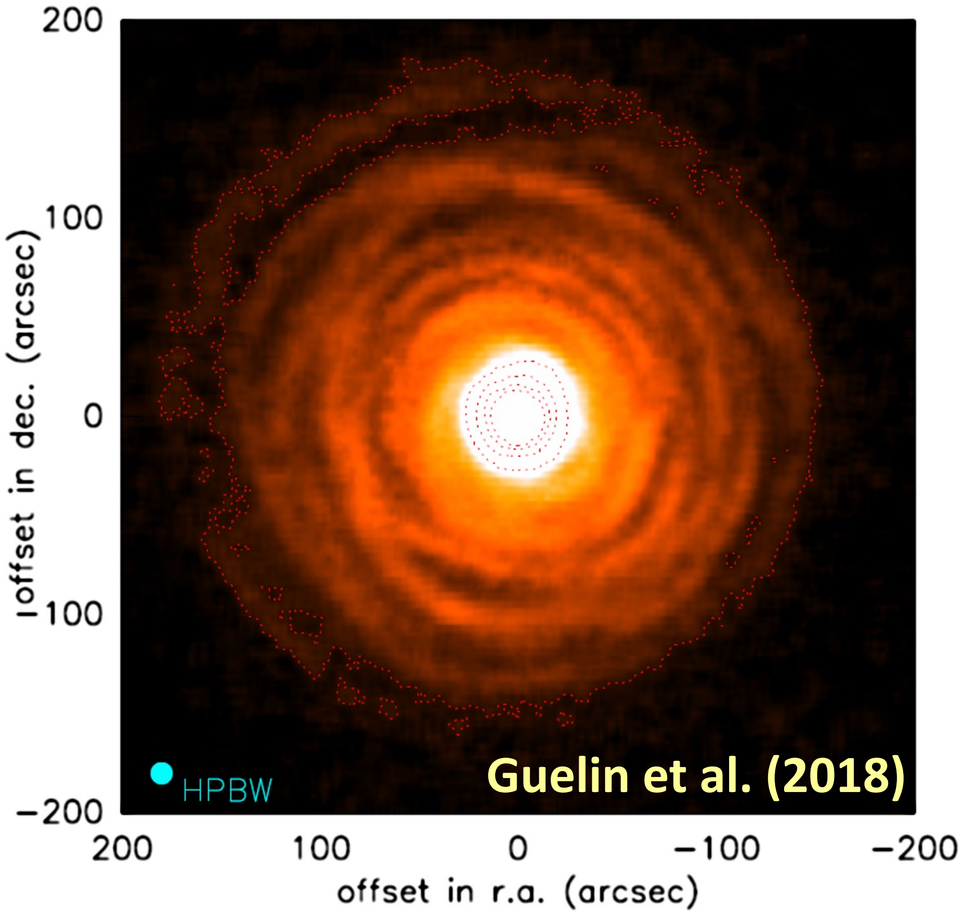
Dust from evolved stars

G. C. Sloan

Fifth Pan Dust Conference, 2025

1) Dust, stars, and the holy grail
2) Oxygen-rich dust
3) Carbon-rich dust
4) Conclusions and random thoughts



IRC +10216: IRAM imaging in CO J=2–1

STScI

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

The Holy Grail

Objective: tie the quantity and properties of circumstellar dust to the properties of the star

- Initial mass
- Initial metallicity
- Dredge-up history
- Mass-loss history
- Other properties: rotation, interaction in binaries, …

Helium fusion on the asymptotic giant branch

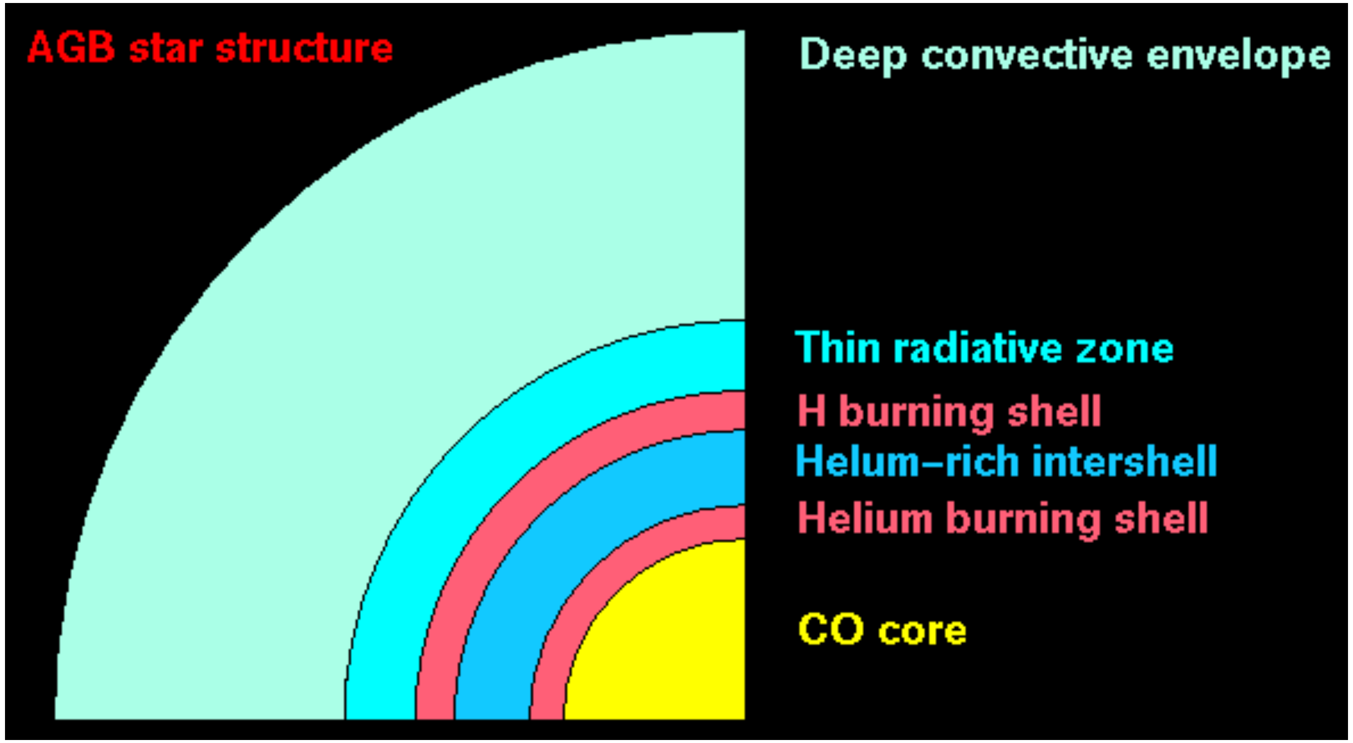


Figure from John Lattanzio's website (not to scale!)

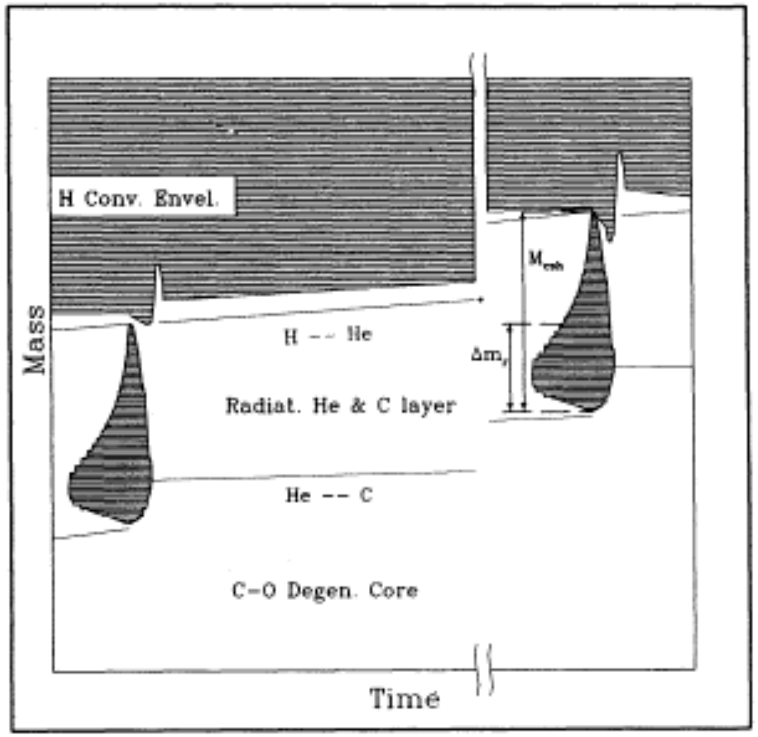


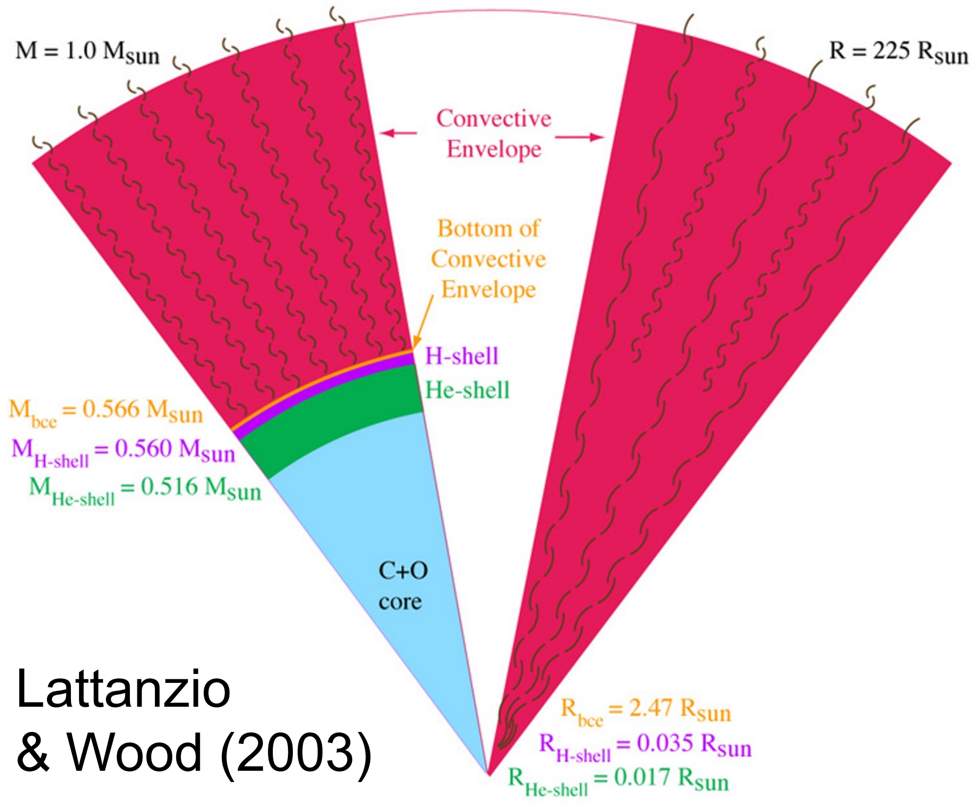
Figure from Busso et al. (1995)

Helium burning – 3-α sequence (Salpeter 1952)
Burns in thermal pulses every 10^4 to 10^5 y

Convective zones overlap in pulses
And dredge up freshly fused C

Stellar pulsations (in the envelope)

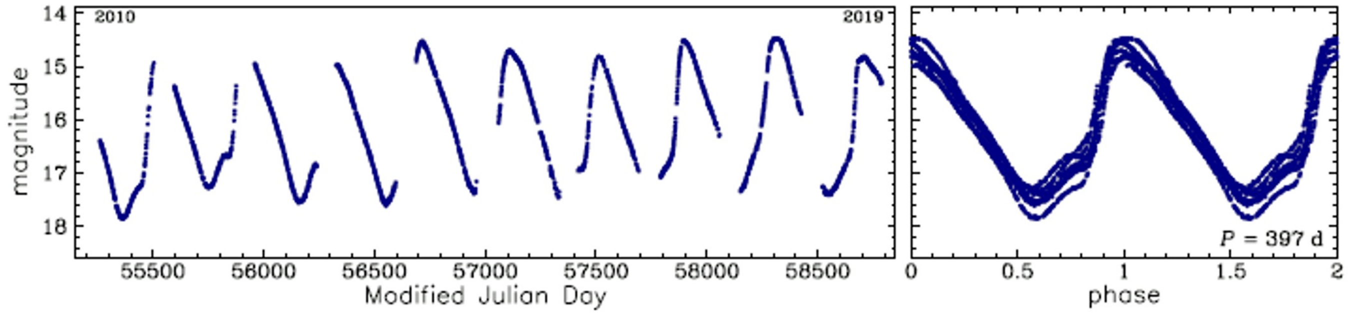
Extended envelope: unstable to pulsations



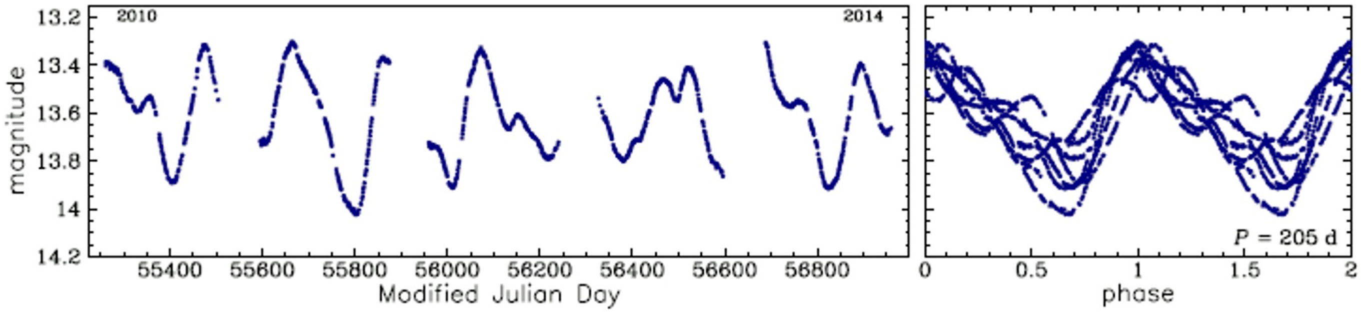
Lattanzio & Wood (2003)

Light curves from OGLE IV
http://ogle.astrouw.edu.pl/atlas

Mira: strong fundamental-mode pulsations



I magnitude



Semi-regular variable: weaker pulsations
Fundamental or first overtone (SRV, SRa, SRb, …)

Irregular variable: higher overtones (Lb, Lc, etc.)

