INSTITUT DE CIÈNCIES DE L'ESPAI

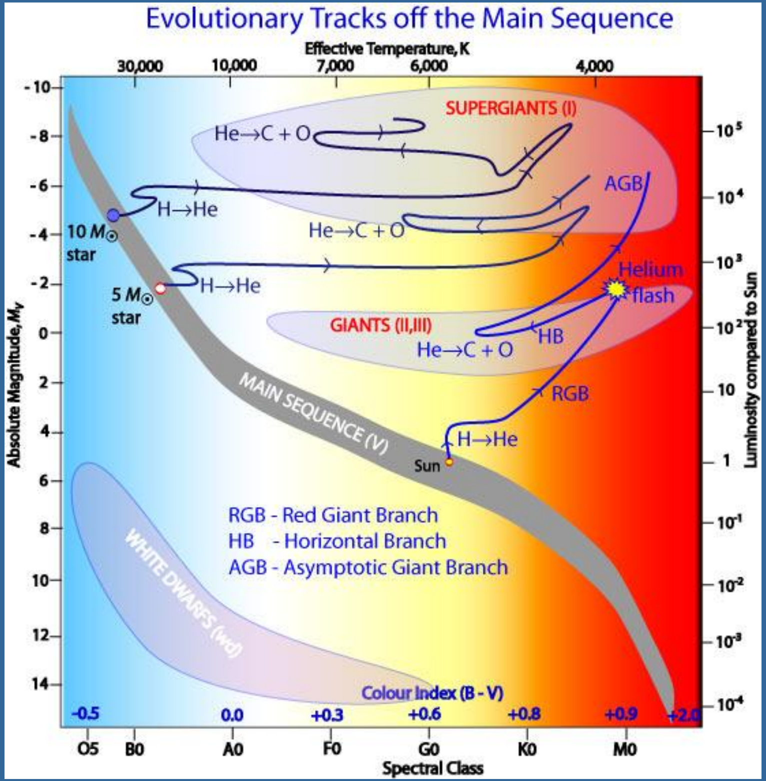
Dust formation in AGB stars

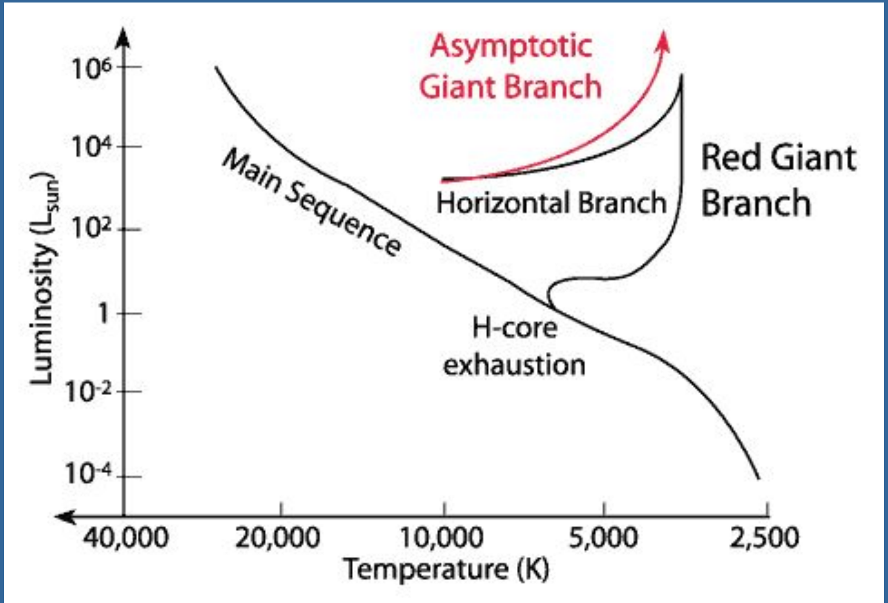
ICE Summer School "Life Cycle of Dust"

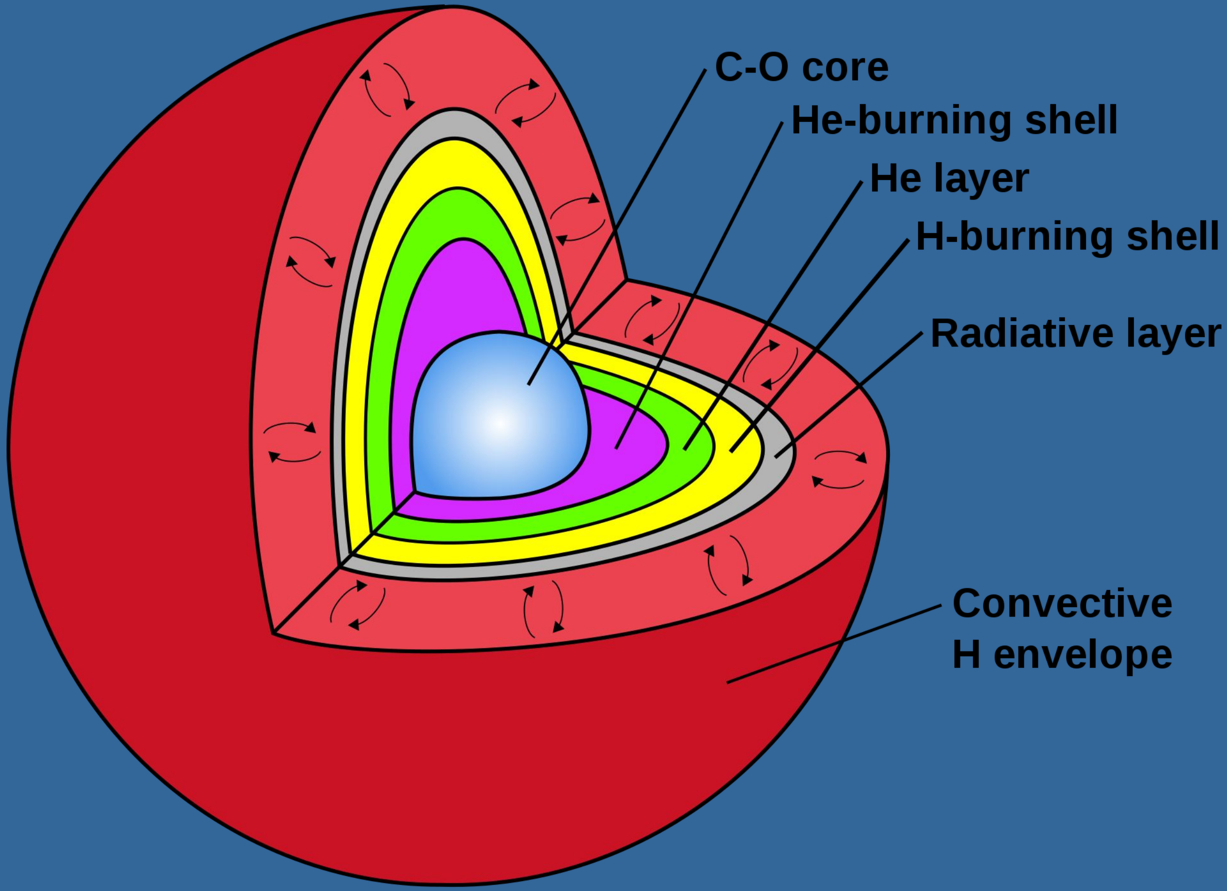
5 July 2023

Ciska Kemper (ICE-CSIC / ICREA / IEEC)

The Asymptotic Giant Branch





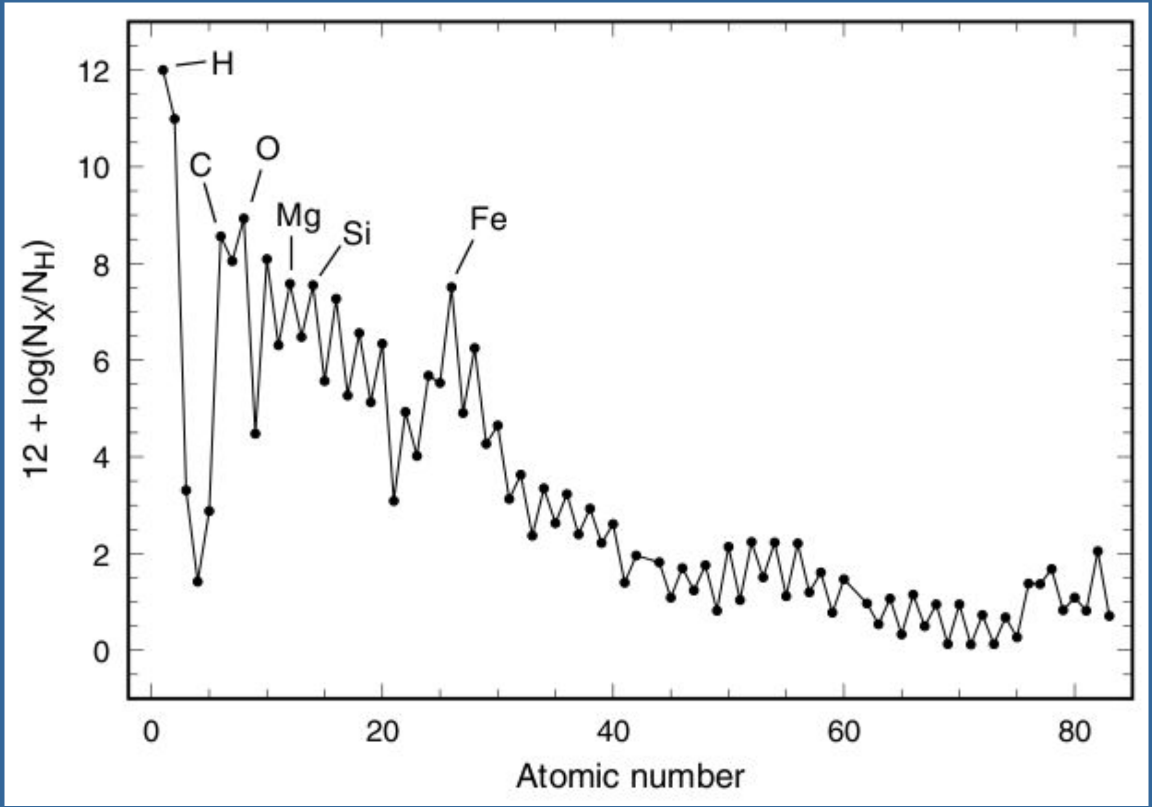

C-O core
He-burning shell
He layer
H-burning shell
Radiative layer
Convective
H envelope

Characteristics of AGB stars

Mass	0.8 - 8 $M_\odot$
Radius	200 - 600 $R_\odot$
T_{eff}	2500 - 3500 K
Luminosity	10^3 - 10^4 $L_\odot$
Mass-loss rate	10^{-8} - 10^{-4} $M_\odot$/yr
Variability period	30 - 2800 days
AGB life time	10^5 - $5x10^6$ yrs

