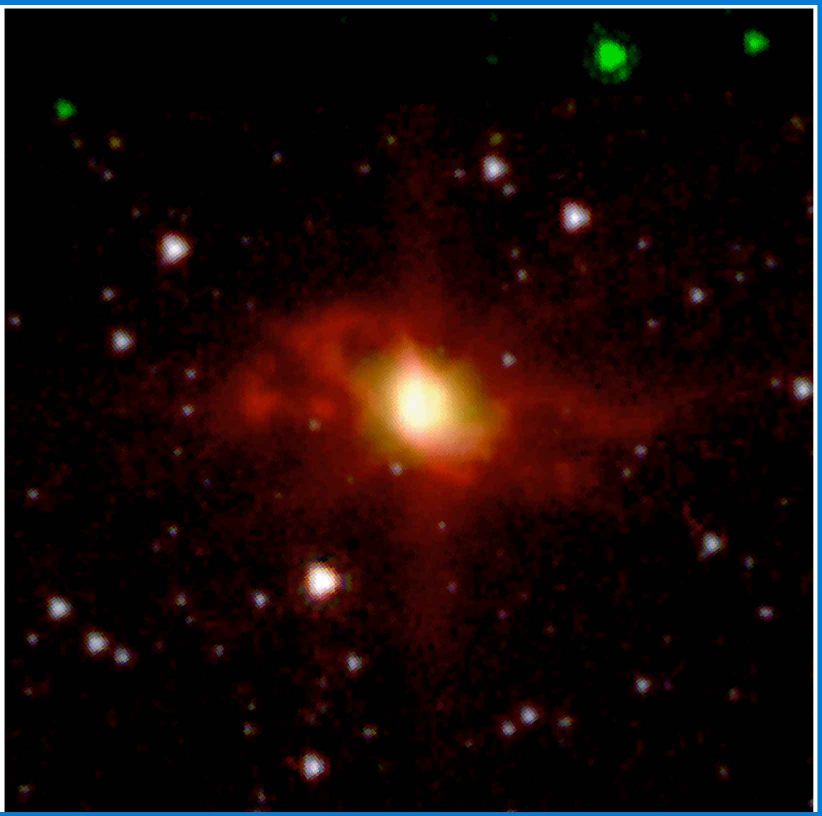
Completely different morphology

HST



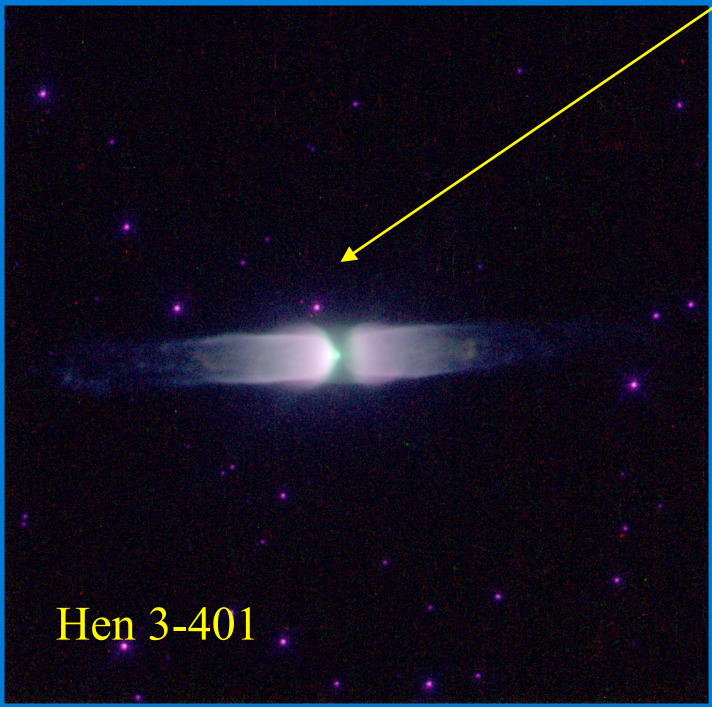
B:[OIII], G:Hα, R:[NII]

Spitzer IRAC



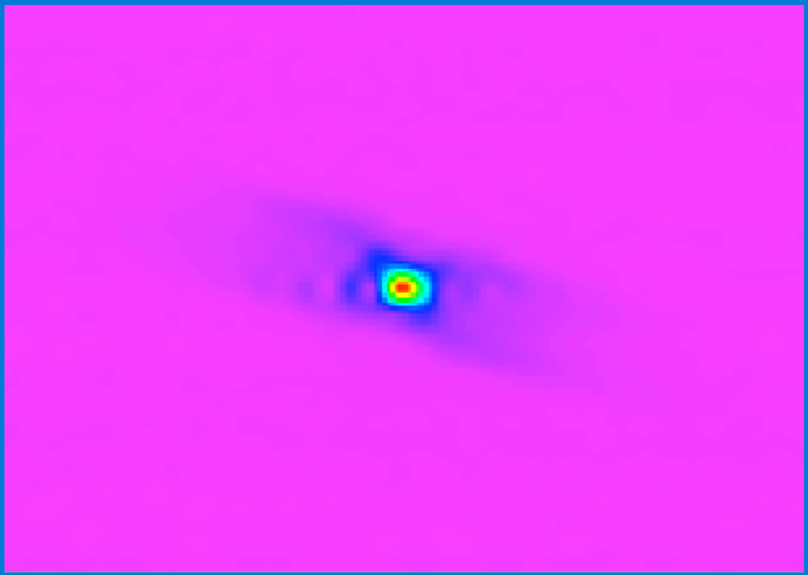
B: 3.6 μm, G: 4.5 μm , R: 8 μm

cold dust still not detected



Dust torus play a role in morphological transformation?

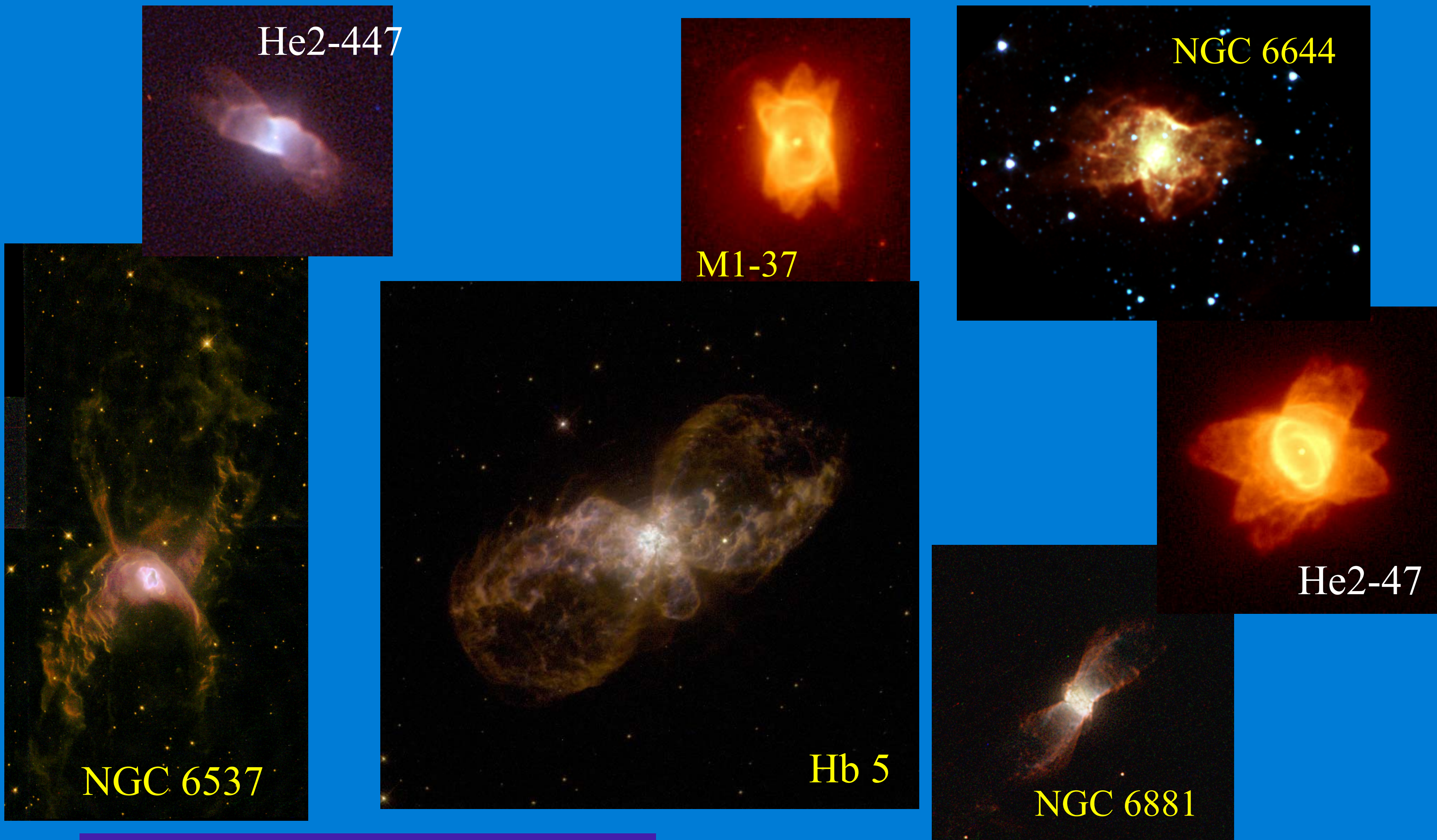
T-ReCS at Gemini South
(10.36, 10.38, 11.66, 12.33, 18.30, 24.56 μm)