The CO paradigm – **CO consumes all of the available C or O**

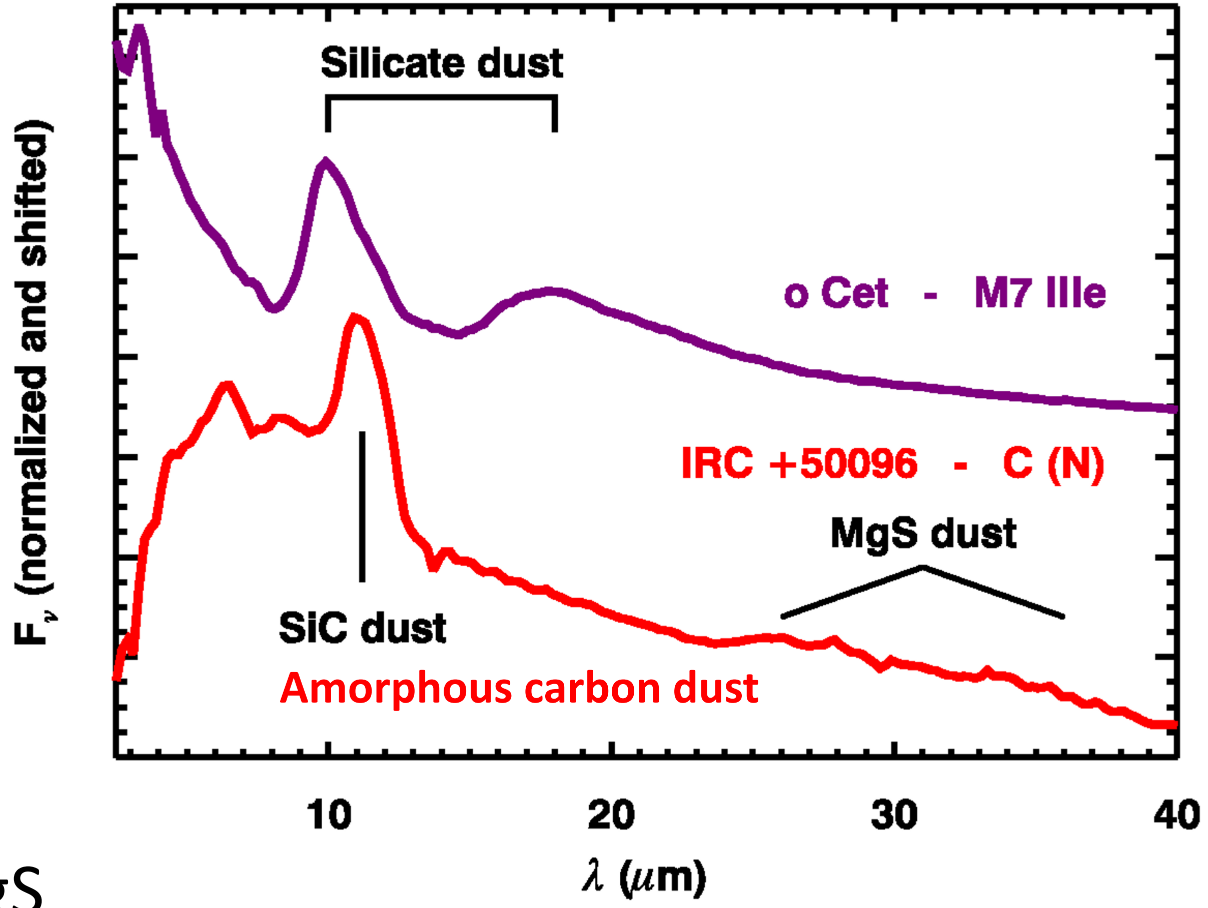
Resulting circumstellar chemistry

Either **O-rich**

- Gas: CO, SiO, OH, H_2O, …
- Dust: Silicates, alumina, …

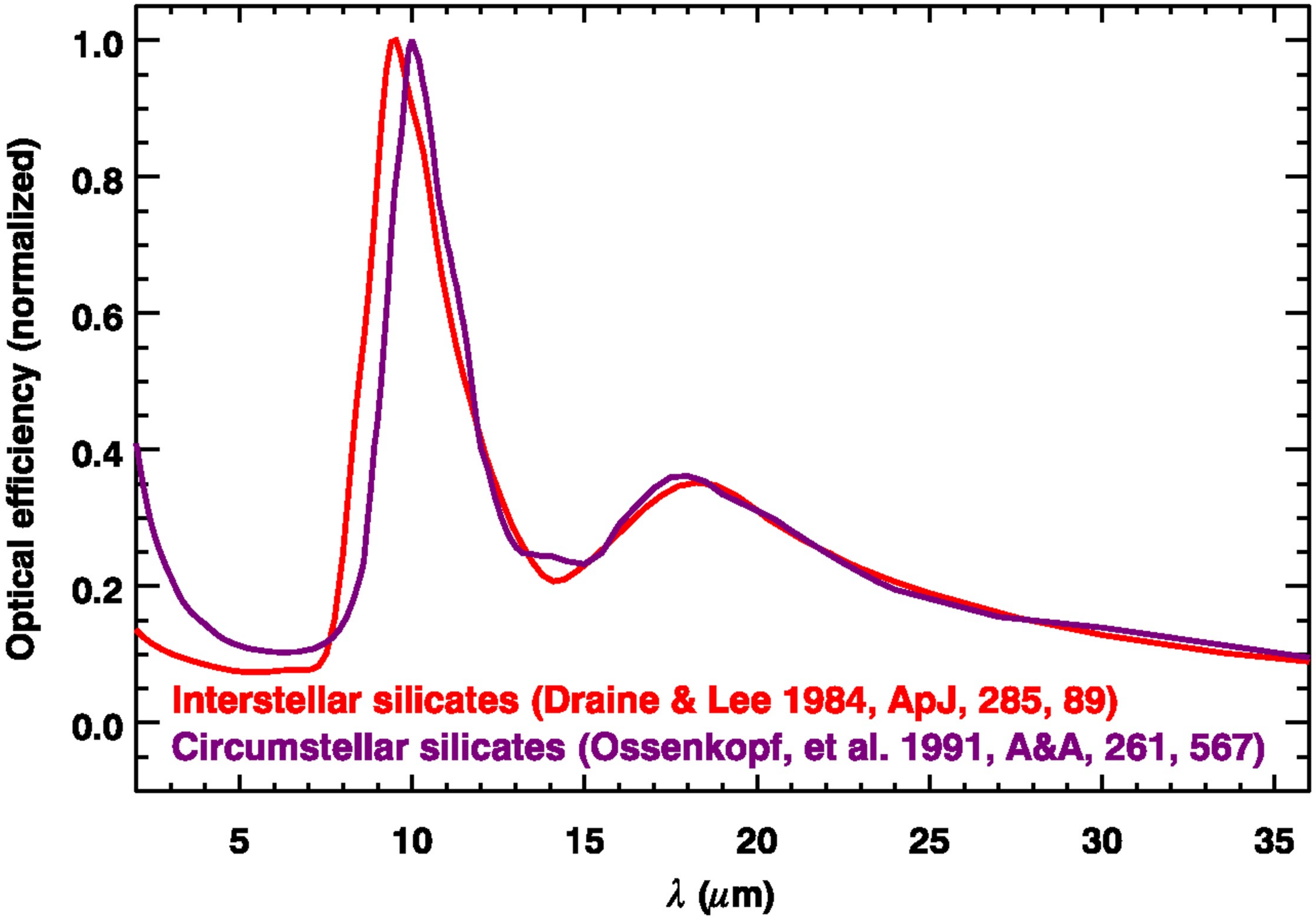
Or **C-rich**

- Gas: CO, C_2H_2, HCN, CS, C_3, …
- Dust: amorphous carbon, SiC, MgS



Spectra from the Short Wavelength Spectrometer (SWS) on the **Infrared Space Observatory (ISO)**

Amorphous silicates



Both sets of optical efficiencies derived from observations

DL – from the Orion Nebula

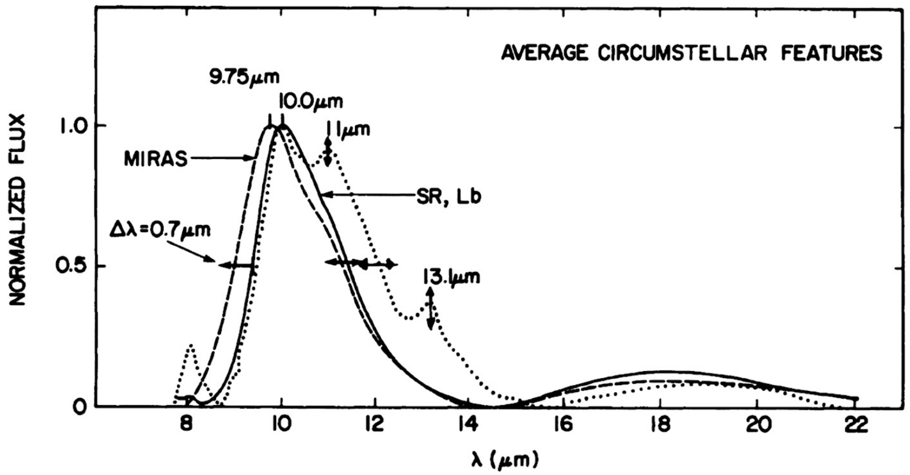
OHM – from oxygen-rich circumstellar dust shells

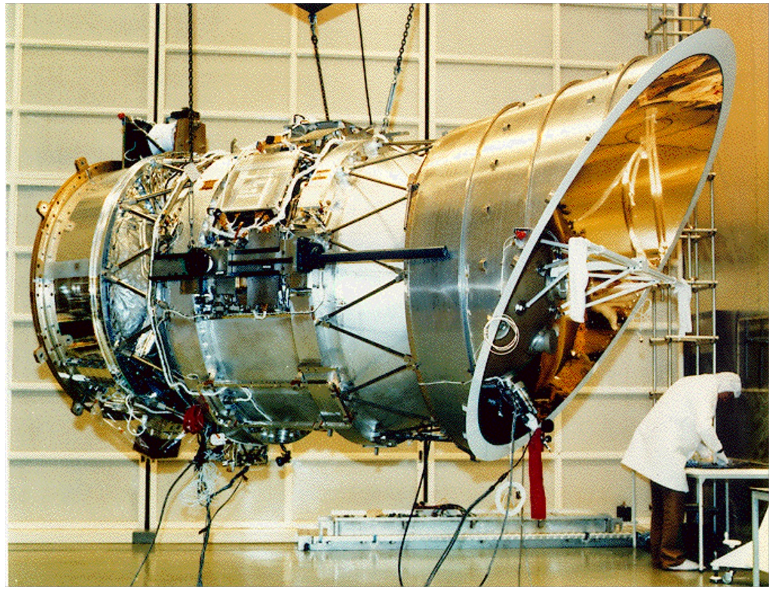
But they differ significantly e.g., at 10 μm

Irene Little-Marenin and oxygen-rich dust

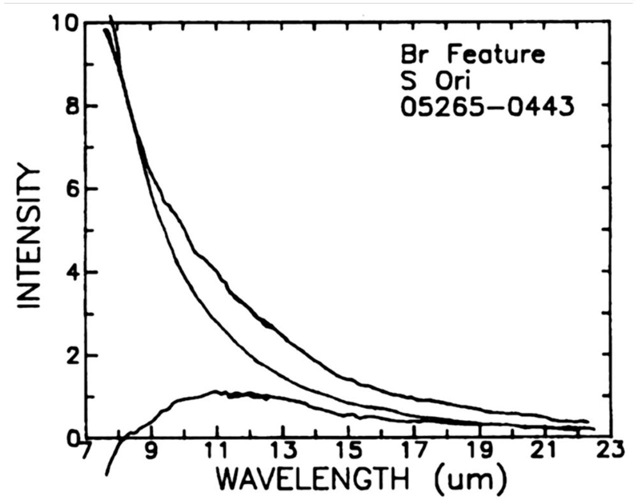
The Infrared Astronomical Satellite (IRAS) – Low-Resolution Spectrometer (LRS)

Little-Marenin found ***much more than just amorphous silicate dust***





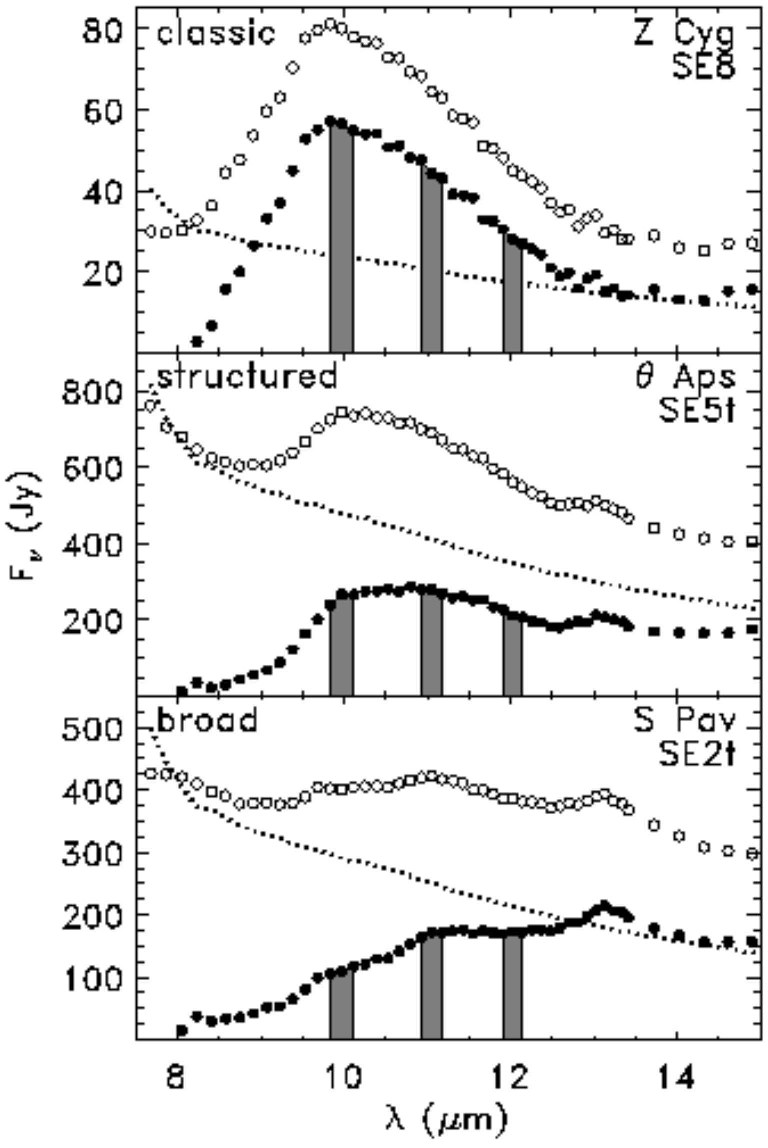
Sil, Sil+, and 3-component spectra



Broad feature

Little-Marenin & Little (1990)