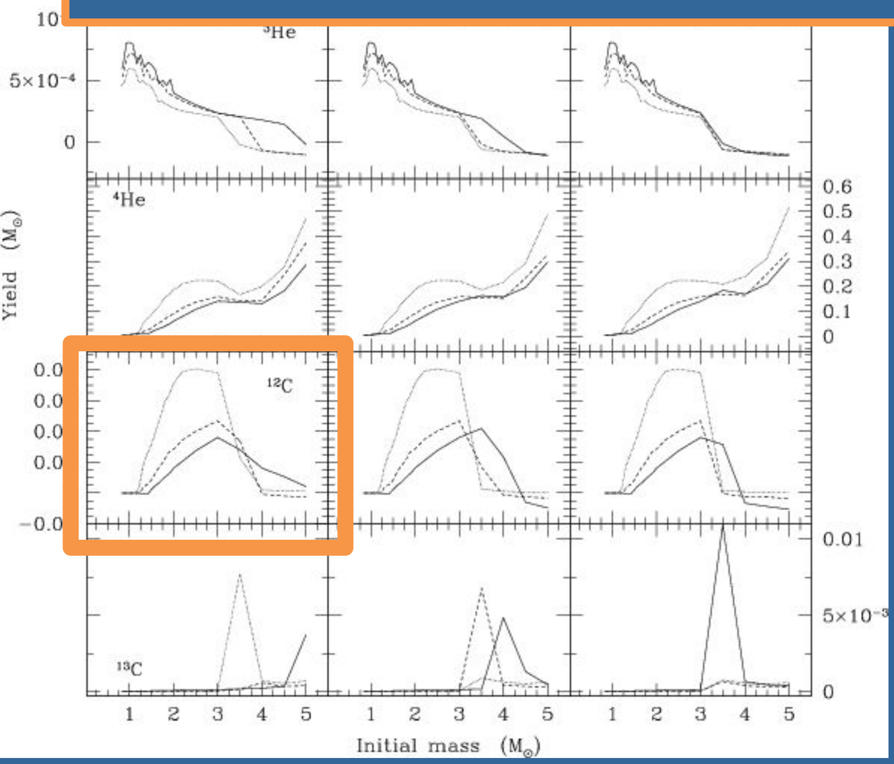
Elemental composition of the ISM

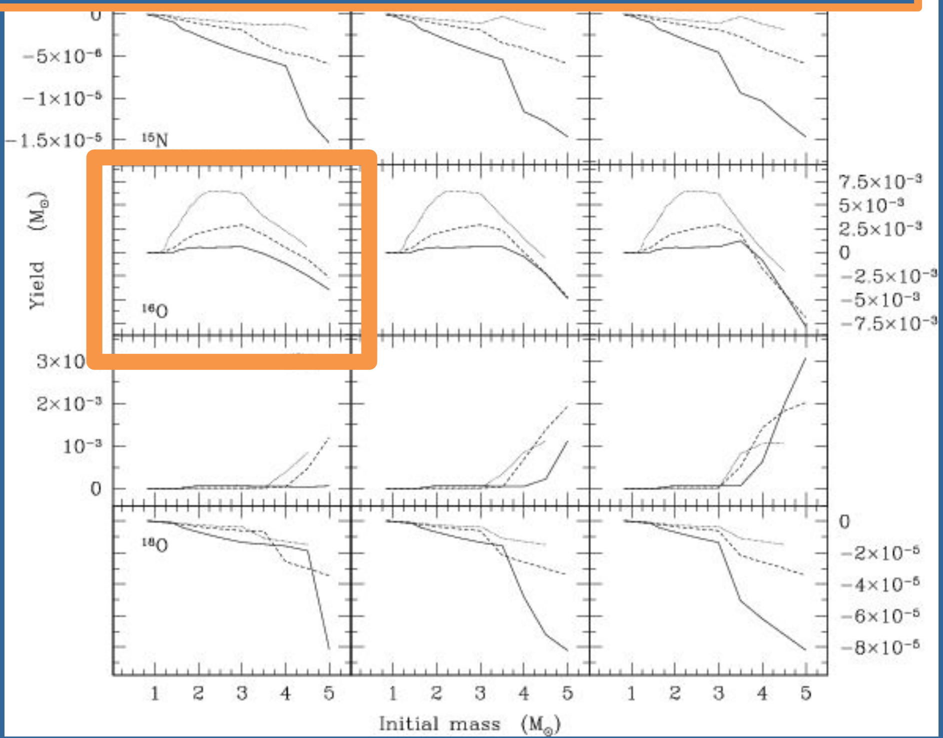
-



Whittet 2003

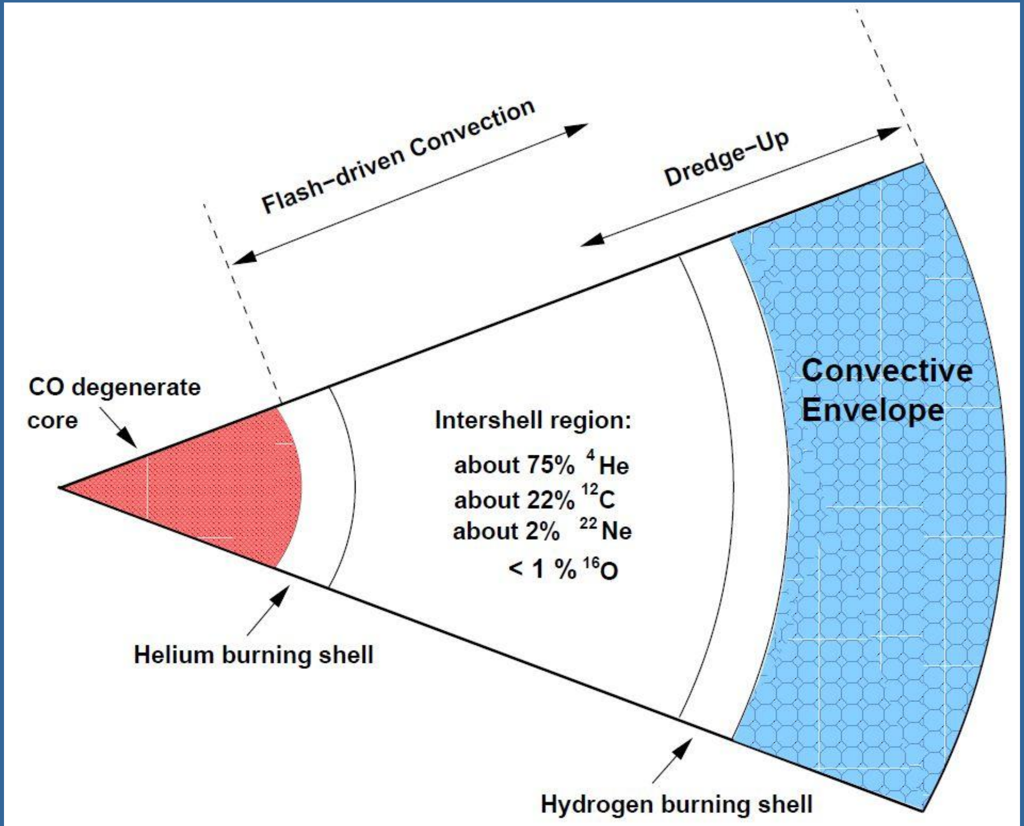
Elemental yield from stars



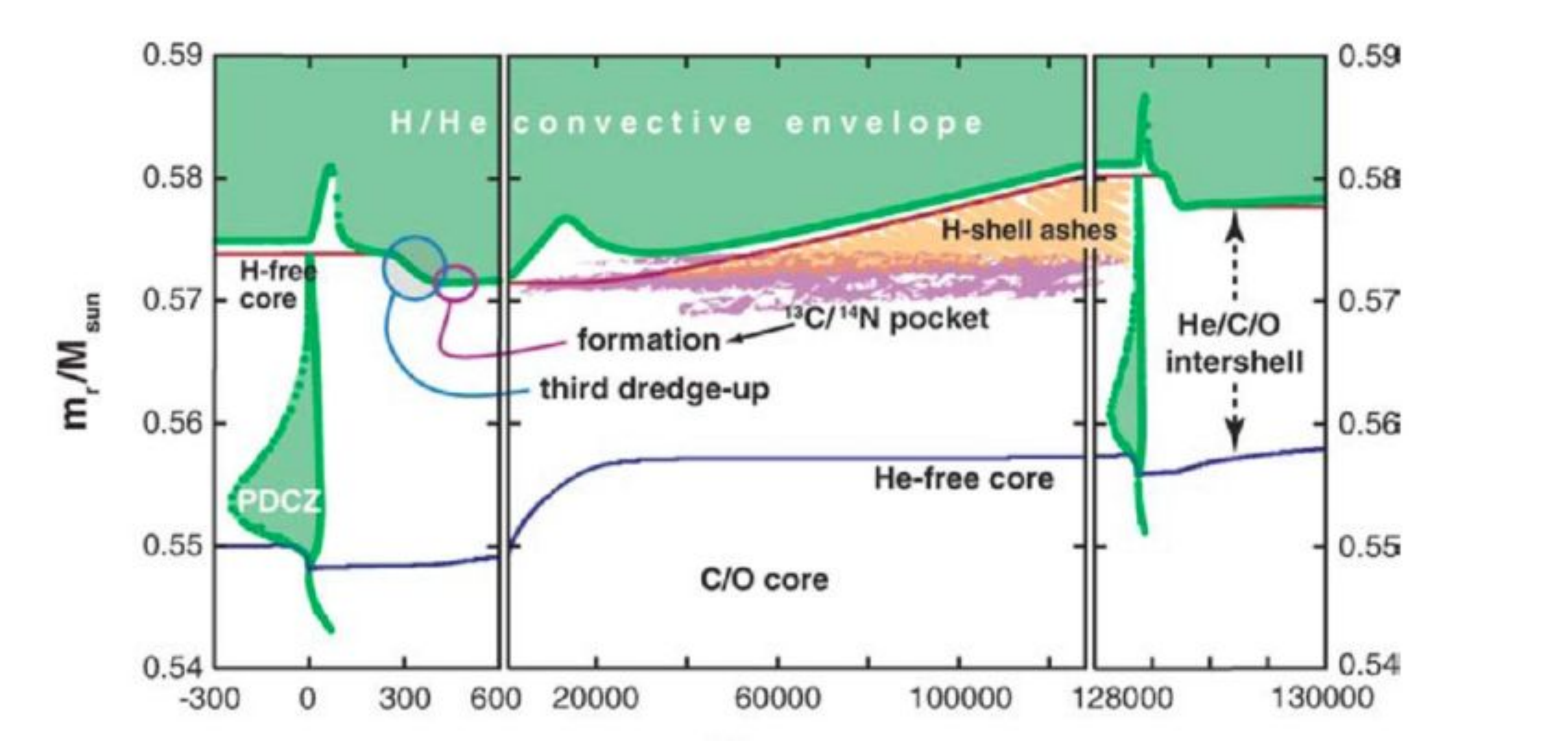


Marigo 2001

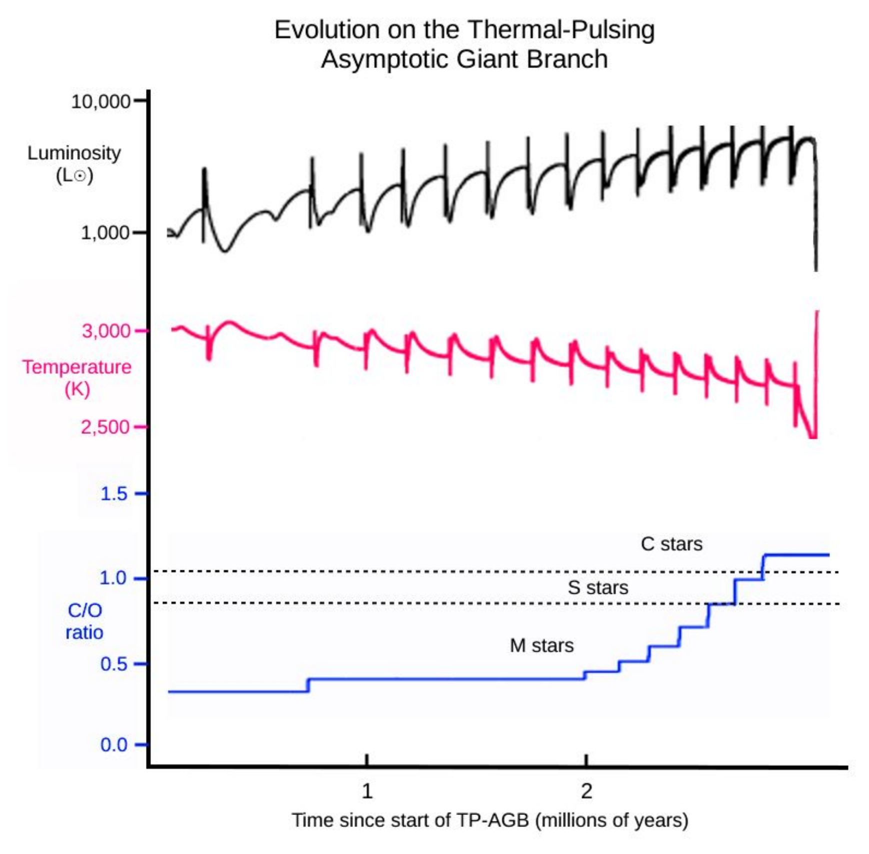
Composition and convection



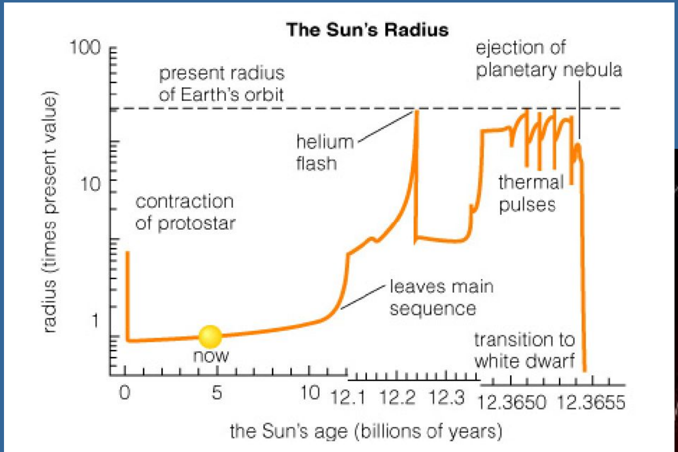
Transport to the surface

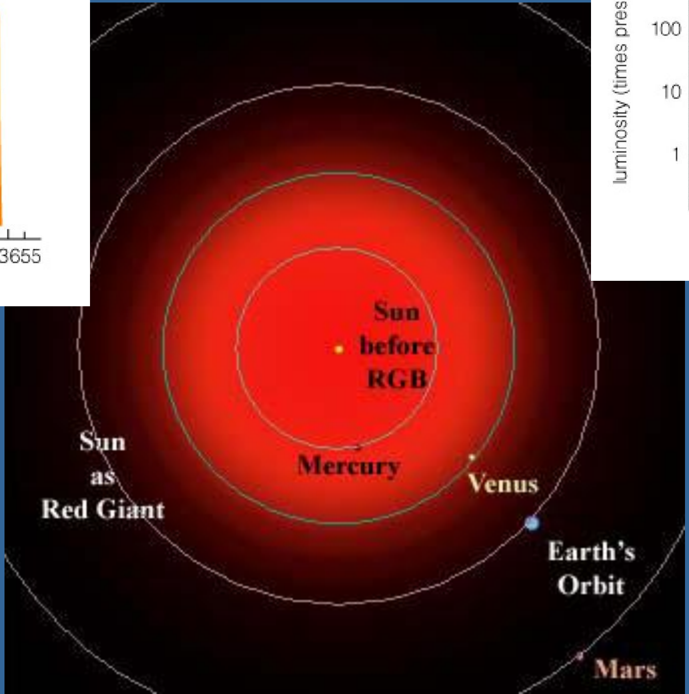


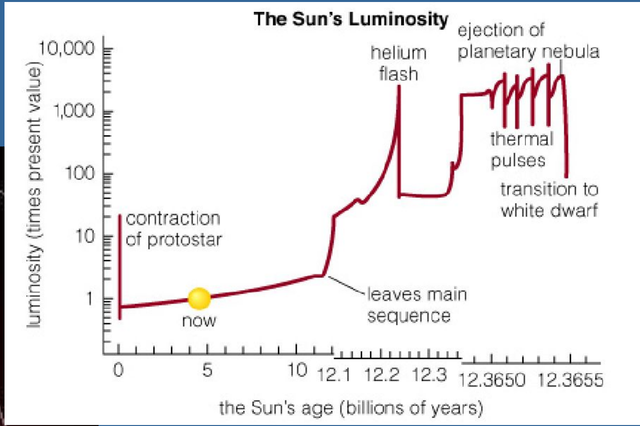
Evolution to a C star through TP



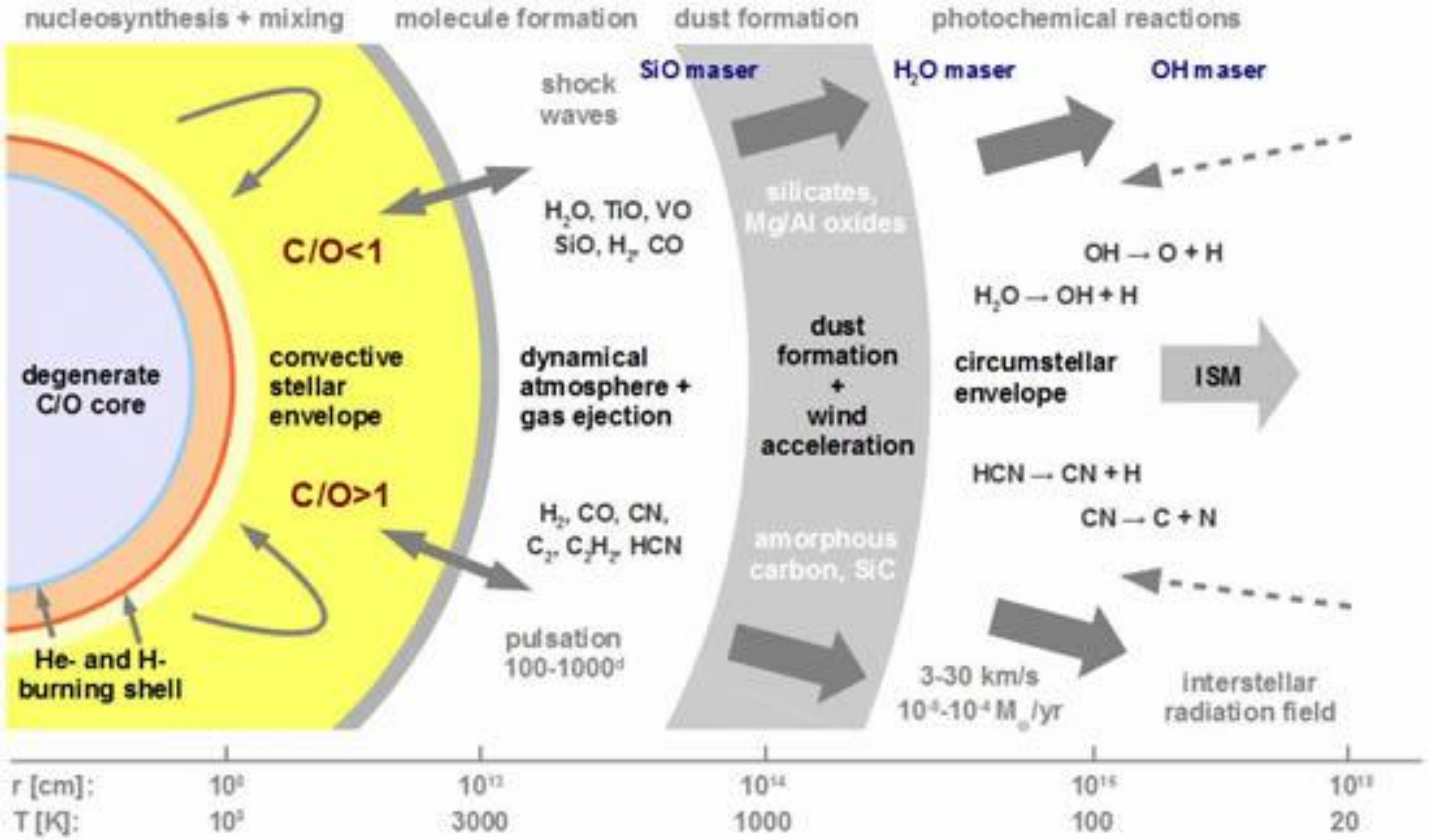
The fate of planetary systems





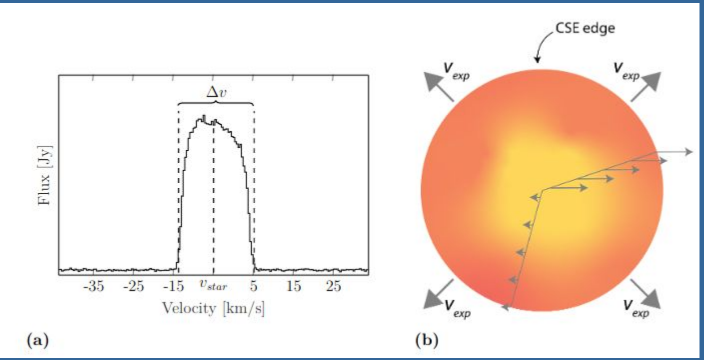


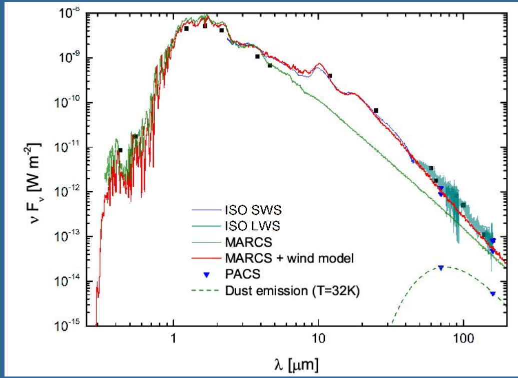
The circumstellar envelope

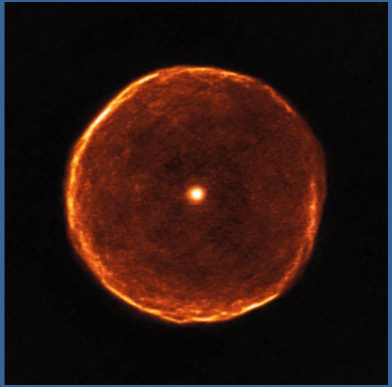


Mass loss on the AGB

- Observed to have a stellar wind
- Infrared excess showing dust is found at some distance from the star (>10 R_*)
- In some cases, detached shells are seen

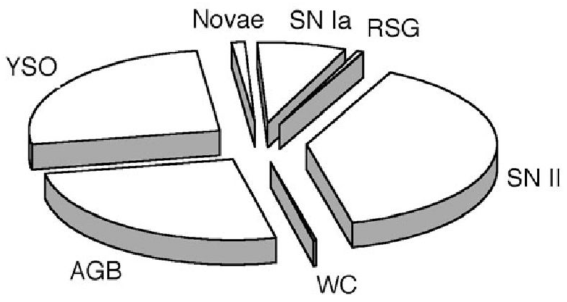






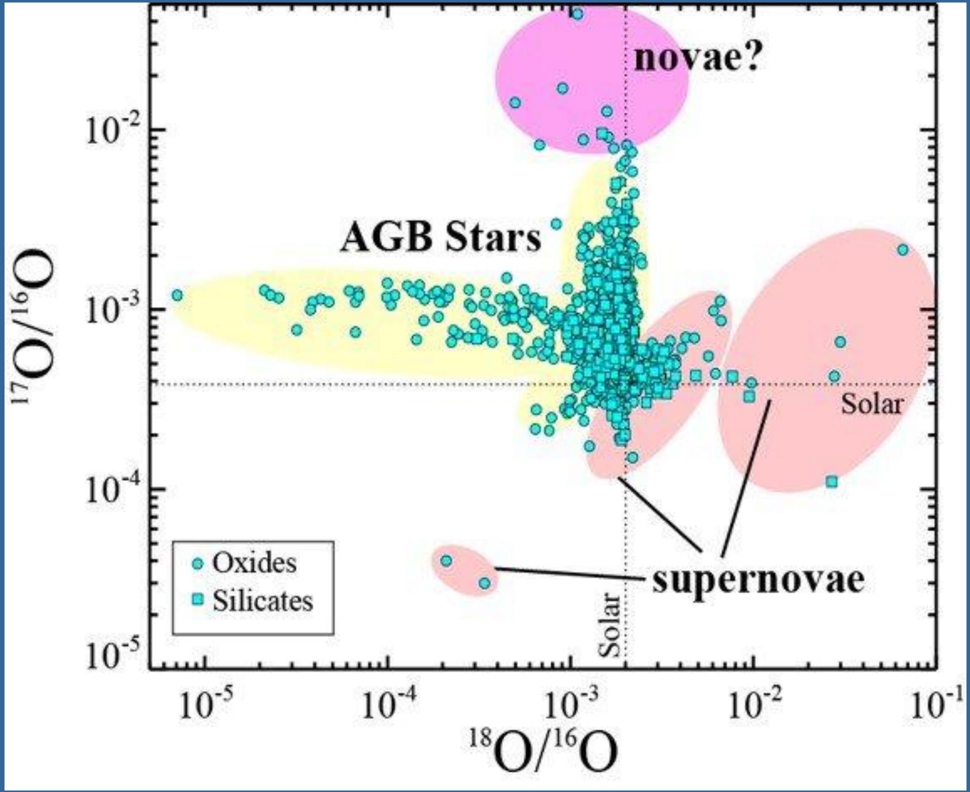
Sources of dust

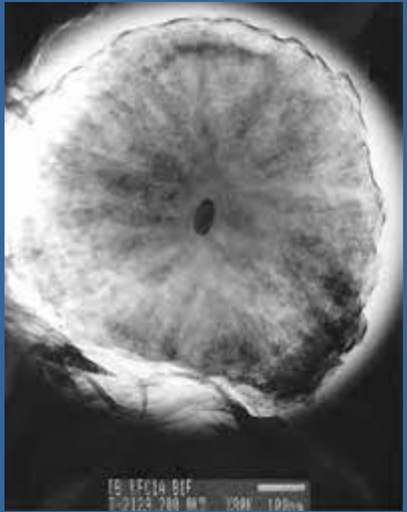
Source	$\dot{M}_H^a$ $[M_\odot\ kpc^{-2}\ Myr^{-1}]$	$\dot{M}_C^b$ $[M_\odot\ kpc^{-2}\ Myr^{-1}]$	$\dot{M}_{sil}^c$ $[M_\odot\ kpc^{-2}\ Myr^{-1}]$
C–rich giants	750	3	–
O–rich giants	750	–	5
Novae	6	0.3	0.03
SN type Ia	–	0.3^d	2^d
OB stars	30	–	–
Red supergiants	20	–	0.2
Wolf Rayet	100	0.06^e	–
SN type II	100	2^d	10^d
YSO	$(1500)^f$		8



