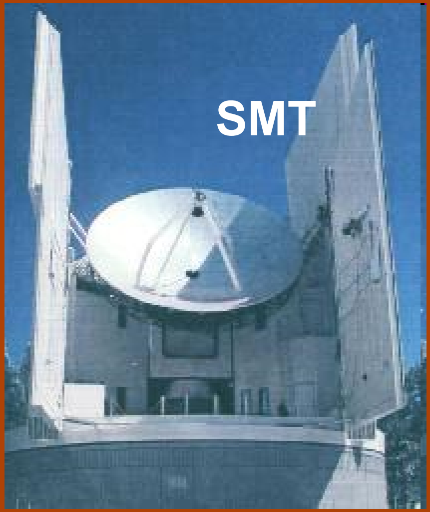
Dust formation in later stages of stellar evolution



D. Hatzidimitriou
University of Athens

21 September 2010

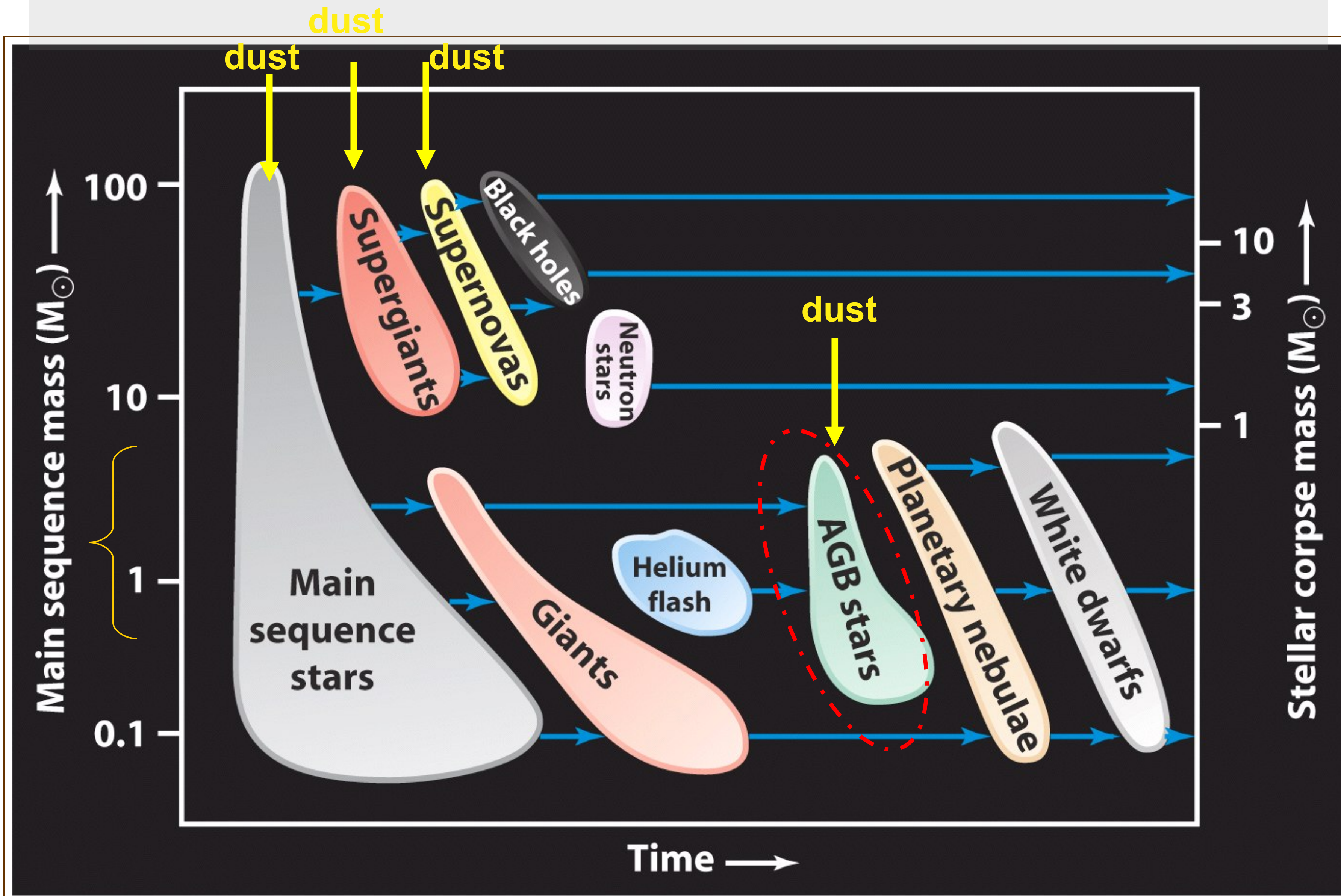
Outline

- **Interstellar dust** plays a crucial role in the evolution of galaxies
- It governs the chemistry and physics of the interstellar medium
- In the local universe, dust forms primarily in the ejecta of stars, but its composition and origin in galaxies at very early times remain controversial

Dust production in later stages of stellar evolution

- **Asymptotic Giant Branch**
  - ✓ Characteristics
  - ✓ Stellar structure
  - ✓ Dust Formation
  - ✓ **Planetary nebula stage**
- **Red Supergiants**
  - ✓ Evolutionary Phase
  - ✓ Dust Formation
- **Supernovae**
  - ✓ Dust production (and destruction)
- **Importance for the Universal Dust Budget**

Stellar Evolution vs Mass



1. Dust Production in evolved low and intermediate mass stars

Asymptotic Giant Branch

Typical AGB star characteristics

Radius	200 - 600 $R_\odot$
Initial Mass	0.8 – 8.0 $M_\odot$
T_{eff}	2000 - 3500 K
*L*uminosity	up to M_{bol} = -7.5
*M*ass loss rate	10^{-8} to 10^{-4} $M_\odot$/yr
*V*ariability period	30 - 2800 days

AGB evolutionary phase: Main points

Evolutionary phase following the horizontal branch (He-core burning)

- **H** and **He burning** in shells around an **inert C-O core**

- The fusion of helium to carbon proceeds by the **triple- alpha sequence** in thermal pulses

- The **thermal pulses** lead to the **dredge-up** of freshly produced **C** to the surface of the star

- If the envelope of the star is not too massive and the dredge-ups are sufficiently strong, then enough **C** reaches the surface to drive the **photospheric C/O ratio over unity**

- The formation of CO molecules will exhaust whichever of the carbon or oxygen is less abundant   chemical dichotomy
  - ✓ **Carbon stars** → carbon-rich dust
  - ✓ **oxygen-rich stars** → **oxygen-rich dust**

- Approaching the tip of the AGB they start to **pulsate**   ***LPVs***

- The pulsation is accompanied by **heavy mass loss** which forms a **circumstellar envelope of gas and dust**

- If the mass loss rate surpasses $\dot{M} \quad 10^{-6} M_{\odot}\, yr^{-1}$ the **dust shell** eventually becomes **opaque** to visible light