The silicate dust sequence



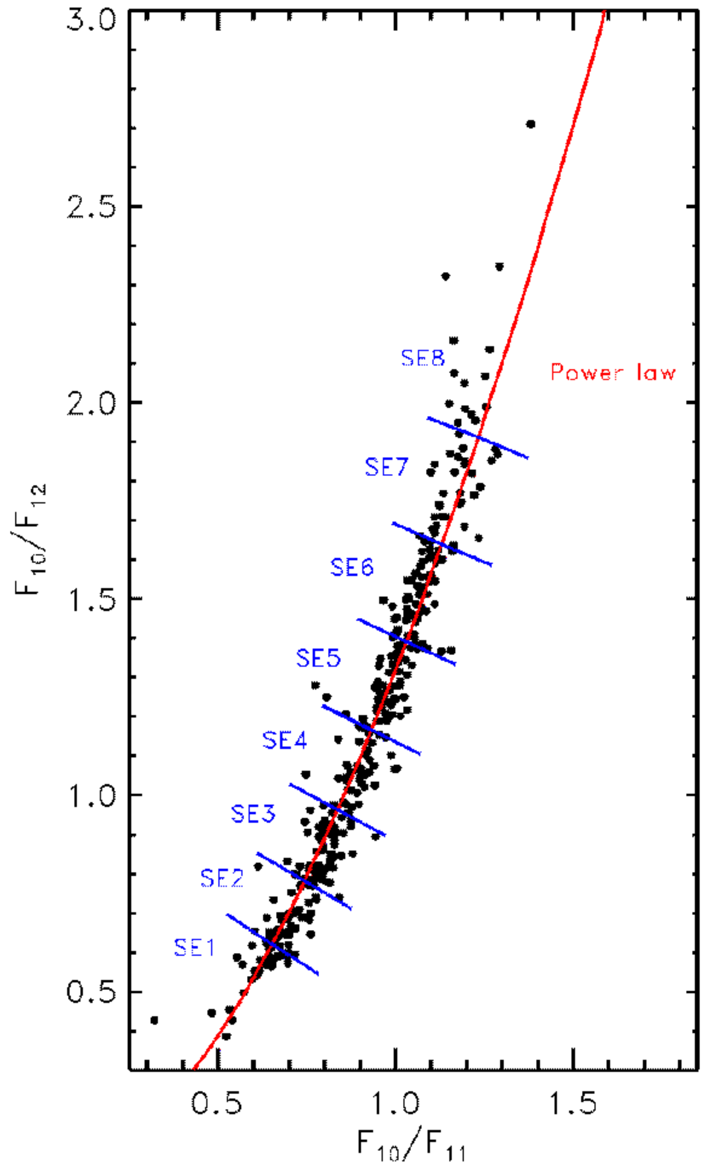
1) Subtract a stellar spectrum
2) Measure dust at 10, 11, 12 μm
3) Find the position on the
silicate dust sequence

SE6–8 = classic silicate emission from **amorphous silicates**

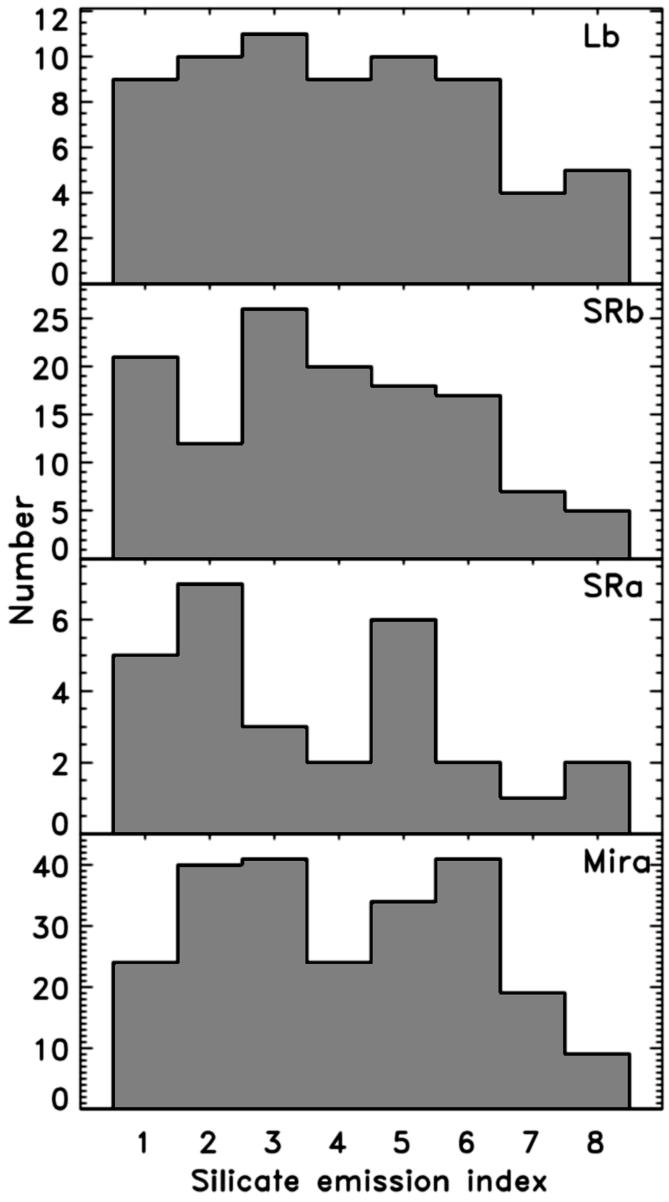
SE3–5 = structured silicate emission

SE1–3 = broad emission from **amorphous alumina**

Sloan & Price (1995, 1998)



Pulsation, initial mass, and O-rich dust chemistry

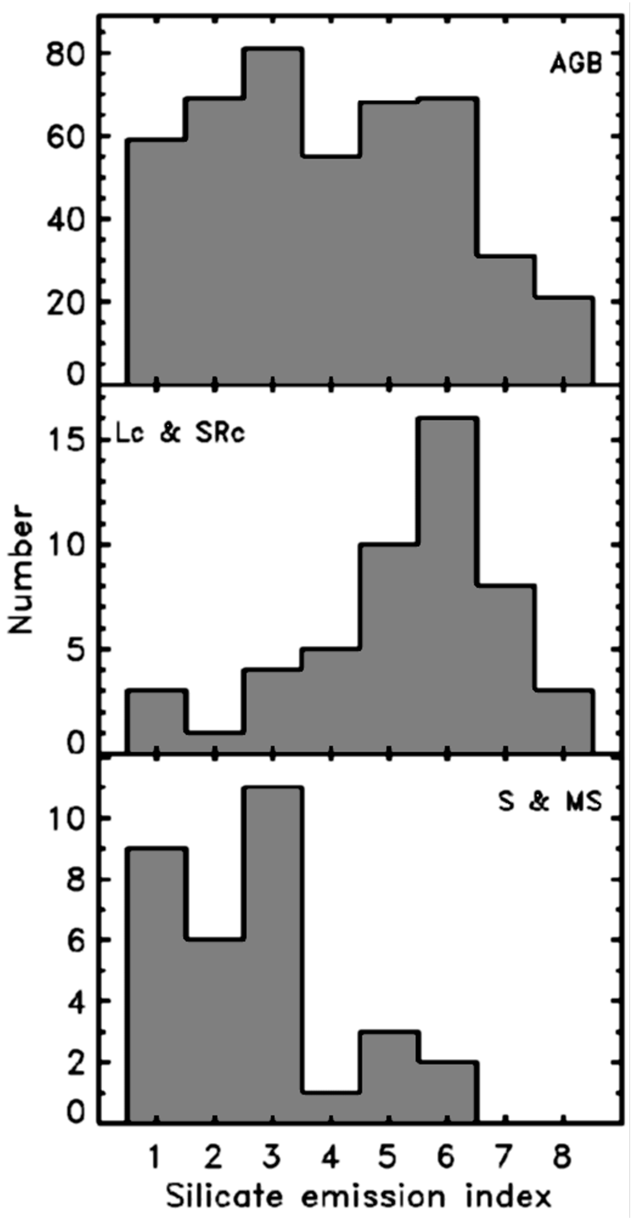


On the AGB, pulsation amplitude and mode don't decide the dust chemistry

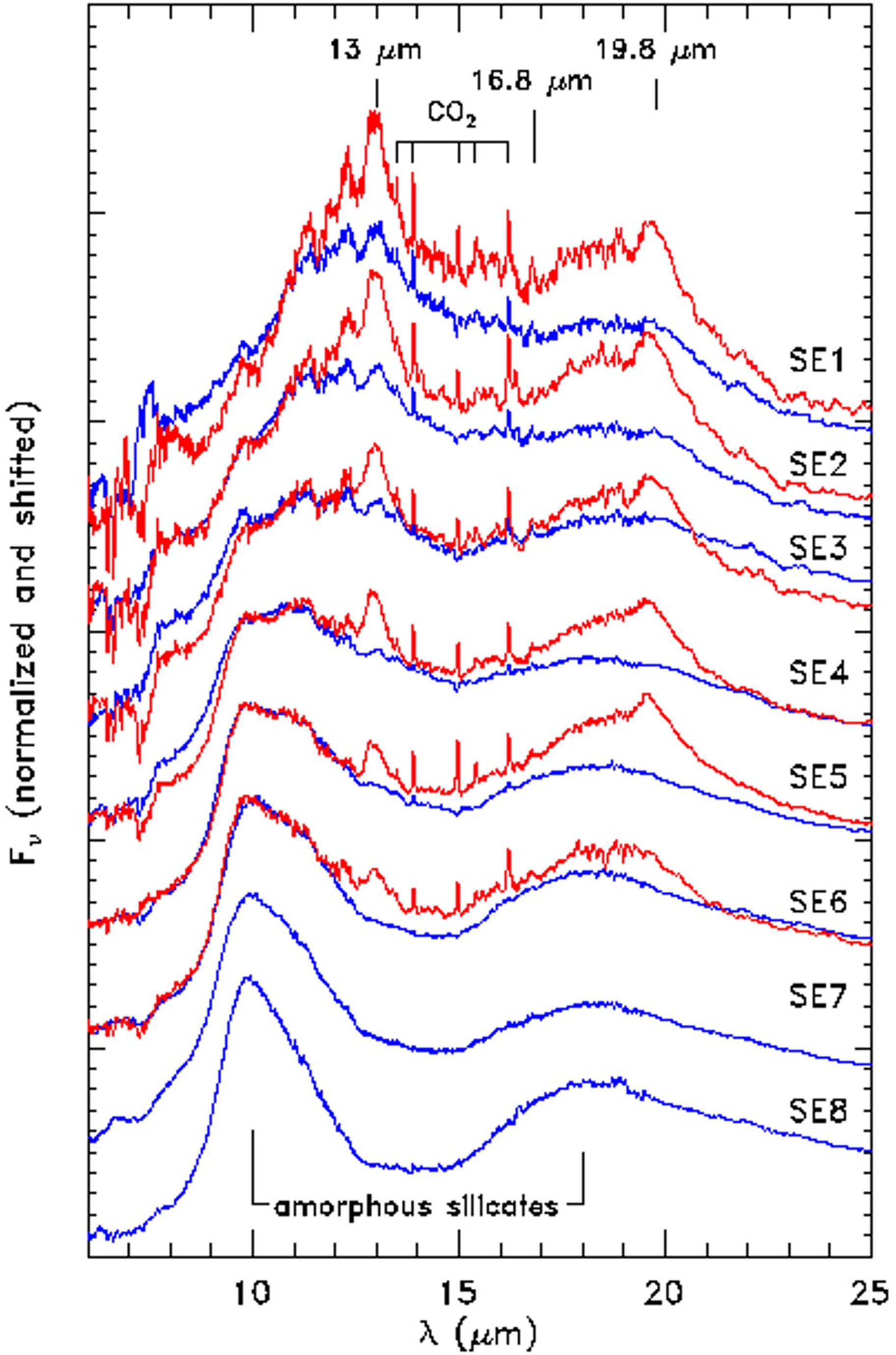
Supergiants mostly make amorphous silicates