At 20 μm we are still seeing warm dust in the torus and the lobes

Muthu et al. 2006

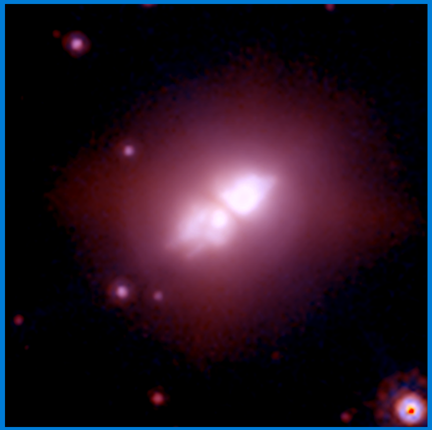
Morphological transformation



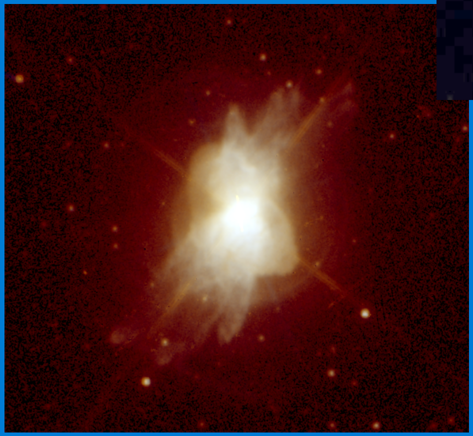
Shaping occurs early, in the PPN stage

The Silkworm Nebula

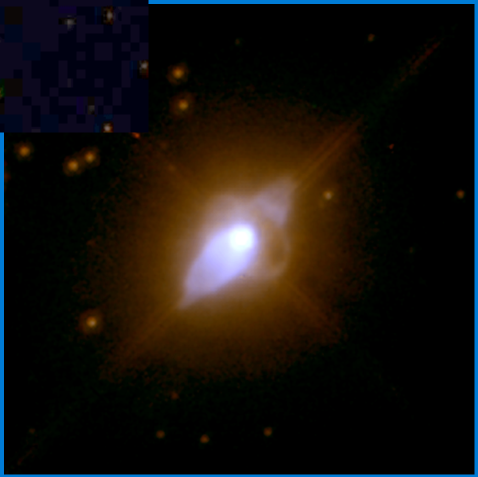
The Cotton Candy Nebula



The Walnut Nebula



The Water Lily Nebula

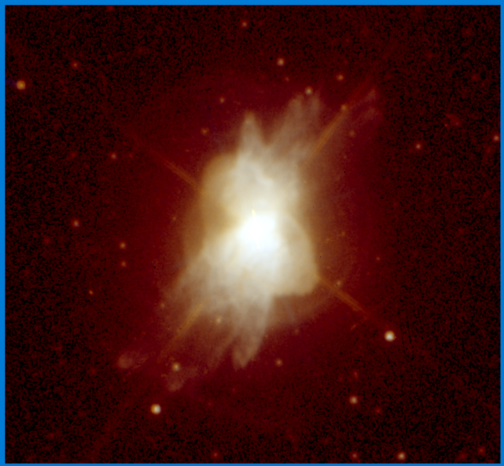


The Spindle Nebula

Bipolar structure clearly defined in mid-IR images

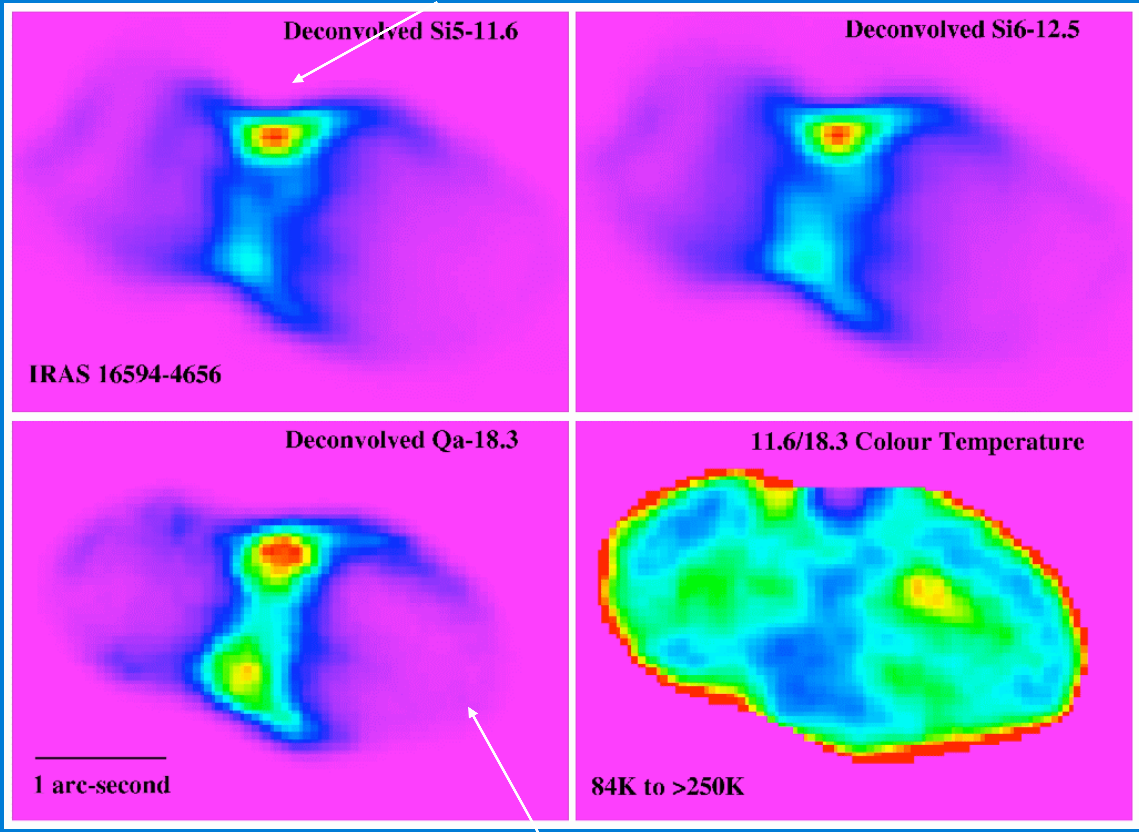
Edge-on torus

T-ReCS, Gemini South

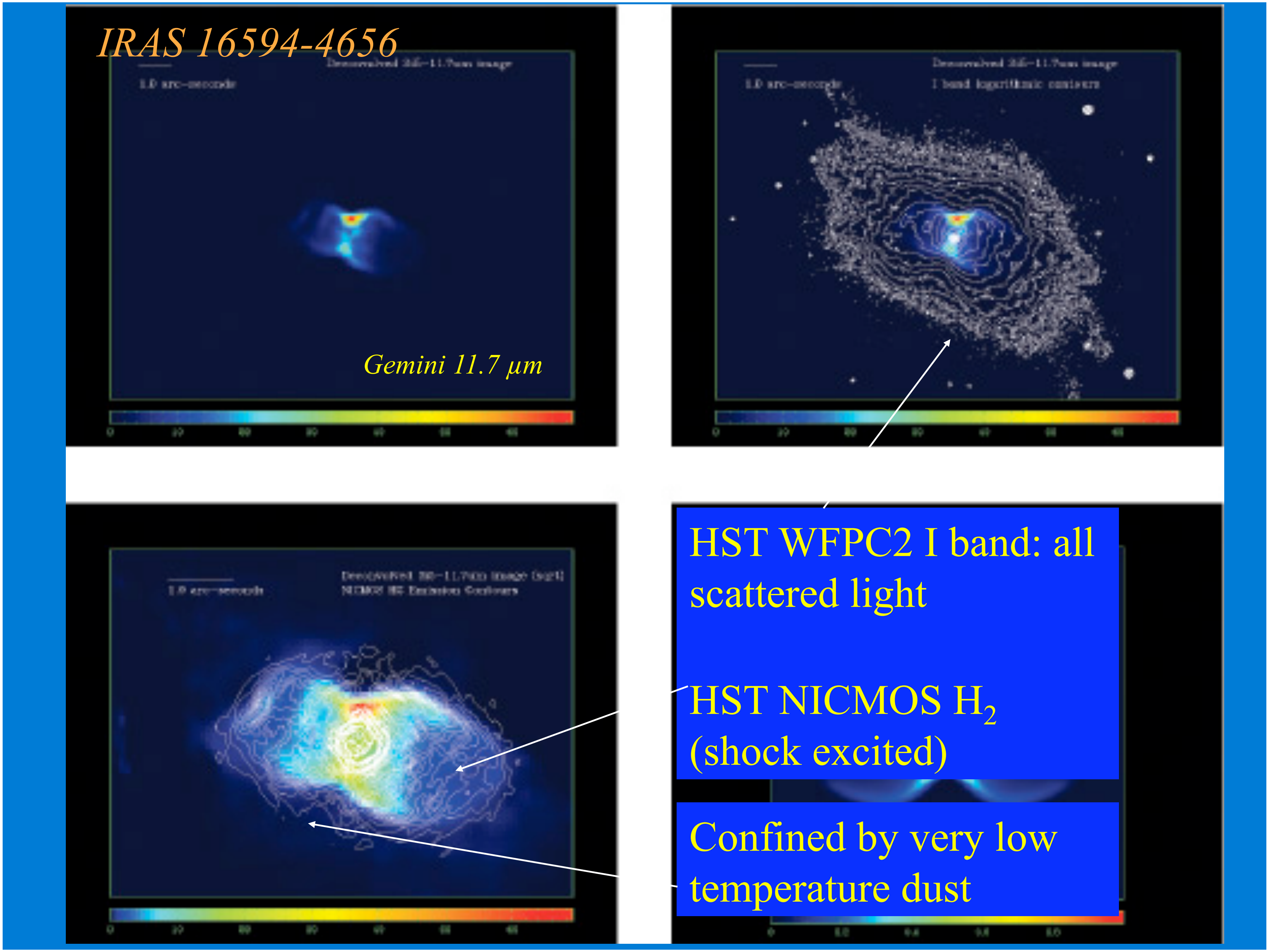


The proto-PN IRAS 16594-4656, the Water Lily Nebula

The optical image has complicated multipolar structure



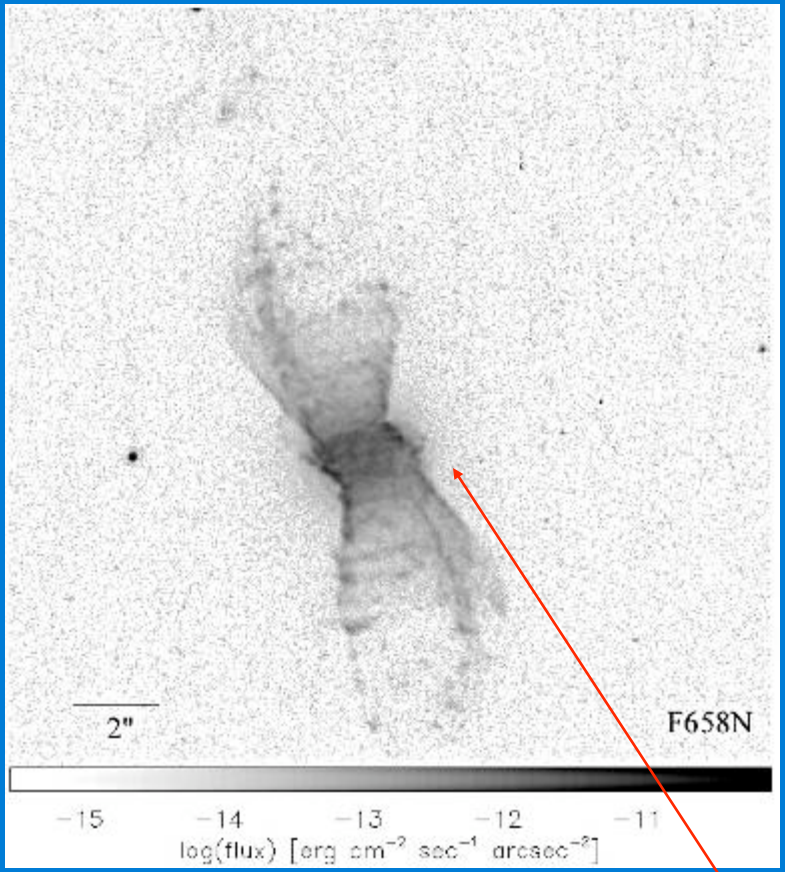
Closed lobes, fast wind yet to break through

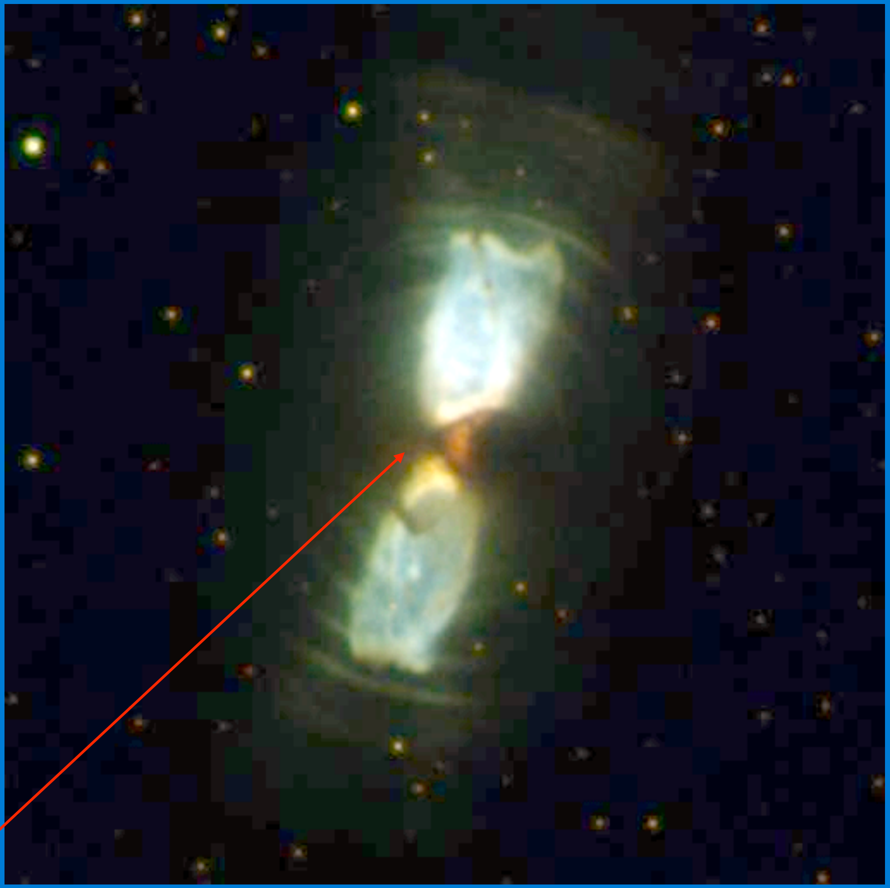


IRAS 16594-4656
Gemini 11.7 µm
HST WFPC2 I band: all scattered light
HST NICMOS H2 (shock excited)
Confined by very low temperature dust

PN: emission lines

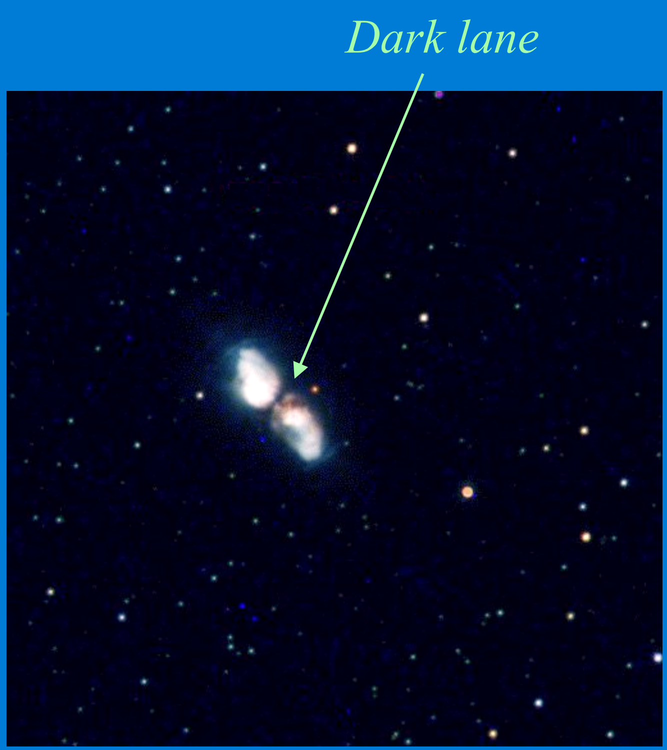
PPN: starlight scattered by dust

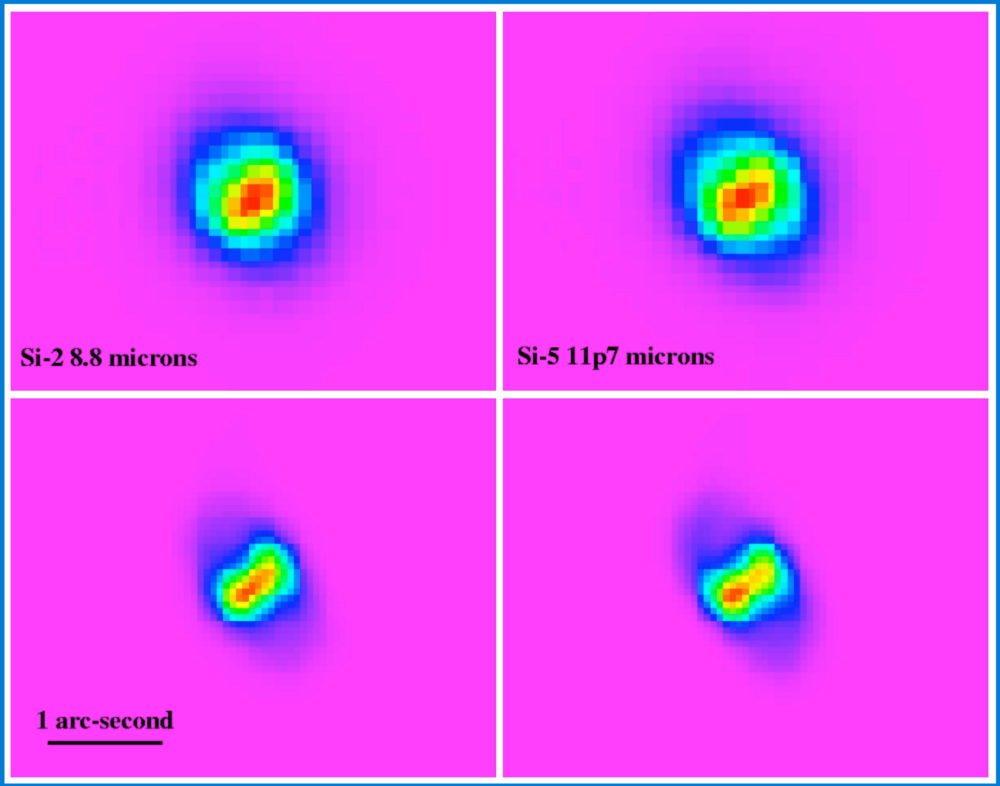




Dust torus

Dust torus revealed





Mid-IR Gemini images

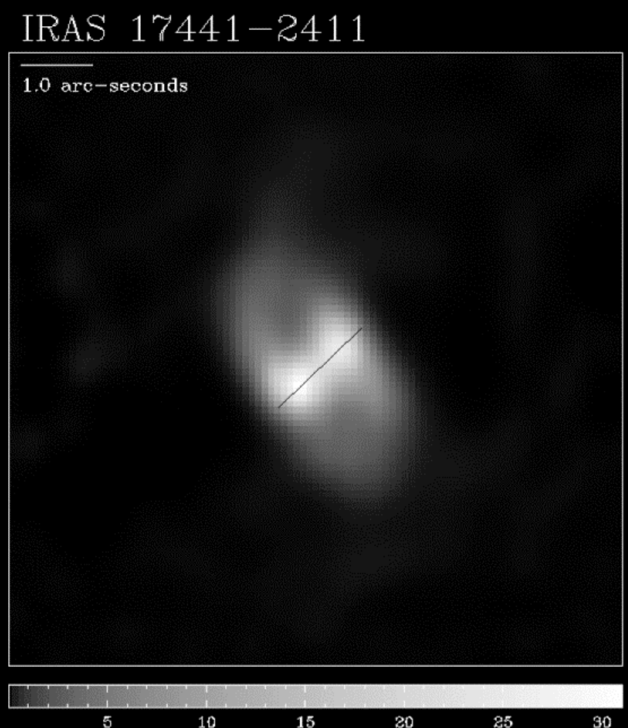
The proto-PN IRAS 17441-2411, the Silkworm Nebula

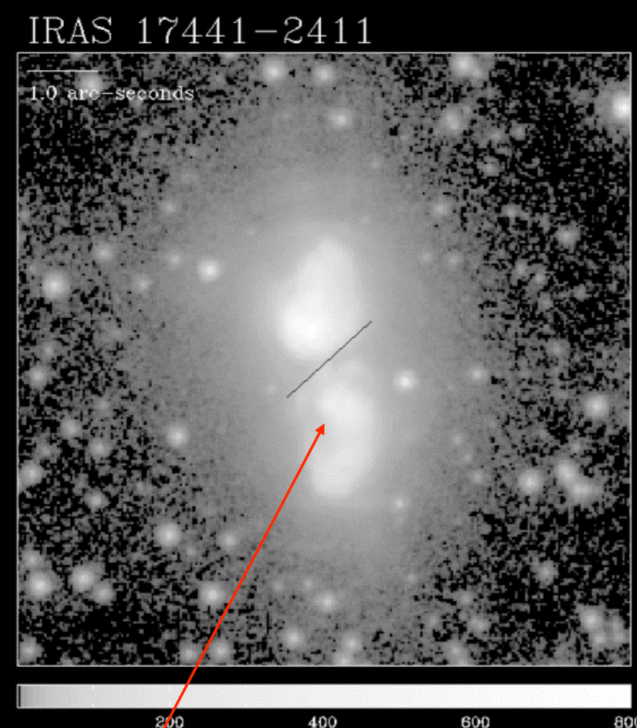
Volk and Kwok (2007)

Equatorial disk as collimating agent

Infrared disk

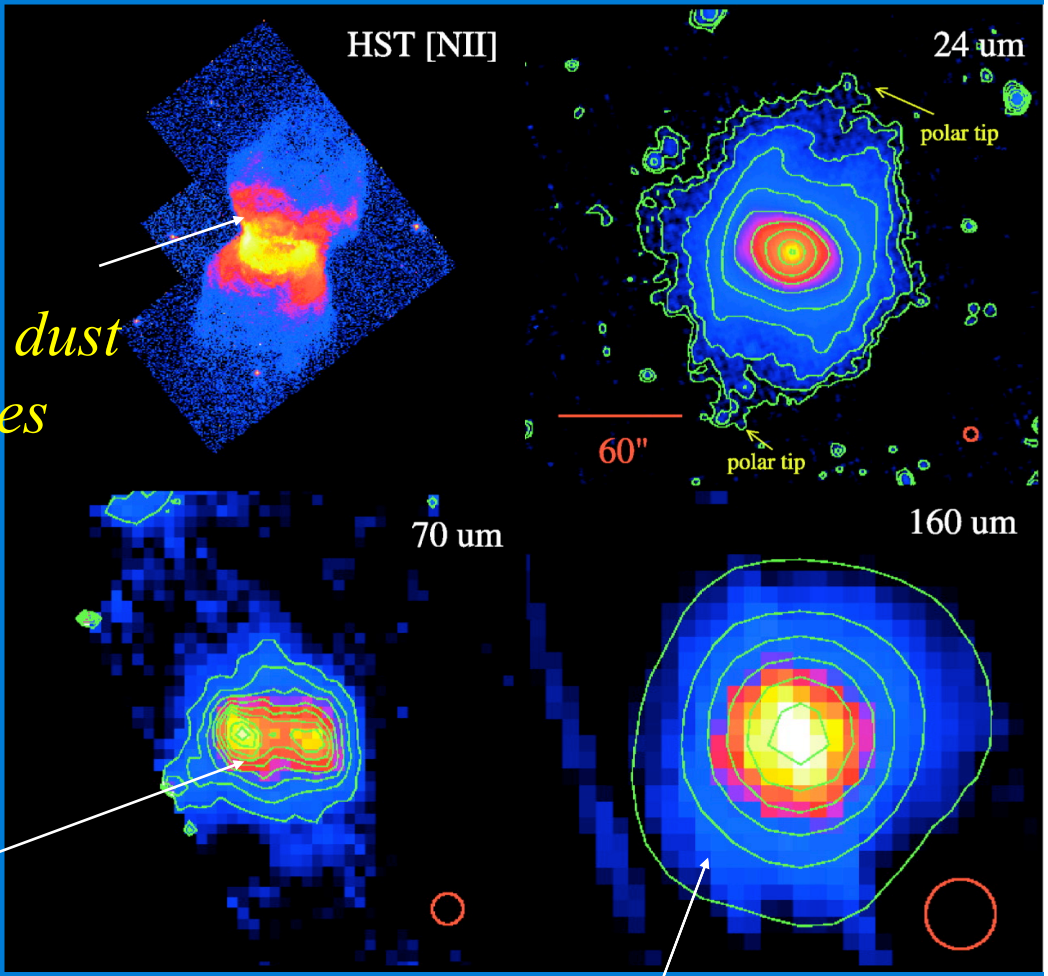
Superimposed on optical image





Misaligned by 23 degrees!