1. Early AGB

- Lower part of Asymptotic Giant Branch

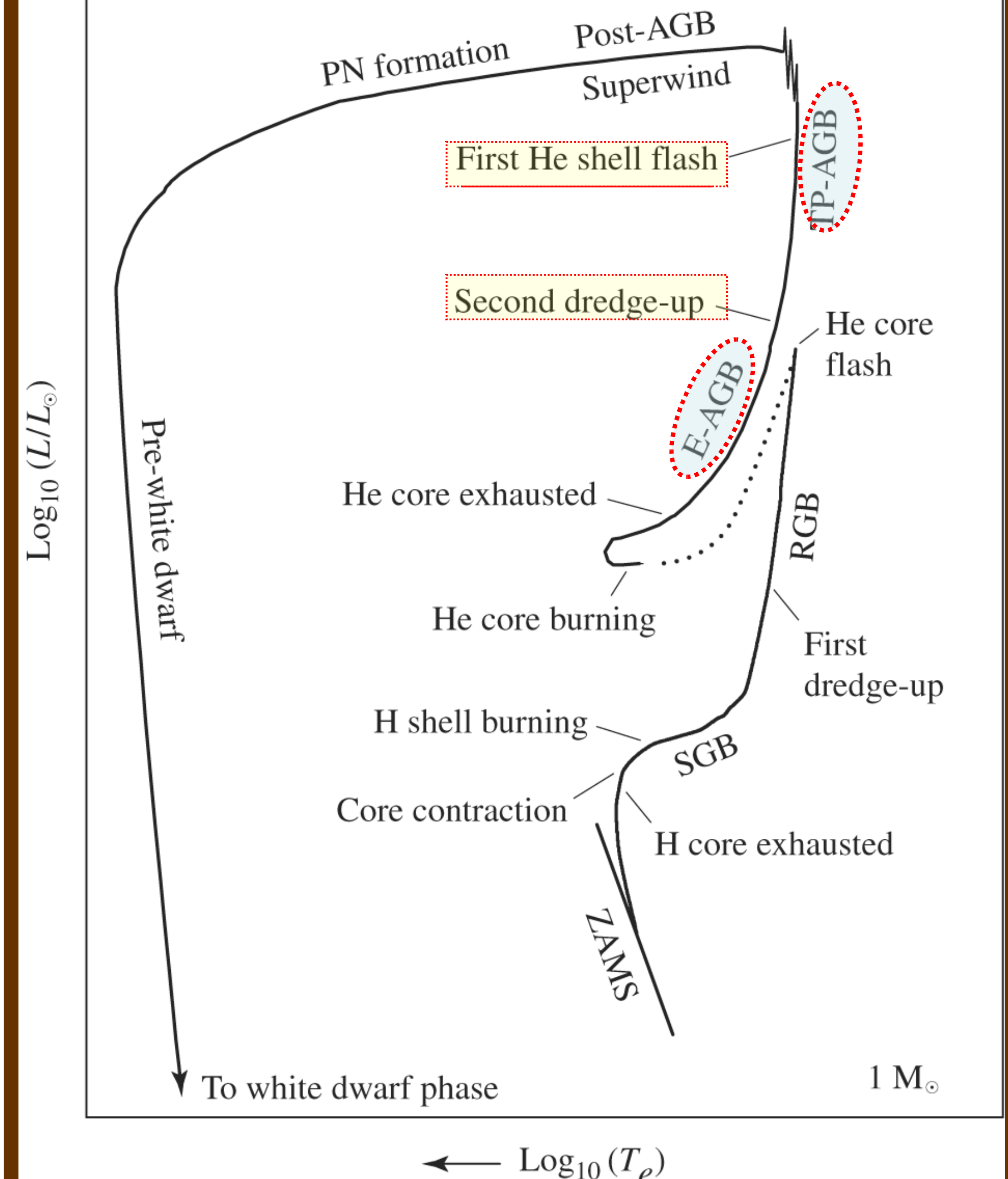
- He shell provides most of the energy
  H shell almost inactive

- *L* increases, *Teff* decreases

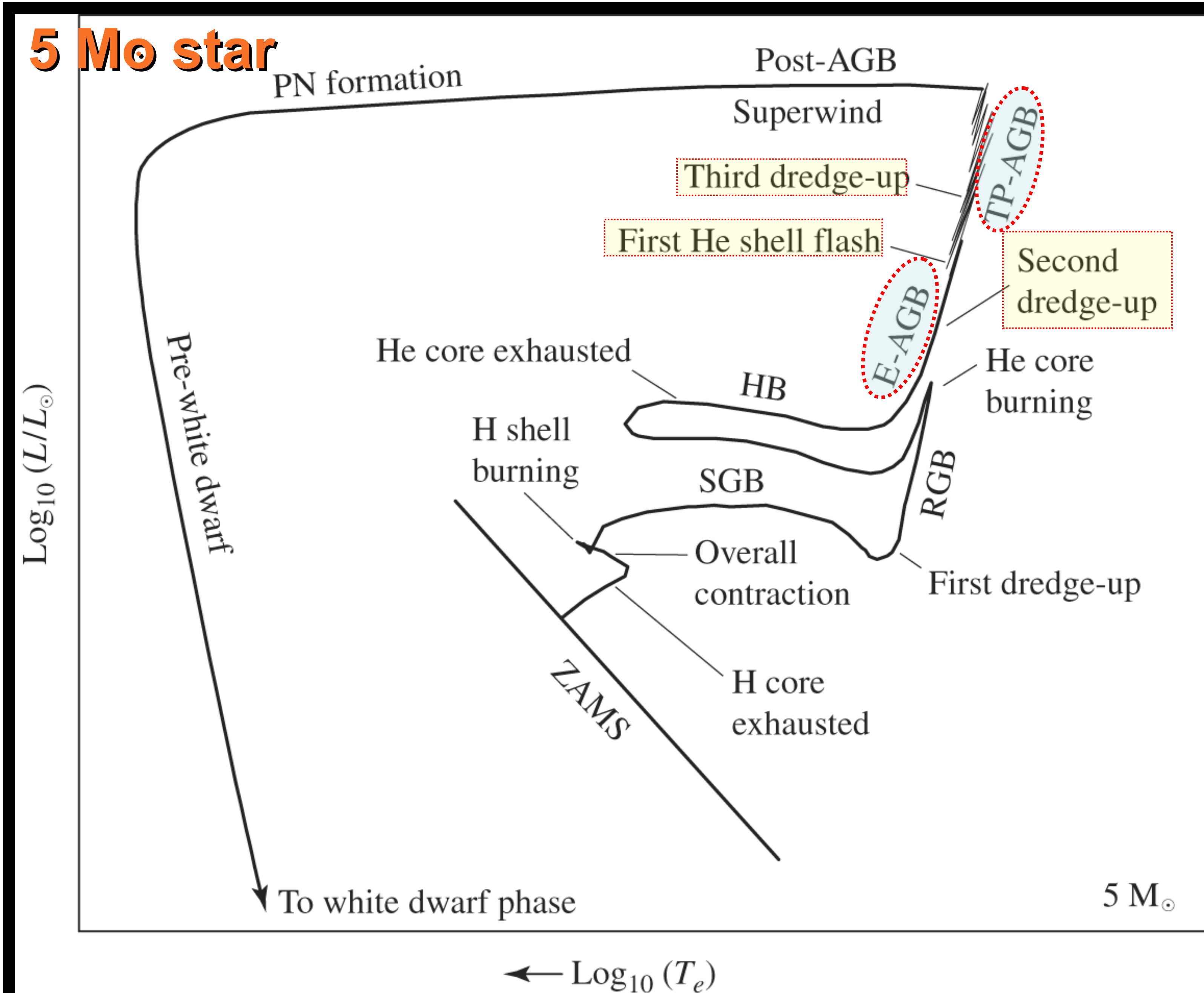
- $M > 4.5\, M_{\odot}$: 2nd dredge up phase increase of ^{14}N, decrease of ^{16}O (deepening of convective envelope, to reach chemical discontinuity between H and He rich region)

- Re-ignition of H shell → start of thermal pulses (TP)

1 Mo star


Post-AGB
PN formation
Superwind
First He shell flash
TP-AGB
Second dredge-up
He core flash
E-AGB
He core exhausted
RGB
He core burning
First dredge-up
H shell burning
SGB
Core contraction
H core exhausted
ZAMS
Pre-white dwarf
To white dwarf phase
1 $M_\odot$
$\text{Log}_{10}(L/L_\odot)$
$\text{Log}_{10}(T_e)$