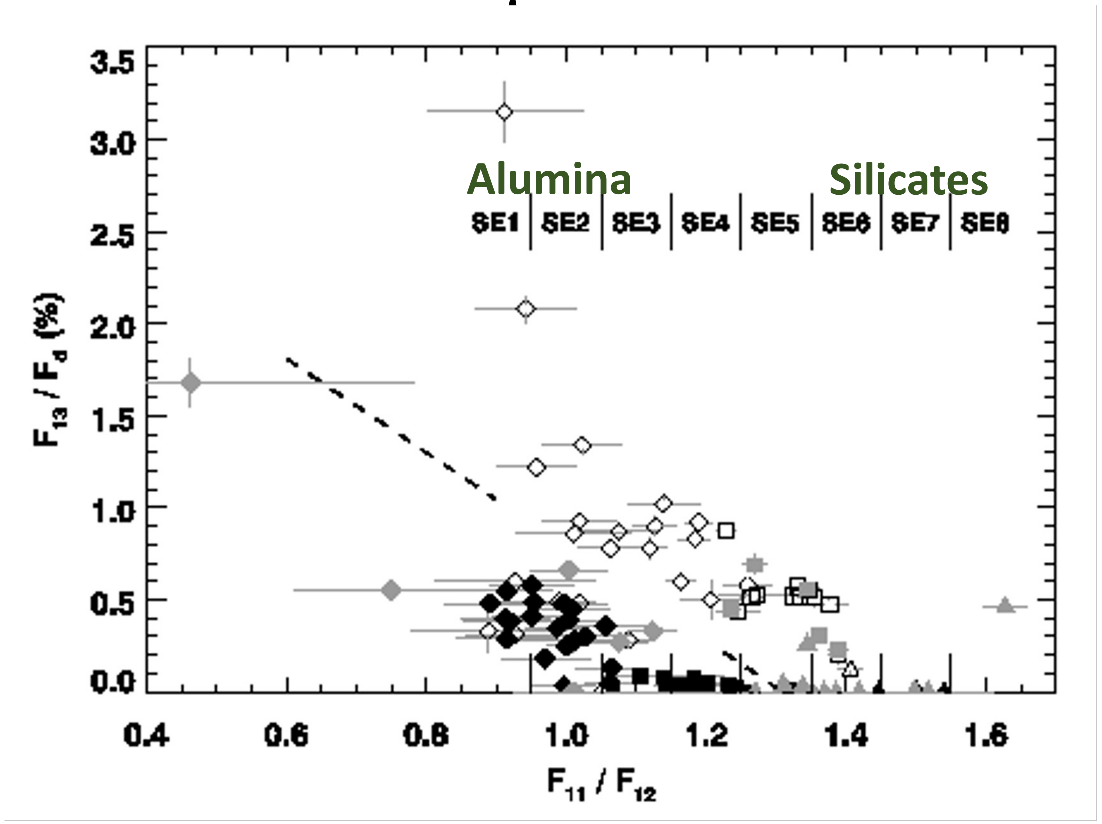
Stars with C/O ~ 1 mostly make amorphous alumina

Sloan & Price (1995, 1998)



The 13 μm feature





Left: spectra **with** and **without** the 13 μm feature

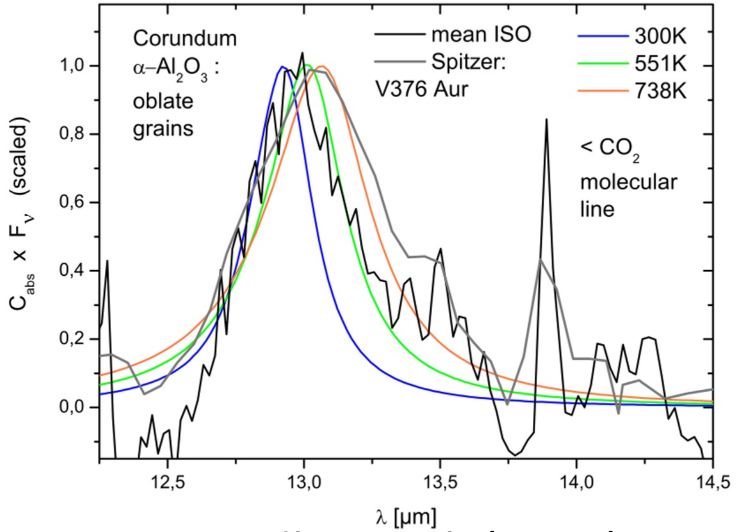
Above: Open symbols = SRb variables

Filled symbols = Miras

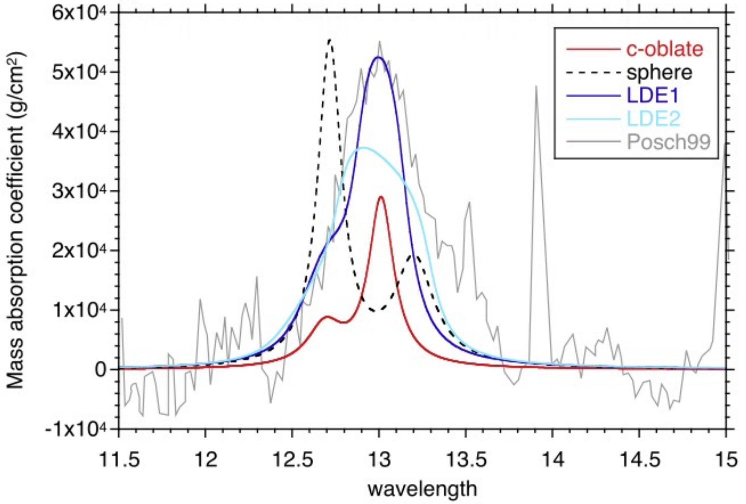
ISO/SWS spectra

Sloan et al. (2003)

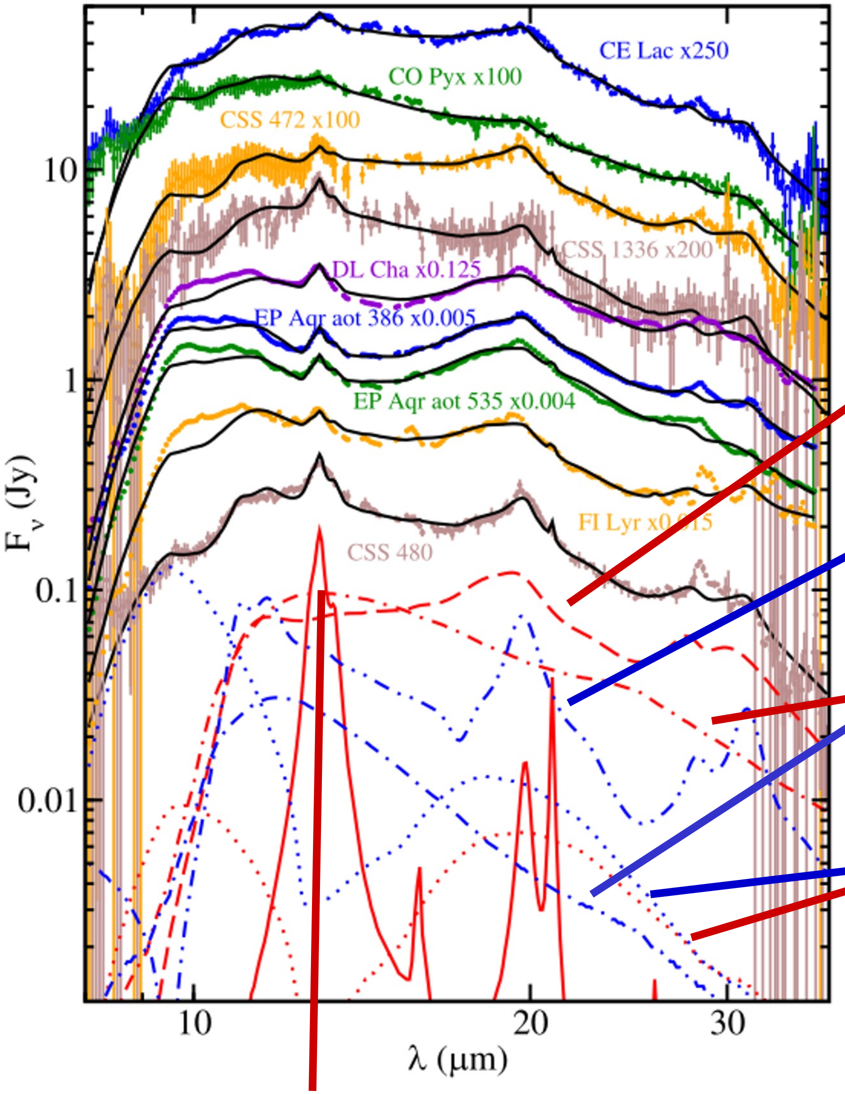
Corundum (α-Al_2O_3) – crystalline alumina



Zeidler et al. (2013)



Takigawa et al. (2015)



Multiple aluminum oxide species are needed to fit the 13, 20, and 28 µm features

Böhmite – γ-AlO(OH)

Bayerite – $AlO(OH)_3$

Amorphous alumina – Al_2O_3

Amorphous silicates (enstatite – $MgSiO_3$)

Corundum – α-Al_2O_3

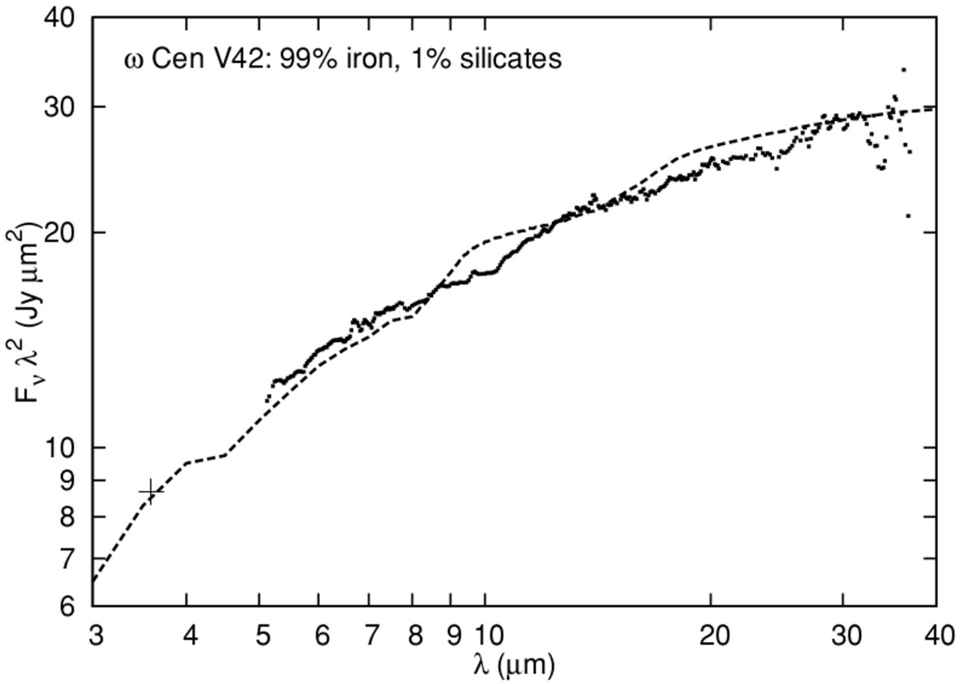
Sargent (2018)

Iron dust

THE ASTROPHYSICAL JOURNAL LETTERS, 717:L92–L97, 2010 July 10 doi:10.1088/2041-8205/717/2/L92

RUSTY OLD STARS: A SOURCE OF THE MISSING INTERSTELLAR IRON?

I. McDONALD[1], G. C. SLOAN[2], A. A. ZIJLSTRA[1], N. MATSUNAGA[3], M. MATSUURA[4,5], K. E. KRAEMER[6], J. BERNARD-SALAS[2], AND A. J. MARKWICK[1]



ω Cen V42 has a featureless dust excess

It could be amorphous carbon or iron
But amorphous carbon is unlikely

Iron is not in the silicates
Maybe this is where it goes

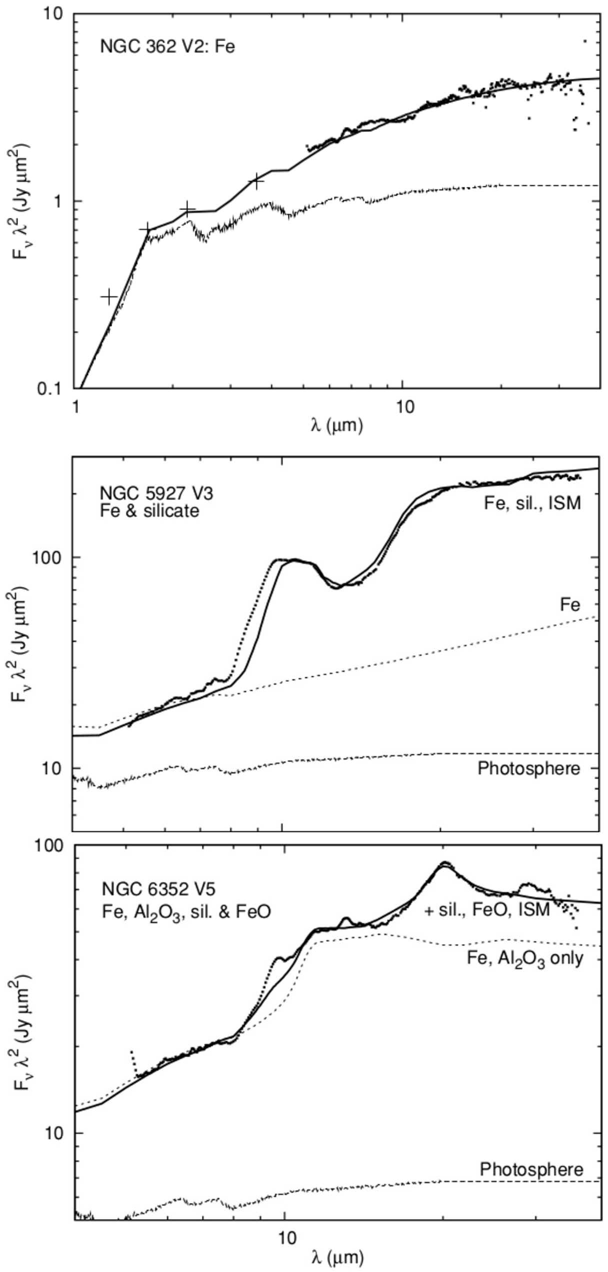
Spectrum from the Infrared Spectrograph (IRS) on the **Spitzer Space Telescope**

More iron dust

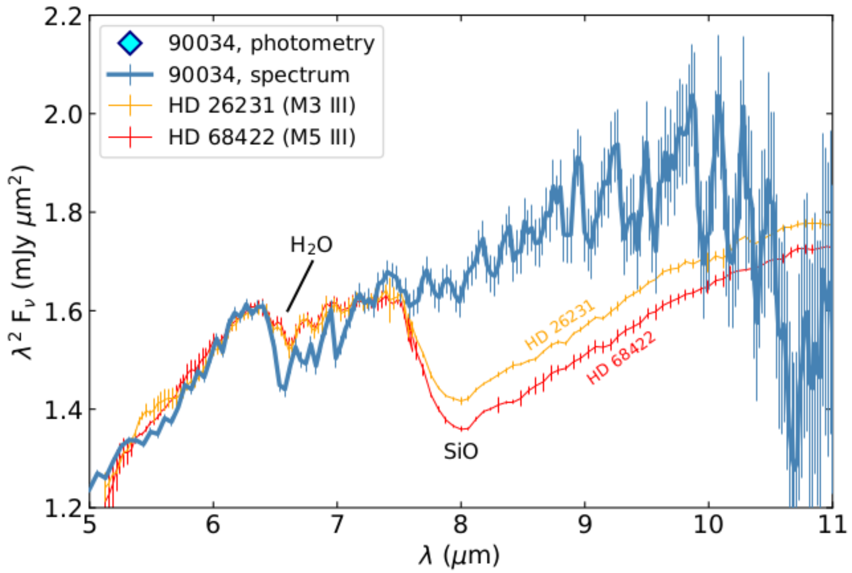
Right: Sextans A 90034 is O-rich
- Has H_2O, but no measurable SiO
- Best fit with **iron dust**