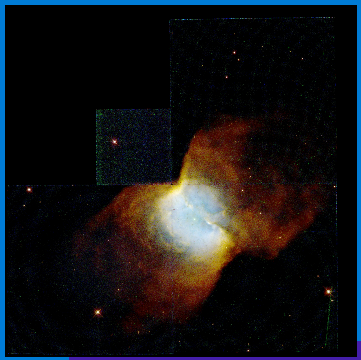
Spitzer MIPS images



Warm dust in lobes

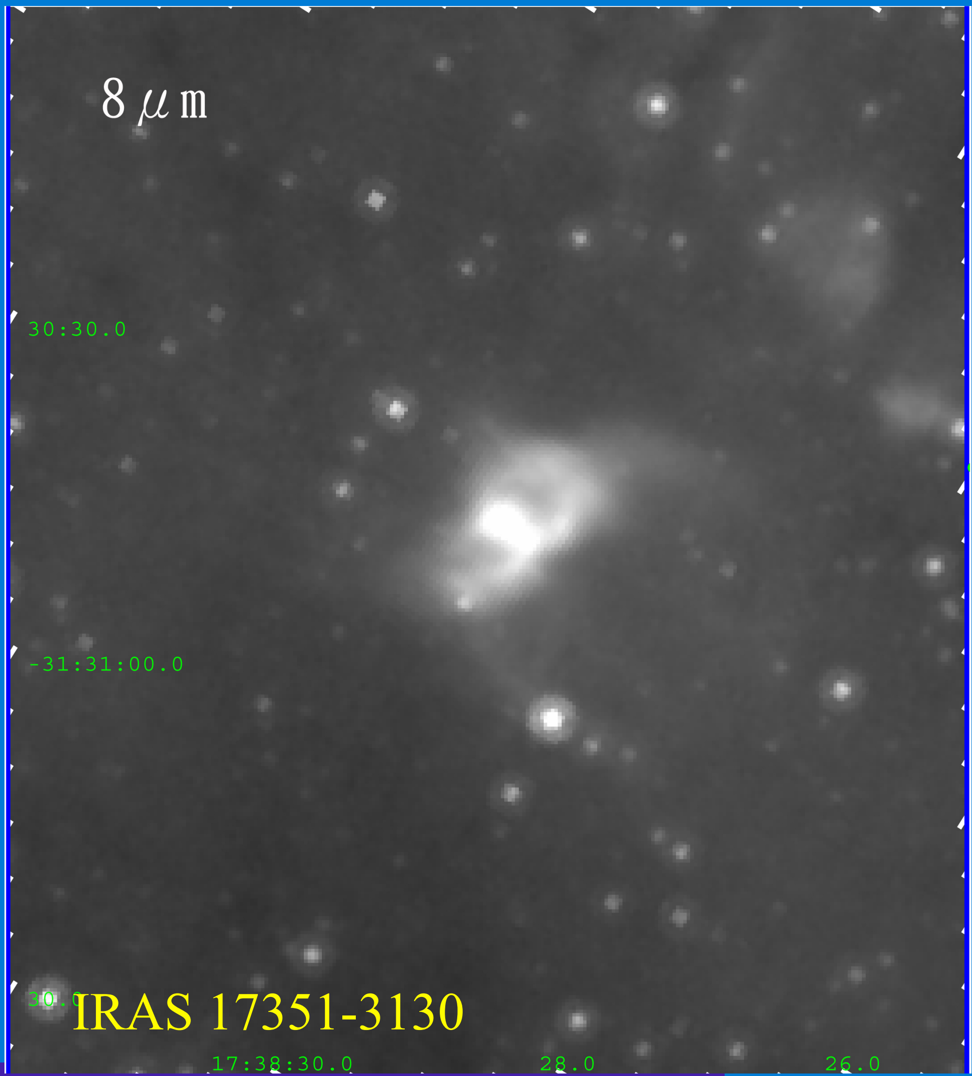
torus

AGB remnant



Su et al. 2004

Morphology and large scale structures

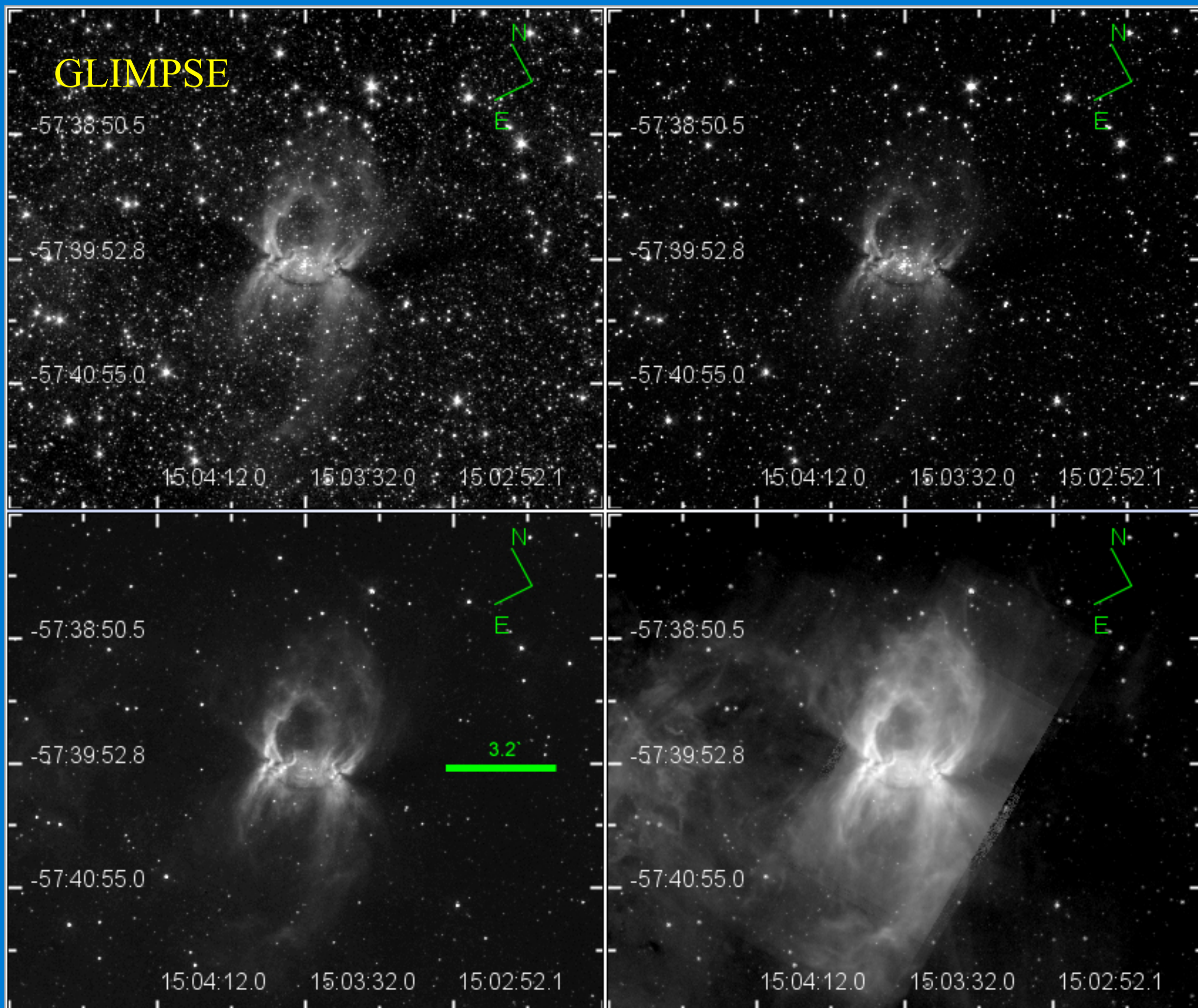


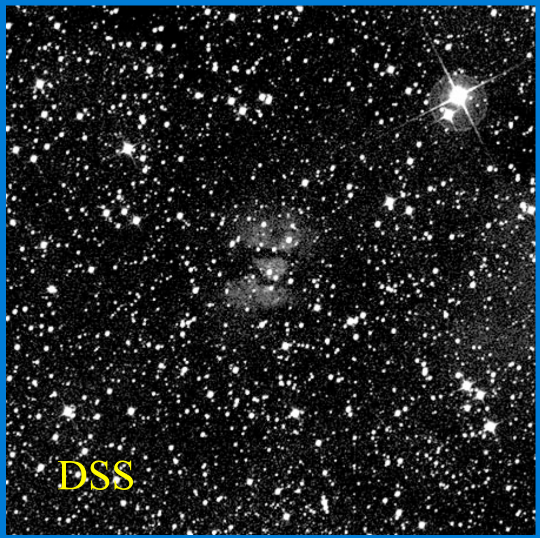
Bipolar morphology revealed by dust in the lobes

Traditional morphological classification is based on optical apparent structures and does not tell the entire story

GLIMPSE 8 μm

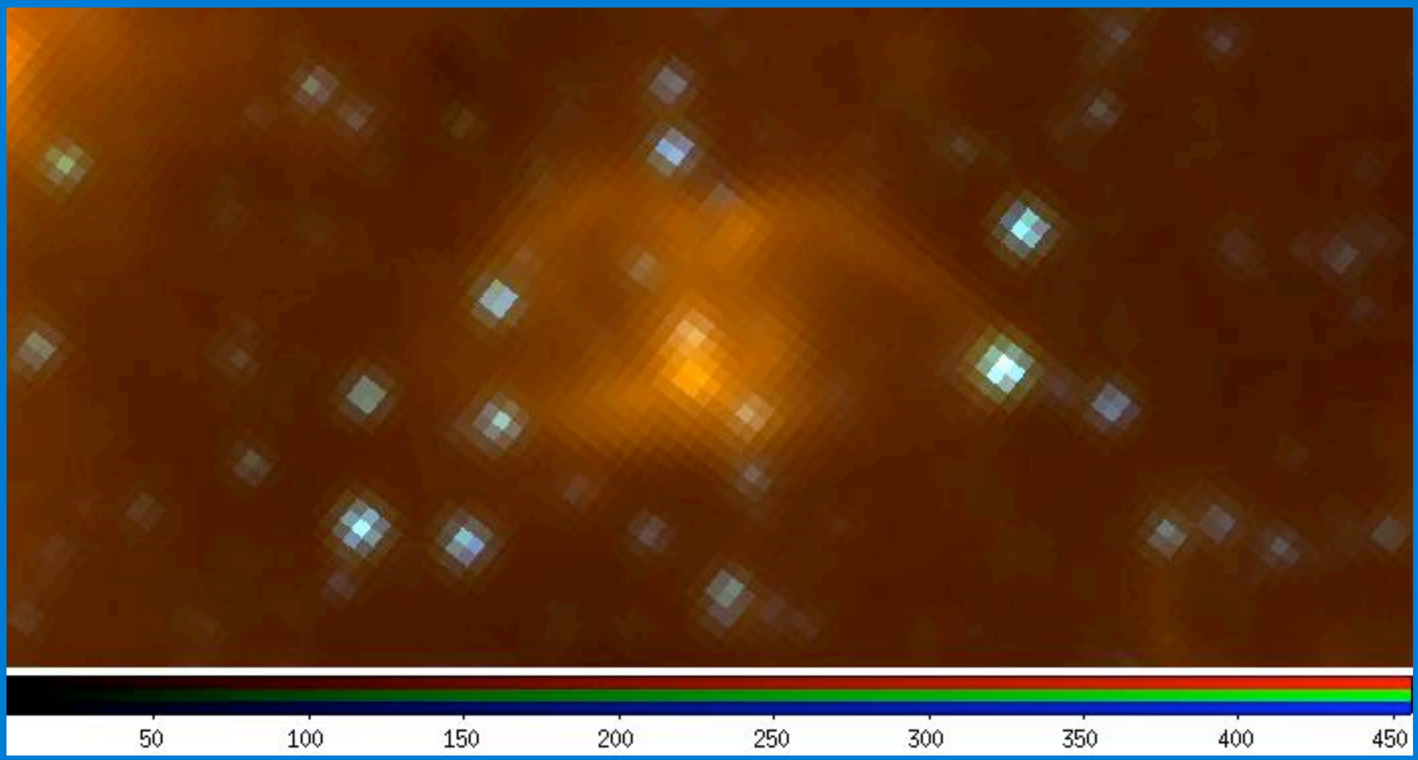
Dust as a tracer of bipolar lobes





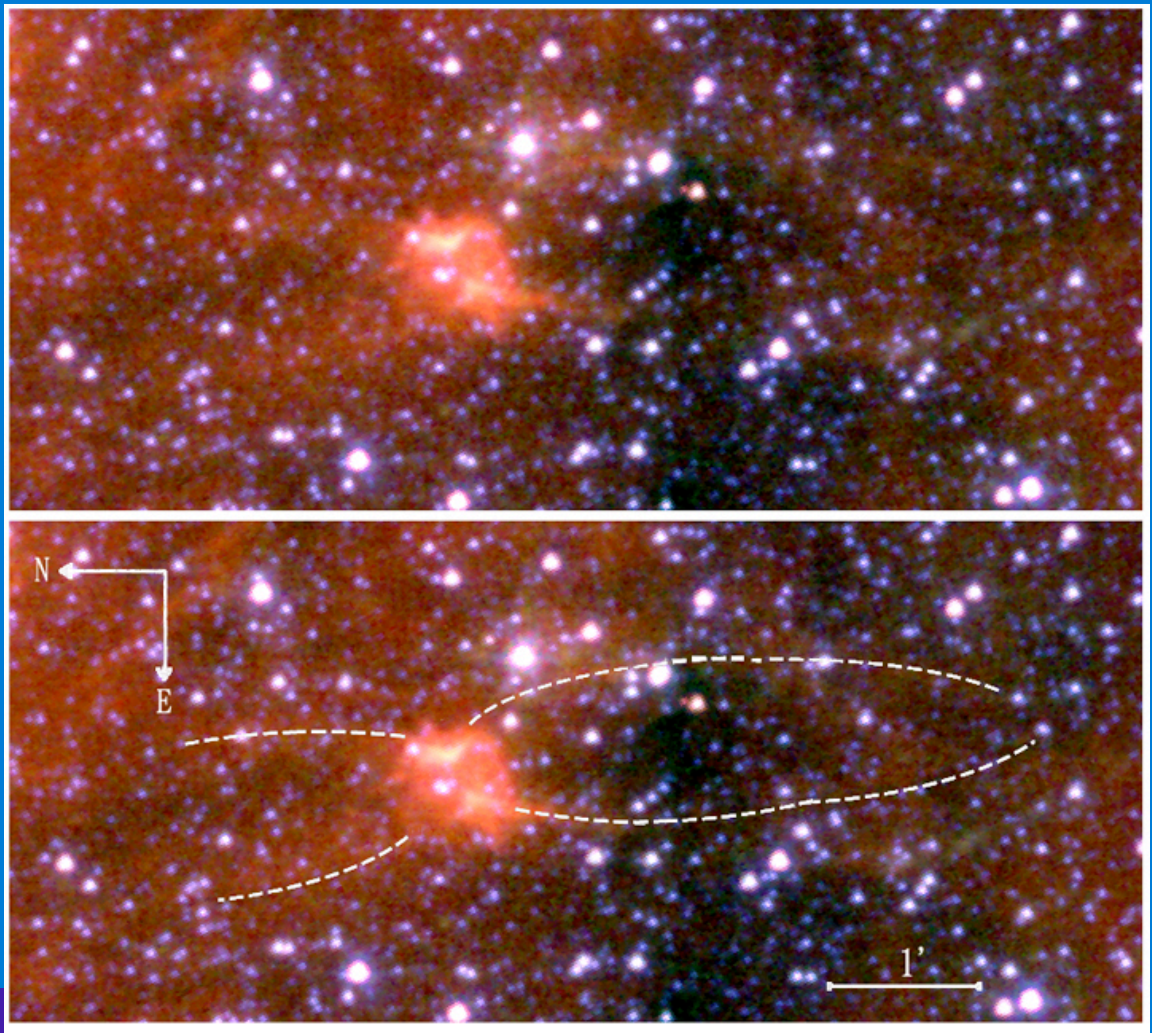
Near invisible in the optical, the bipolar nebula is bright in the IR

Infrared bipolar



Discovered in the GLIMPSE field, invisible in the optical

Wide field imaging



M1-41, GLIMPSE color composite

Model of PN

- Most of the mass of a PN is in the remnant AGB (spherical) envelope
- Post-AGB collimated fast outflows create cavities in the envelope (channeled by a torus?)
- PPN: dust scattering of visible photons from the central star lead to bipolar nebulosity
- PN: UV photons from the now hot central star ionize the low-density cavity, illuminating the bipolar region

Far IR imaging

- high spatial resolution far-IR imaging will reveal the cold dust component of PN, therefore tracing the distribution of mass
- Infer the mechanism of collimation and shaping

Kinematic components

- AGB mass loss
- Equatorial outflow ("torus")
- Collimated fast outflow
- Swept up shell

Kinematic structure to be studied by integral field spectroscopy

implications

- PN are bright and have been extremely well studied in the optical by both imaging and spectroscopy
- Yet we do not understand the origin of their structure other than they are the result of interacting winds dynamics
- Lessons can be applied to WR nebulae, SN, YSO, AGN

Synthesis of complex organic compounds in post-AGB evolution

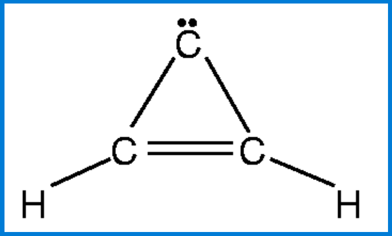
- AGB: over 60 gas-phase molecules including chains and rings
- Late AGB (extreme carbon stars): acetylene
- PPN: aromatics and aliphatics
- PN: strong aromatics