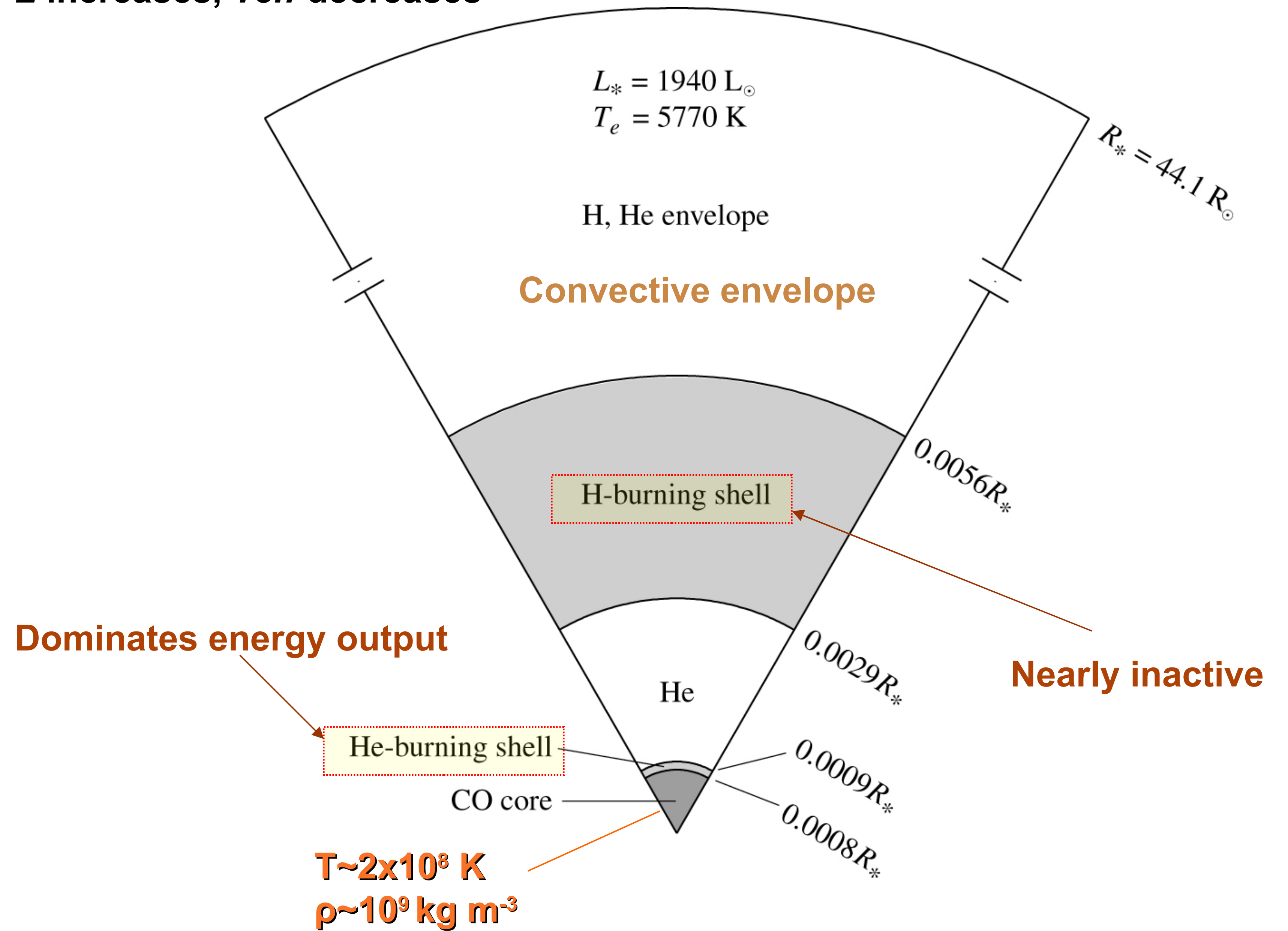
5 Mo star



Post-AGB
PN formation
Superwind
Third dredge-up
TP-AGB
First He shell flash
Second dredge-up
E-AGB
He core exhausted
HB
He core burning
H shell burning
SGB
RGB
Overall contraction
First dredge-up
Pre-white dwarf
ZAMS
H core exhausted
To white dwarf phase
5 M⊙
Log10 (L/L⊙)
← Log10 (Te)

Early AGB 5 M ʘ star

L **increases,** ***Teff*** **decreases**



2. AGB Thermal Pulse Phase

1. **Quiet phase**
   H-shell provides *Luminosity*, He-ashes drop onto Helium layer below
   Temperature increases in **He shell**
2. **Shell Flash**
   He-shell ignition → expansion of H-shell → cooling → nuclear burning switches off
3. **Cooling of He shell**
   Reduction of energy production
4. **Third dredge up**
   Convective envelope reaches burning layers producing C
5. **Quiet phase**
   Recovery of H-burning shell

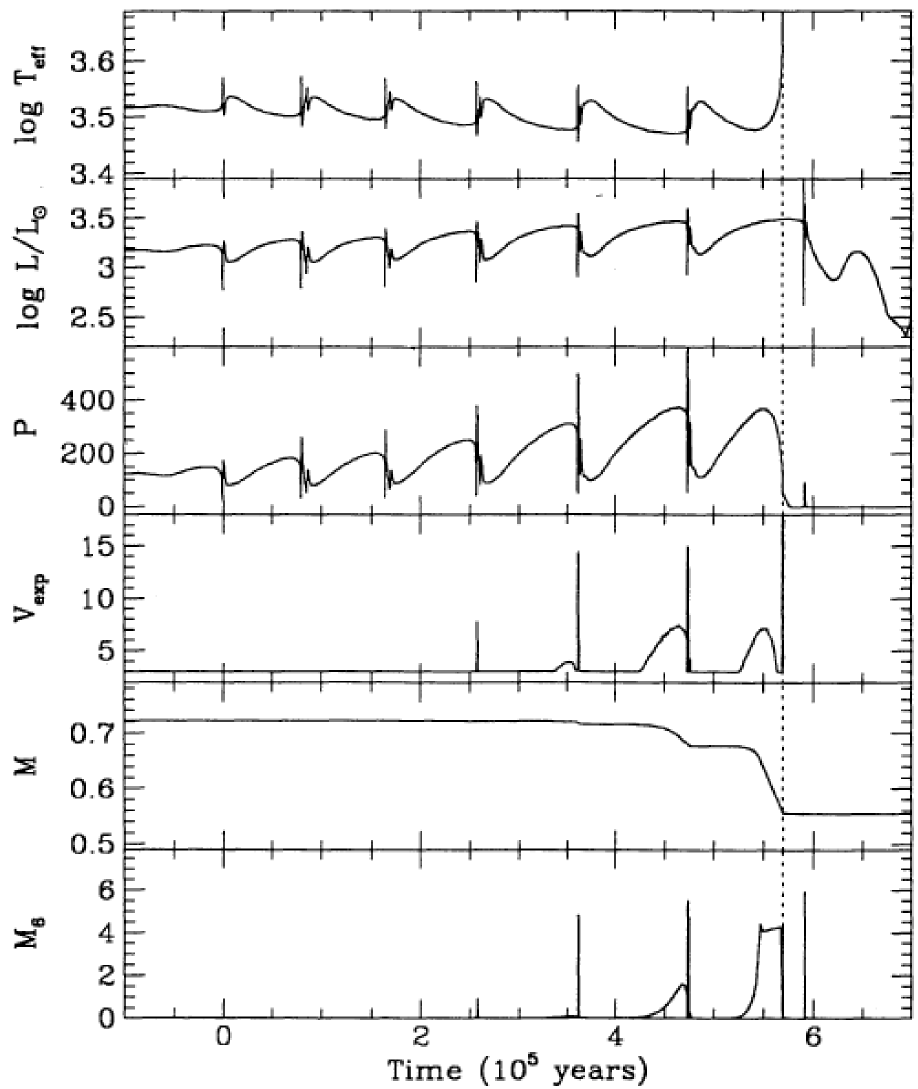


FIG. 3.—Time dependence of various quantities during the TP-AGB phase of a star with $(M, Y, Z) = (0.945, 0.25, 0.008)$. The abscissa represents the time after the first major thermal pulse. The dotted vertical line at right represents the end of the AGB phase, as defined in the text. M_6 is the mass-loss rate in units of $10^{-6}\ M_{\odot}\ yr^{-1}$.