Tielens et al. 2005

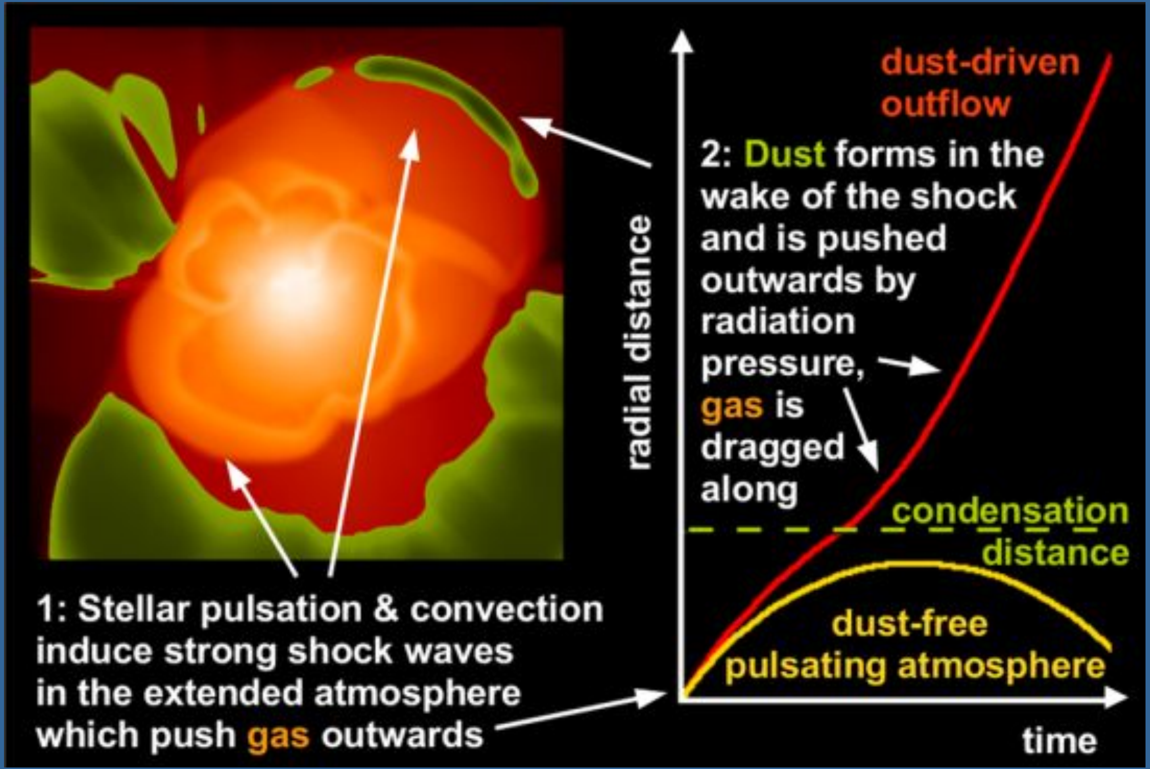
Evidence from presolar grains





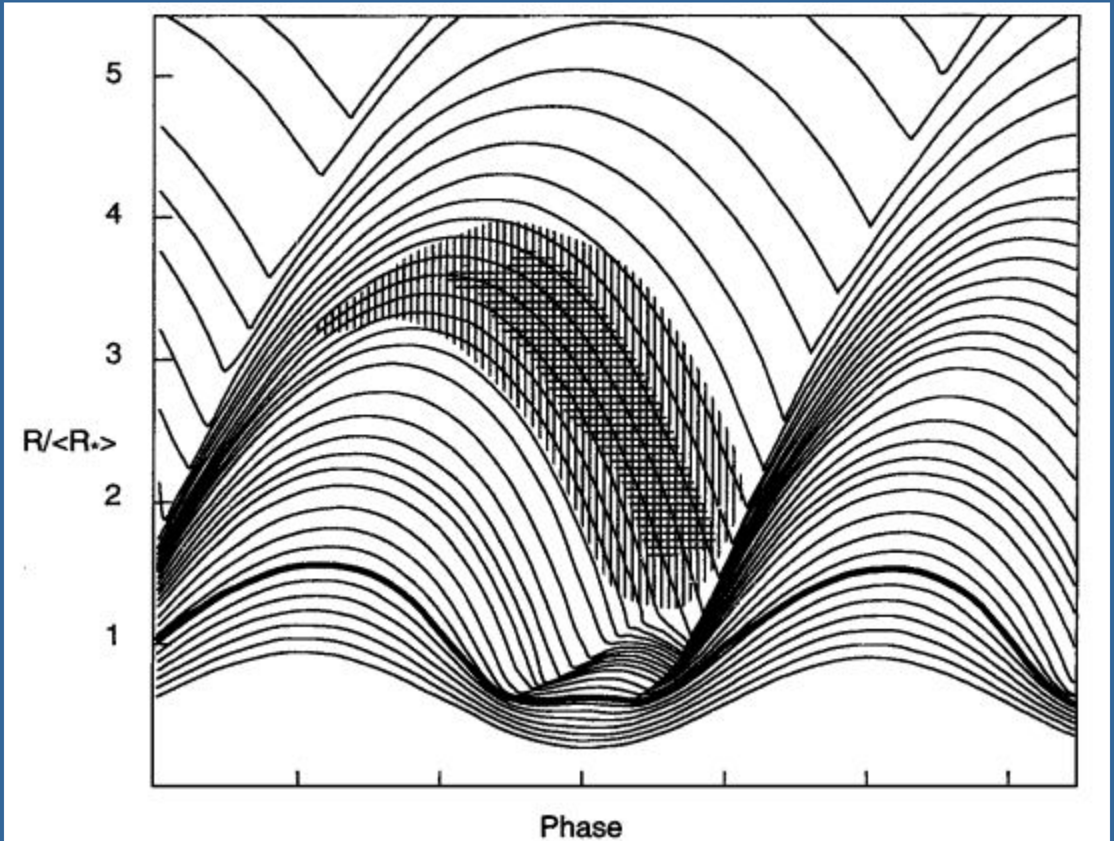
Expanded from Clayton & Nittler 2004

The dusty wind



Höfner & Olofsson 2018

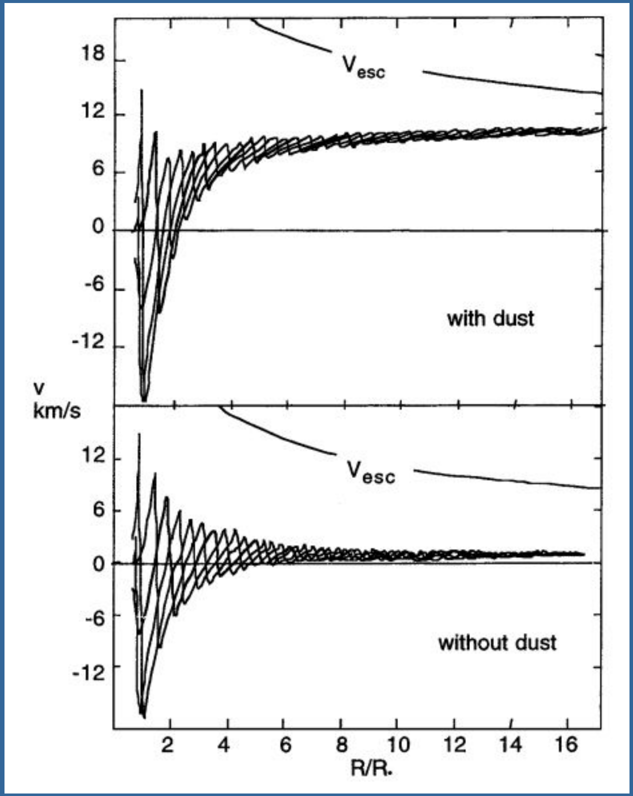
Density waves in pulsating stars



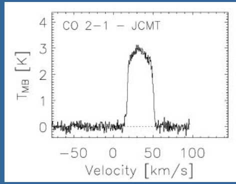
Willson 2000

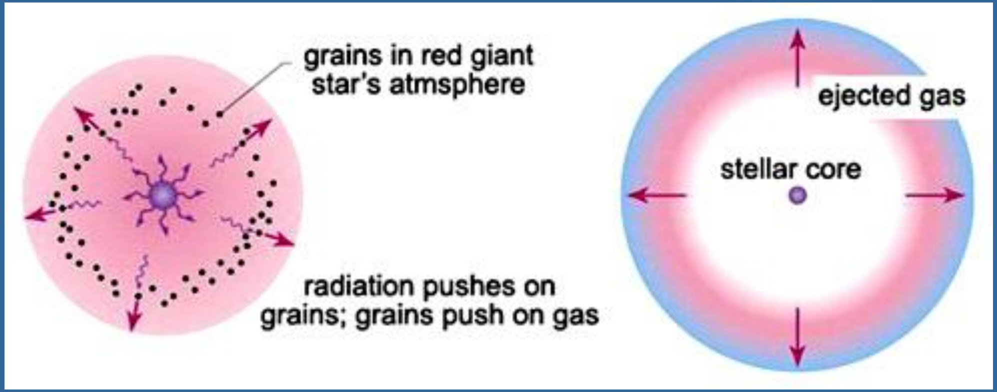
Velocity profile

Willson 2000



- Stellar pulsation does not lead to a wind without dust formation
- $v_{exp} \approx$ 10-50 km/s





Radiation pressure

$$(I/c)C_{\mathrm{pr}}$$

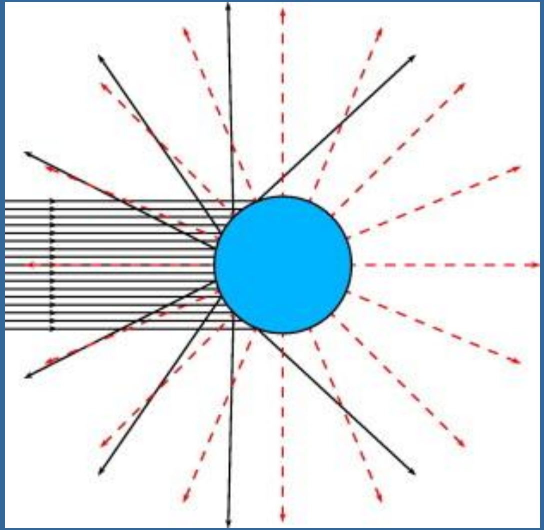
$$Q_{\mathrm{pr}} = C_{\mathrm{pr}}/\pi a^2$$

$$Q_{\mathrm{pr}} = Q_{\mathrm{abs}} + \{1 - g(\theta)\}Q_{\mathrm{sca}}$$

$$F_{\mathrm{pr}} = \pi a^2 \langle Q_{\mathrm{pr}} \rangle \left(\frac{L}{4\pi r^2 c} \right)$$

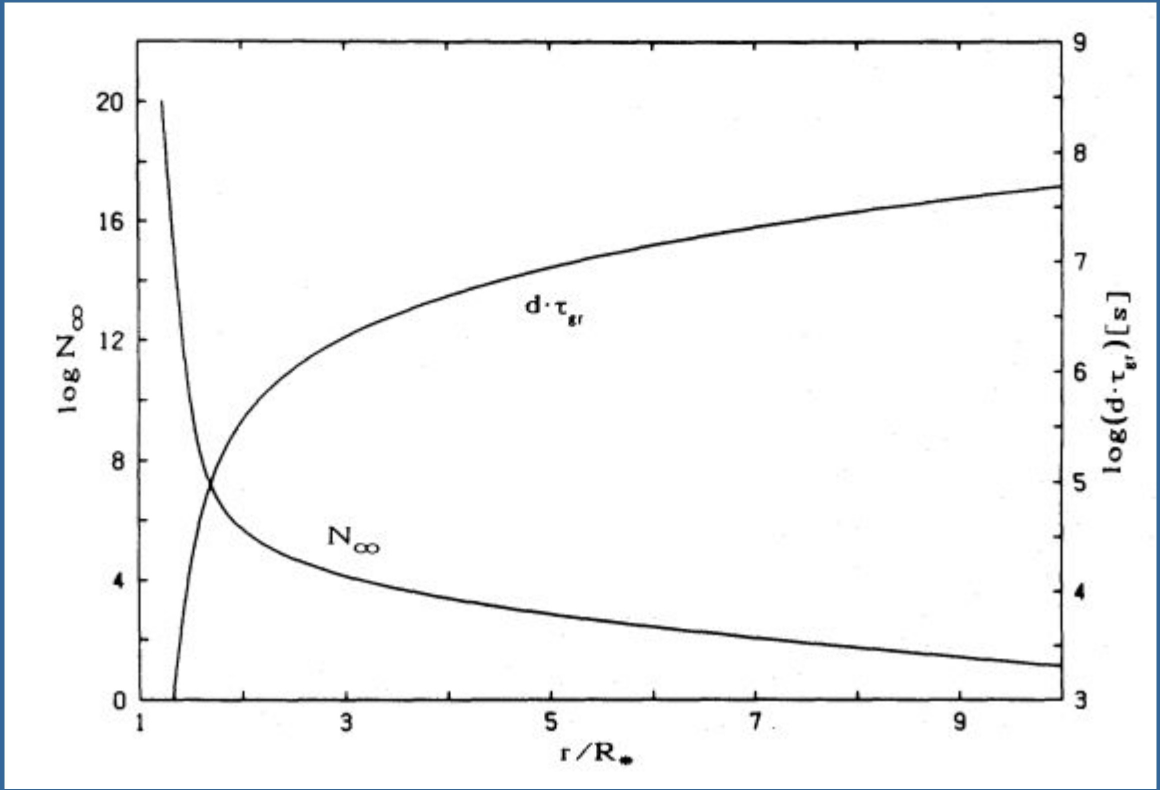
$$F_{\mathrm{gr}} = \frac{GMm_{\mathrm{d}}}{r^2}$$

$$\frac{F_{\mathrm{pr}}}{F_{\mathrm{gr}}} = \frac{3L}{16\pi GMc} \left\{ \frac{\langle Q_{\mathrm{pr}} \rangle}{as} \right\}$$



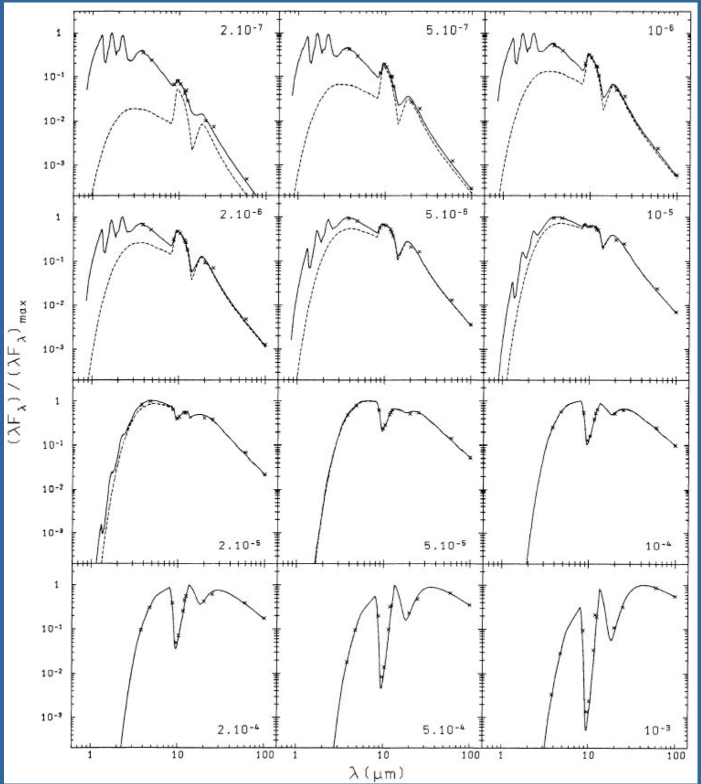
F_{pr}/F_{gr}:
~2000 for carbon grains
~40 for silicate grains