By comparing the spectra of AGB-PPN-PN, we can trace the path of organic synthesis

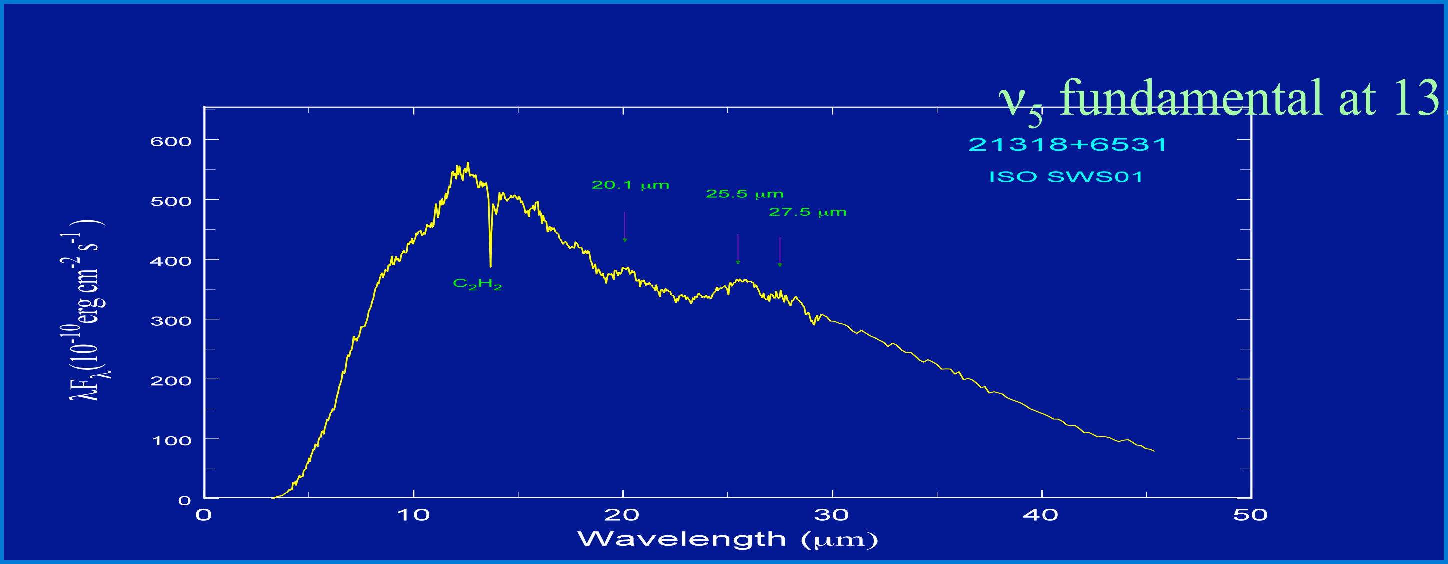
Kwok, Volk & Hrivank 1999, A&A, 350, L35; Kwok, Volk, & Bernath 2001, ApJ, 554, L87; Kwok 2004, Nature, 430, 985

Circumstellar molecules

- Rotational transitions of over 60 molecules have been detected in the circumstellar envelopes of AGB stars
- Inorganics: CO, SiO, SiS, NH_3, $AlCl$, ..
- Organics: C_2H_2, CH_4, H_2CO, CH_3CN, ..
- Radicals: CN, C_2H, C_3, HCO^+
- Rings (C_3H_2), chains (HC_9N)

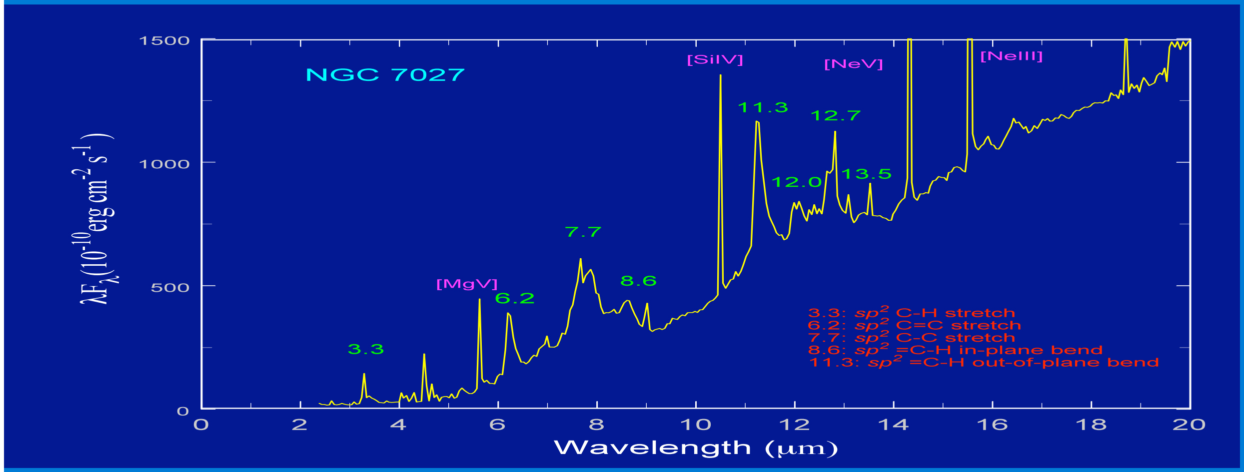


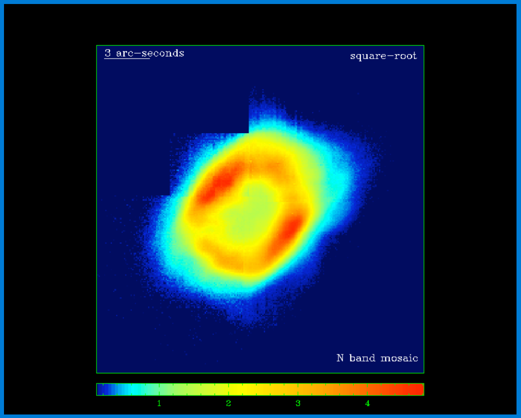
Acetylene: signature of extreme carbon stars



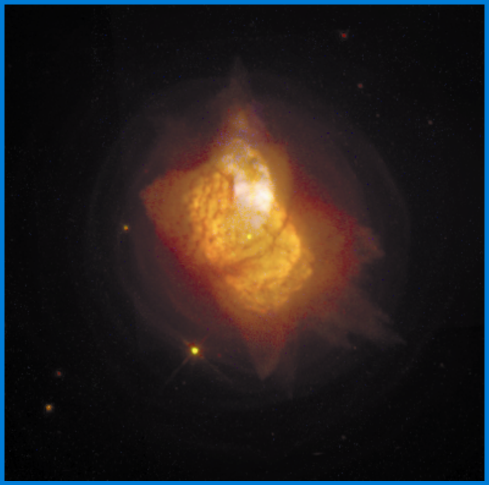
ν_5 fundamental at 13.7 μm.

Aromatic Compounds in PN



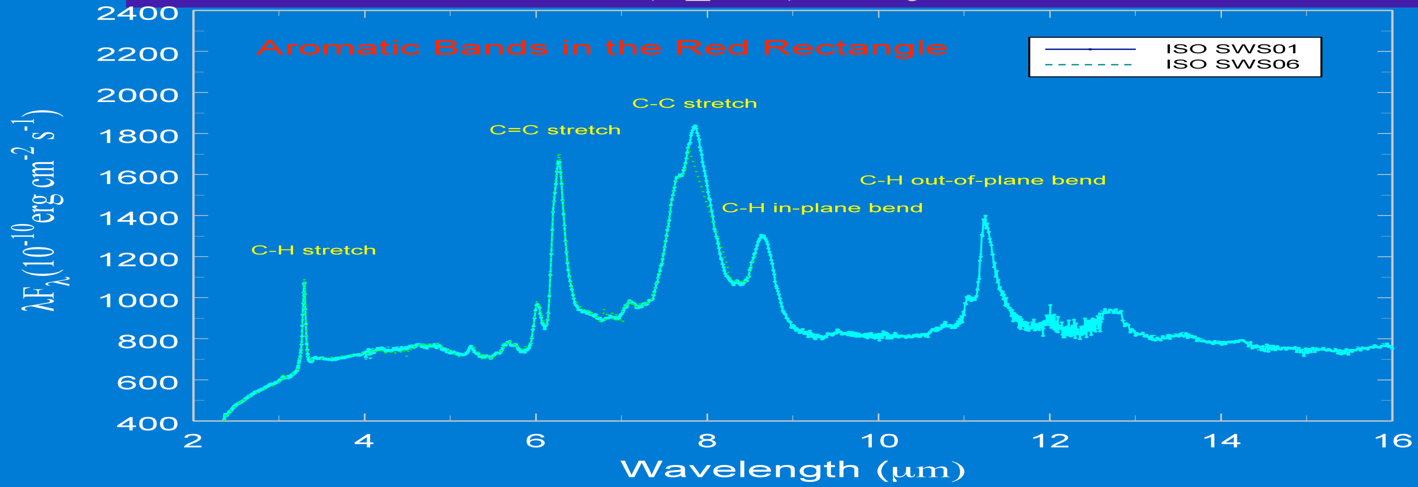


Gemini OSCIR



Aromatic compounds must have been synthesized in the post-AGB evolution

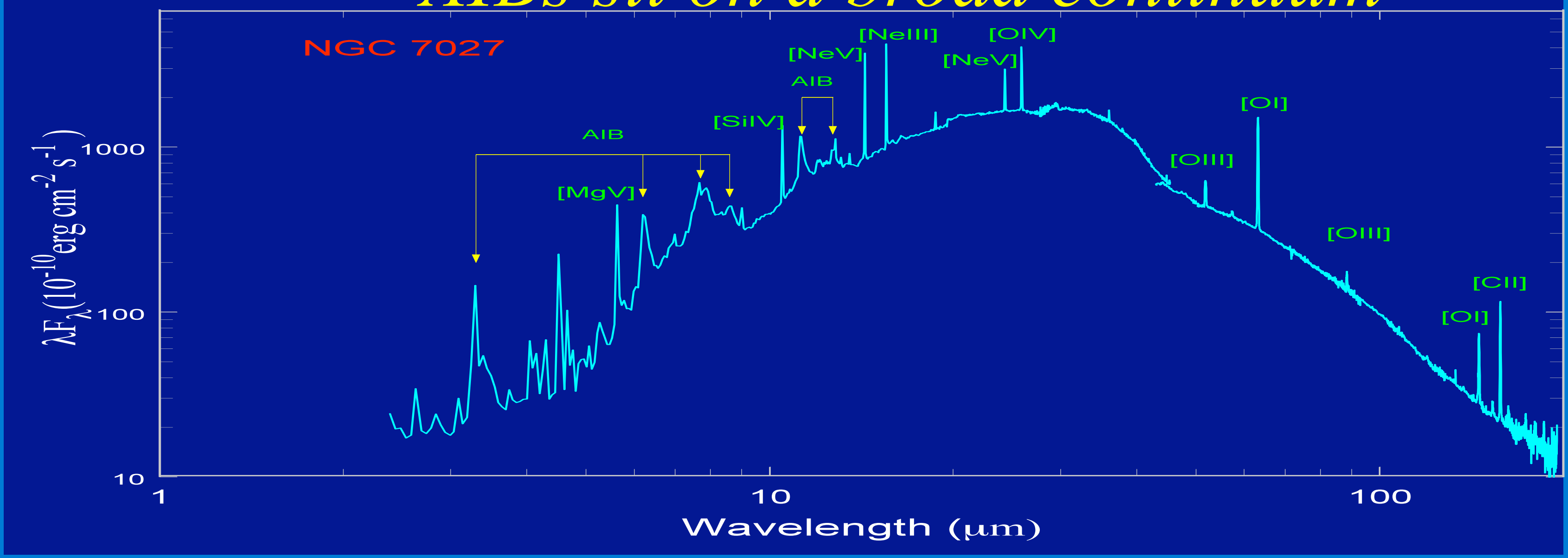
Aromatic (sp^2) hydrocarbon bands



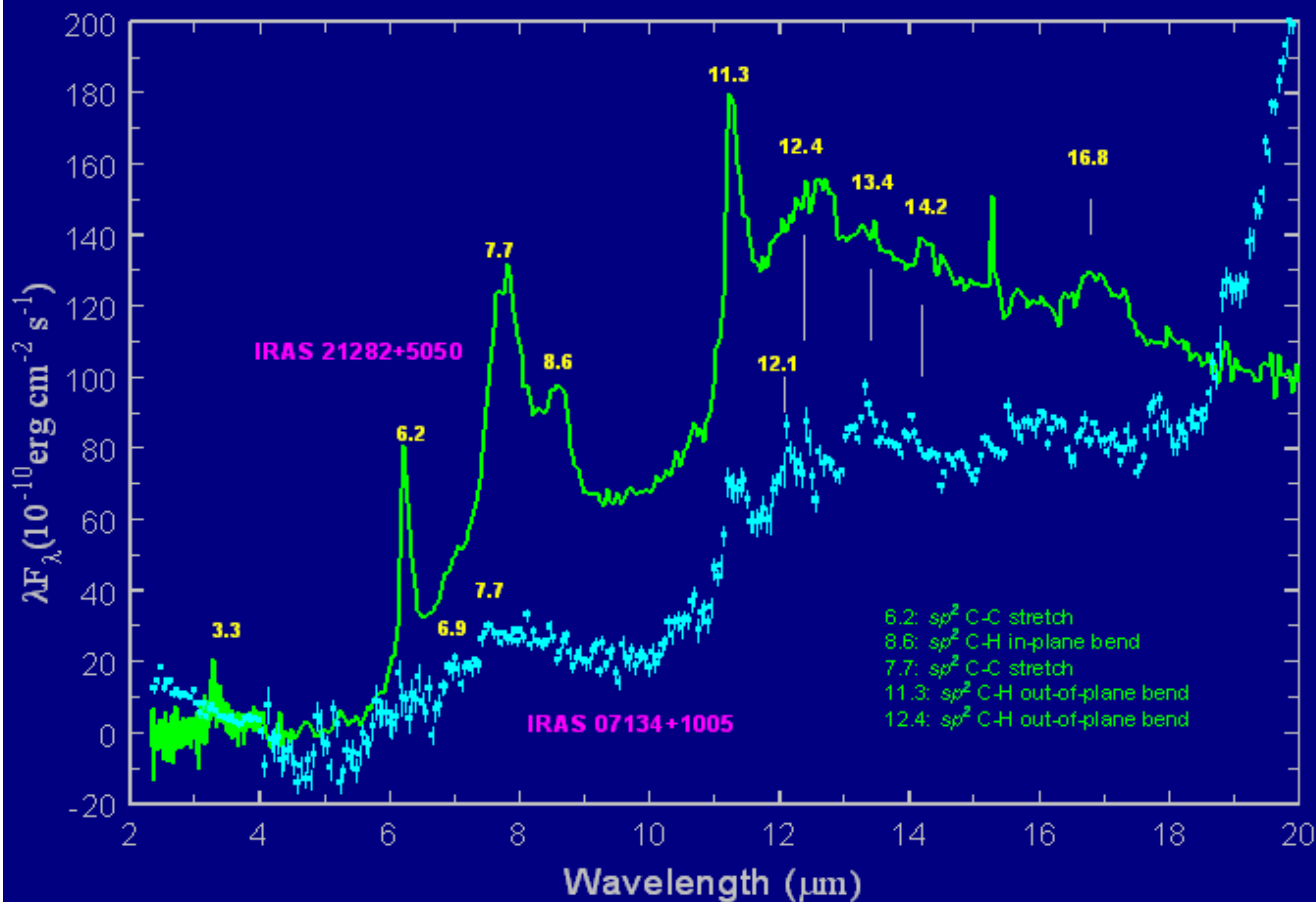
Knacke 1977, Nature 269, 132

Duley & Williams 1979, Nature 277, 40

AIBs sit on a broad continuum



Aromatic and aliphatic features in PPN

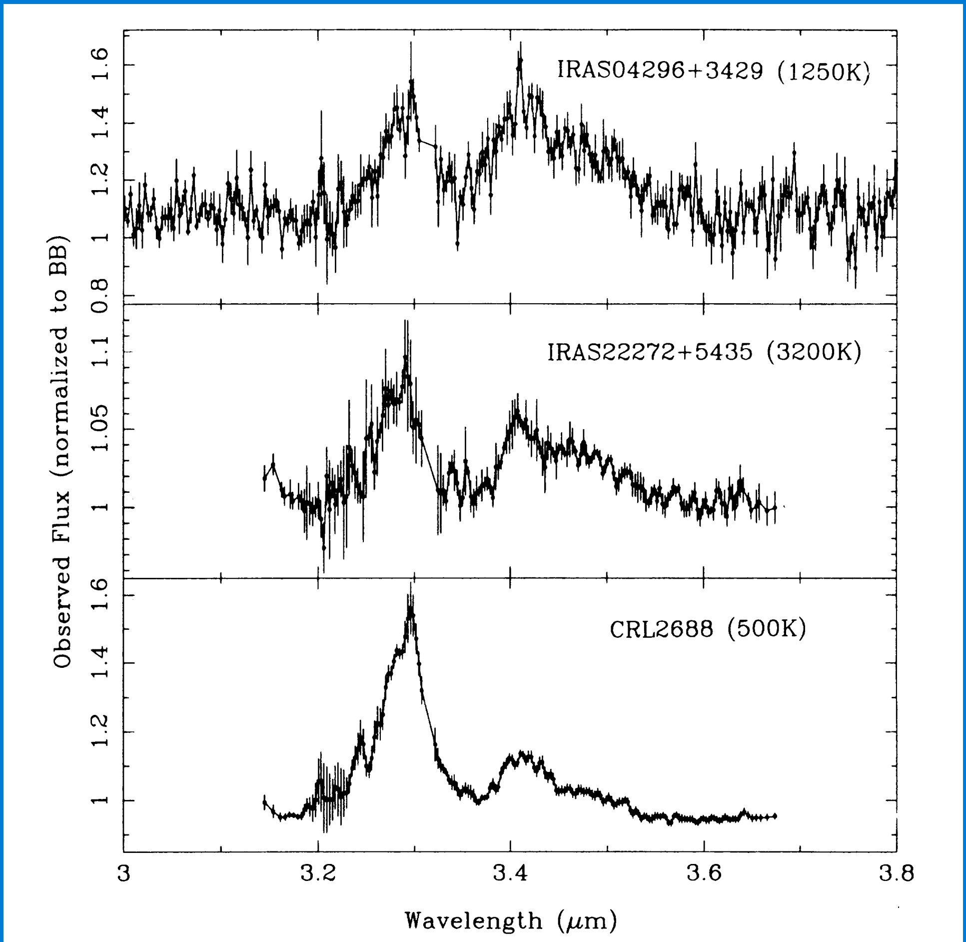


3.4 µm aliphatic C-H stretch

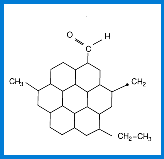
- 3.38 µm: asymmetric CH_3
- 3.42 µm: asymmetric CH_2
- 3.46 µm: lone C-H group
- 3.49 µm: symmetric CH_3
- 3.51 µm: asymmetric CH_2

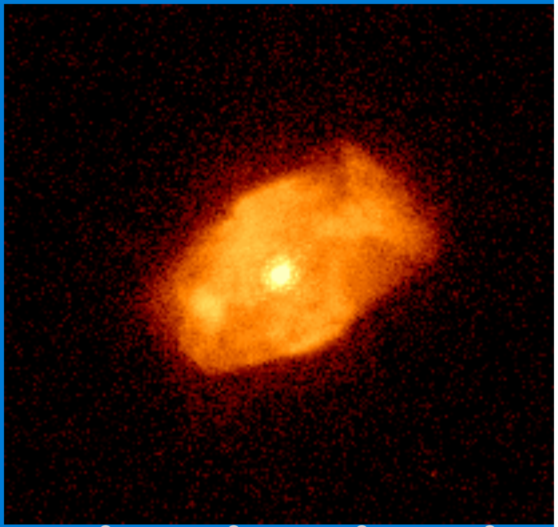
Not pure aromatics!