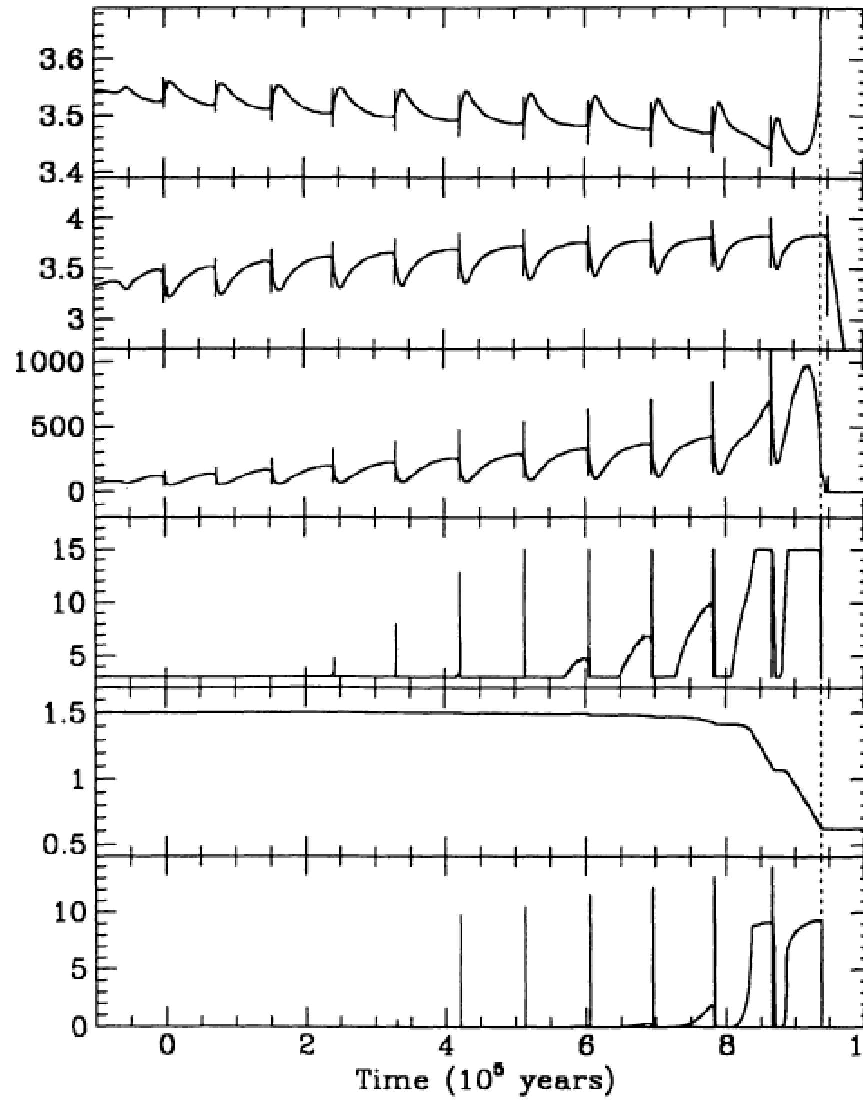
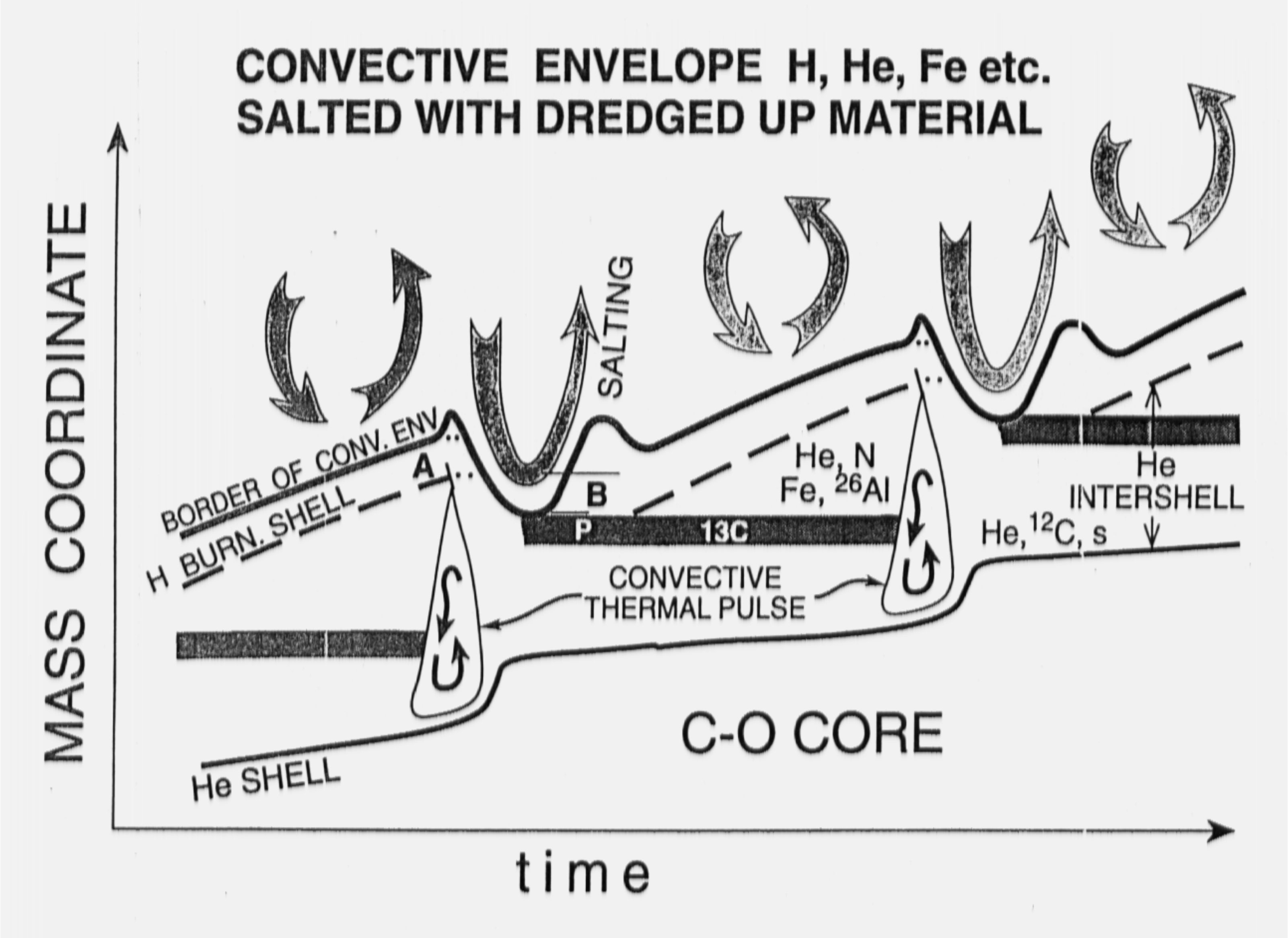


FIG. 5.—Same as Fig. 3, except for $(M, Y, Z) = (1.5, 0.25, 0.008)$

Vassiliadis & Wood 1993

THE AGB ENGINE

(Busso, Gallino, Wasserburg 1999 ARA&A, 37, 239)