Time scales to grow dust grains

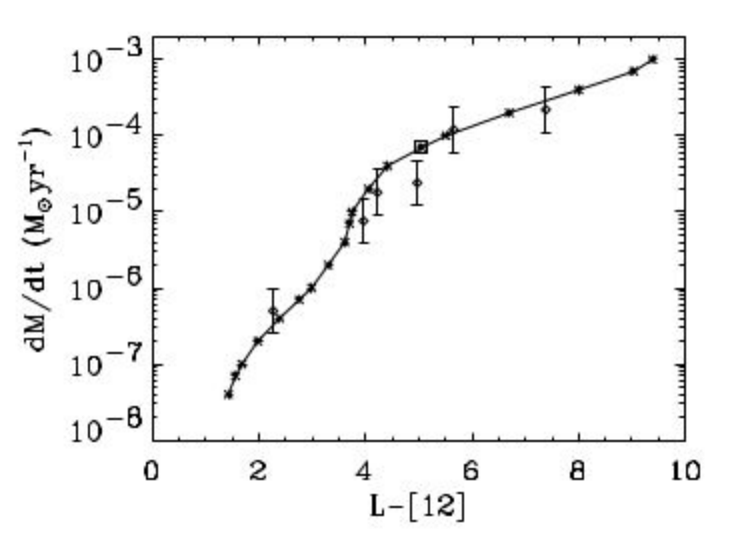


Dominik et al. 1989

Modelling the dust shell

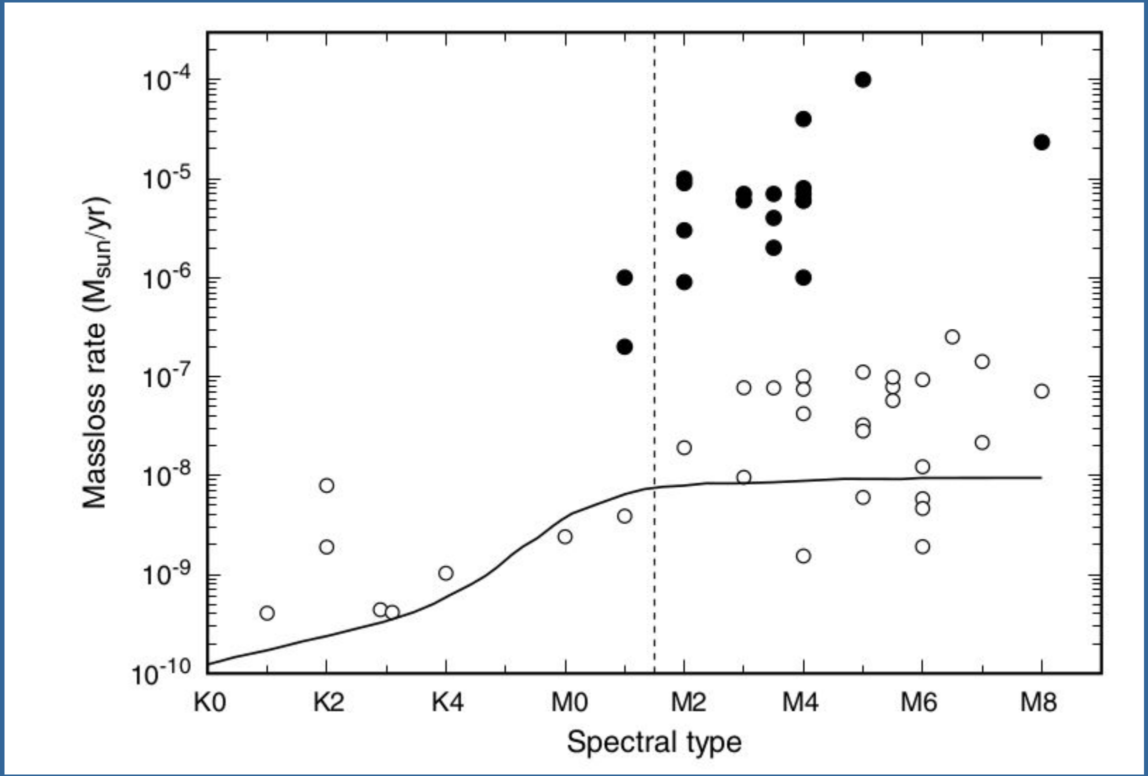


Bedijn 1987



Kemper et al. 2001

Observed mass-loss rates

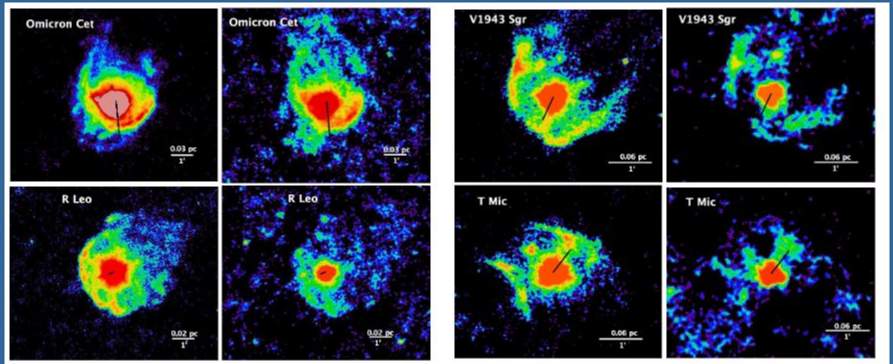


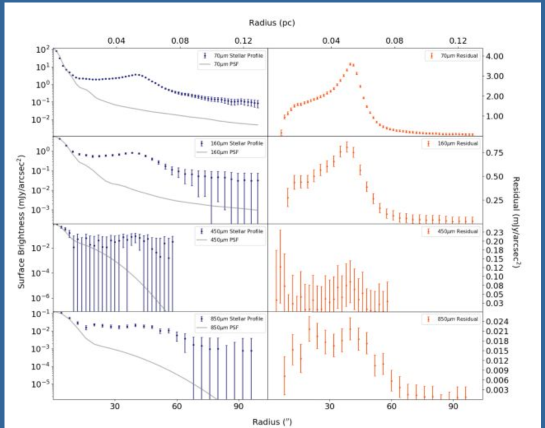
Whittet 2003

The extent of the dust shell

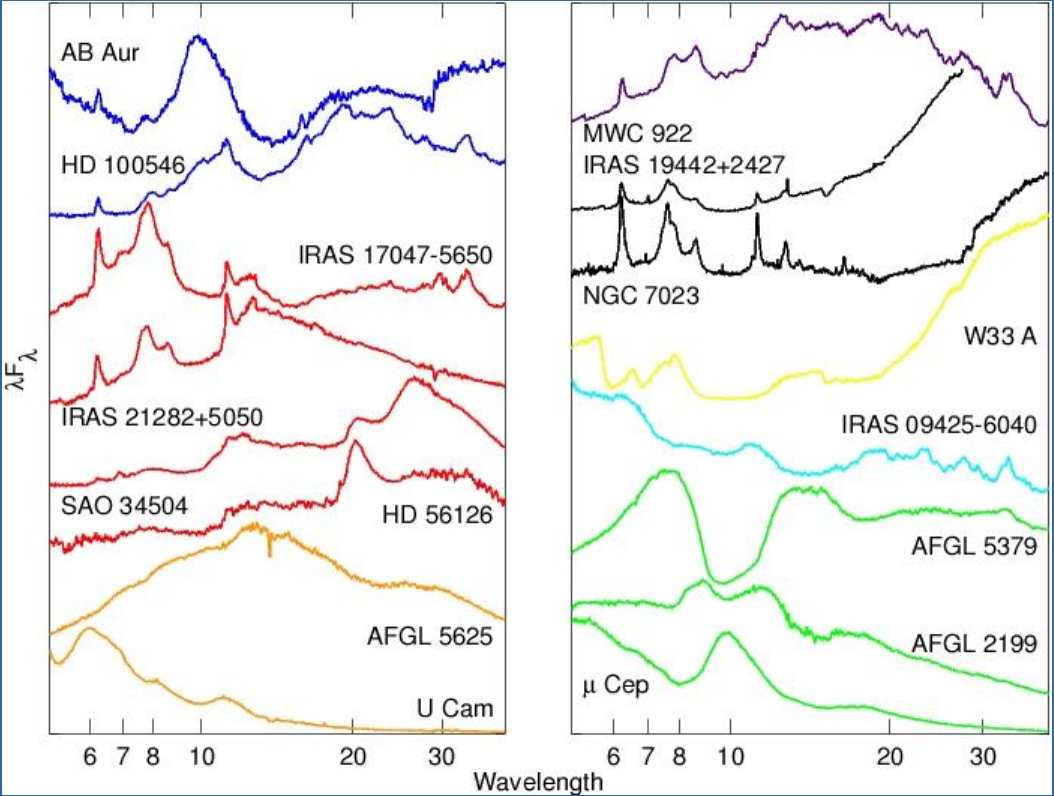
- Active investigation
- History of mass loss
- Dust survival upon entrance in ISM; shock

(Ladjal et al. 2010, Cox et al. 2012, Dharmawardena et al. 2019, Scicluna et al. 2022, Maercker et al. 2022)

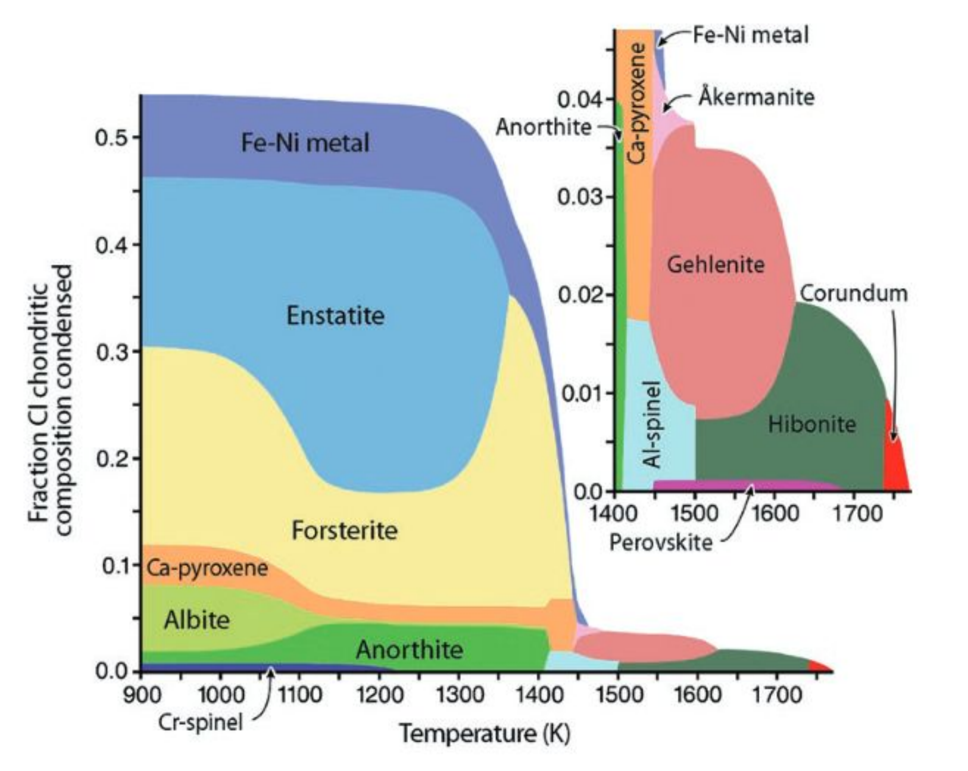




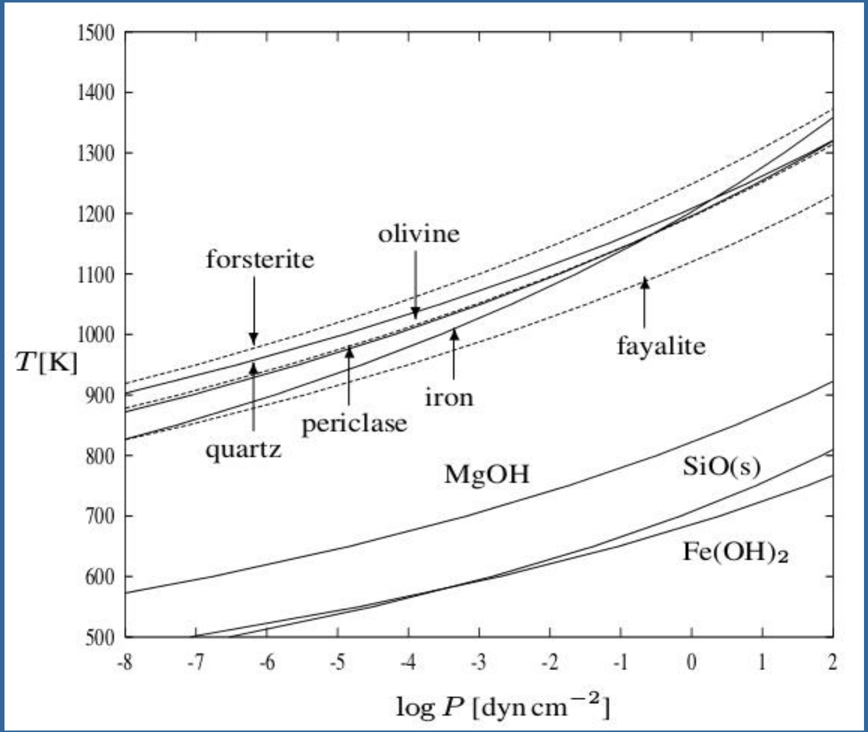
The infrared spectral zoo



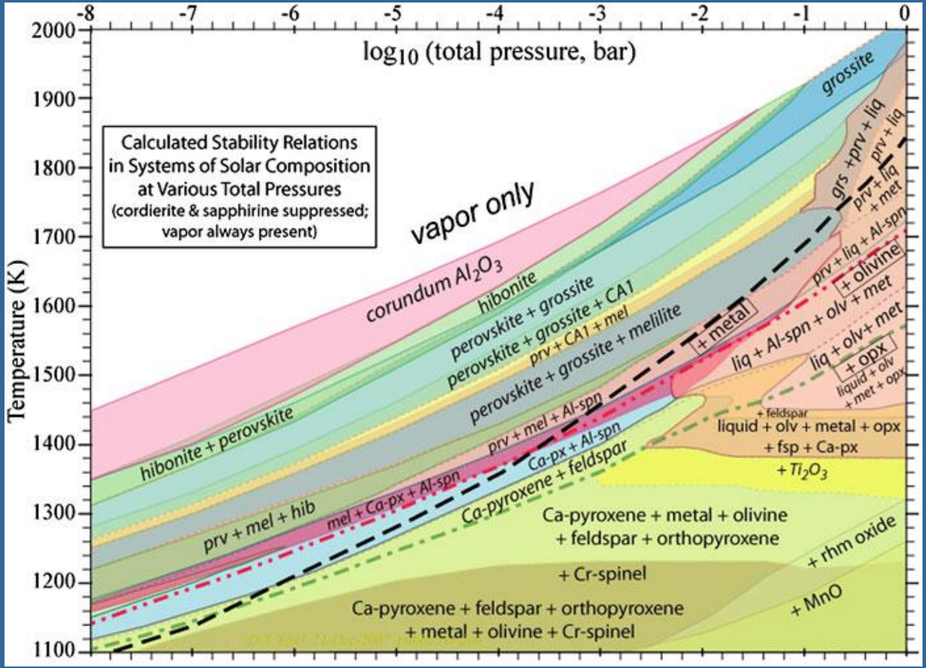
Condensation of Solar System solids



Stability limits



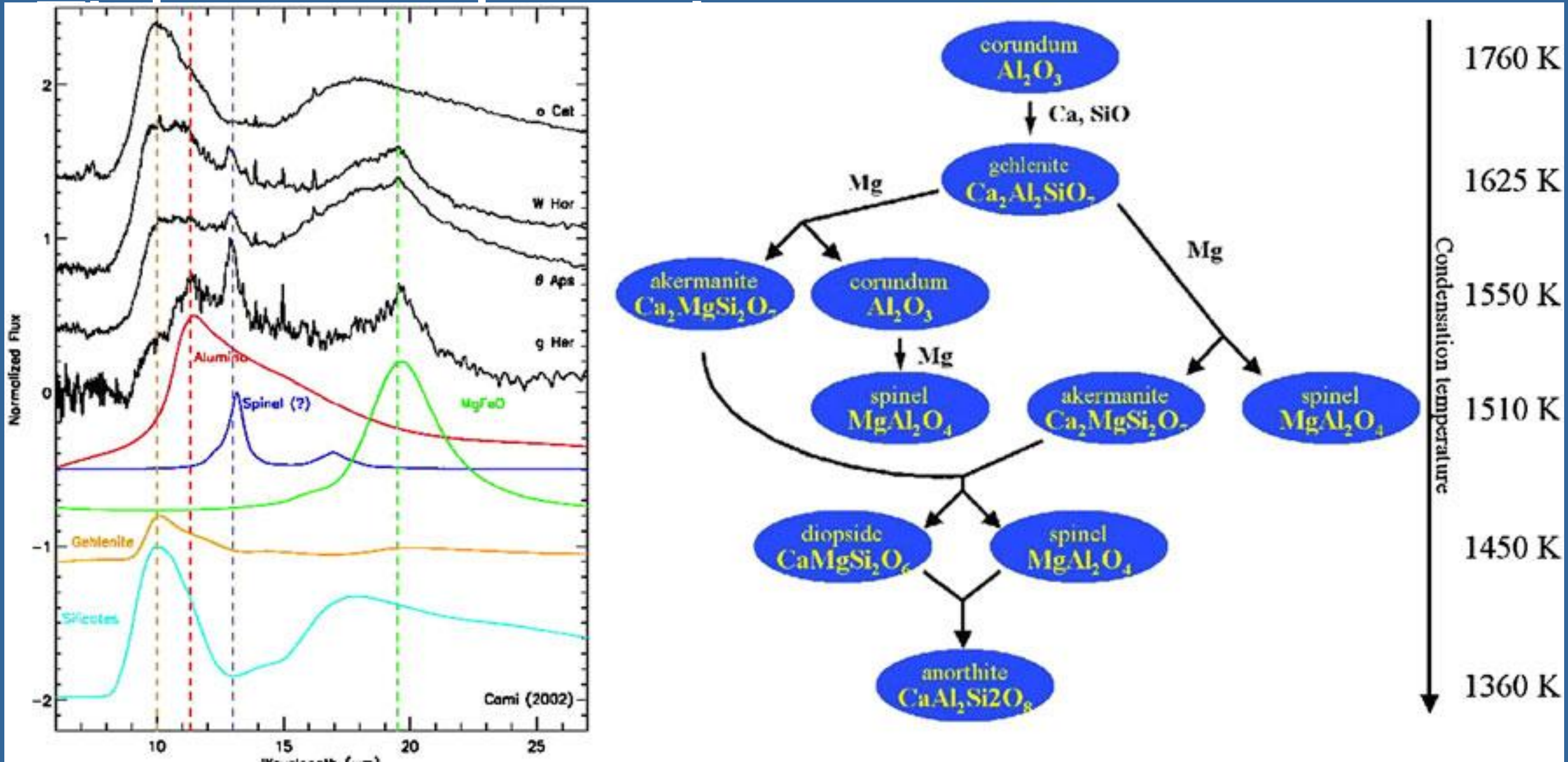
Gail & Sedlmayr 1999



Tielens 2022, reproduced from Ebel 2006

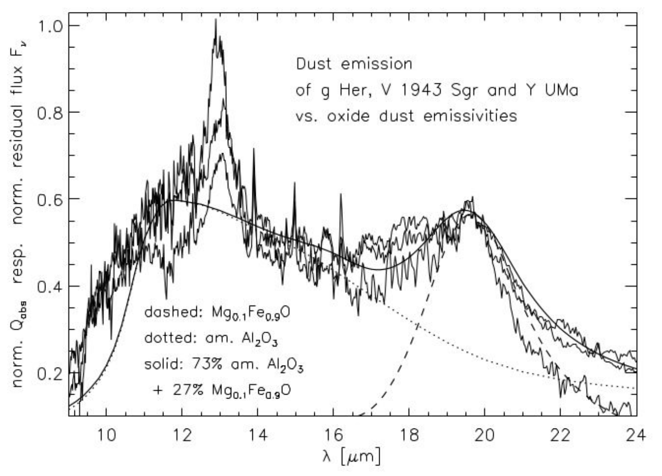
Condensation predictions

Tielens 2022, Cami 2001



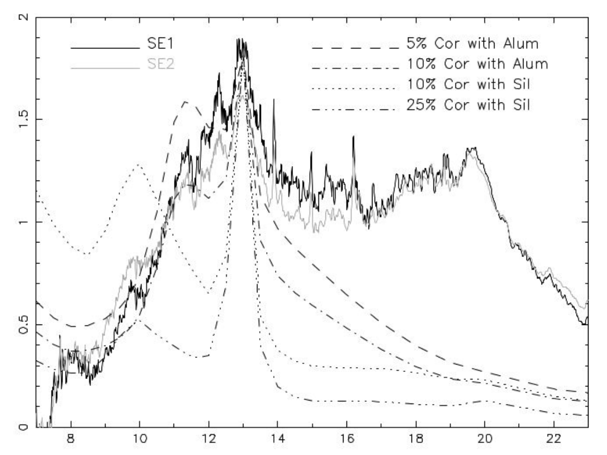
Early condensates

Mg-Fe oxides



Posch et al. 2002

Corundum (Al_2O_3)