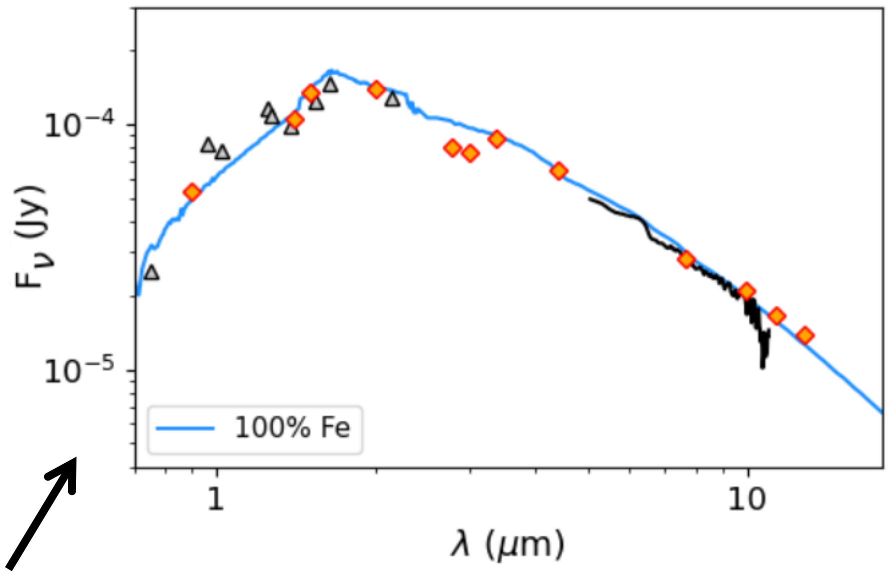
Left: More iron-dust candidates in globular clusters

System	**[Fe/H]**
NGC 362	–1.2
NGC 5927	–0.4
NGC 6352	–0.7
ω Cen	–1.6
Sextans A	–1.5 to –1.8



McDonald et al. (2010)

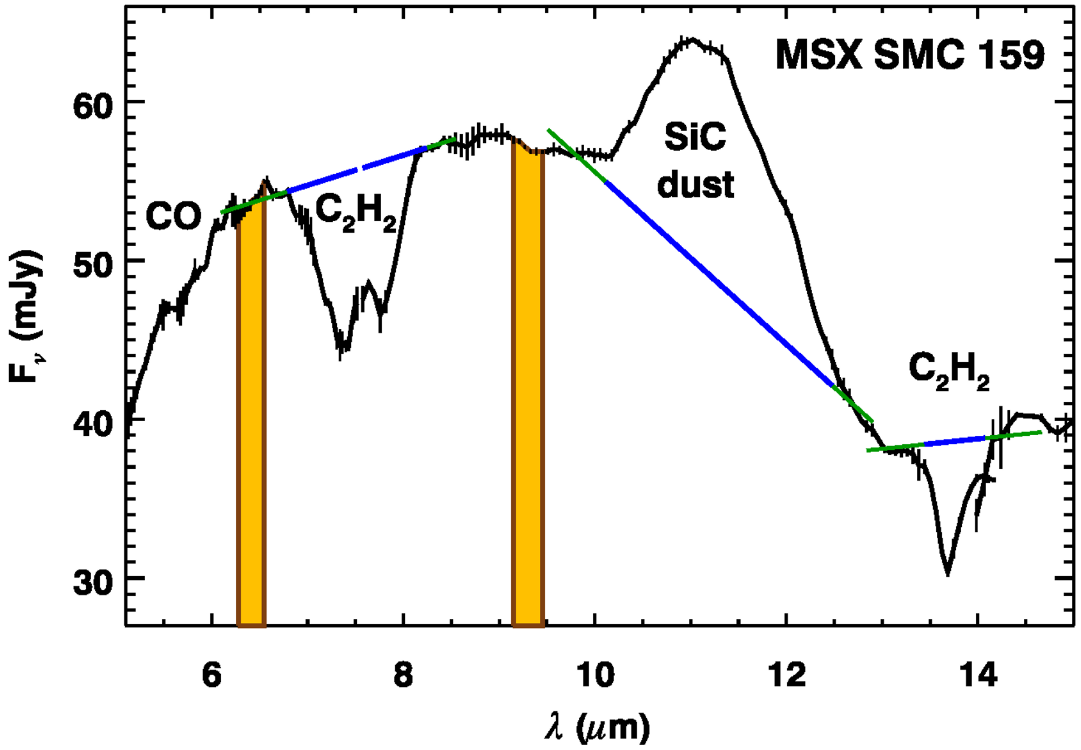




Spectrum from the MIRI Low-Resolution Spectrograph (LRS) on **JWST**

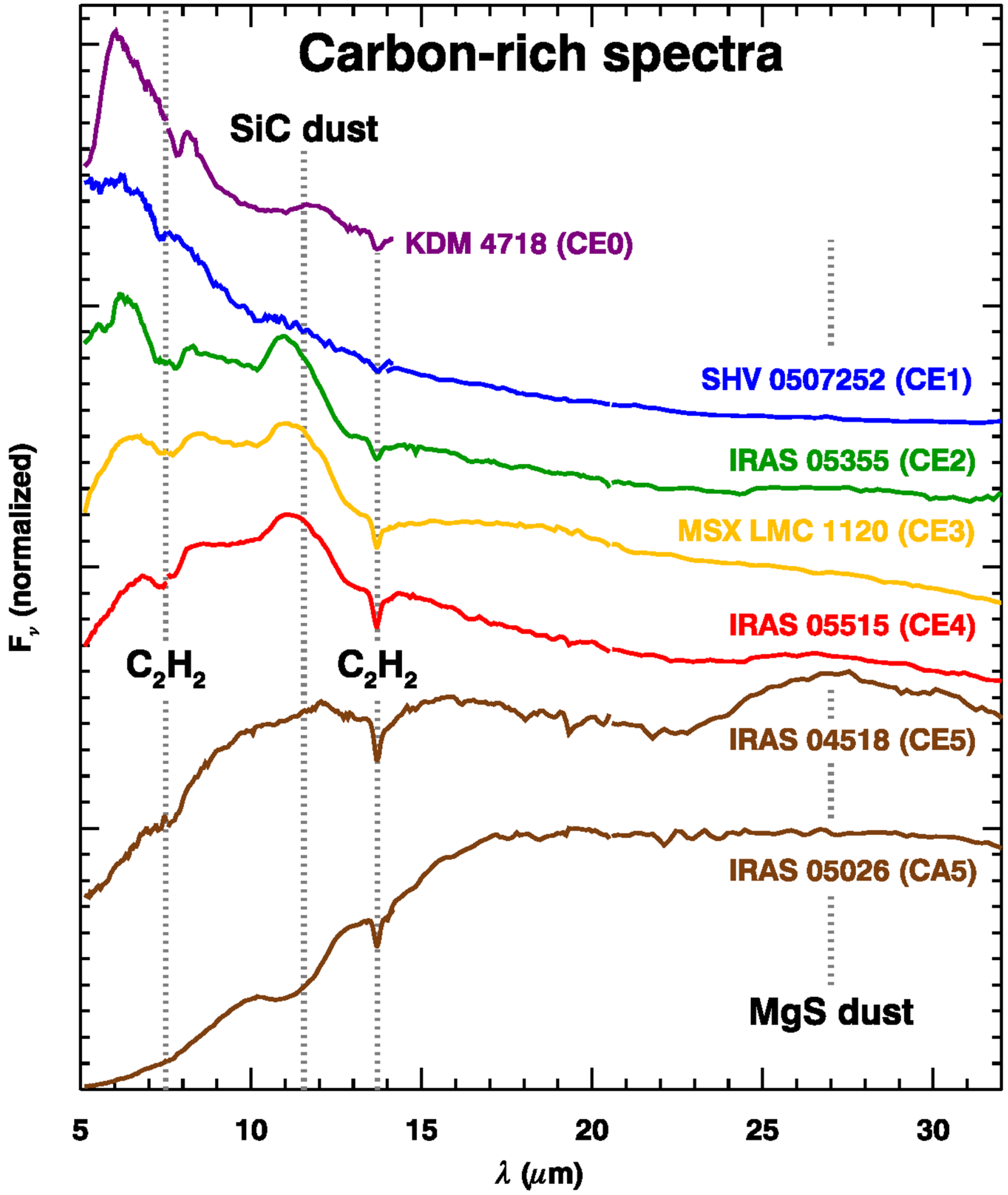
Boyer et al. (2025)

The Manchester Method



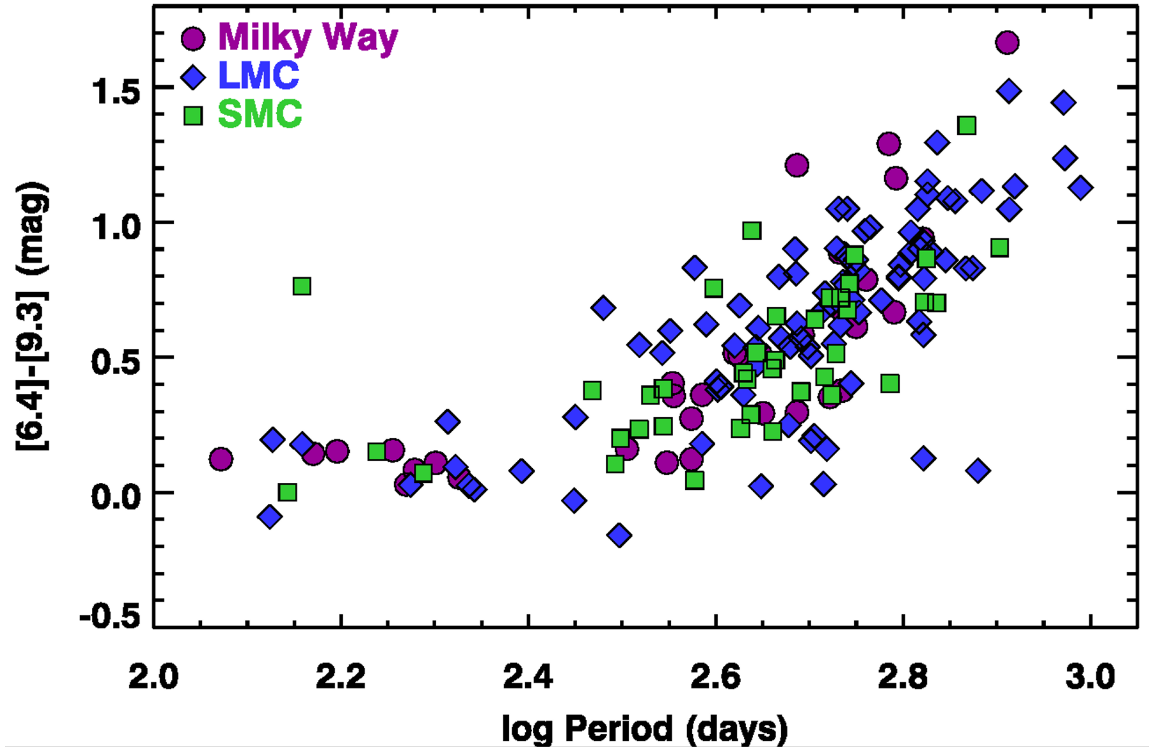
Introduced by Sloan et al. (2006), Zijlstra et al. (2006)

[6.4] – [9.3] color – measures amorphous carbon dust content



Spitzer/IRS spectra

Metallicity and carbon-rich dust production



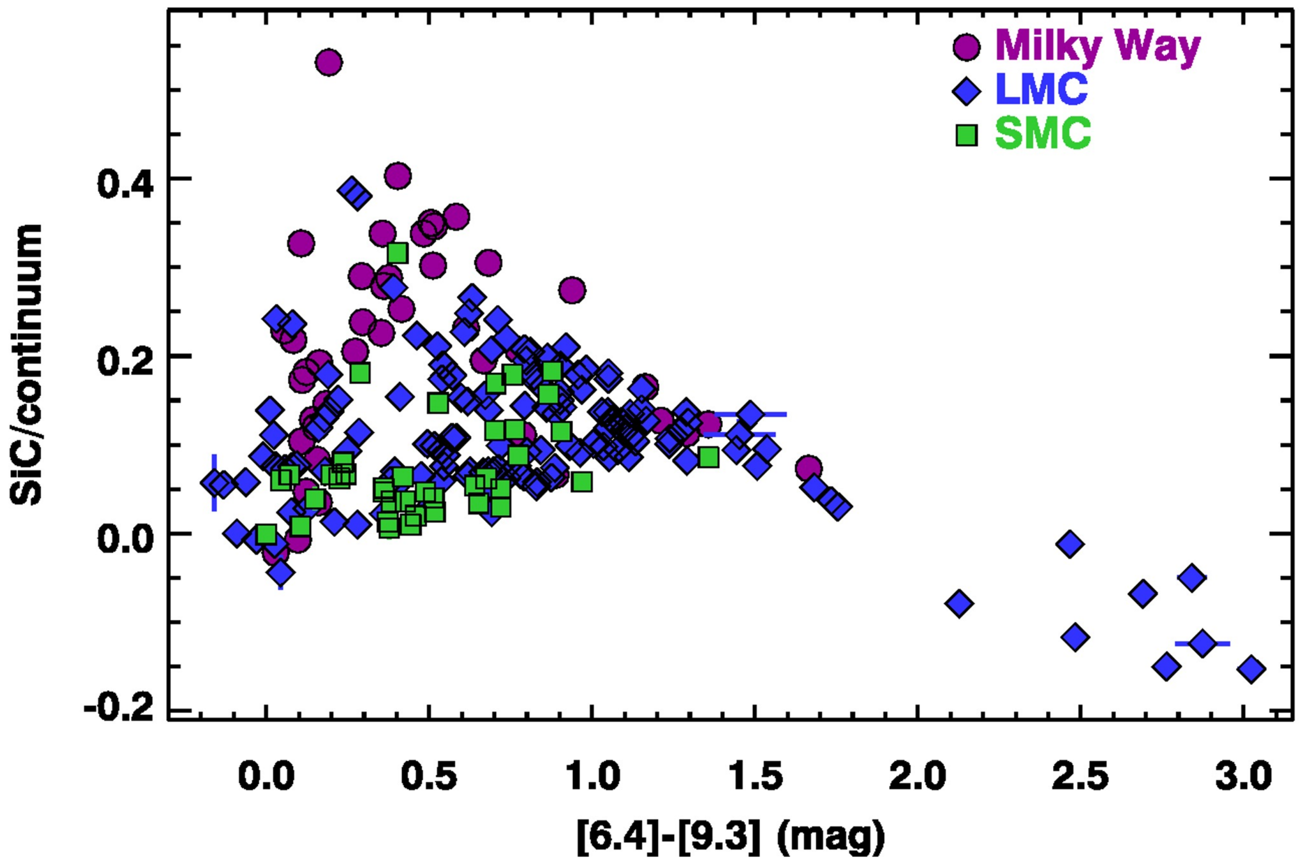
Galaxy	[Fe/H]
Milky Way	0.0
LMC	–0.3 to –0.5
SMC	–0.5 to –0.8