Dredge-ups

- The bottom of the Convective Envelope (CE) moves downward
- The CE penetrates a nuclear processed zone
- Products of nuclear burning are carried to the surface

✓ they can be observed
✓ return to the ISM via mass loss

	1st D-up	2nd D-up	3rd D-up
Phase	RGB	E-AGB	TP-AGB
Products of	Central H-burning	Shell H-burning	**Carbon, s-process elements**

Hot Bottom Burning

- In more massive AGB stars ($M_{initial} > 4\ M_{\odot}$) the convective envelope becomes so extended downwards that it can cut into the hydrogen burning shell during the interpulse phase (hot bottom burning) or envelope burning

- Temperatures in excess of $50 \cdot 10^6$ K are reached a the convective envelope and material burnt there immediately mixed to the surface

Extra He, N, Li & isotopes of Ne, Na, Al, and Mg – from the Ne-Na and Mg-Al cycles

- Due to CNO cycling of the envelope ^{12}C can be transformed into ^{13}C and ^{14}N. Consequently, a low $^{12}C/^{13}C$ ratio is a typical signature for HBB which can **prevent AGB stars from becoming carbon stars**

Chemical branches of AGB stars

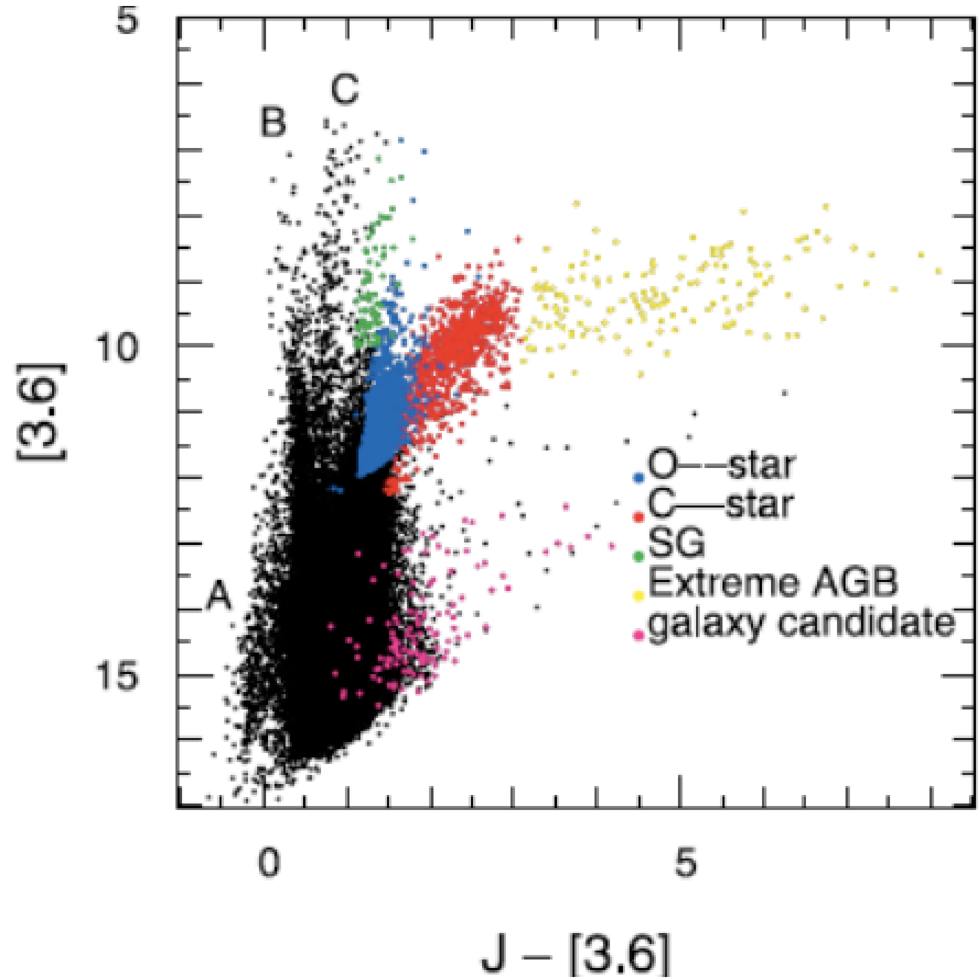
Three different chemical branches of AGB stars, depending on their progenitor mass:

- low-mass stars → O-rich AGB stars
- intermediate-mass stars → C-rich AGB stars
- high-mass stars → O-rich extreme AGB
  ('hot bottom burning' at the base of the convective envelope, prevents the formation of C (instead, production of N is favoured) **OH/IR sources (OH maser lines)**

both the lower and upper mass limits decrease in more metal-poor environments

Garcıa-Lario & Perea-Calderon (2004), Karakas & Lattanzio (2007)

AGB IR CMD

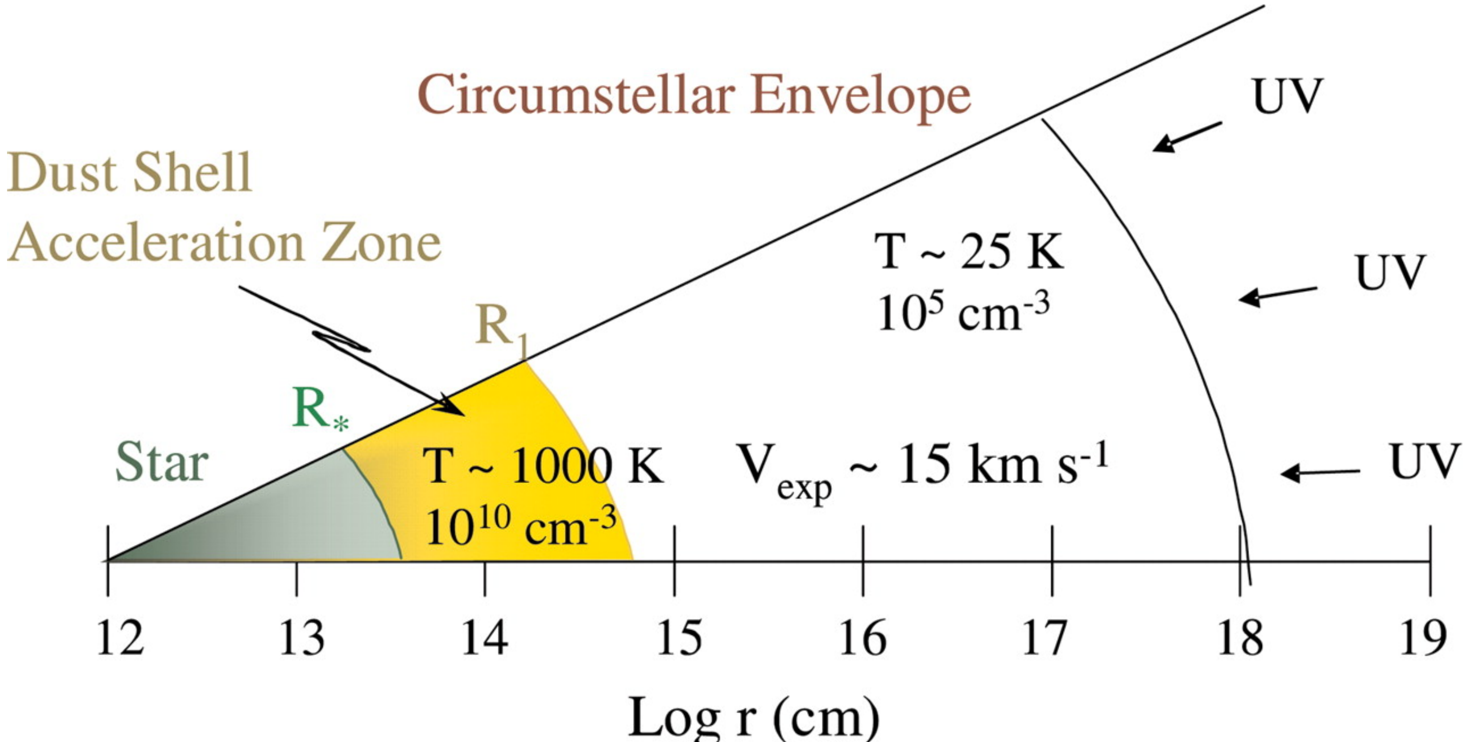


Blum et al (2006, AJ, 132, 2034)

Dust production in AGB stars
The Circumstellar Envelope

- The large AGB mass-loss rates play a key role in the **cosmic circuit of matter**
- This mass loss consists of both **gas** and **(sub)micron-sized solid “dust” particles**

Cross section of a circumstellar envelope, plotted in terms of log r, where r is the distance from the central star.