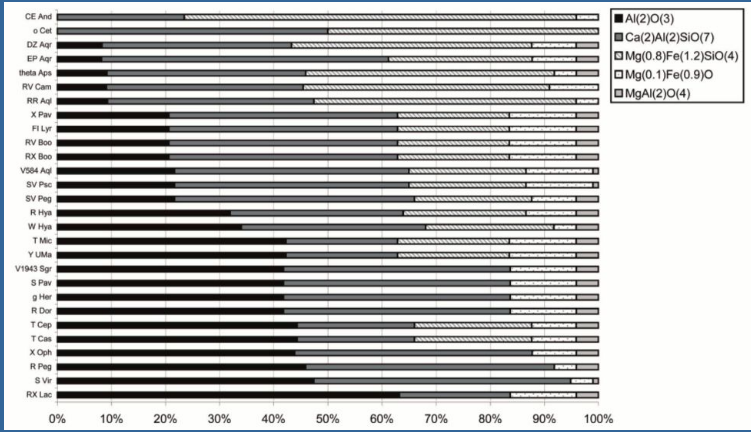


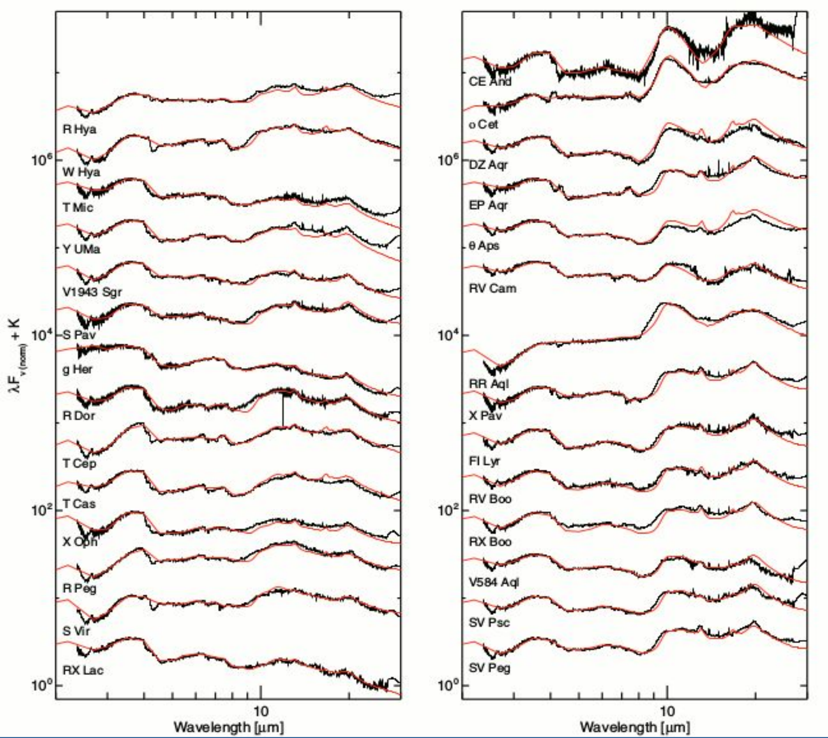
Depew et al. 2006

Early condensates: systematic fits

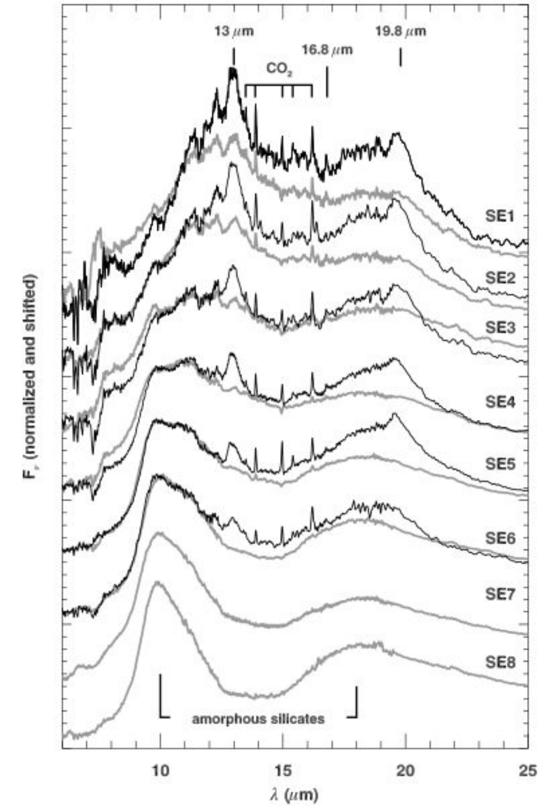
alumina
mellilite
silicates
periclase
spinel

Heras & Hony 2005



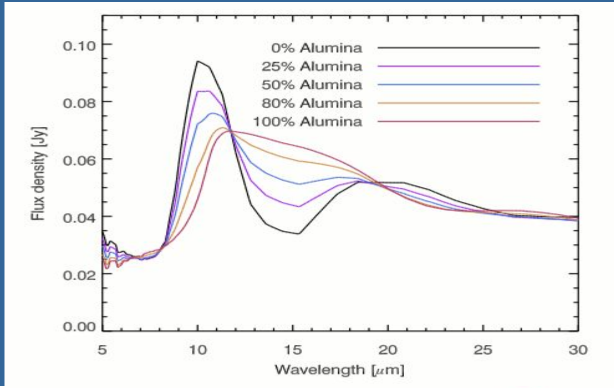


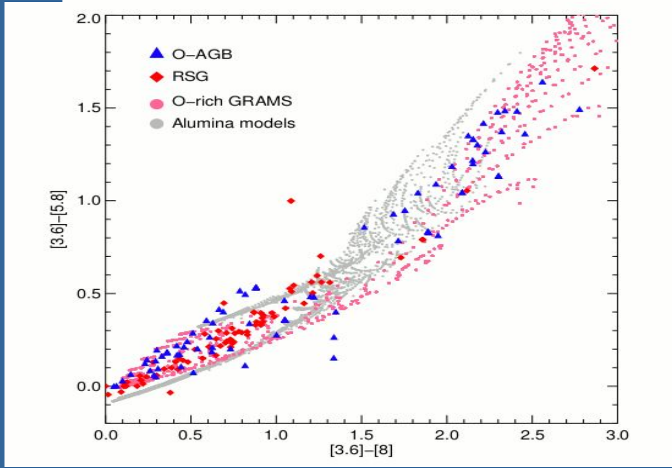
Silicates and alumina (Al_2O_3)

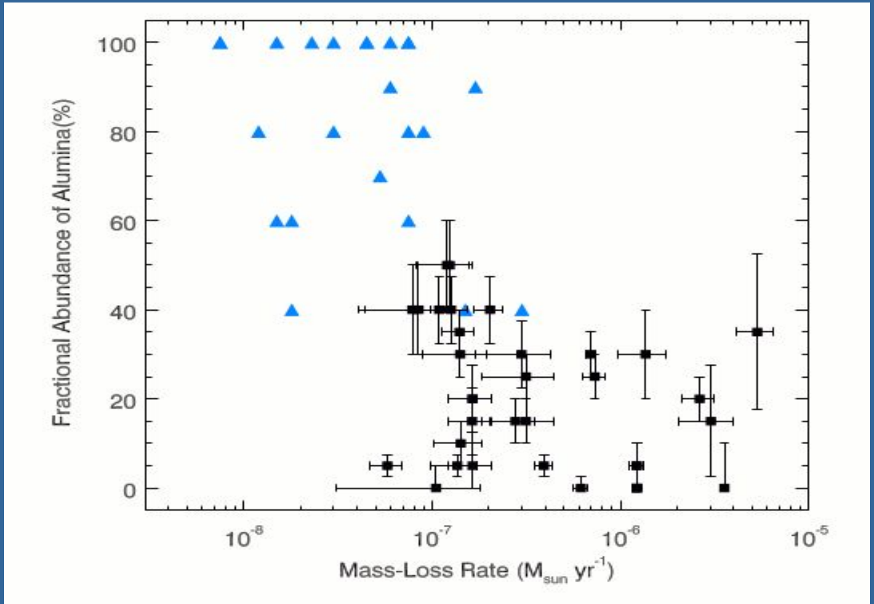


Sloan et al. 2003

Modelling alumina and silicates

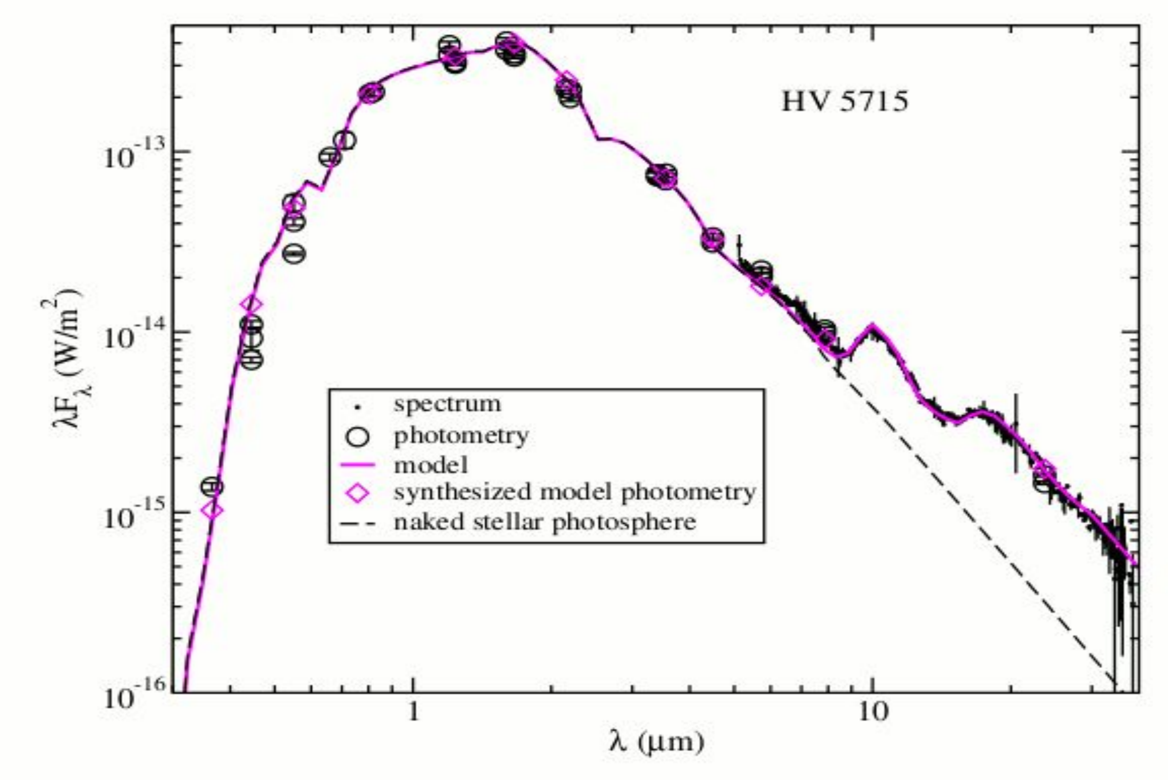






Jones et al. 2014

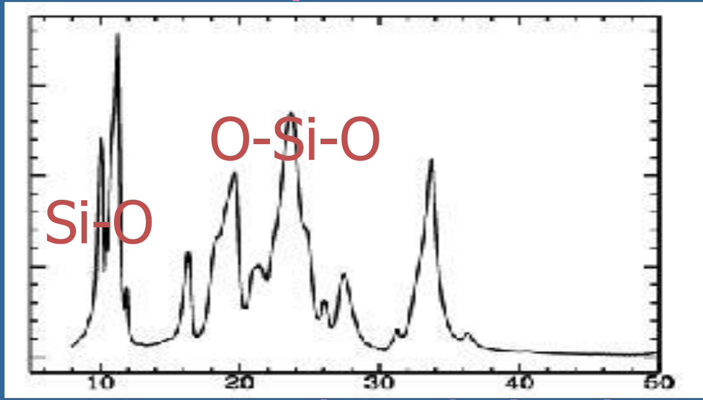
Amorphous silicates



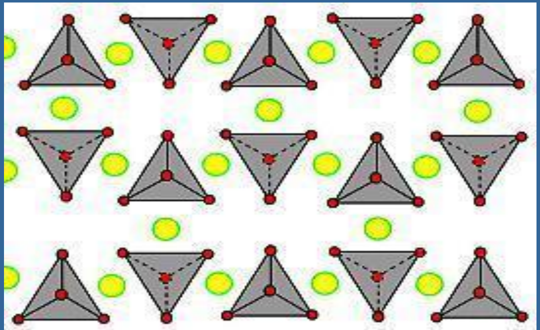
Sargent et al. 2010, 2011

Crystallinity of silicates

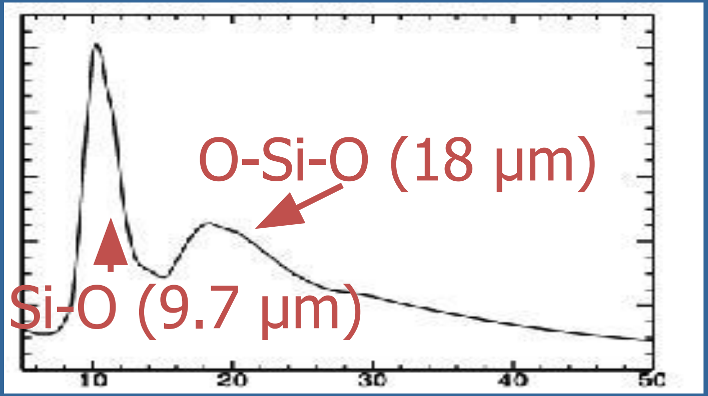
Crystalline



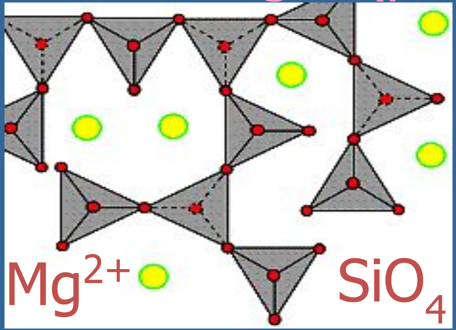
→Wavelength (μm)



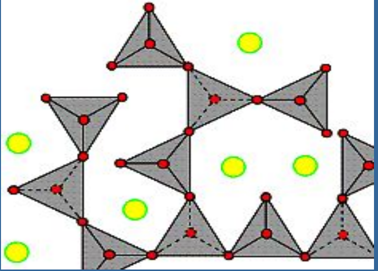
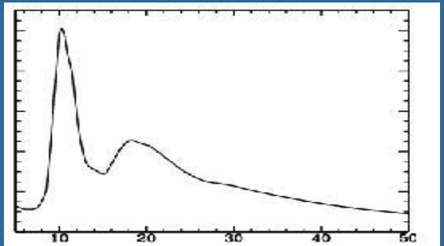
Amorphous

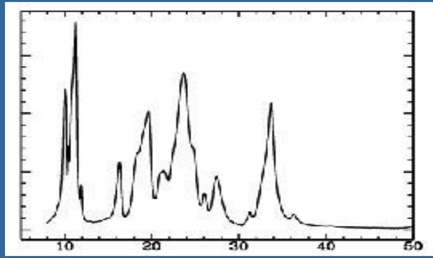


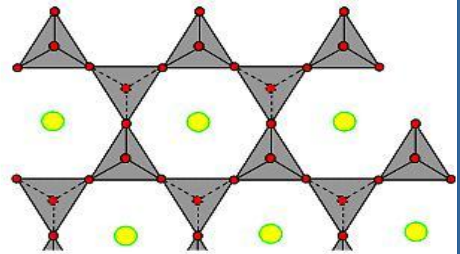
→Wavelength (μm)



Crystallinity of silicates



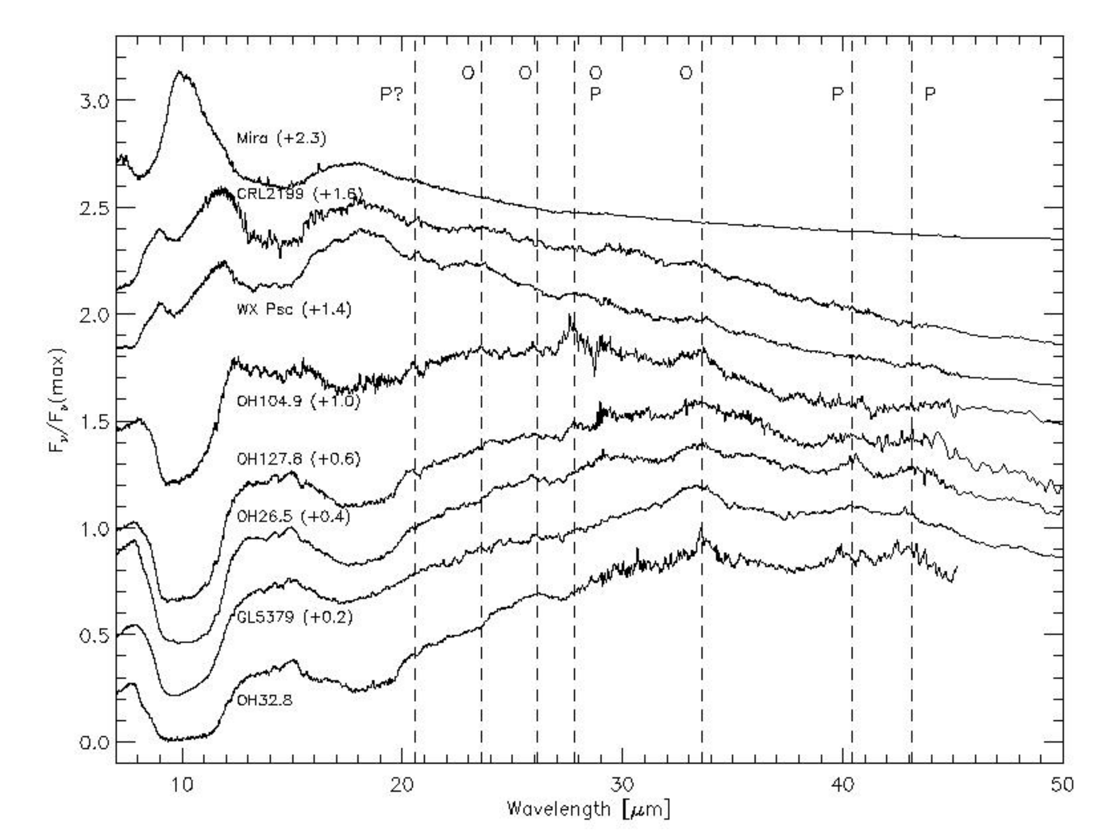


T_{glass} ~1000 K (T_{evap} ~1500 K)

$T_{cond} > T_{glass}$: atoms in mineral are mobile, crystallization may occur

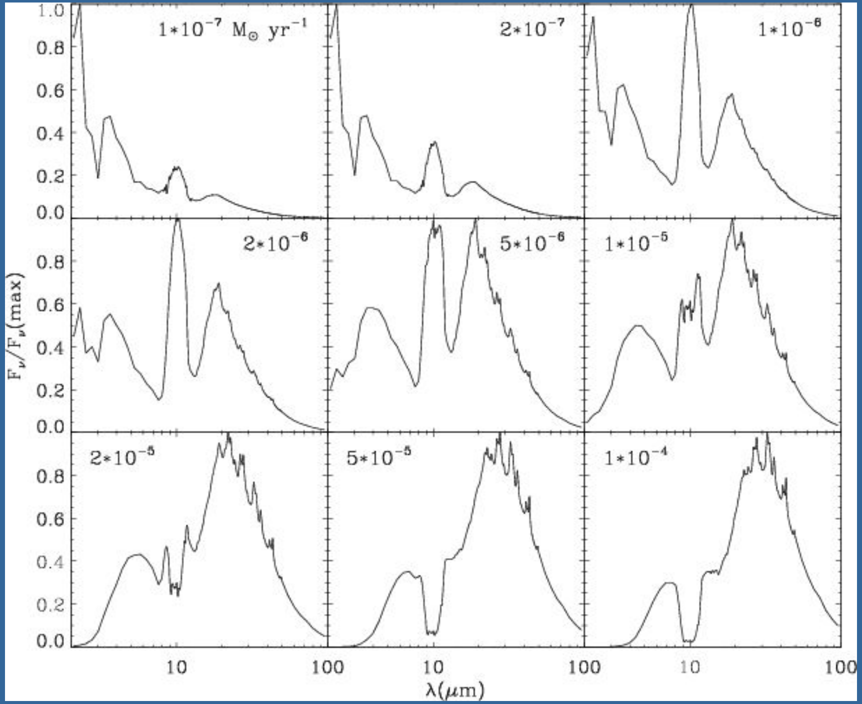
$T_{cond} < T_{glass}$: immediate freeze out → amorphous silicate

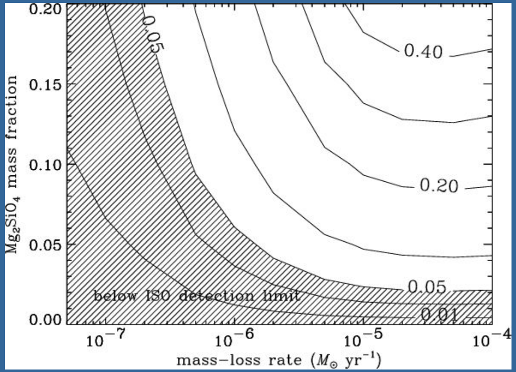
A trend with mass-loss rate?