3 µm spectra of PPN



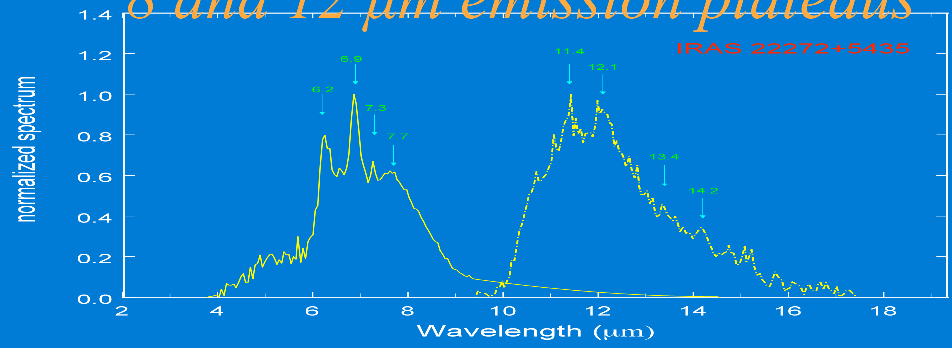
Aliphatic sidegroups

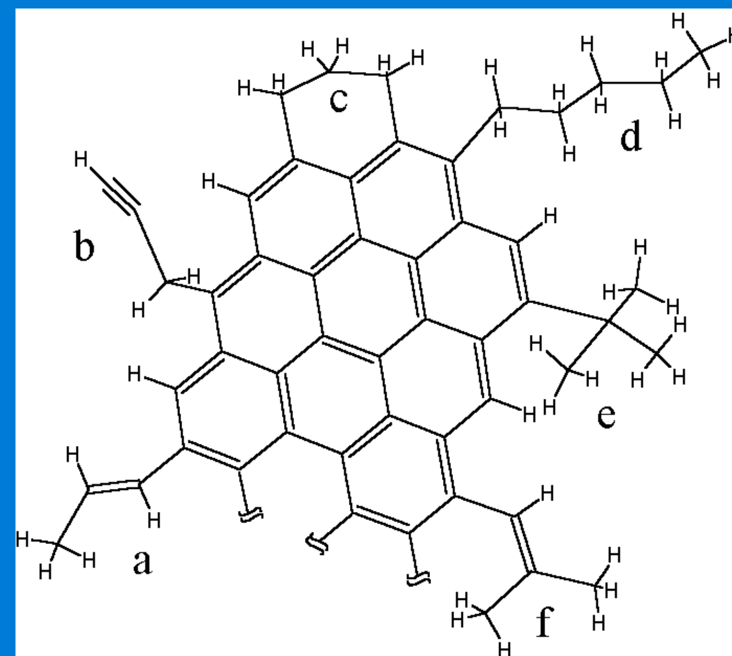




Aliphatic bending modes

8 and 12 μm emission plateaus

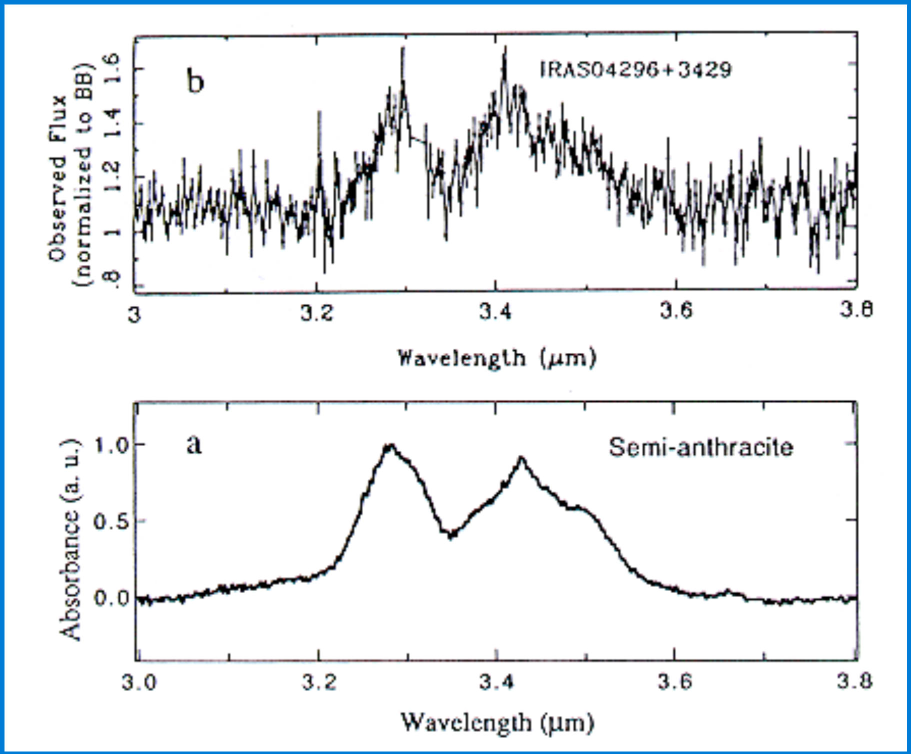


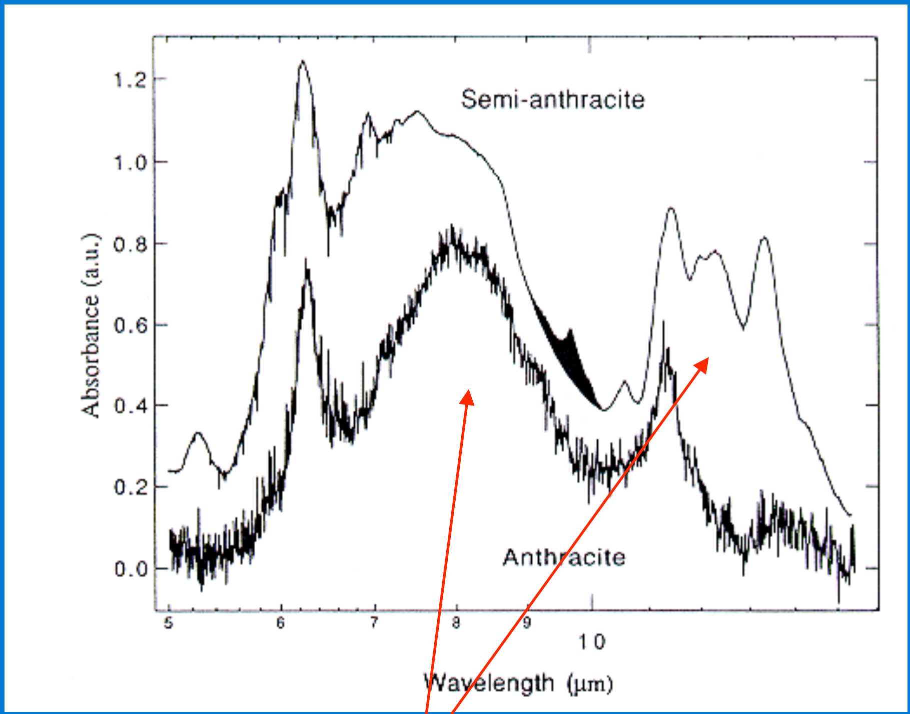


Kwok et al. 2001

- 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”).

Infrared Spectrum of Coal





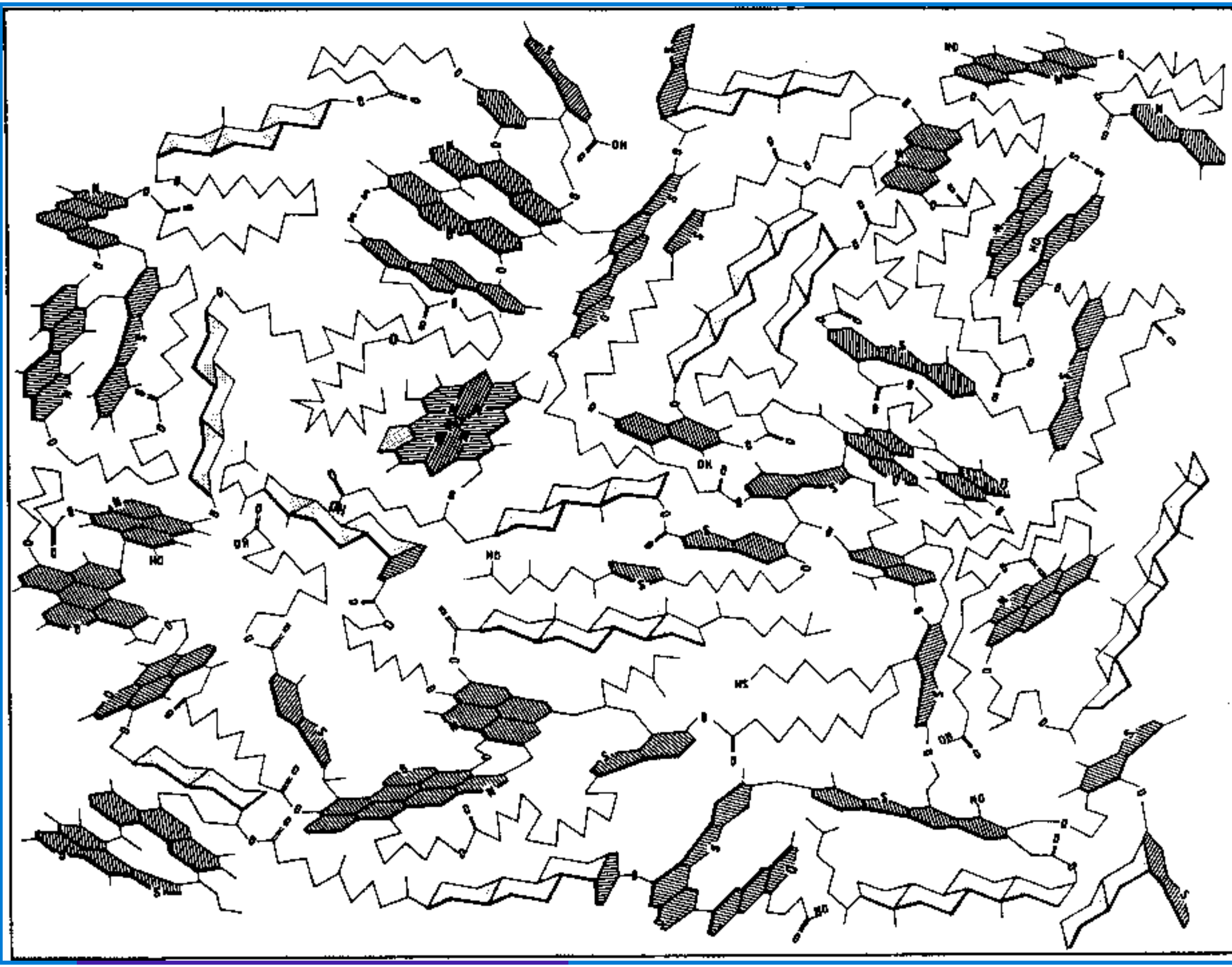
Guillois et al. 1996

Emission plateaus

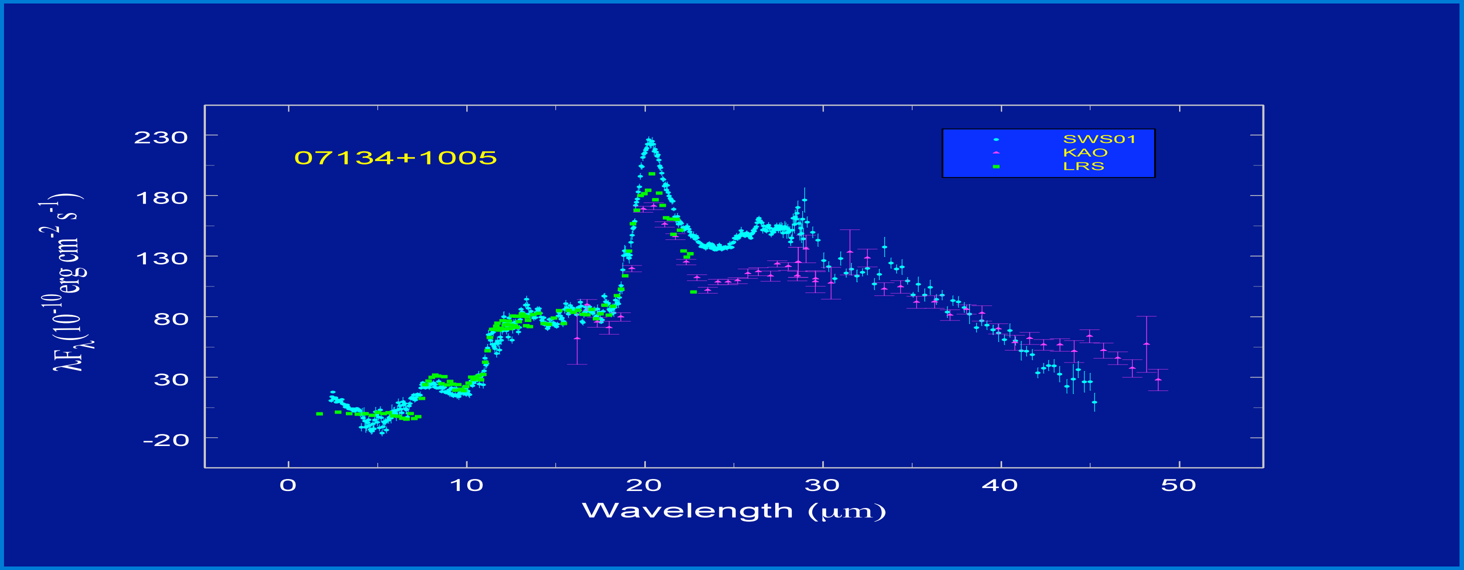
The chemical structure of the carrier is similar to that of coal and kerogen