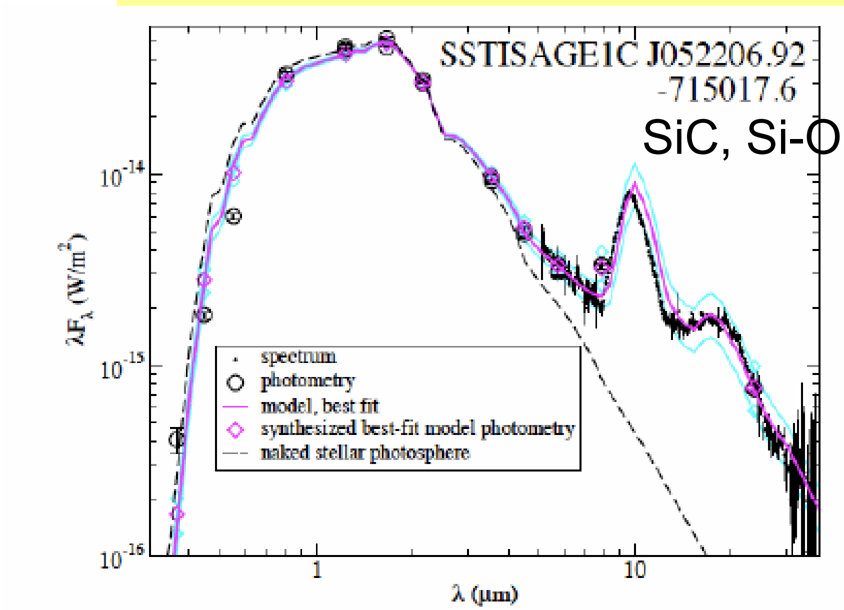


Ziurys L M PNAS 2006;103:12274-12279

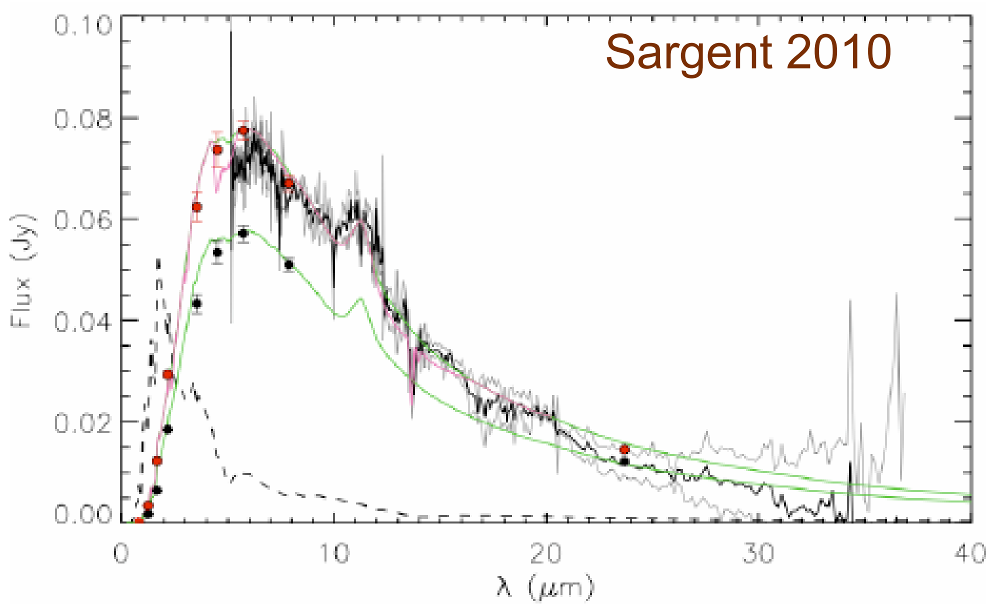
Spectral Energy Distribution of dusty AGB stars

- Dust in the circumstellar shells of AGB stars leads to a significant change in the overall **spectral energy distribution** (SED) compared to dust-free objects
- Dust attenuates stellar radiation in the blue and visual range and reradiates corresponding emission at **mid- infrared wavelengths** ("infrared excess")
- The spectrum of the infrared excess contains **broad spectral features characteristic of specific dust species**