The amount of dust produced by carbon stars does NOT depend strongly on their initial metallicity

Carbon stars make and dredge up all the carbon they need to make dust

Sloan et al. (2016)

Metallicity and SiC dust



Most carbon stars in the Galaxy make a lot of SiC

Most carbon stars in the SMC don't

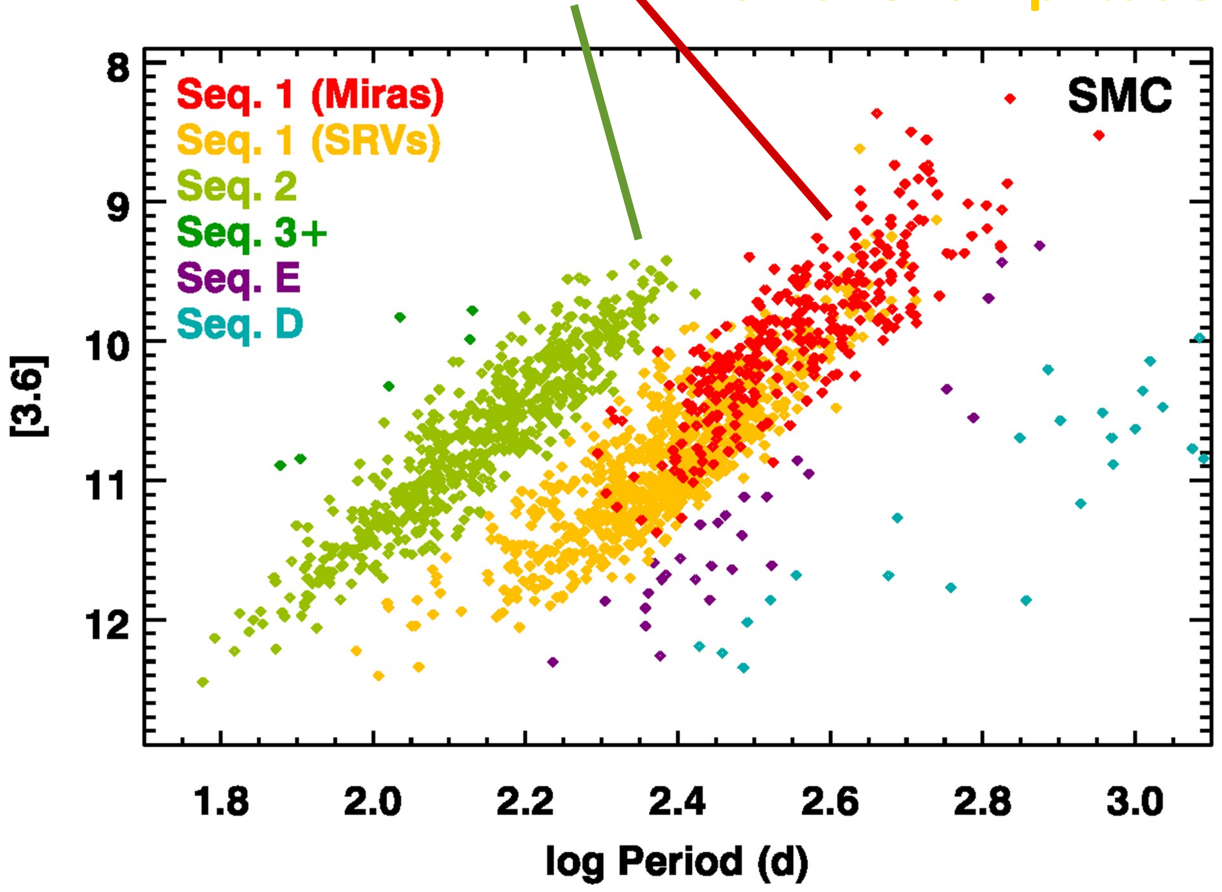
That is consistent with their initial metallicity and Si abundance

Figure from Sloan et al. (2016), based on spectra from many papers

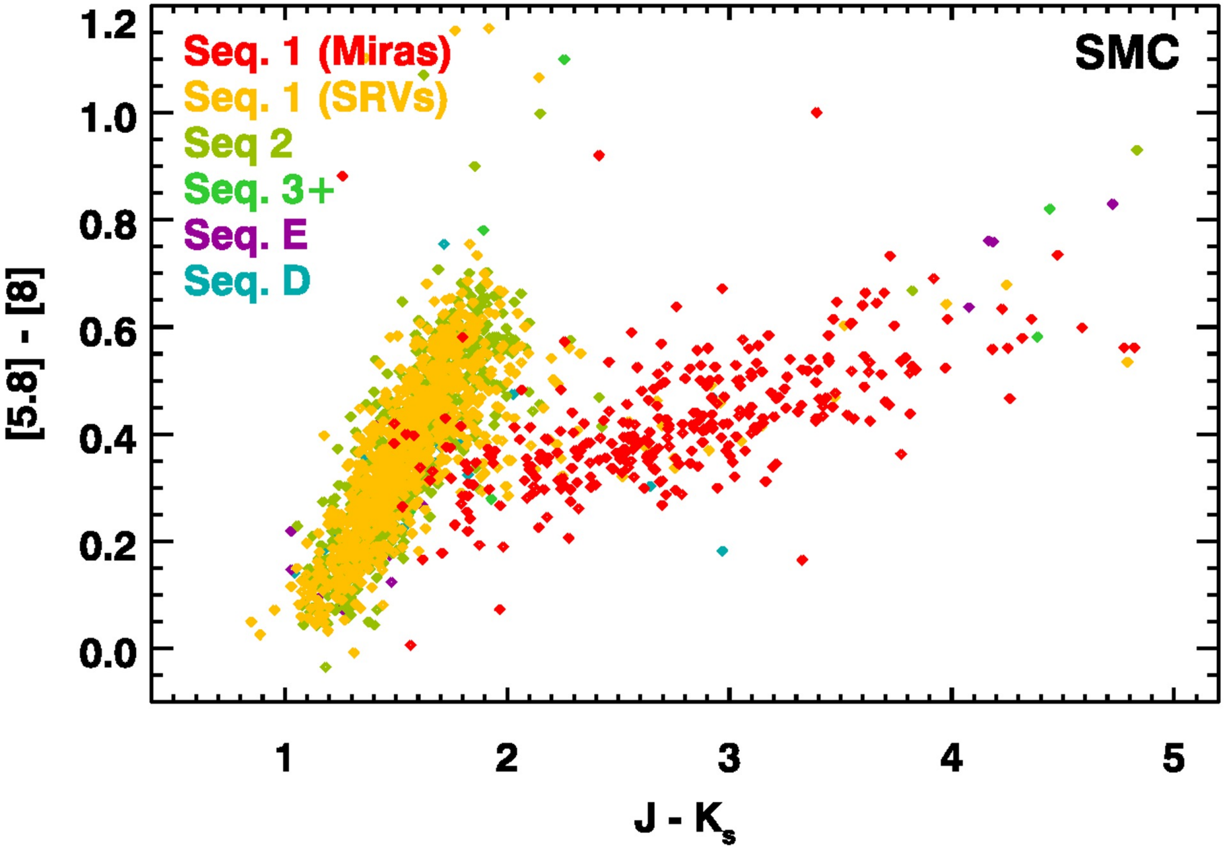
Pulsation and dust in carbon stars

Fundamental mode
First overtone mode

Larger amplitude
Smaller amplitude



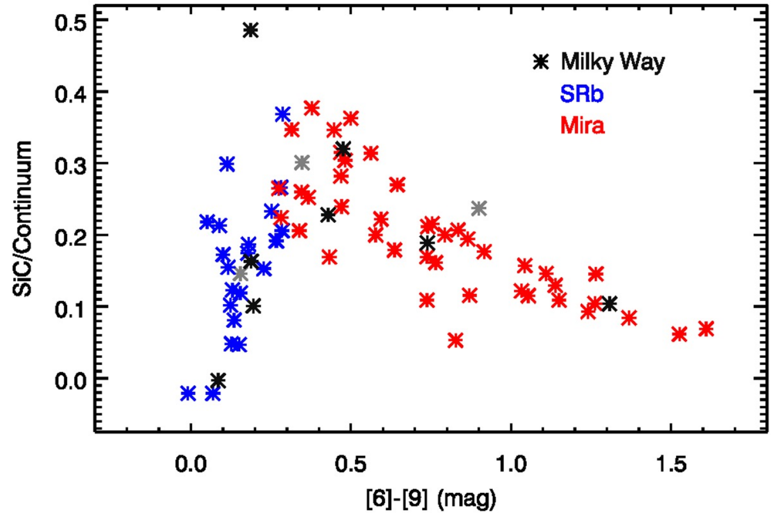
Miras produce more dust than SRVs

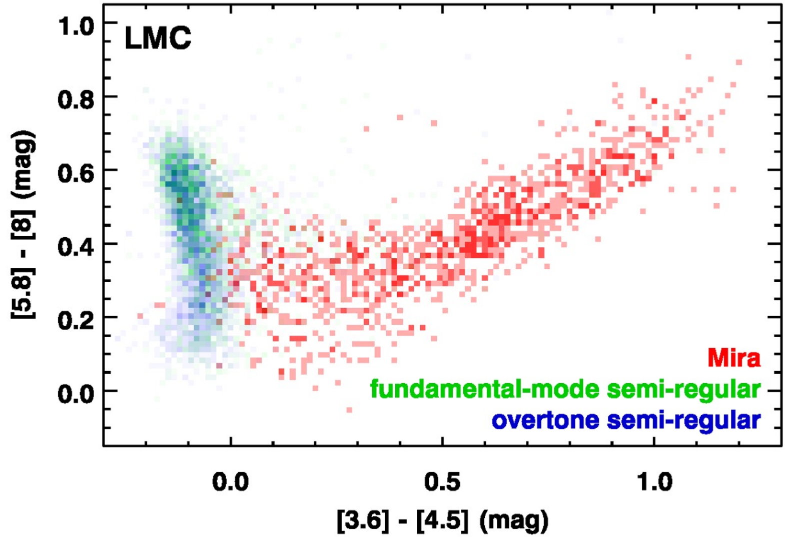


Sequences as defined by Fraser et al. (2005)

Sloan et al. (2017)

The carbon dust dichotomy

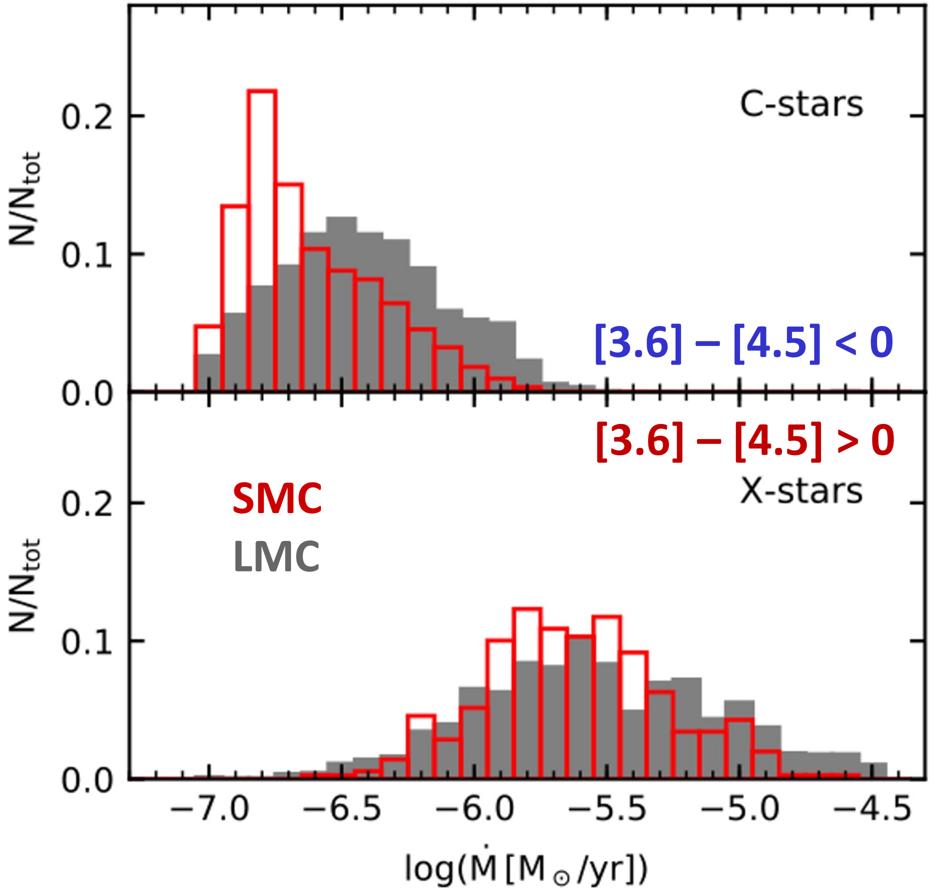




Kraemer et al. (2019)