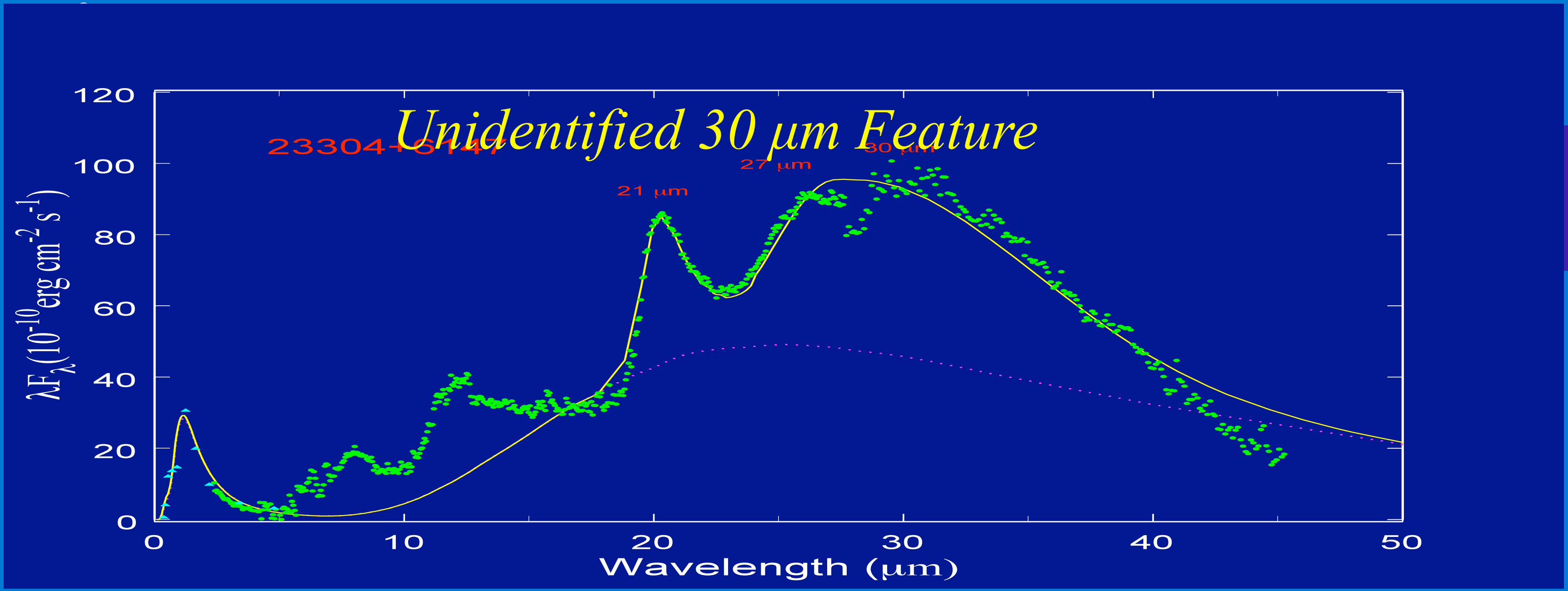
Kerogen

- random arrays of aromatic carbon sites, aliphatic chains ($(-CH_2-)_n$), and linear chains of benzenic rings with functional groups made up of H, O, N, and S attached
- a solid sedimentary, insoluble, organic material found in the upper crust of the Earth



Carbon-rich PPN with the Unidentified 21 μm Feature




Unidentified 30 µm Feature
23304+6147
21 µm
27 µm
30 µm
$\lambda F_\lambda (10^{-10} erg\ cm^{-2} s^{-1})$
Wavelength (µm)
0
20
40
60
80
100
120
0
10
20
30
40
50

<table>
<tr><th>UIR features (μm)</th><th>Origins</th><th>Extreme Carbon Stars</th><th>Proto-Planetary Nebulae</th><th>Planetary Nebulae</th></tr>
<tr><td>3.3, 6.2, 7.7, 11.3</td><td>aromatic stretch and bending modes</td><td>no</td><td>yes</td><td>strong</td></tr>
<tr><td>3.4, 6.9</td><td>C-H aliphatic stretch and bend</td><td rowspan="2">no</td><td rowspan="2">yes</td><td rowspan="2">weak</td></tr>
<tr><td>12.1, 12.4, 13.3</td><td>C-H out-of-plane bend with 2, 3, 4 adjacent H atoms</td></tr>
<tr><td>broad 8, 12</td><td>-</td><td>no</td><td>yes</td><td>yes</td></tr>
<tr><td>21</td><td>-</td><td>weak</td><td>strong</td><td>no</td></tr>
<tr><td>25.5, 27.2</td><td>-</td><td>yes</td><td>yes</td><td>yes</td></tr>
</table>

Chemical evolution from AGB to PN

- Extreme carbon stars ($t \sim 10^4$ yr): $C_2H_2 \Rightarrow C_6H_6$
- PPN ($t \sim 10^3$ yr): clusters of aromatic rings with peripheral aliphatic bonds
- PN ($t \sim 10^4$ yr): loss of H and a progressive formation of clusters of rings into more structured units

Complex amorphous organic solids are being synthesized in large quantities in the late stages of stellar evolution and ejected into the ISM

Photochemistry

- The 8 and 12 μm plateau features are due to a variety of alkane and alkene groups attached to hydrogenated aromatic rings.
- When exposed to UV light, the aliphatic side groups are modified, leading to larger aromatic rings.
- Isomerization, bond migrations, cyclization reactions.
- Ring closure and cycloaddition transform alkenes into ring systems.
- H loss leads to fully aromatic rings

Net result: UV transforms aliphatic to aromatic groups

Advantages of circumstellar chemistry

- Single energy source
- Simple geometry
- Well-determined physical environment (density *ρ(r)*, temperature *T(r)*, radiation background *I(r)*)
- Chemical time scale defined by dynamical time scale (AGB: 10^4 yr, PPN: 10^3 yr, PN: 10^4 yr)

Implications

- PPN and PN are the only objects that we can directly see complex organics forming, with a synthesis time scale of 10^3 yr
- These organics are similar to the *insoluble organic matter (IOM)* seen in meteorites, comets, asteroids, and IDPs
- The discovery of presolar grains gives direct proof that stellar grains have reached the Solar System

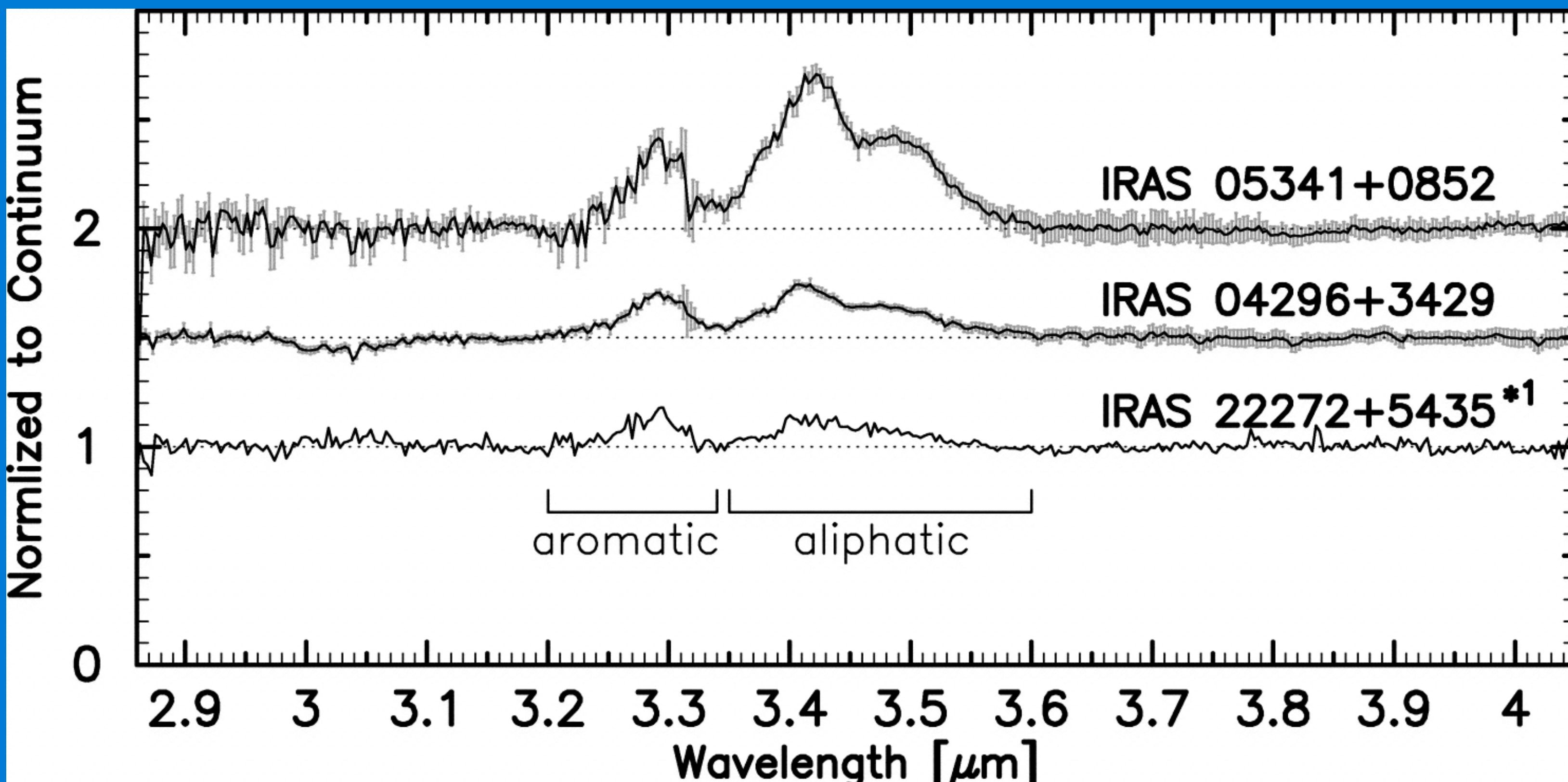
Stellar Solar System connection

SOFIA imaging observations

- Broad band far IR imaging: distribution of cold dust beyond the warm torus
- Narrow band imaging: distribution of complex organics
- Optically thin: no extinction effects, direct tracer of dust density and temperature

Diffraction-limited 3-μm spectroscopy

Subaru IRCS



05341: unresolved, 04296: 400-640 AU, 22272: extends to 2000 AU

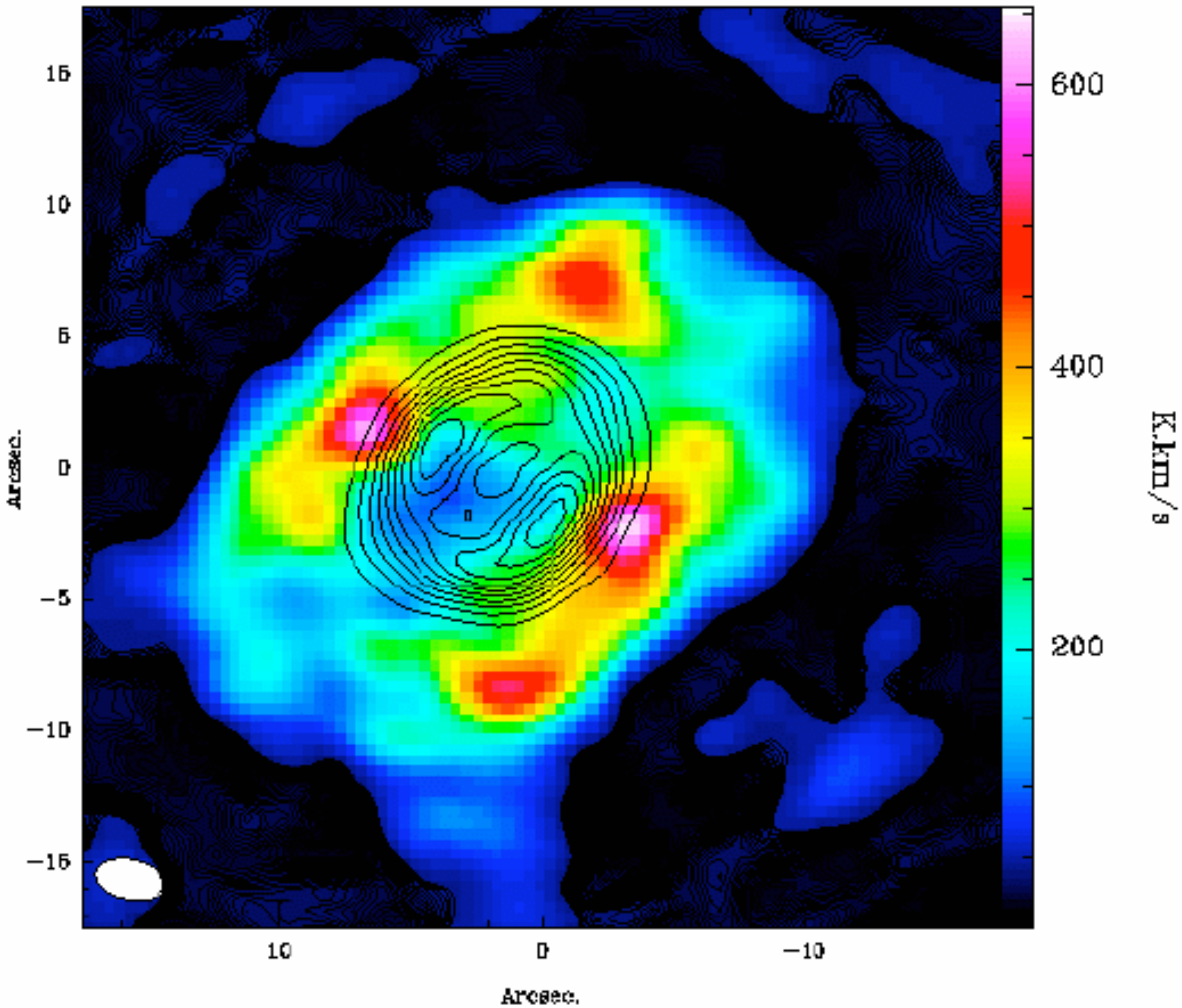
100-160 mas

Goto et al. 2007

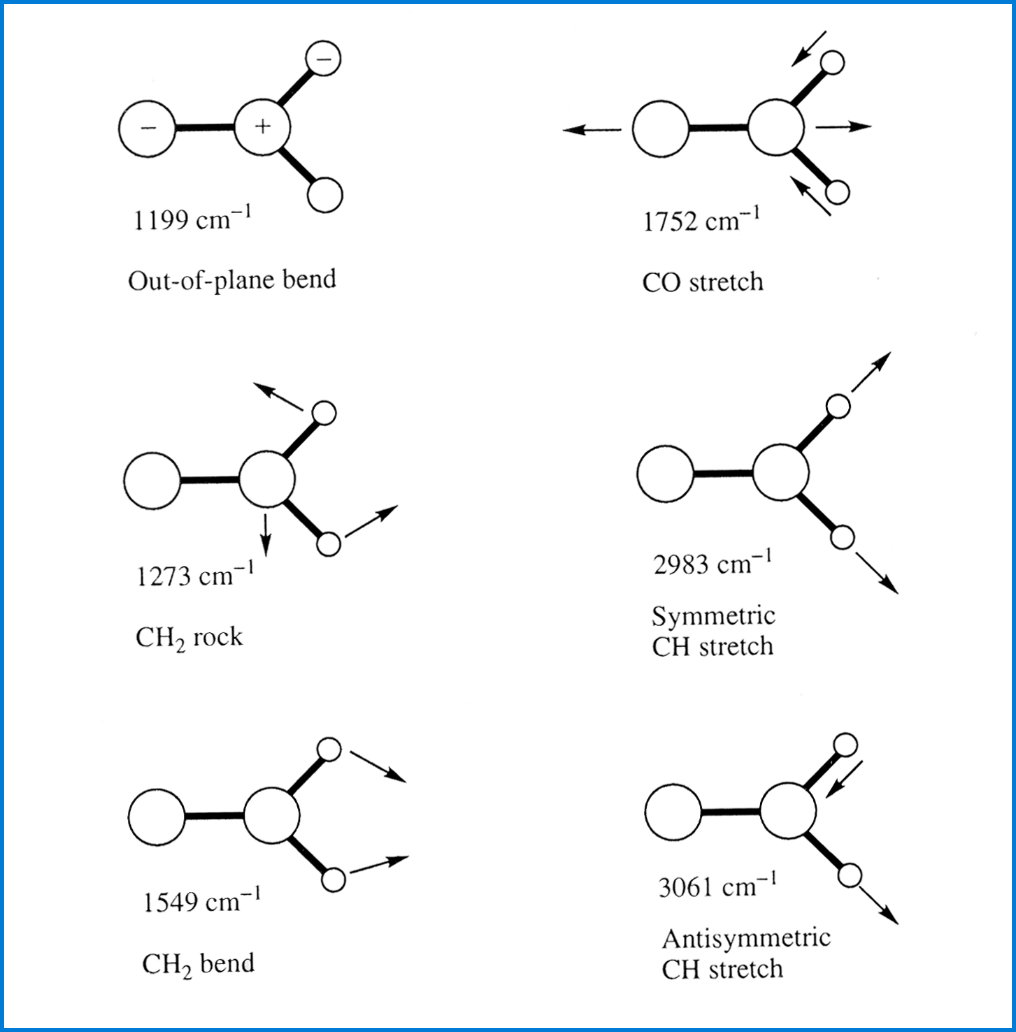
Molecules in Planetary Nebulae

- OH, CO, CO^+, CH, CH^+, HCN, HNC, HCO^+, H_2O, N_2H^+, CN, CS, C_2H, C_3H_2, SiS,
- 0.2 $M_{\odot}$ of ionized gas, 3 $M_{\odot}$ of molecular gas

CO outside of the ionized shell



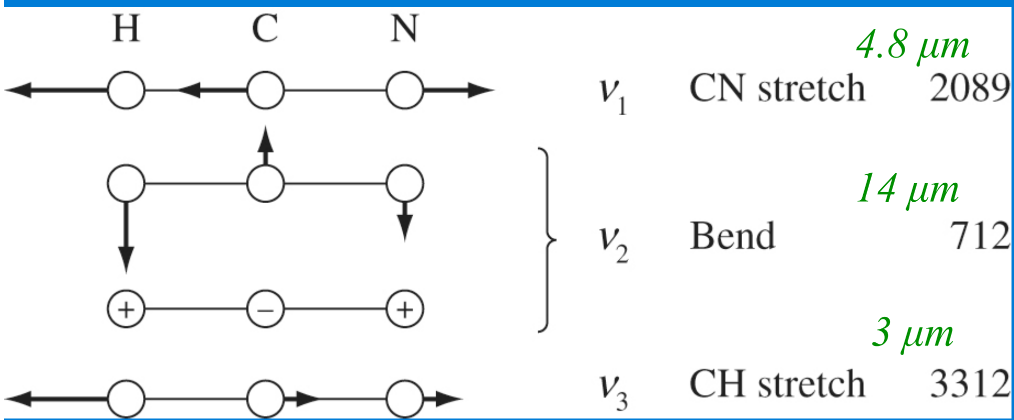
Stretching and Bending Modes of Polyatomic Molecules