SED's: MCPS U,B,V,I. 2-MASS J,H,K, Spitzer IRAC 4.5, 8μ and MIPS-24μ

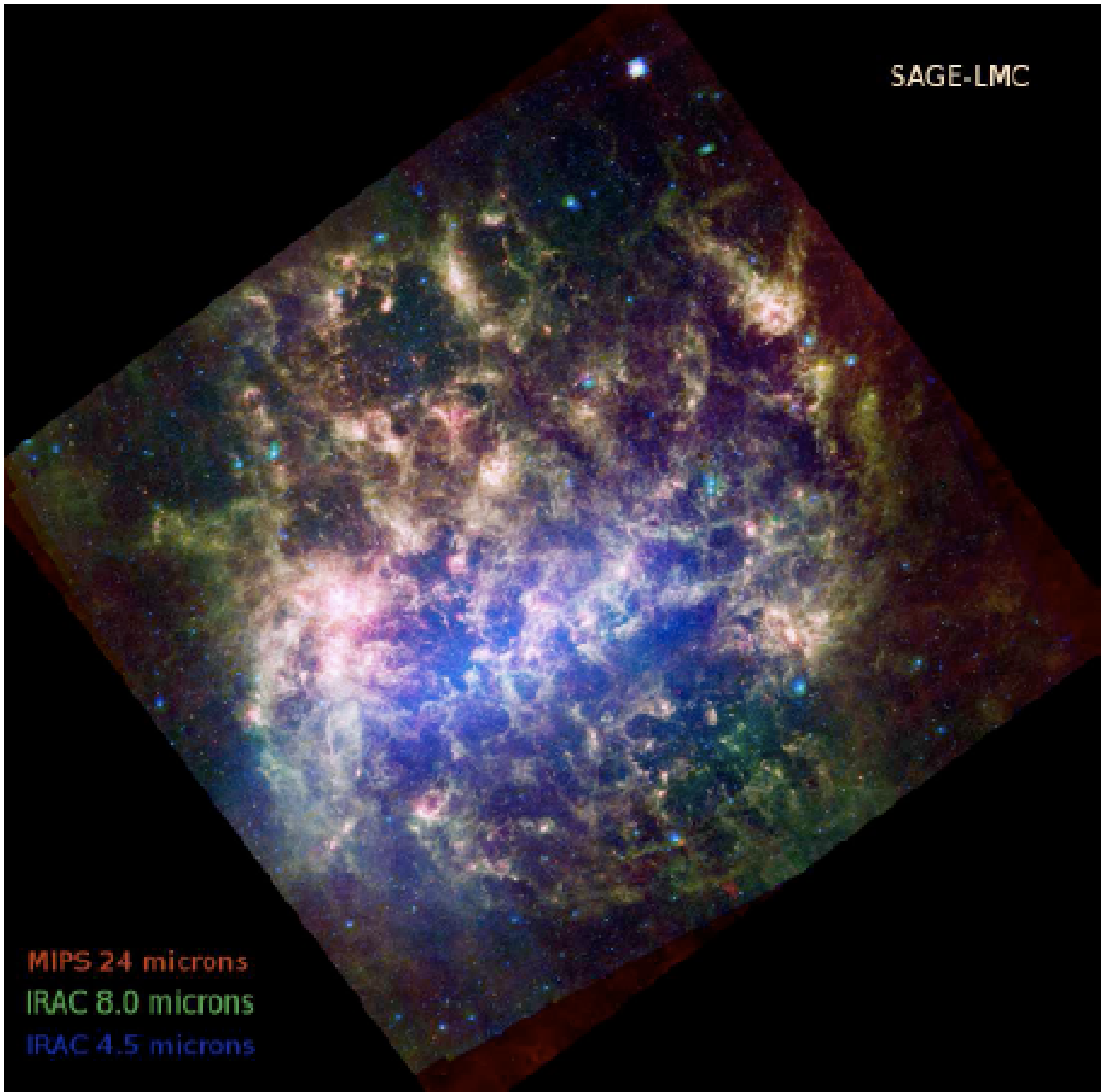


SED of O-rich AGB star



SED of C-rich AGB star

IRAC and MIPS surveys of 7°x7º area of LMC, *Spitzer* Legacy program (Meixner et al 2006, AJ, 132, 2268)



Astro-chemistry in Circumstellar Envelopes of AGB stars

The flow of gaseous material from the star, results in temperature and density gradients in the CE that create a complex chemical environment

- hot, thermodynamically controlled synthesis
- molecule "freeze-out"
- shock-initiated reactions
- photochemistry governed by radical mechanisms

O-rich AGB stars (M spectral type)

- Strong triple bond between O and C in CO → **all *C* blocked into *CO* molecules**

  → no *C* is available for formation of dust grains
- ***O*** not engaged in *CO* **+ *Mg*** and ***Si*** → ***MgO*, silicates** and ***H_2O***

  → bind together to produce **grains of silicates**

- Two typical features at **10*μ*** and **18*μ*,** either in absorption or in emission, attributed to stretching and bending modes of ***Si−O* bonds** and ***O −Si− O* groups** and clearly probe the existence of **silicate grains**

- **Cold silicates** are suited to thick shells with the 10μ feature in absorption, whereas warm silicates are more appropriate to thin shells with the 10μ feature in emission

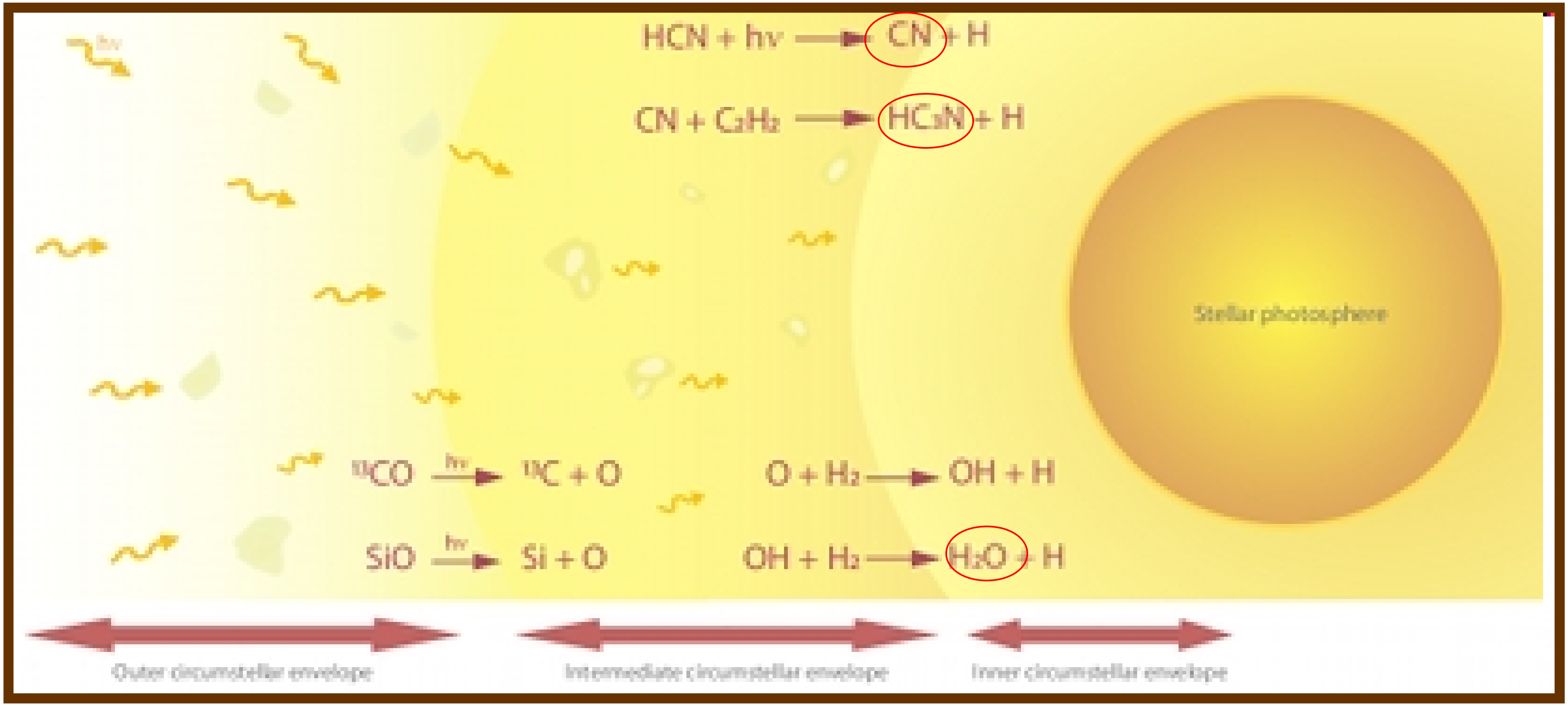
- In many spectra AGB with high mass-loss rates, there are prominent bands of **crystalline silicates**, for instance enstatite ($MgSiO_3$) and forsterite (Mg_2SiO_4)

- an emission band at about 13 μ has been detected that could be due to *aluminum oxide*