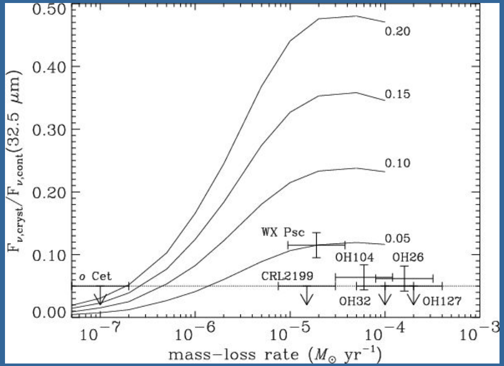
Sylvester et al. 1999

… maybe not!

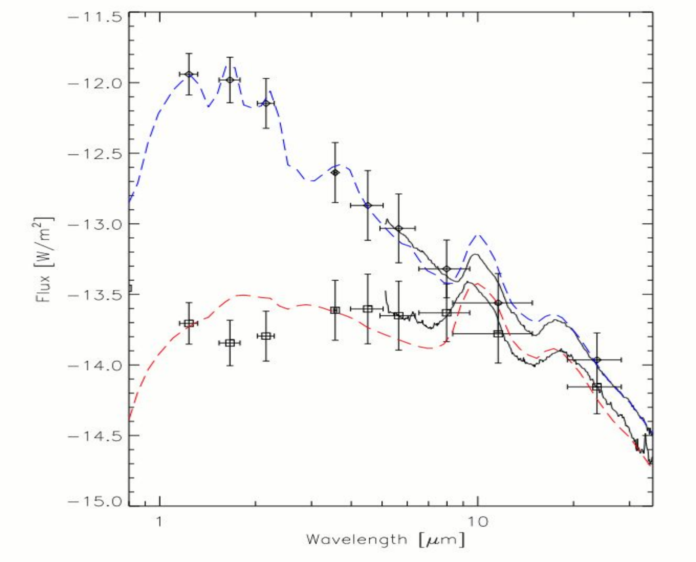


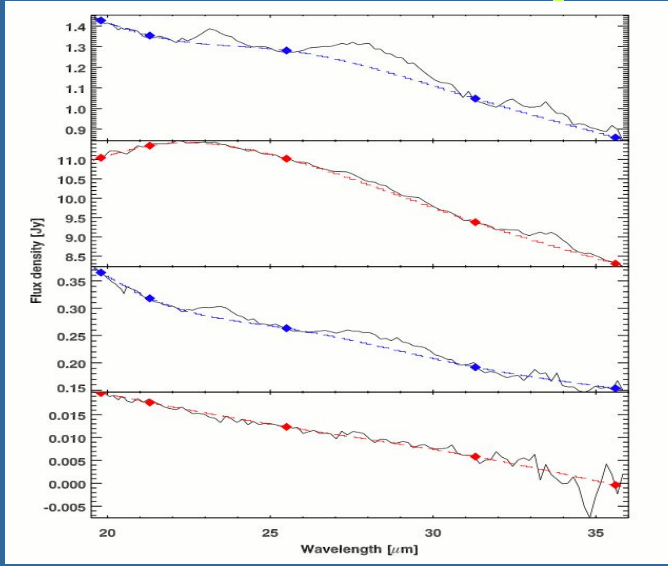


Kemper et al. 2001



Crystallinity and metallicity





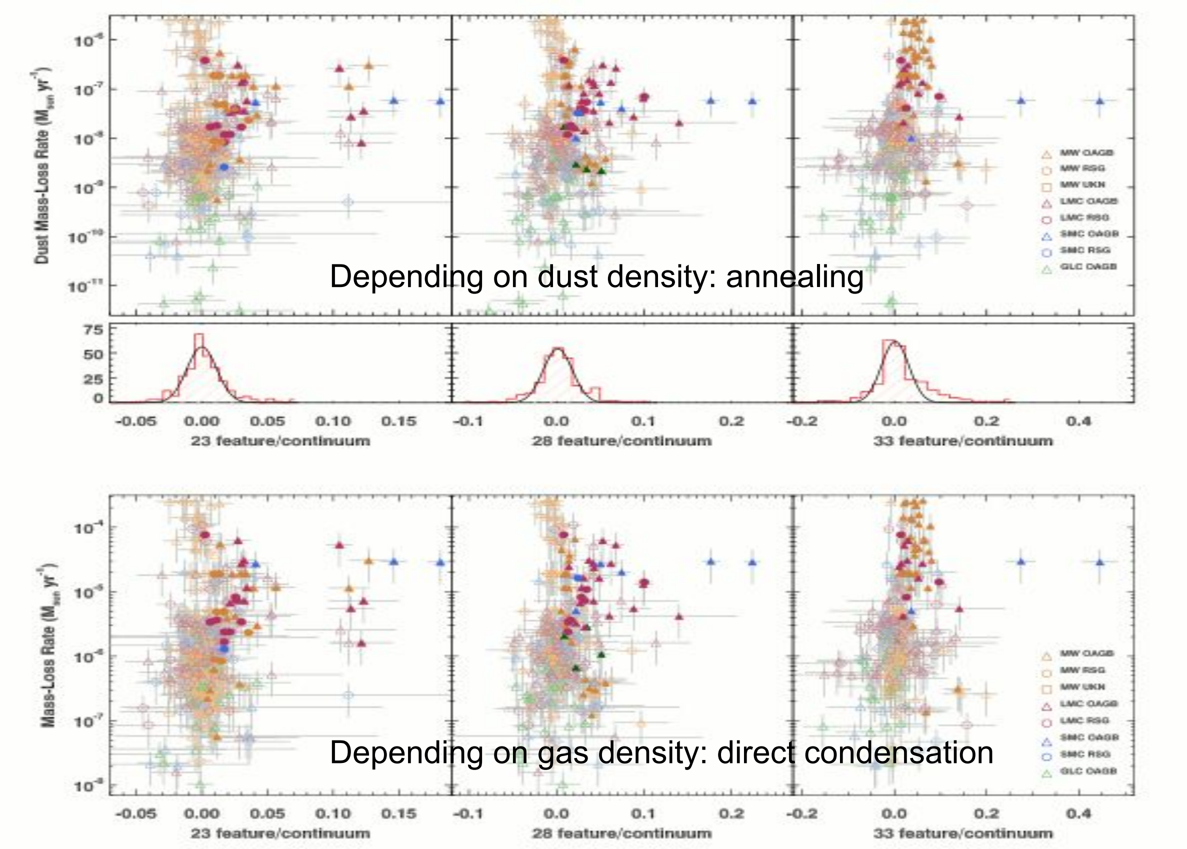
Jones et al. 2012

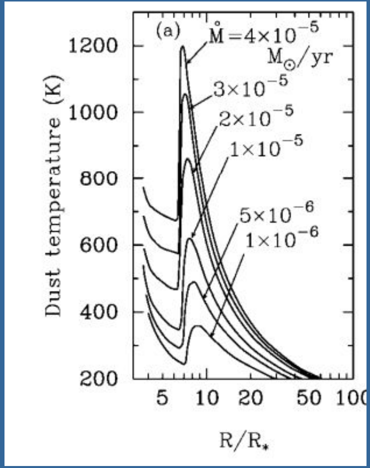
O-AGBs and RSG in the LMC, SMC and MW

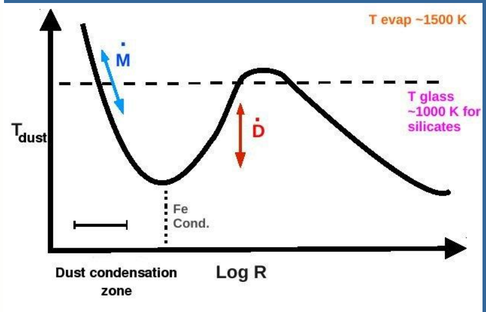
dM/dt determined with SED fitting

Crystalline silicates

Sogawa & Kozasa 1999







Jones et al. 2012

Crystalline silicates

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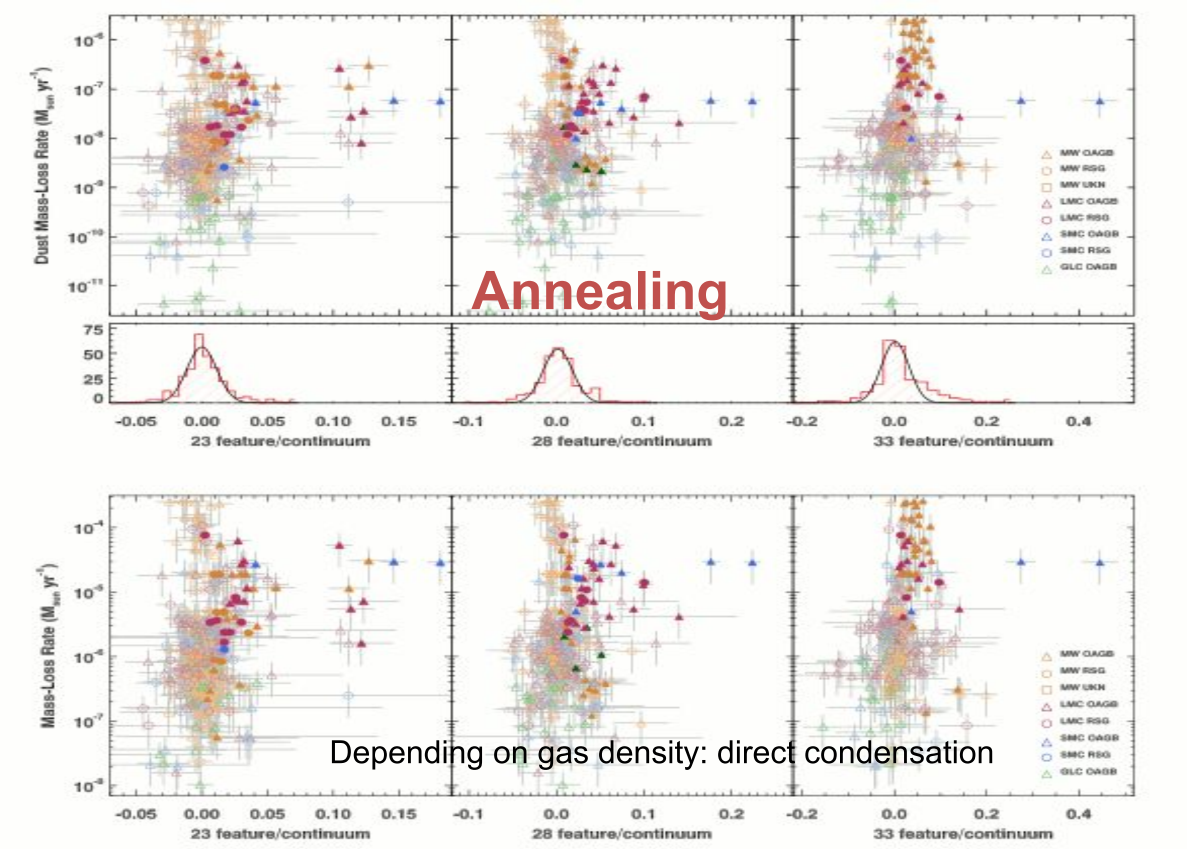
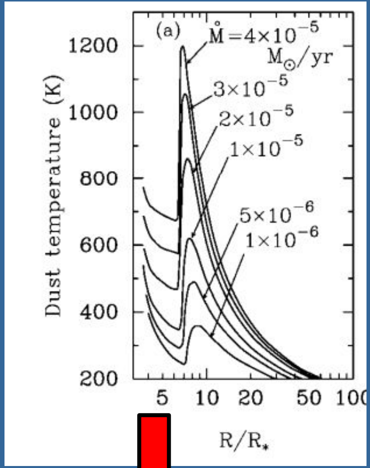
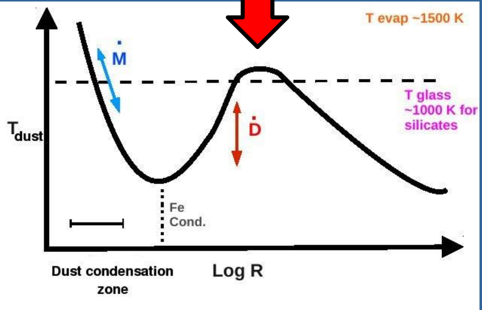
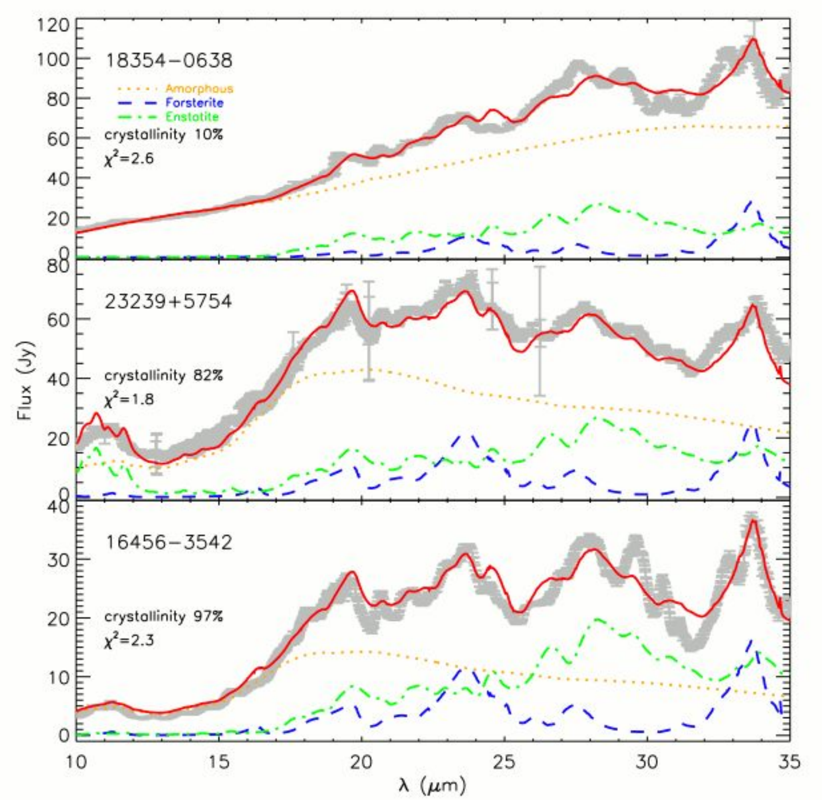






Jones et al. 2012

Highly crystalline AGB stars



Generally a crystallinity of 5~10% is observed

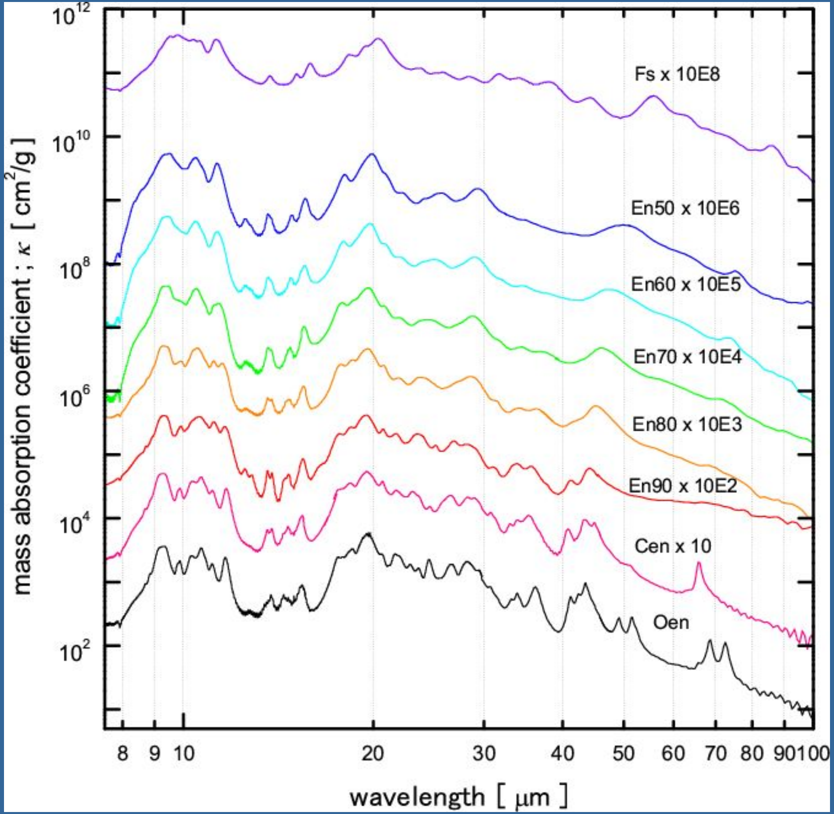
A good quantification is lacking

Jiang et al. 2013

Crystallinity not well quantified

- This becomes important when comparing with ISM dust in our on Milky Way and external galaxies
- Open PhD project @ICE to address this
- See : https://www.ice.csic.es/about-us/jobs
- *Understanding and quantifying crystalline silicate production by evolved stars*
- RL3, supervisor: F. Kemper
- Deadline: 7 July 2023

Fe^{2+}-content of silicates

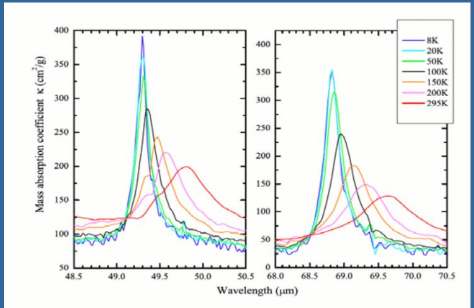


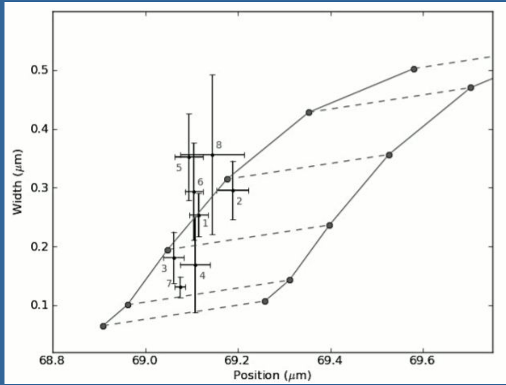
Chihara et al. 2002

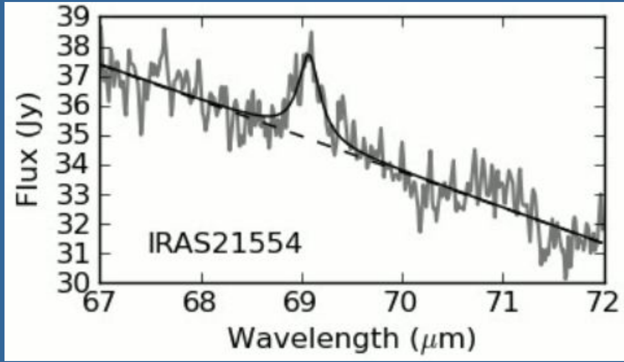
Fe^{2+}-content of silicates

Amorphous silicates: unknown
Crystalline silicates: almost completely Mg-rich (forsterite: $Mg_{2(1-x)}Fe_{2x}SiO_4$) x=0%