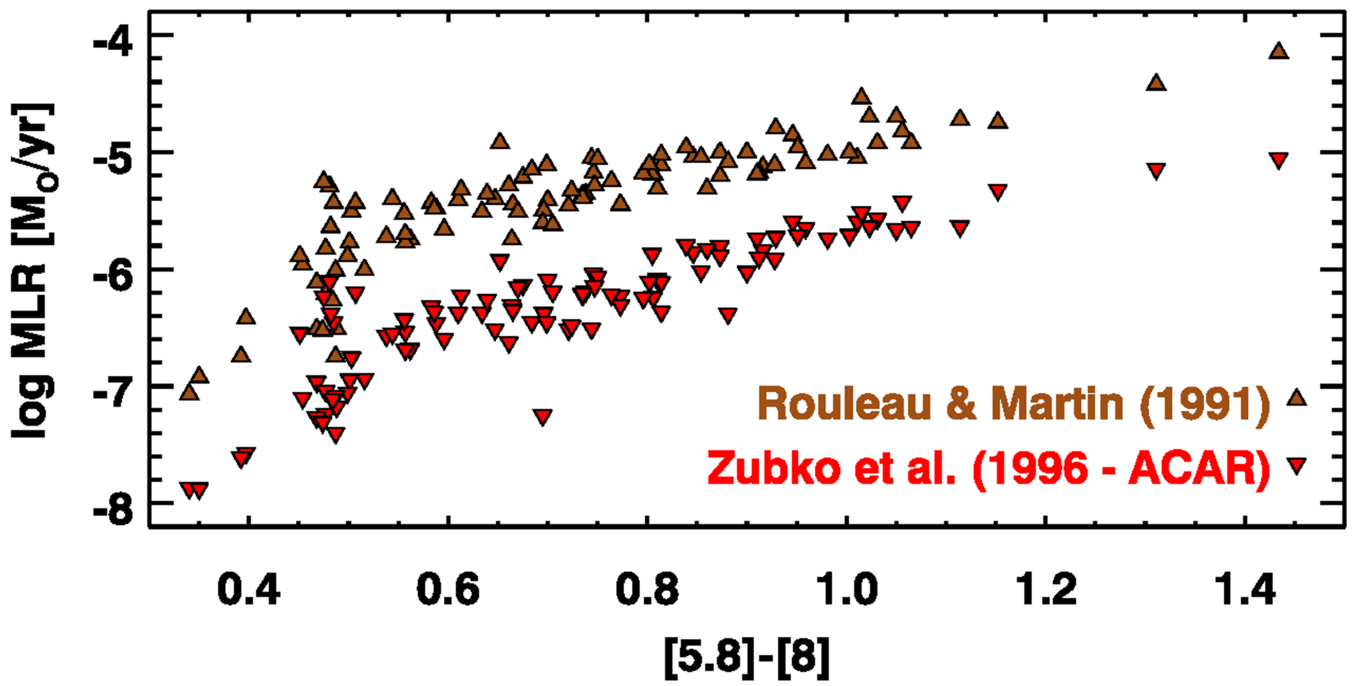
SiC dominates what little dust the semi-regulars make

Miras produce more dust, and it's mostly amorphous carbon



Nanni et al. (2019)

Which amorphous carbon? It matters



Groenewegen & Sloan (2018)

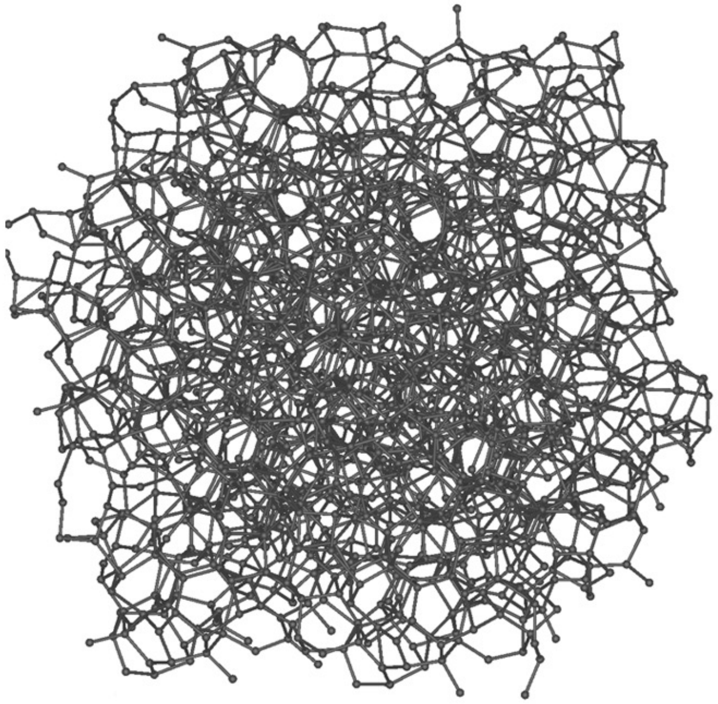
Assumed optical constants for amorphous carbon change mass-loss and dust-production rates by a factor of several

Impacts global dust budgets

See:

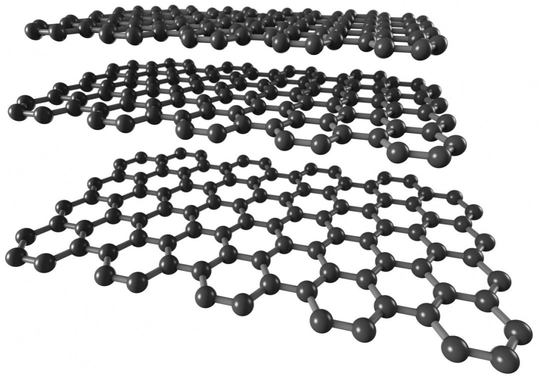
Matsuura et al. (2009)
Boyer et al. (2012)
Matsuura et al. (2013)

And what is amorphous carbon, anyway?



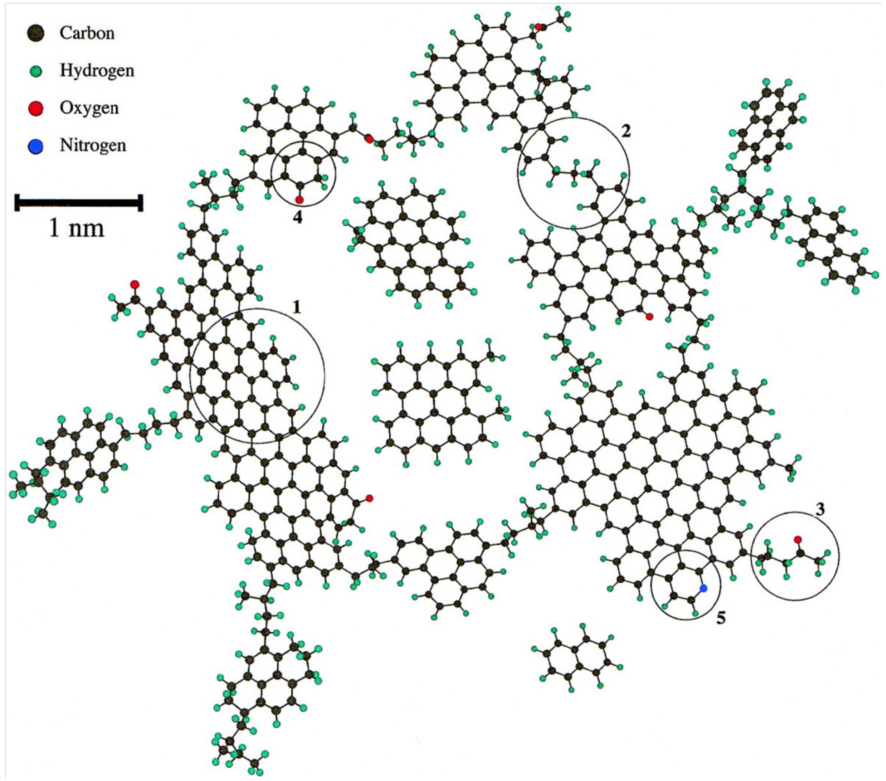
Amorphous carbon

Wikipedia



Graphite

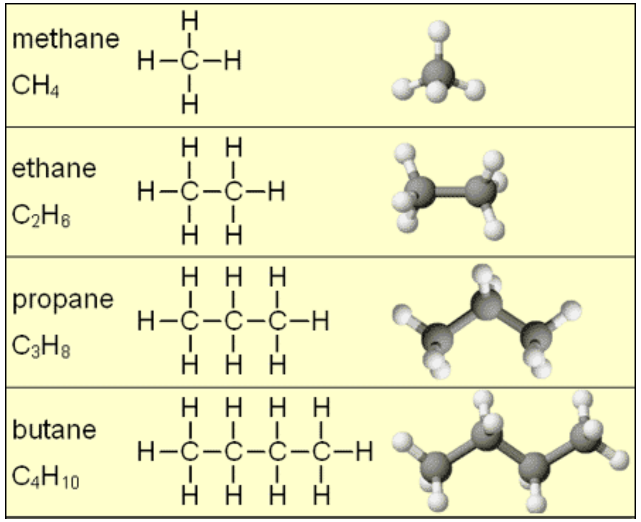
Nisenet.org

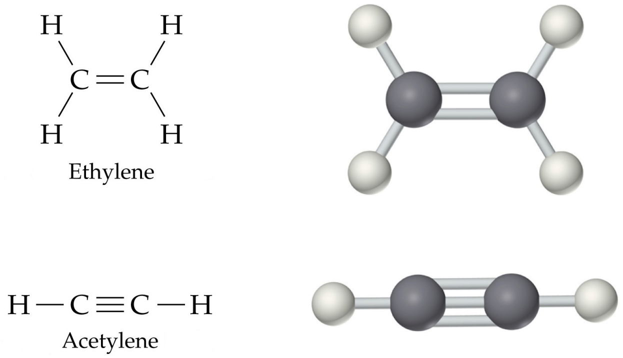


Almost Hydrogenated Amorphous Carbon

Pendleton & Allamandola (2002)

Aliphatic vs. aromatic hydrocarbons





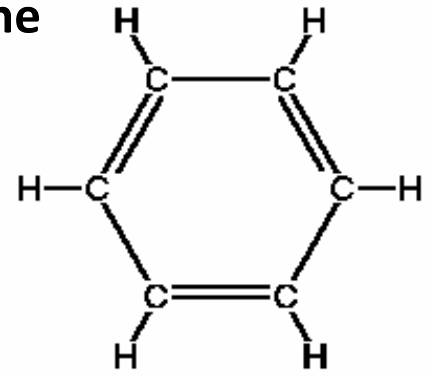
Aliphatic: All the electrons are localized

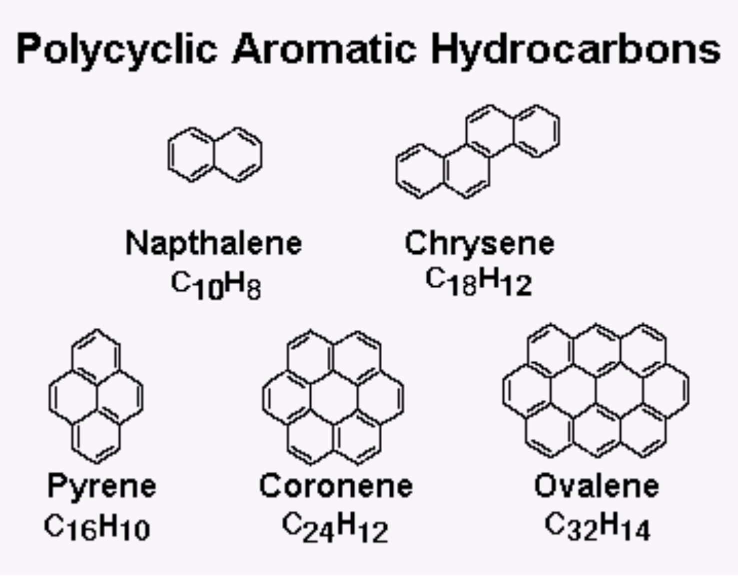
Aromatic: The electrons in the C-C bonds float around the rings

Aromatic molecules are more efficient radiators and absorbers

The opacity of amorphous carbon depends on the aliphatic/aromatic ratio

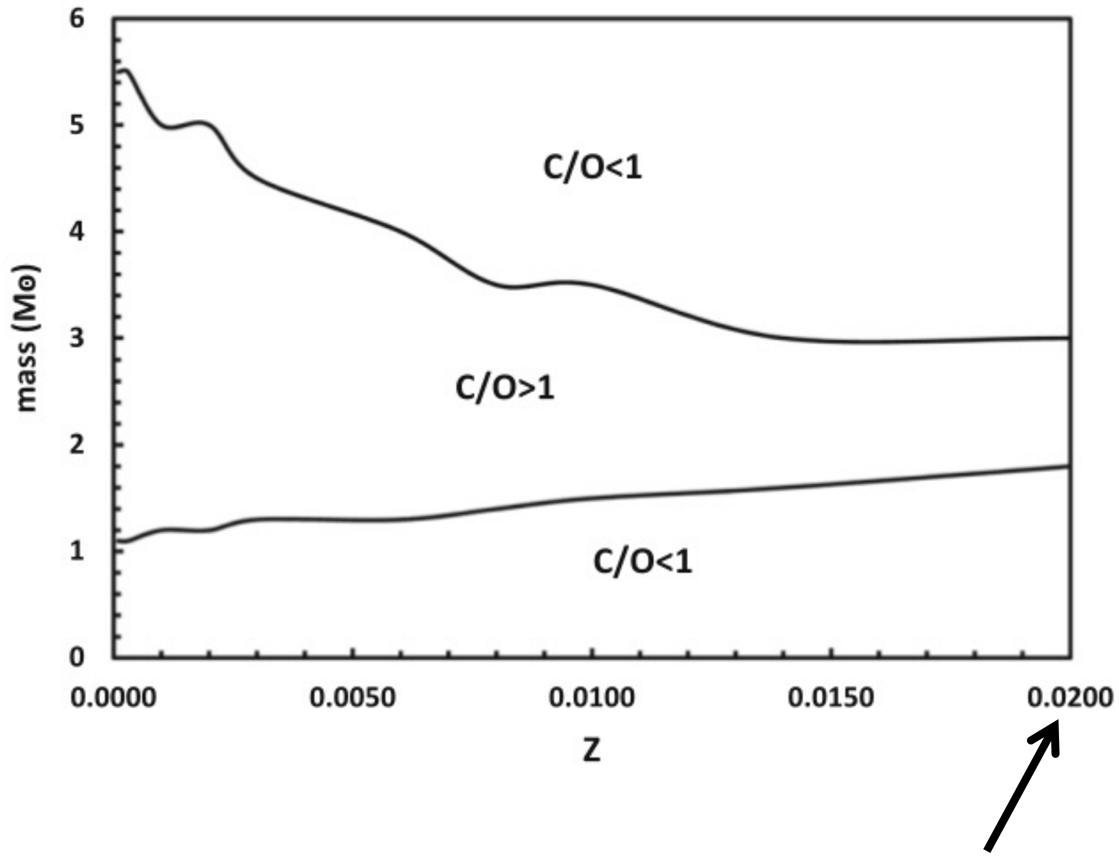
Benzene
C_6H_6





NASA Ames Astrochemistry Lab.