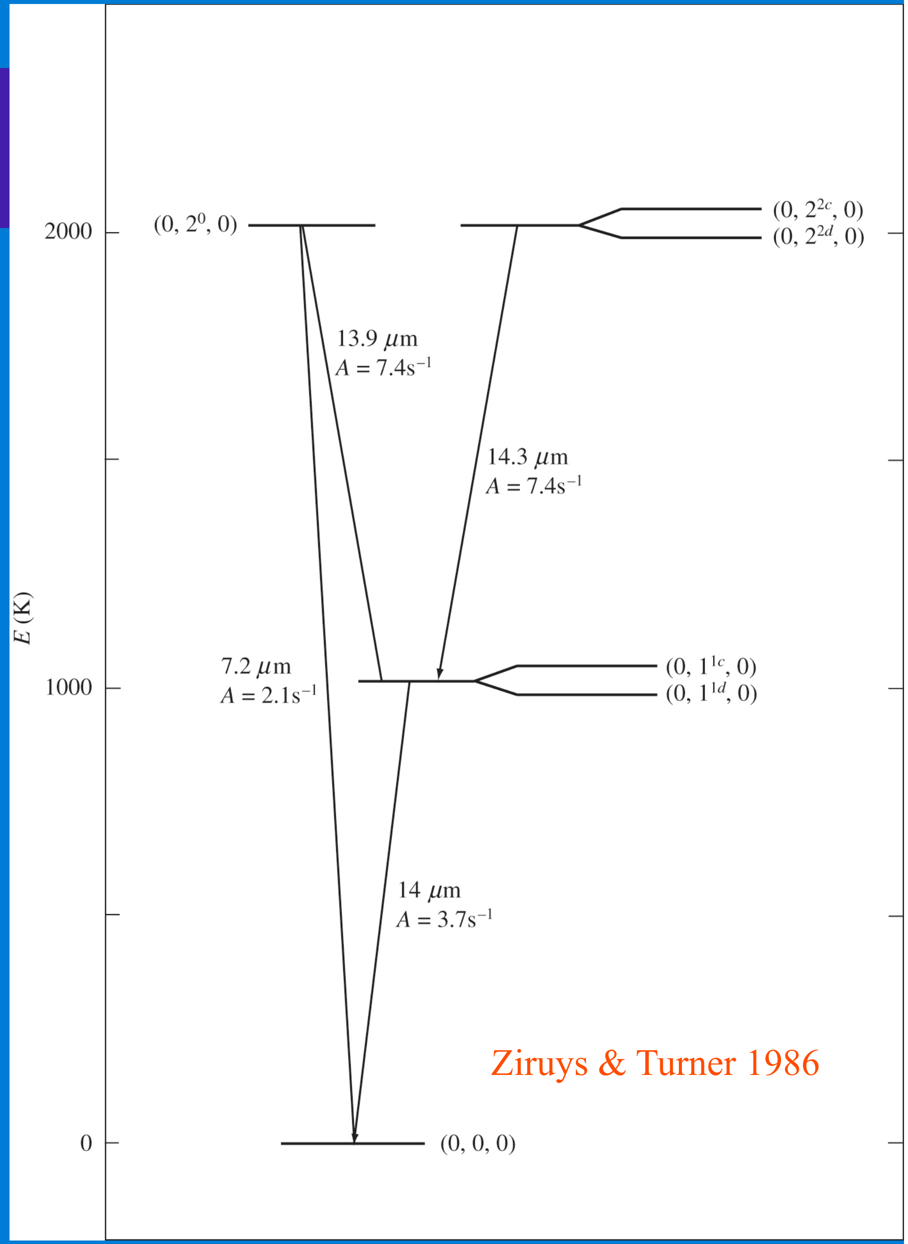


Bissonnette 2003, Handbook of Molecular Physics and Quantum Chemistry

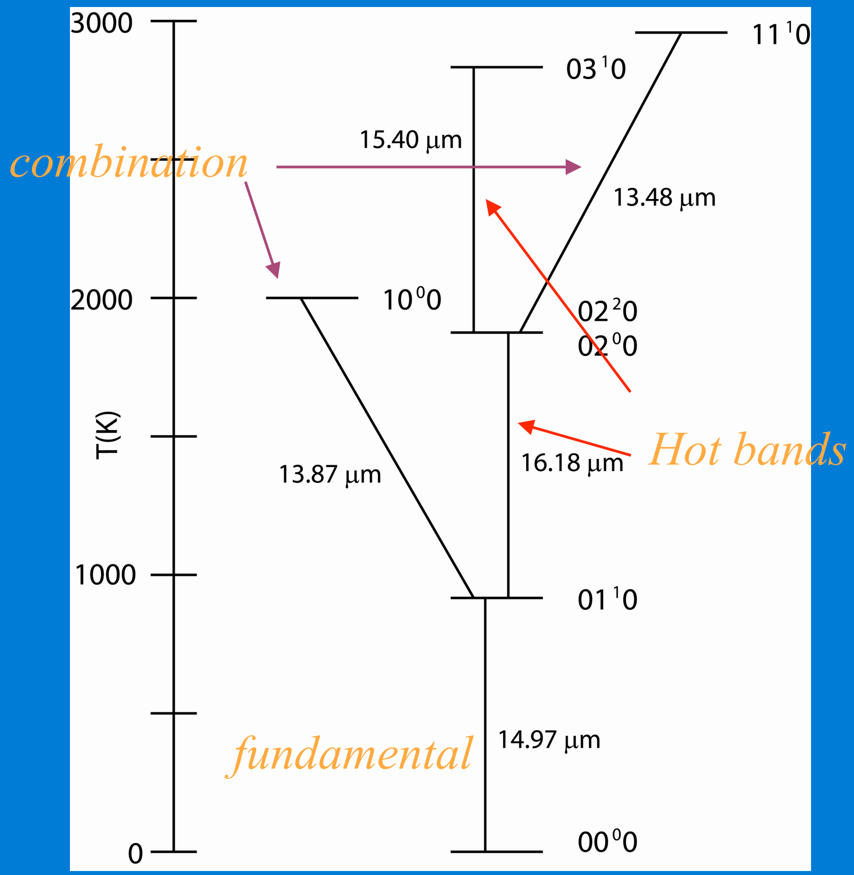
Linear molecule

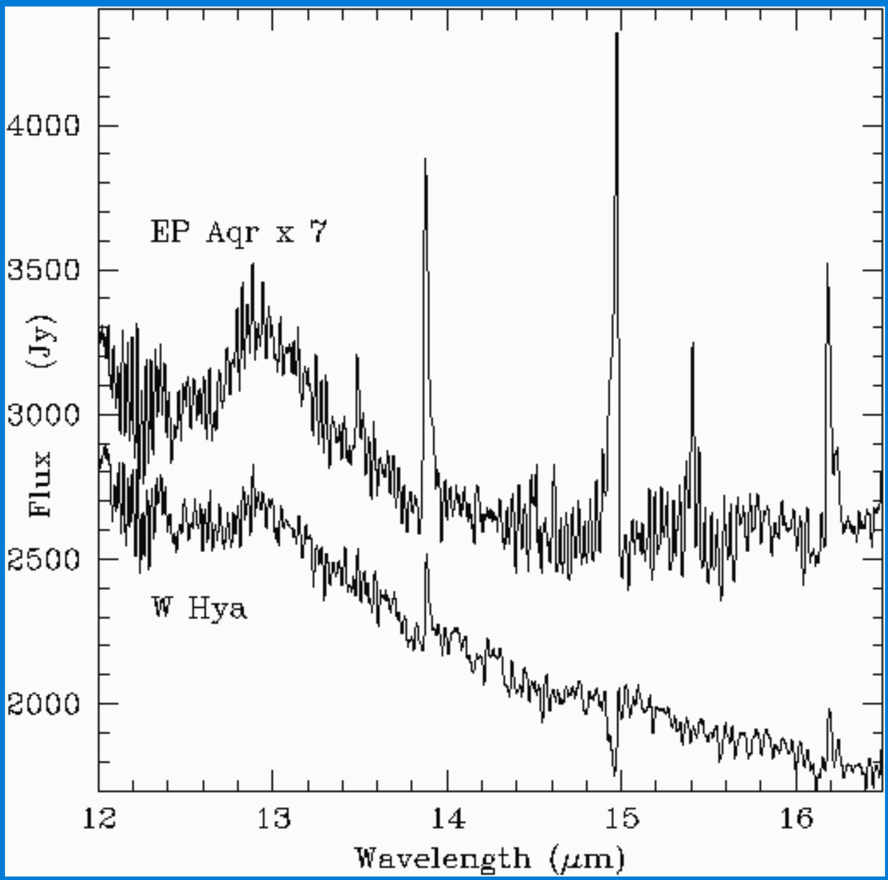
- HCN: 2 stretching frequencies and 1 bending frequency





Bending modes of CO_2

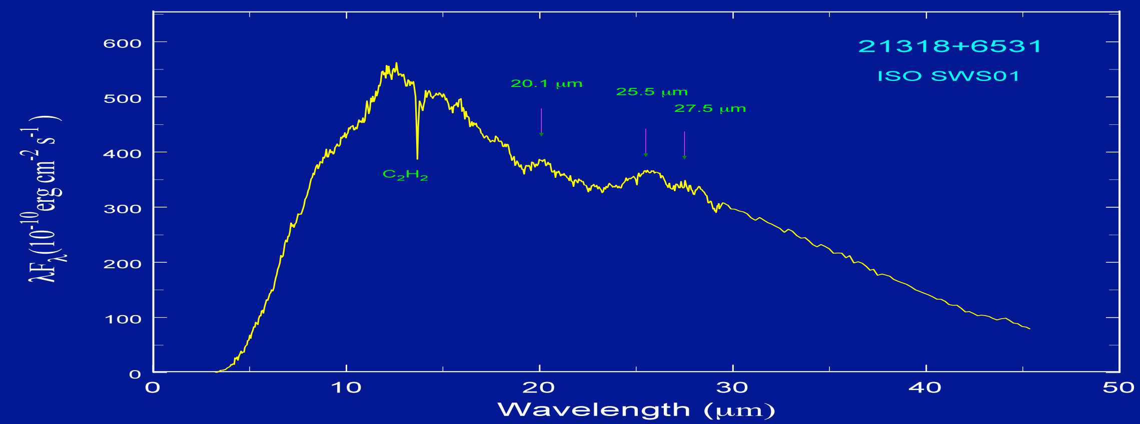




Combination band: transitions involving changes in two or more modes

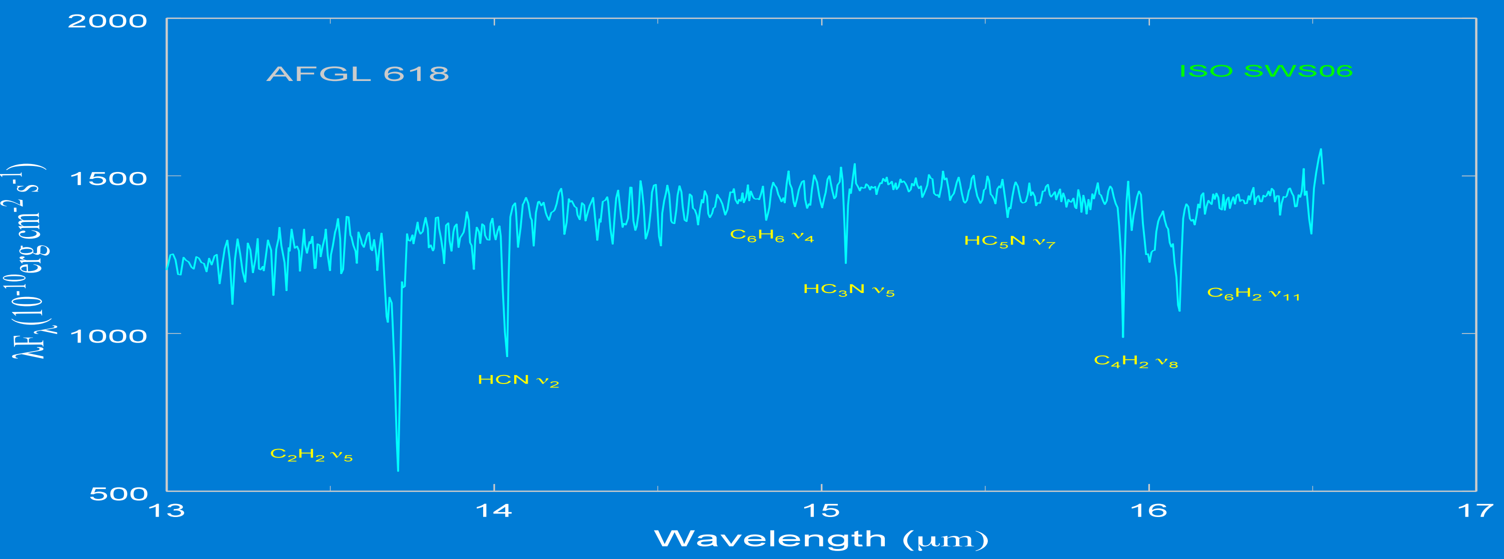
Acetylene: signature of extreme carbon stars

ν_5 fundamental at 13.7 μm.



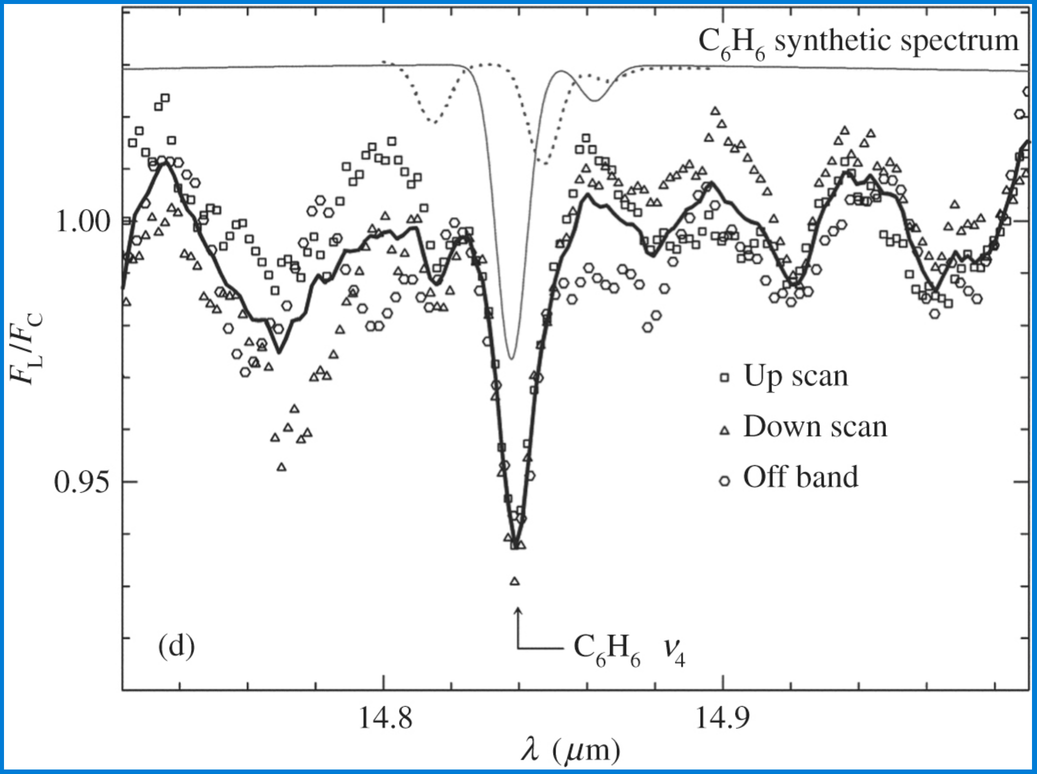
- 3 stretching and 4 bending modes
- The ν_5 *cis*-bend at 13.7 μm is observed in extreme carbon stars

Vibrational-rotational transitions of polyynes and cyanopolyynes



Benzene

- 20 vibrational modes, 4 are infrared active
- ν_4 of C_6H_6 at 14.84 µm



Cernicharo et al. 2001

Pure carbon chains C_n

- No permanent electric-dipole moment
- Have asymmetric stretching modes at ~5 μm and bending modes ~100 μm.
- C_3 (ν_3 at 4.90 μm) and C_5 (ν_5 at 4.62 μm) detected in carbon stars