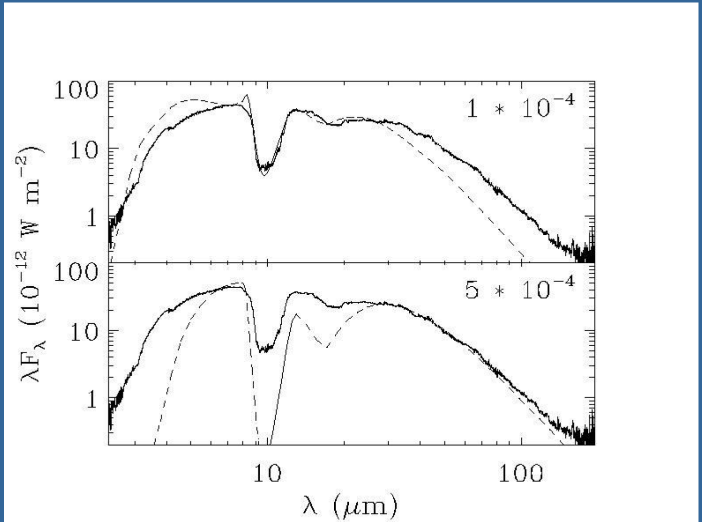
de Vries et al. 2014



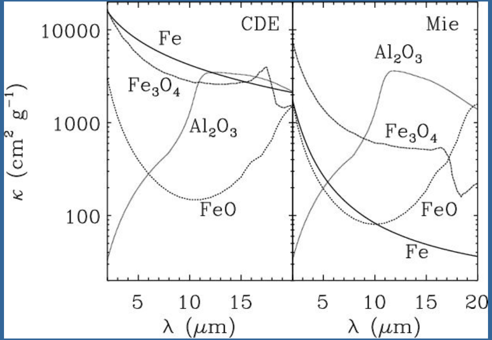


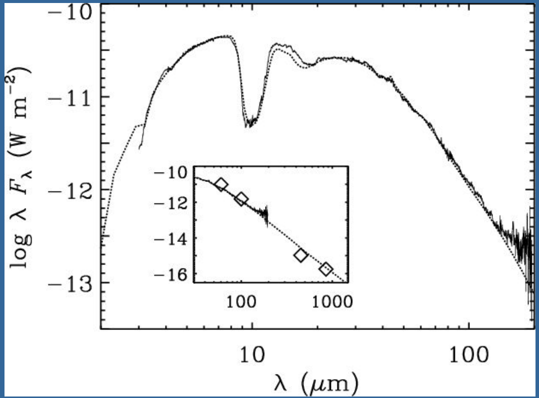


Metallic iron

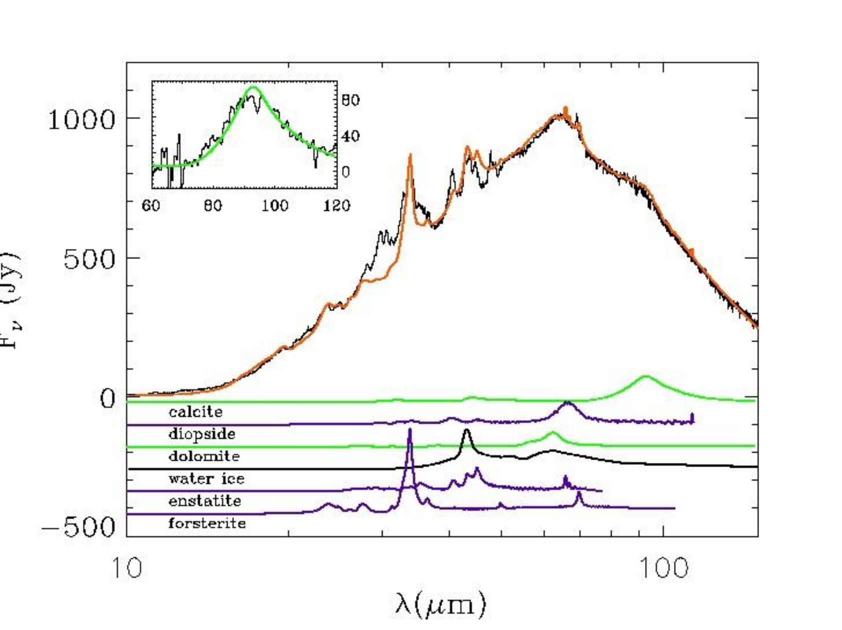


Kemper et al. 2002



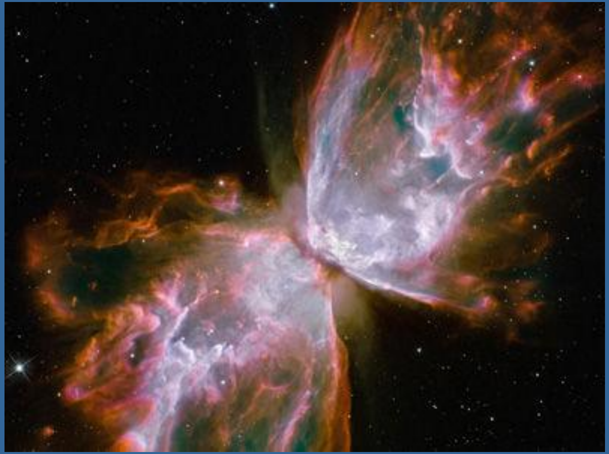


Carbonates



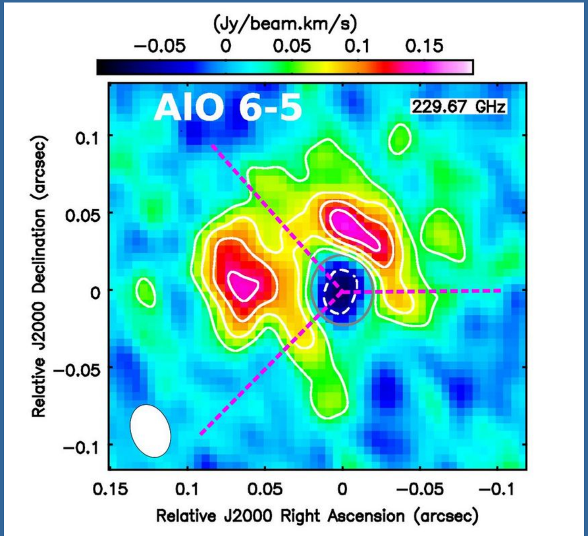
Kemper et al. 2002

Note lake sediment but formed as dust.
Successfully reproduced in lab.

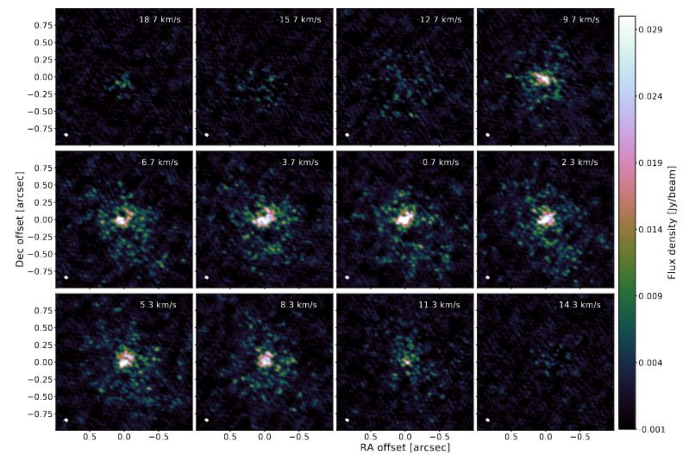


Dust-forming molecules

Spatially resolved observations with ALMA



AlO in o Cet *(Kaminski et al. 2016)*



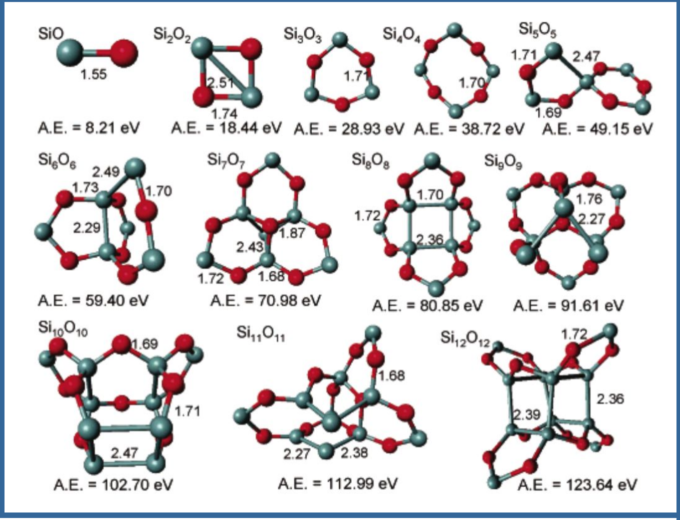
SiO in IRC -10529 *(Gottlieb et al. 2021)*

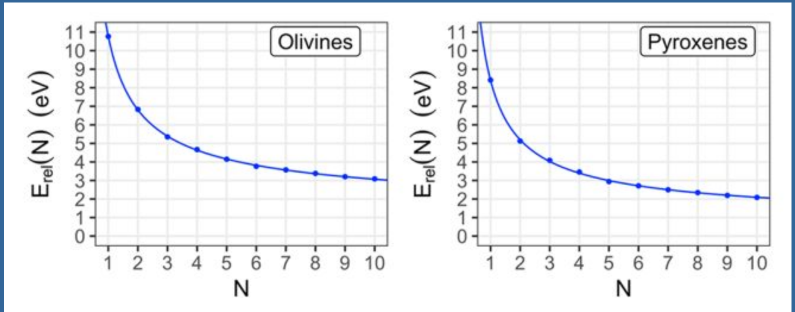
Spatially resolved CO

physical conditions

gas-to-dust ratio

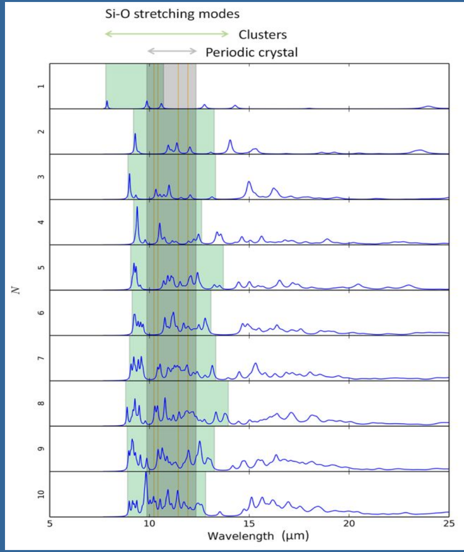
The missing link: nanosilicates



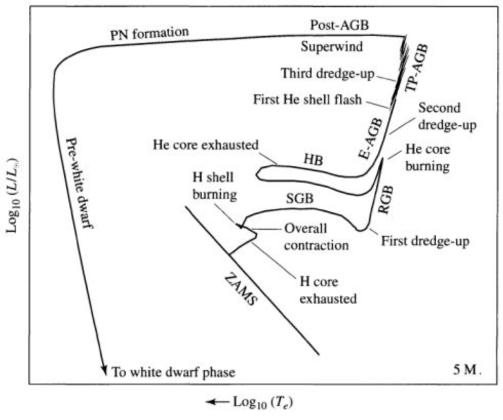


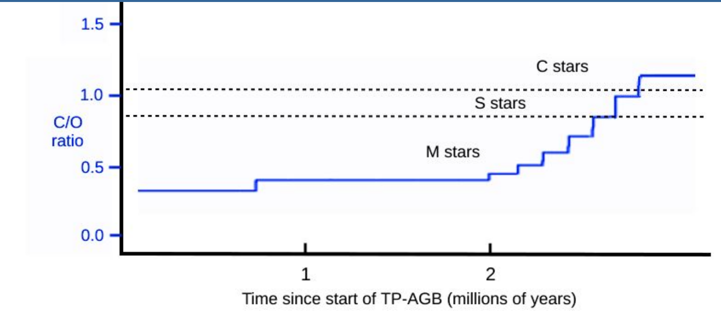
structures and energies of Si_xO_x nanoclusters *(Reber et al. 2006)*

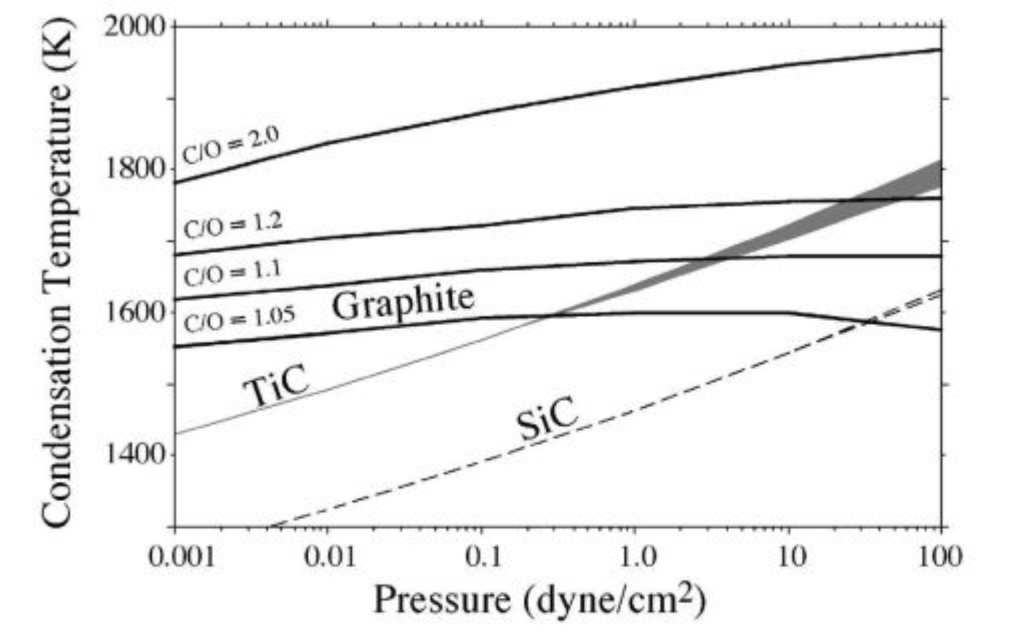
structures, energies and IR spectra of Mg-rich silicate nanoclusters *(Macià Escatllar et al. 2019)*