Mass limits and evolutionary timescales



Straniero et al. (2023)

$Z_\odot$ (roughly)

We should expect carbon stars to make dust as early as z ~ 11

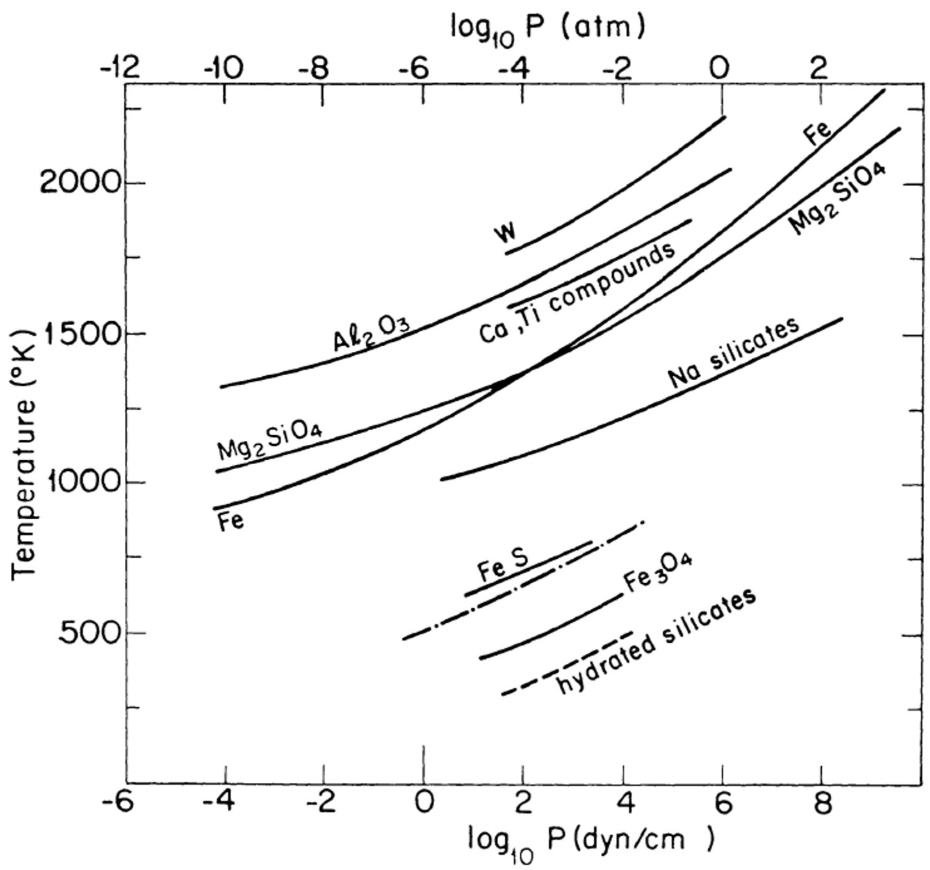
Upper mass limit set by proton capture (hot-bottom burning)

Lower mass limit set by dredge-up efficiency

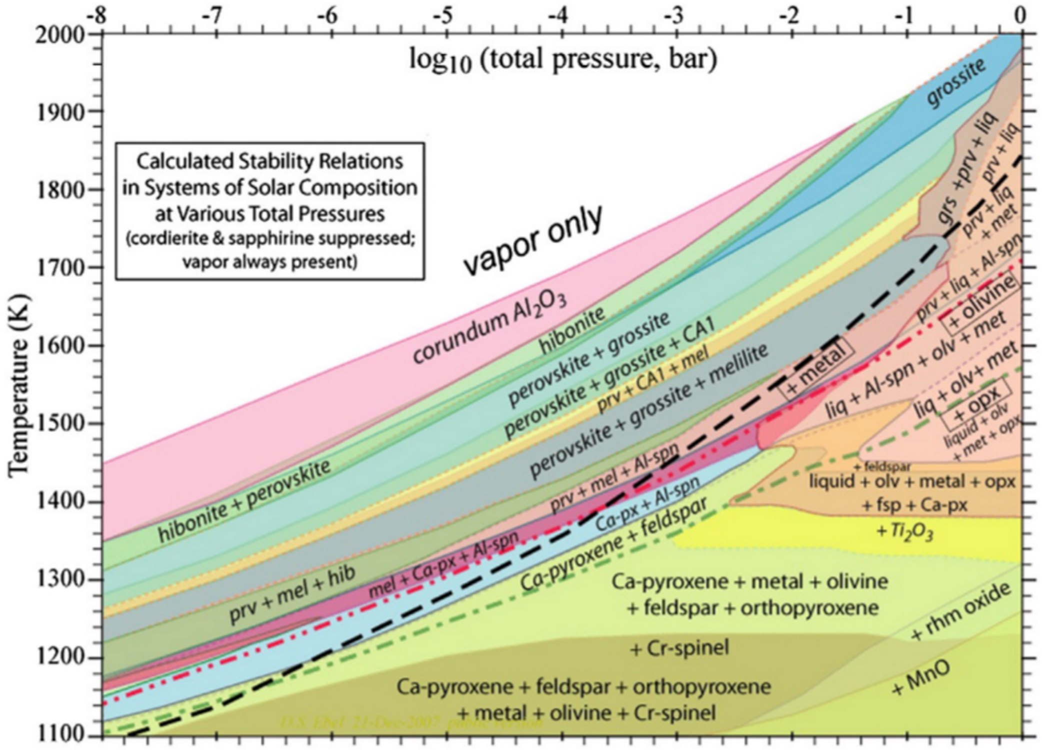
A 5 $M_\odot$ star with [Fe/H] = –2 needs < 100 My to reach the AGB (Herwig 2004)

JWST has observed galaxies with stars at z ~ 14 (e.g., Naidu et al. 2025), which is ~300 My after the Big Bang

Dust condenses from molecular gas



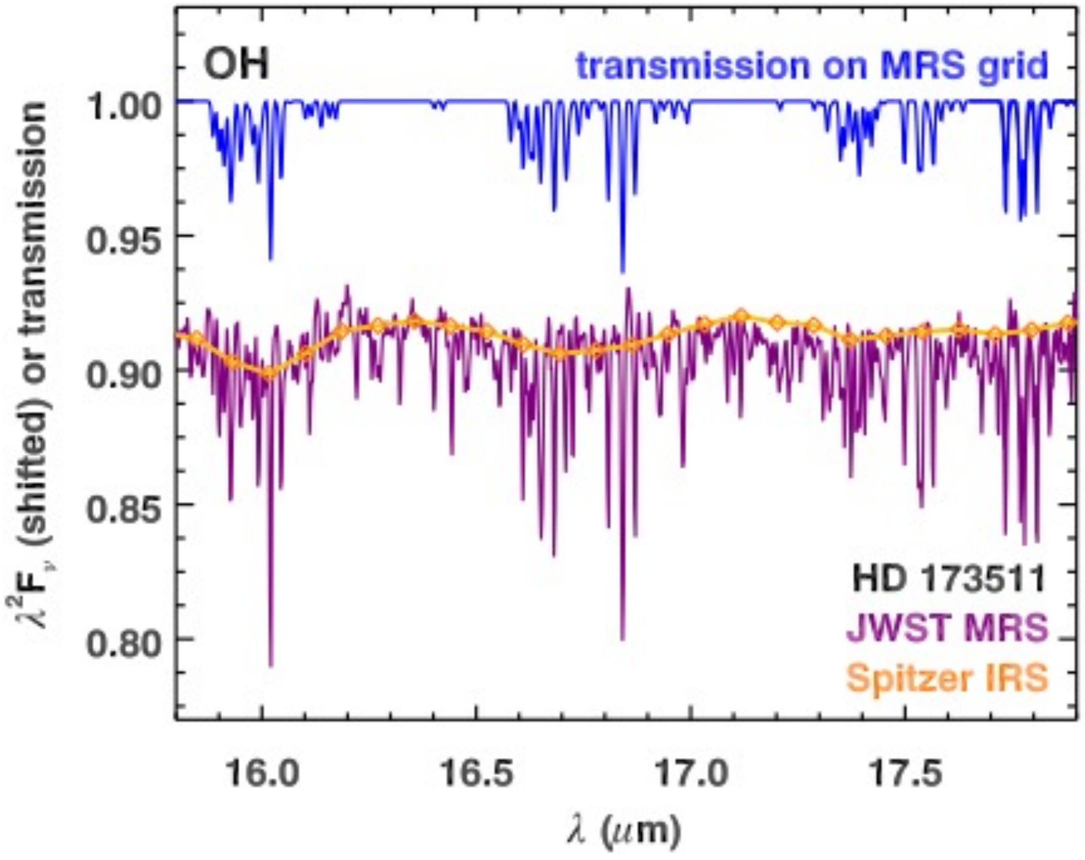
Salpeter (1977)



Tielens (2022) (from Ebel 2006)

To understand the grains, you need to investigate the gas

Molecules – the opportunity



Sloan et al. (in prep.)

JWST is obtaining spectra with $\lambda/\Delta\lambda \sim 3000$

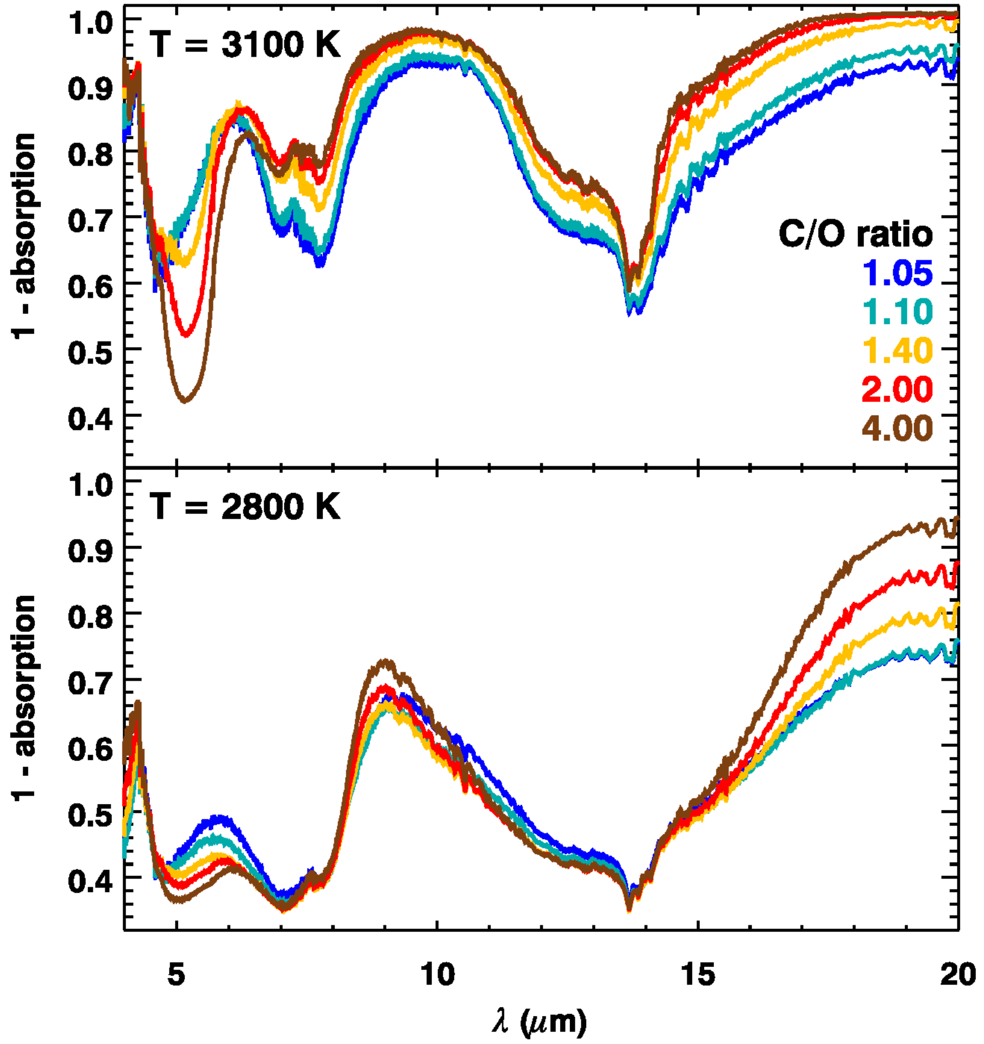
NIRSpec: 0.7 – 5.1 μm

MRS on MIRI: 4.9 – 28 μm

That resolves the line structure within molecular bands

Example: OH (and H_2O) in a K giant

Molecules – the danger



Sloan et al. (submitted)

Left: Hydrostatic models of carbon by stars by B. Aringer et al. show that molecular absorption affects ***all wavelengths*** at T = 2800 K

So where, exactly, is the stellar continuum?

This problem affects the Manchester Method

Poster 3 has more on carbon-rich molecular spectra

Relating the dust to the star

O-rich

- Supergiants make amorphous silicates
- Stars with C/O ~ 1 make amorphous alumina
- Semi-regular variables make more crystalline alumina

C-rich

- Amorphous carbon production does not change (much) with metallicity
- But SiC may depend on metallicity
- Semi-regulars produce less dust, which is mostly SiC
- Miras produce more dust, mostly amorphous carbon

Things to watch out for

- Automated analysis is needed for large spectroscopic samples
    - but it comes with dangers

- Beware the differences in dust opacities

- Identifying the dust really requires two resonances in the infrared
    - E.g. silicate dust at 10 and 18 μm
    - More dangerous: Alumina at 11 μm, SiC dust at 11.3 μm, MgS dust at 30 μm
    - Or no resonances: amorphous carbon, iron dust

- Molecular absorption complicates the dust analysis