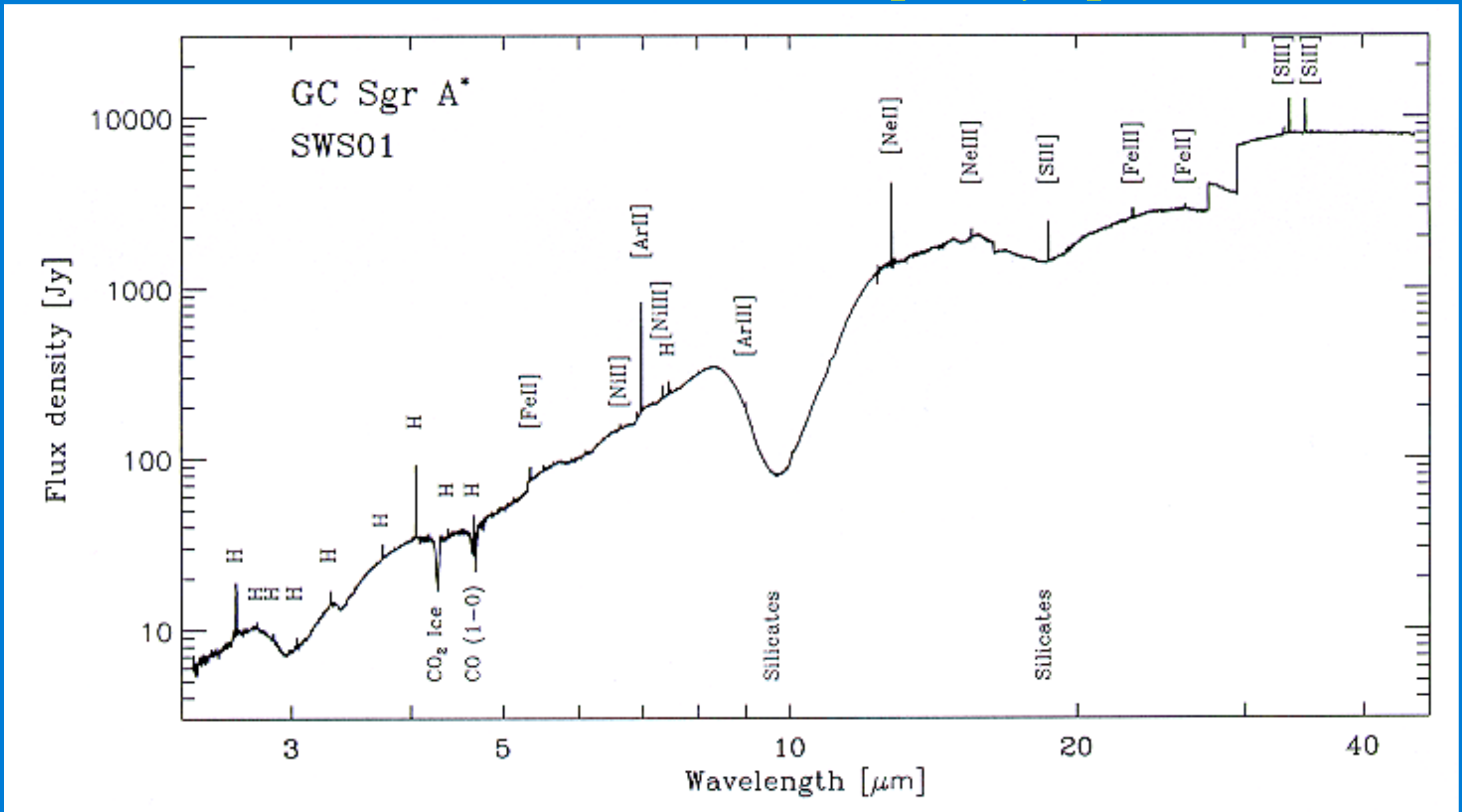
Triatomic C_3

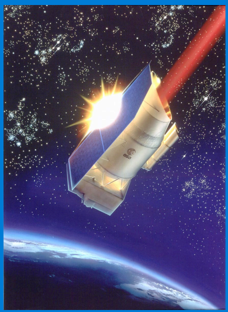
- ν_2 bending mode of C_3 at 158 μm.
- Interstellar C_3 in absorption against IR continuum sources (e.g., Sgr B2)
- For the higher members of the pure carbon chain, the bending mode frequencies are poorly known.

Will be detectable by SOFIA

Fine structure lines in the IR

Transitions within the same term split by spin-orbit interaction





Rest wavelengths determined by space observations

Neutral Atoms

- Forbidden ($\Delta\ell=0$) fine structure transitions
- CI: $^3P_2$-$^3P_1$ (370 μm) and $^3P_1$-$^3P_0$ (609 μm)
- OI: $^3P_1$-$^3P_2$ (63 μm) and $^3P_0$-$^3P_1$ (145 μm)

$A=7.9\text{x}10^{-9}\ s^{-1}$

Common ions

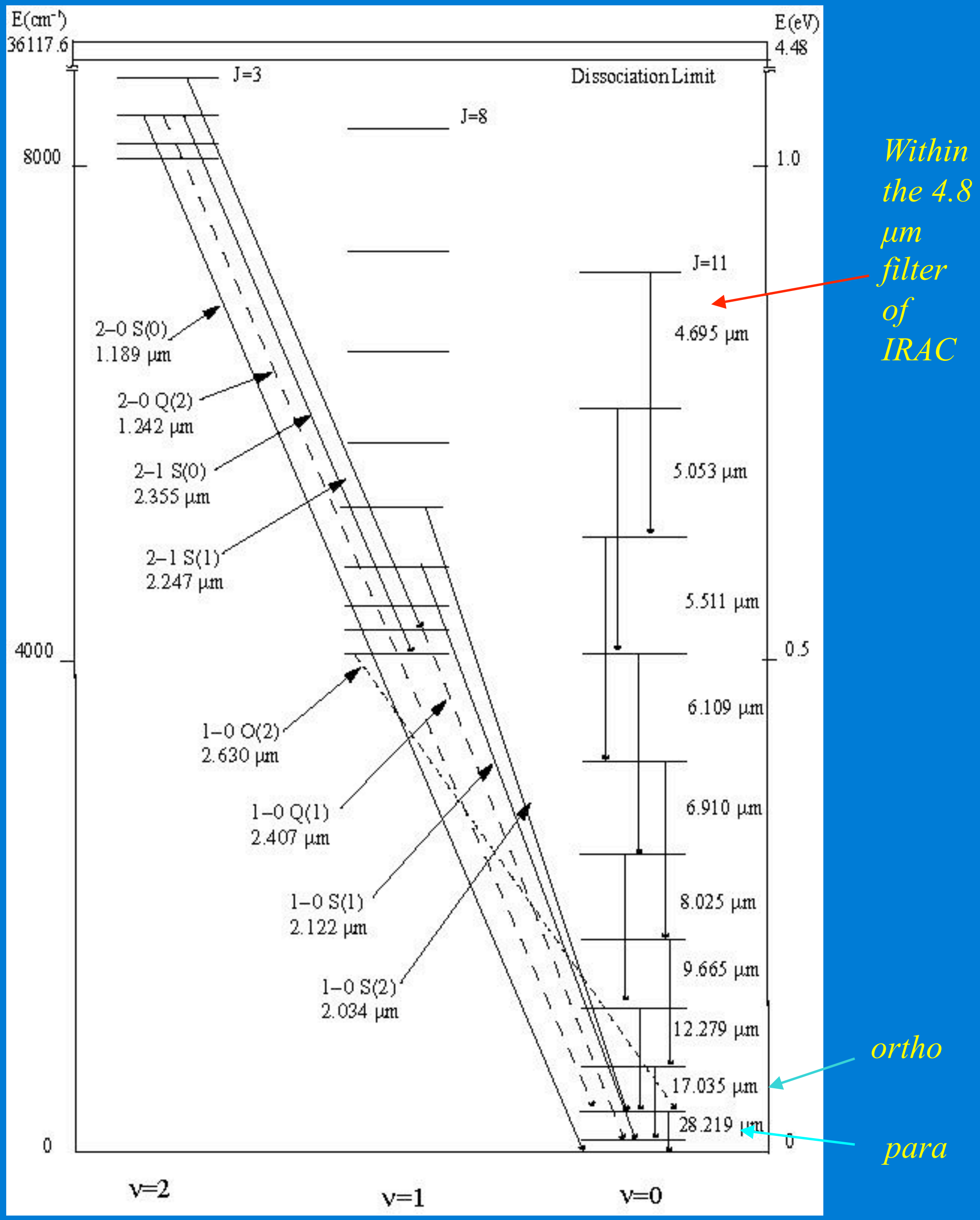
- $^2P_{3/2}$=$^2P_{1/2}$ line of C^+ at 158 μm
- $^3P_2$-$^3P_1$ (122 μm) and $^3P_1$-$^3P_0$ (205 μm) lines of N^+
- $^3P_2$-$^3P_1$ (52 μm) and $^3P_1$-$^3P_0$ (88 μm) of O^{++}

Hyperfine lines

- Atoms with odd number of nucleons have hyperfine structures
- The ground state of H ($1^2S_{1/2}$) has two hyperfine states (F=0 and 1), with a magnetic dipole transition at λ21 cm
- $^2P_{3/2}$=$^2P_{1/2}$ $F=2\text{-}1$ $^{13}C^+$ line at 158 μm

H_2

- Two identical nuclei, no permanent electric or magnetic dipole moments
- Only electric quadrupole transitions possible
- O: ΔJ=-2, Q: ΔJ=0, S: ΔJ=2

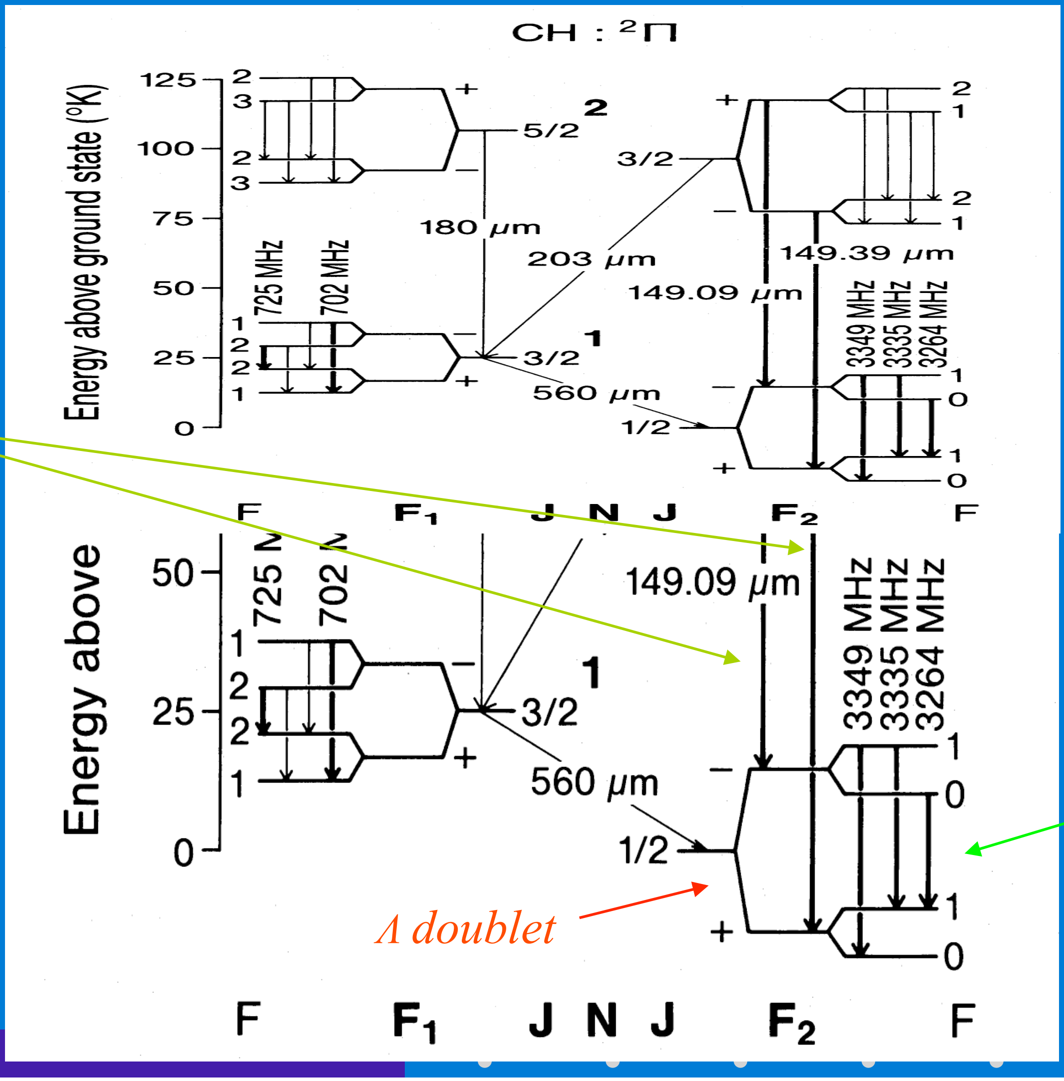


HD

- Ground-state *v=0, J=1-0* transition at 112.072 μm
- *J=2-1* 56.230 μm
- Accurate determination of abundance of HD
- When fractionation is not a factor, HD/H_2 reflects the D/H ratio, and this permitted line is an excellent probe of the abundance of H_2.

The CH radical

Rotational lines in THz range, first detected by KAO



hyperfine

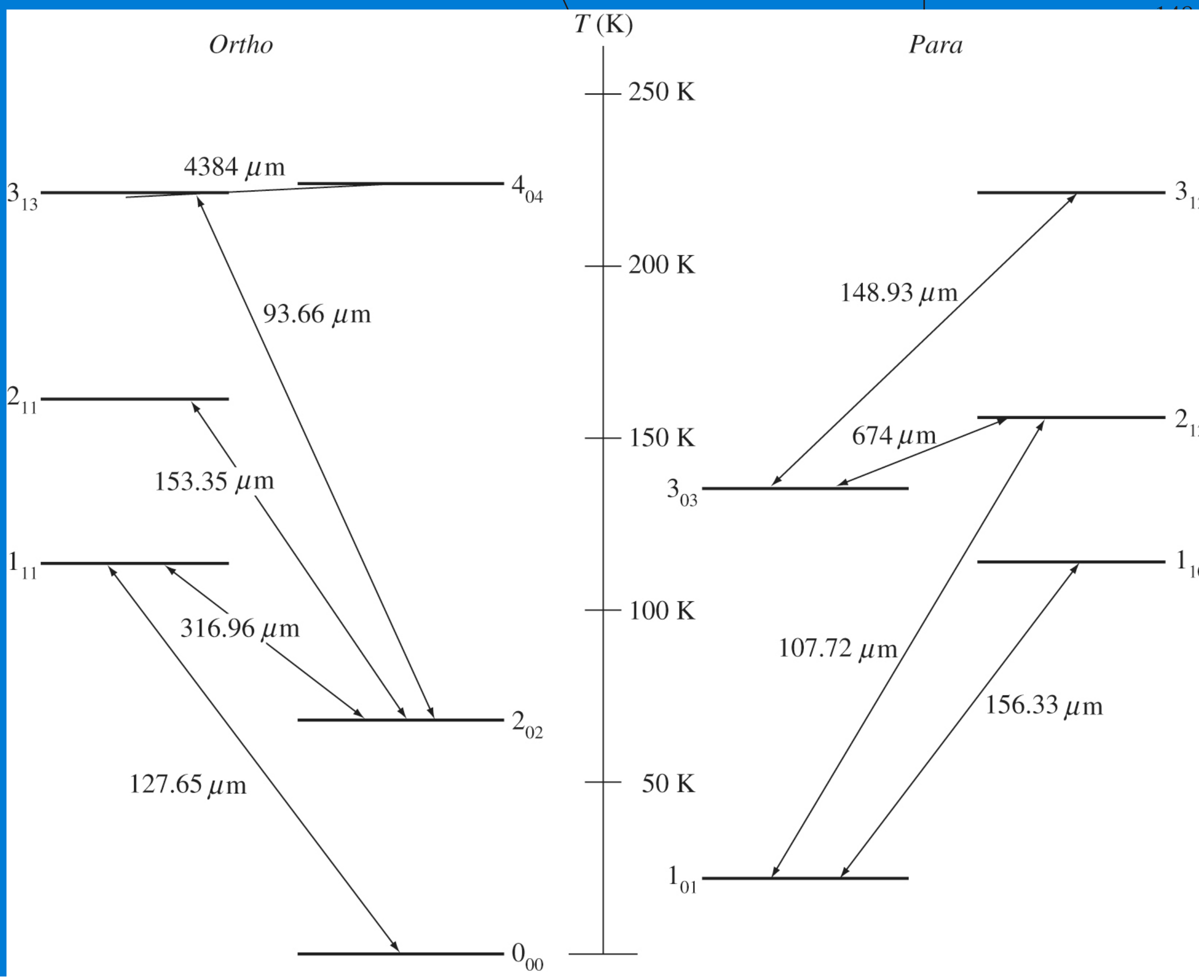
Two unpaired electrons

Methylene (CH_2)

- Simplest neutral polyatomic molecule with a triplet electronic ground state $^3B_1$ $(S=1)$
- Asymmetric top ($N_{K-1, K1}$)
- Fine structure states $J=N-1, N, N+1$
- Two H atoms each with $I=½$, CH_2 can be in ortho ($I=1$) or para ($I=0$) forms
- Ortho has hyperfine states: $F=J-1, J, J+1$

Low rotational levels of CH_2

ortho *para*



All lines in the far IR

Far IR spectroscopy

- Many common atoms and ions have fine-structure lines in the IR
- The rotational transitions of light molecules are in the submm
- SOFIA will be able to detect the stretching and bending modes of molecules

Observational goals

- High-resolution mid-IR imaging can map out the distribution of "dark matter" in PN and help understand the origin of bipolar/multipolar morphology
- Imaging spectroscopy can map the distribution of aromatic/aliphatic organics and help understand the formation of these species

Larger questions

- Are the formation of organics associated with a particular phase of outflow?
- Is there a common link between the complex organics seen in evolved stars, in the Solar System, in the diffuse ISM, and external galaxies?

Kwok, S. 2000 Origin and Evolution of Planetary Nebulae, CUP
Kwok, S. 2004 The Synthesis of Organic and Inorganic Compounds in Evolved Stars, *Nature*, **430**, 985
Kwok, S. 2009 Organic Matter in Space: from Stars to the Solar System, *Astrophys. Sp. Sc.*, 319, 5