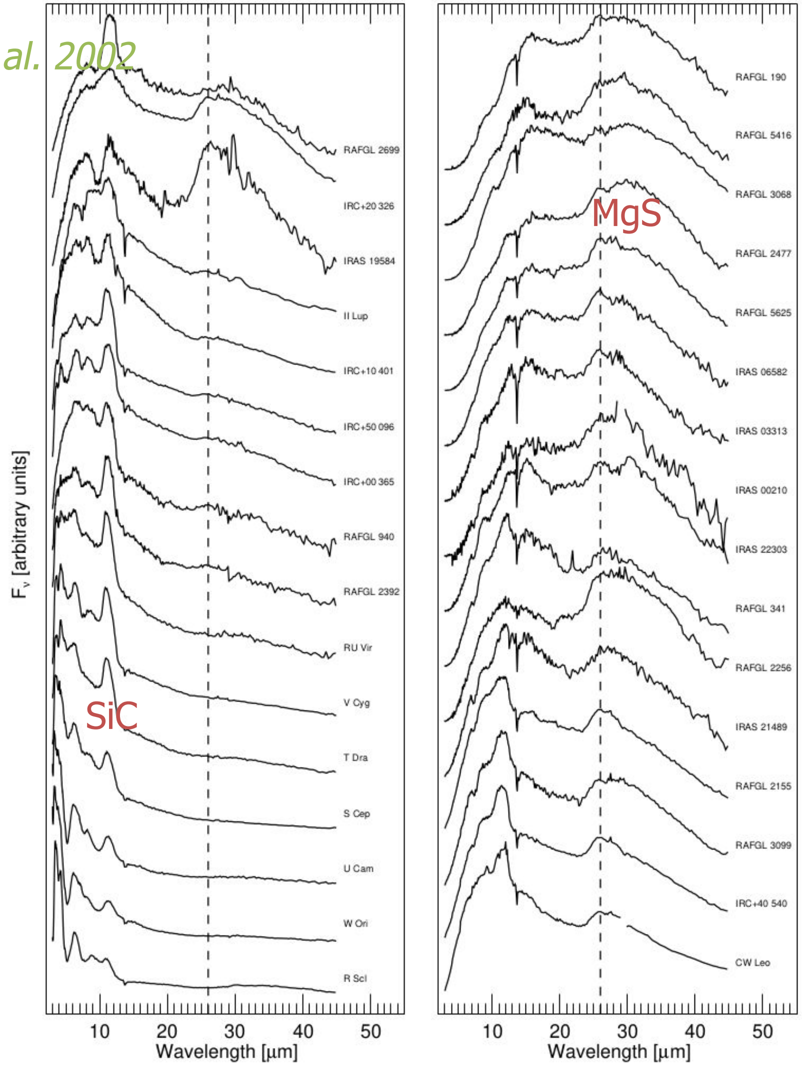
Carbon-rich species

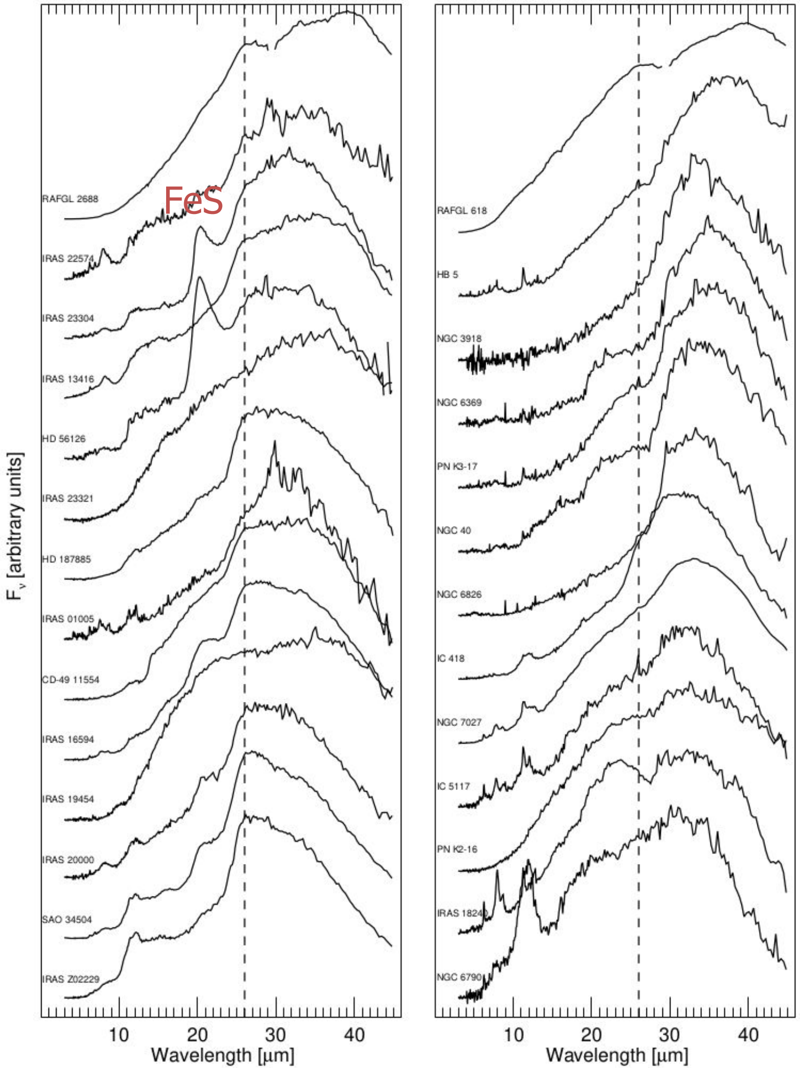




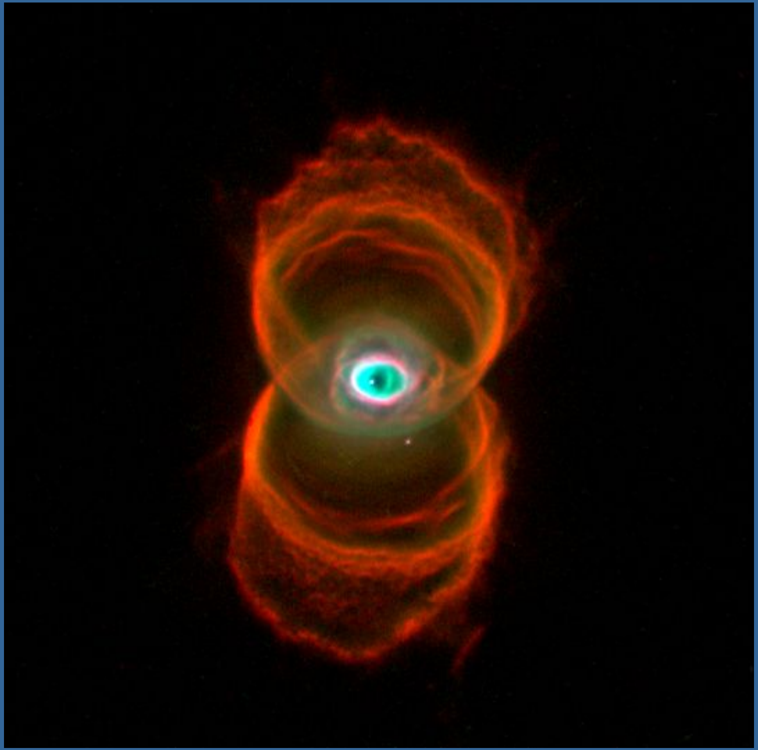


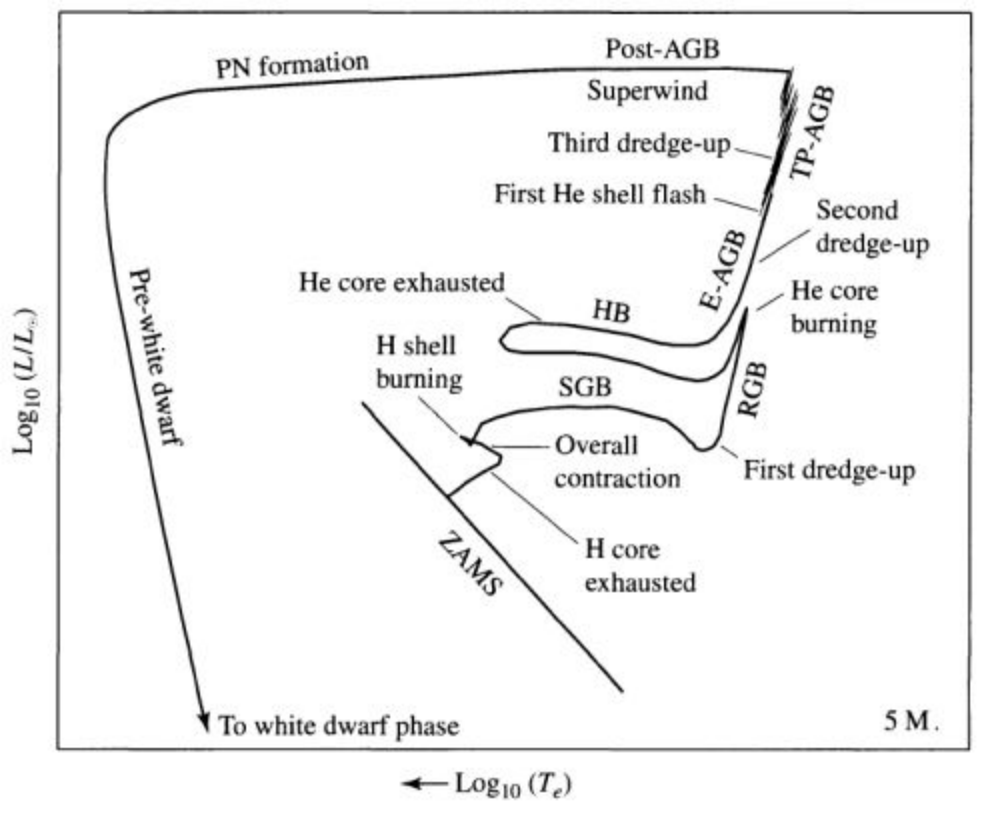
Hony et al. 2002



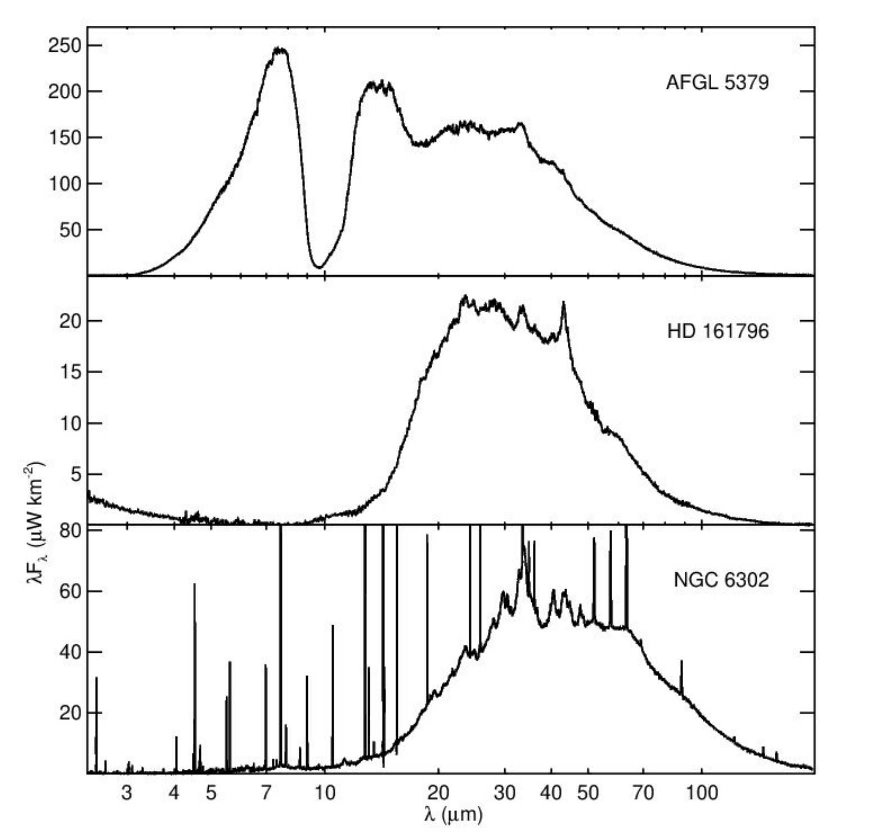


Post-AGB and PN evolution



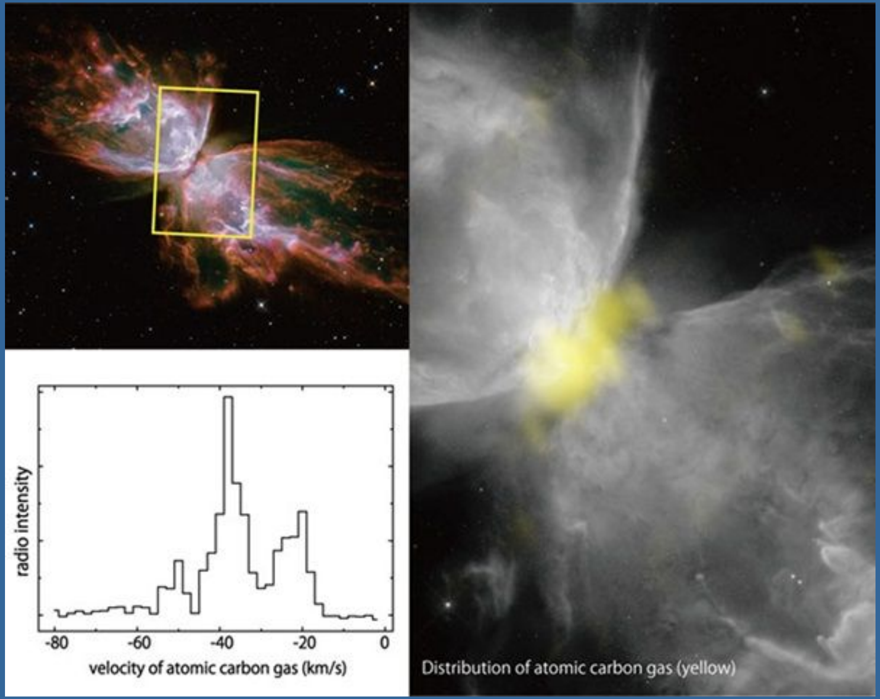


SED evolution



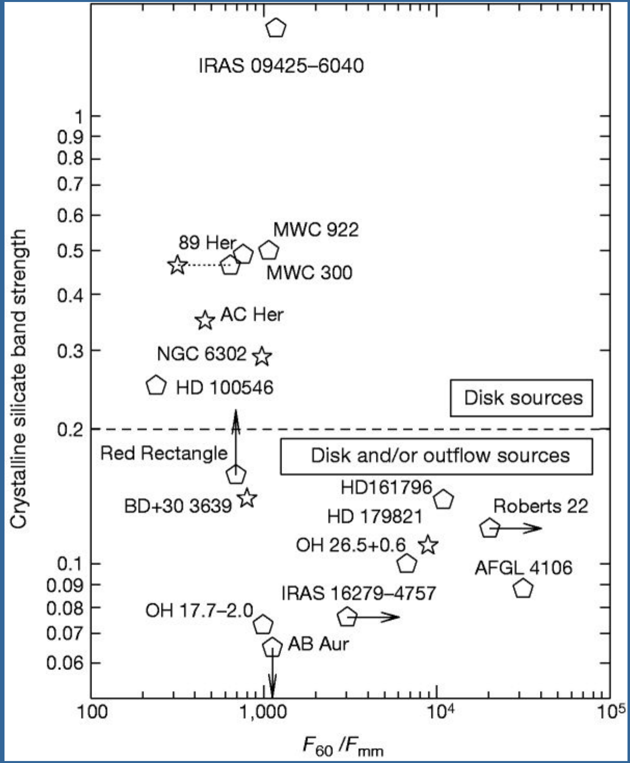
Habing 2004

Circumstellar disk & bipolar outflow

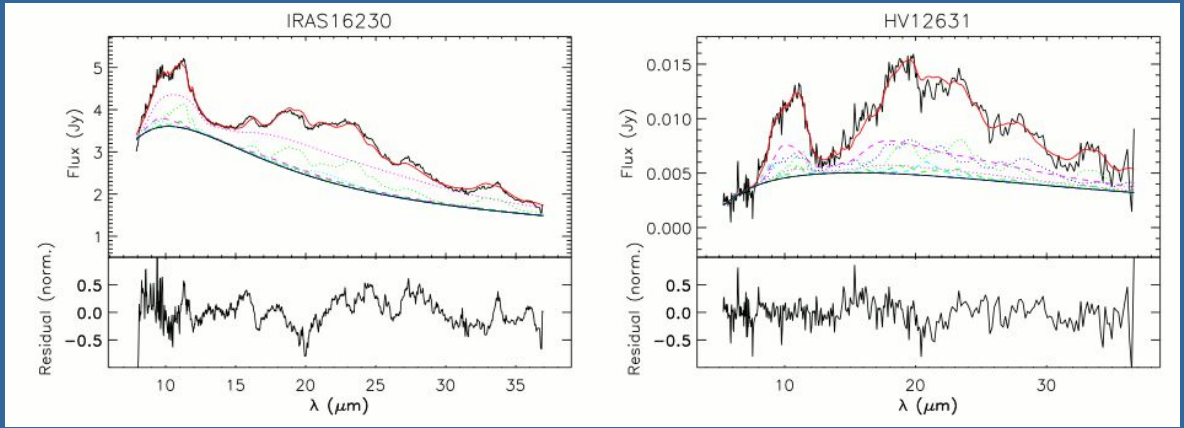


ALMA Band 8 commissioning data (NAOJ, 2013)

Crystallinity in disk sources

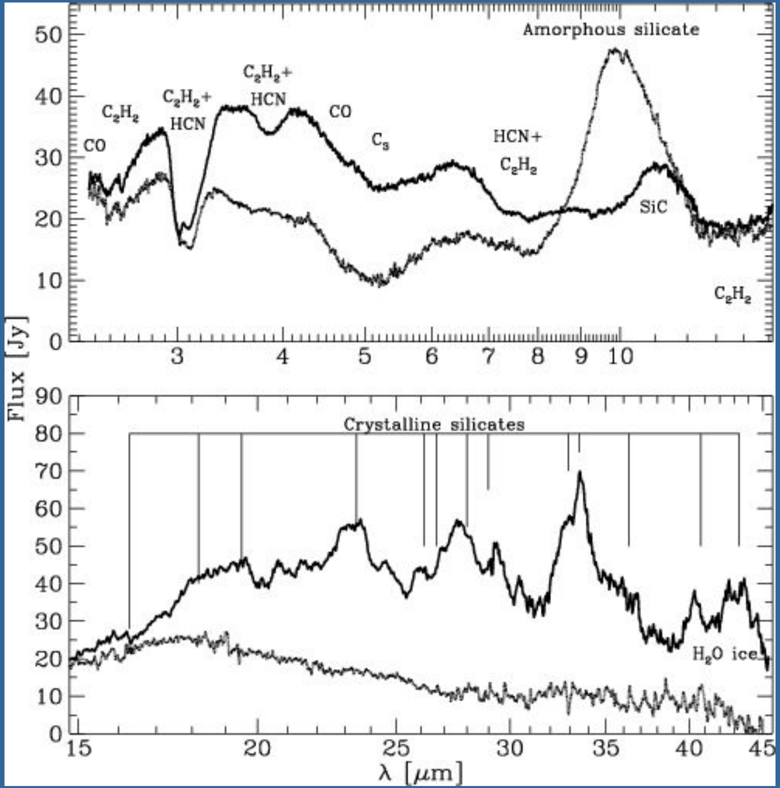


Molster et al. 1999

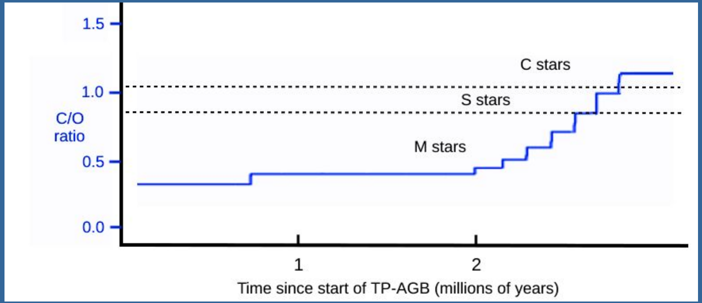


Gielen et al. 2011

Dual chemistry

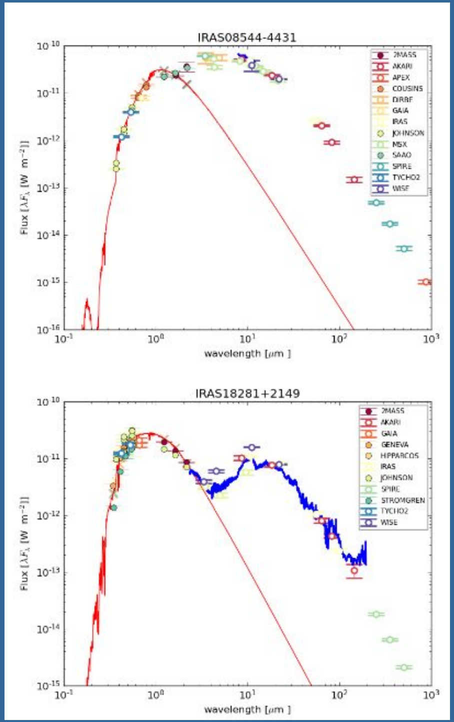


Silicate dust is preserved in a disk, as the star has become carbon-rich



Molster et al. 2001

Secondary planetary systems

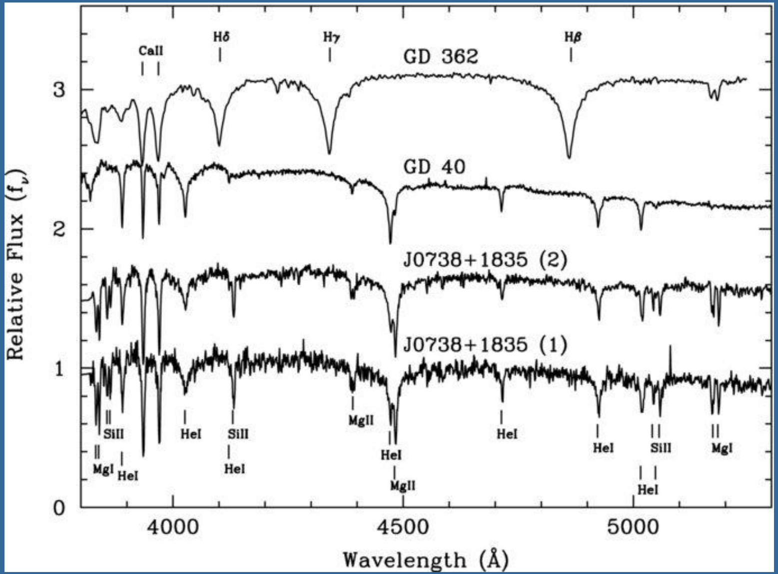


Circumstantial evidence:

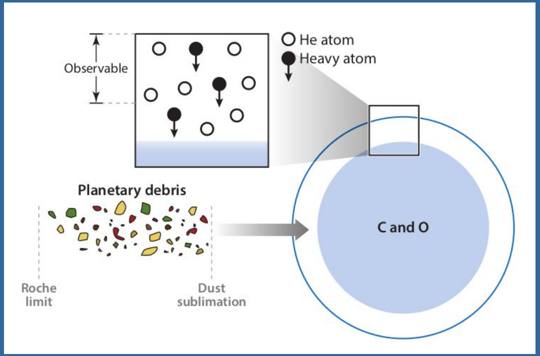
- Transitional disks (left)
- Grain growth

Kluska et al. 2022

The white dwarf phase



Dufour et al. 2010



Jura & Young 2014

- Swept up ISM dust
- Disintegrating primary planets/asteroids
- Disintegrating secondary planets/asteroids