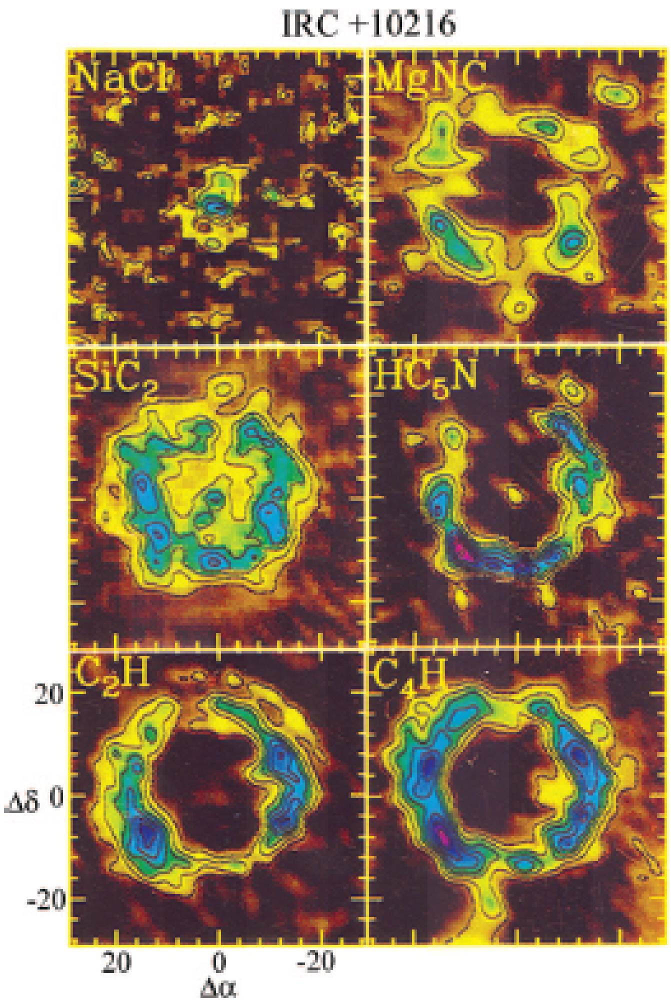
C-rich AGB stars

- Dredged-up C stops the formation of O-rich dust
  Formation of C-rich compounds
- Dominant dust grains: amorphous carbon (*AMC*), silicon carbide, and magnesium sulphide (*MgS*)
- By loosing mass at very high rates, CS get enshrouded by thick envelopes of C-rich dust which makes the envelopes more and more optically thick
- The CE absorbs and scatters the UV-optical radiation into the IR and radio range
- Almost all C-rich stars show an emission feature at 11.3μ, due to silicon carbide (*SiC*)
- The grains of SiC can be
  - hexagonal or rhombohedral *α* SiC (AGB IR spectra)
  - and cubic *β* SiC (all meteoritic grains) problem?
- There is observational evidence of dust forming around a carbon star in a nearby galaxy with a low abundance of heavy elements, 25 times lower than the solar abundance. The production of dust by a carbon star in a galaxy with such primitive abundances raises the possibility that carbon stars contributed carbonaceous dust in the early universe. (Sloan et al. 2009, Science)

Chemical processes in the CE of a carbon-rich AGB star



Example: Circumstellar envelope of C-rich star IRC10216



>50 different chemical compounds

exotic species such as C_8H, C_3S, SiC_3, and AlNC (*Aluminum* isocyanide)

Table 1. Confirmed molecular identifications in IRC+10216

CO	CCH	HC_3N	CCS	SiO	NaCl
CS	C_3H	HC_5N	C_3S	SiS	AlCl
CN	C_3O	HC_7N	C_3N	SiC	KCl
HCN	C_4H	HC_9N	C_5N	SiN	AlF
HCCH	C_5H	H_2C_4	HC_4N	SiC_2	MgNC
HNC	C_6H	H_2C_6	c-C_3H_2	SiC_3	MgCN
H_2CCH_2	C_7H	HC_2N	CH_3CN	SiCN	AlNC
CH_4	C_8H	C_3	CP	SiC_4	KCN
NH_3	C_2	C_5	PN	SiH_4	NaCN
H_2S					

Maps from the Plateau de Bure interferometer showing the molecular distributions of various species in the envelope of IRC10216:

Outer shell: MgNC, C_2H, HC_5N, and C_4H

Inner shell: NaCl

Intermediate regions : SiC_2

The detached dust shells of carbon star variables AQ Andromedae, U Antliae, and TT Cygni

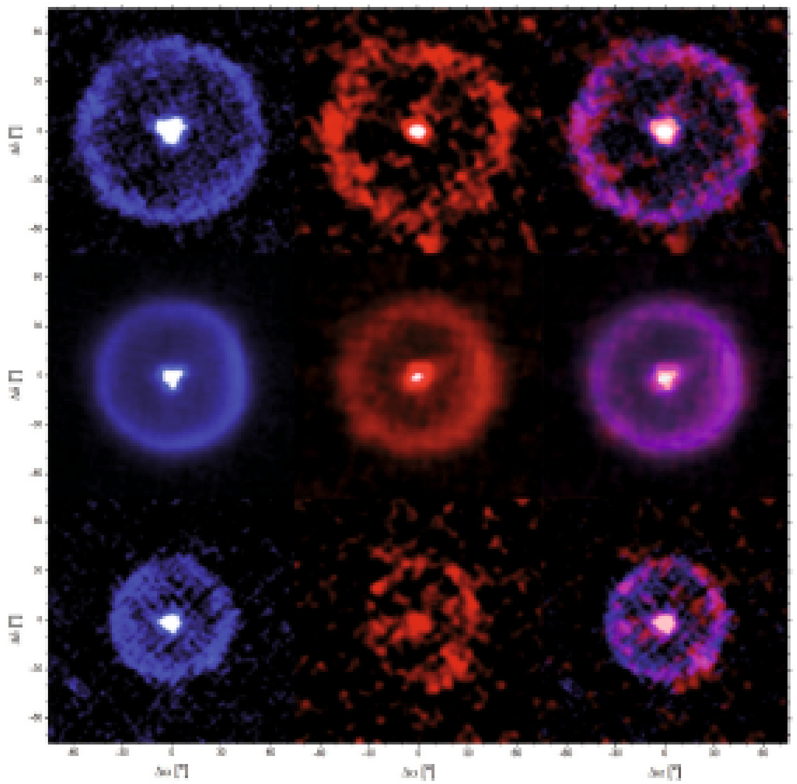
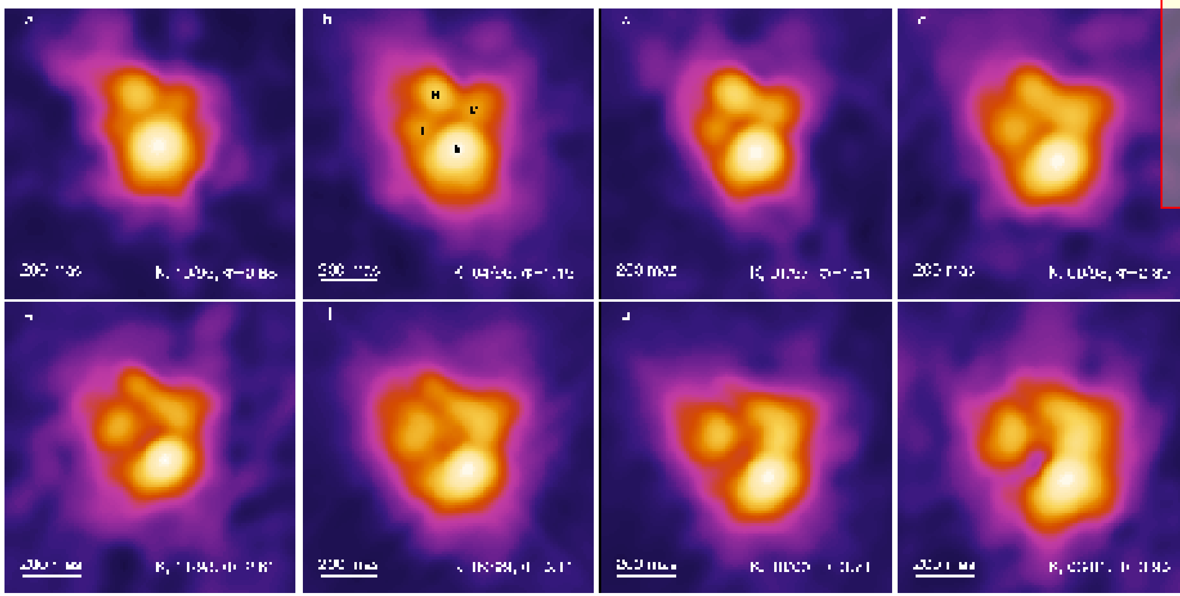


Fig. 1. *Herschel*-PACS scan maps (*left to right*: at 70 μm, 160 μm, two colour composite) of AQ And, U Ant, and TT Cyg (*top to bottom*).

F. Kerschbaum et al. 2010 A&A 518, L140

Carbon Star IRC+10216 at 2.2 micro-meter Evolution 1995-2001

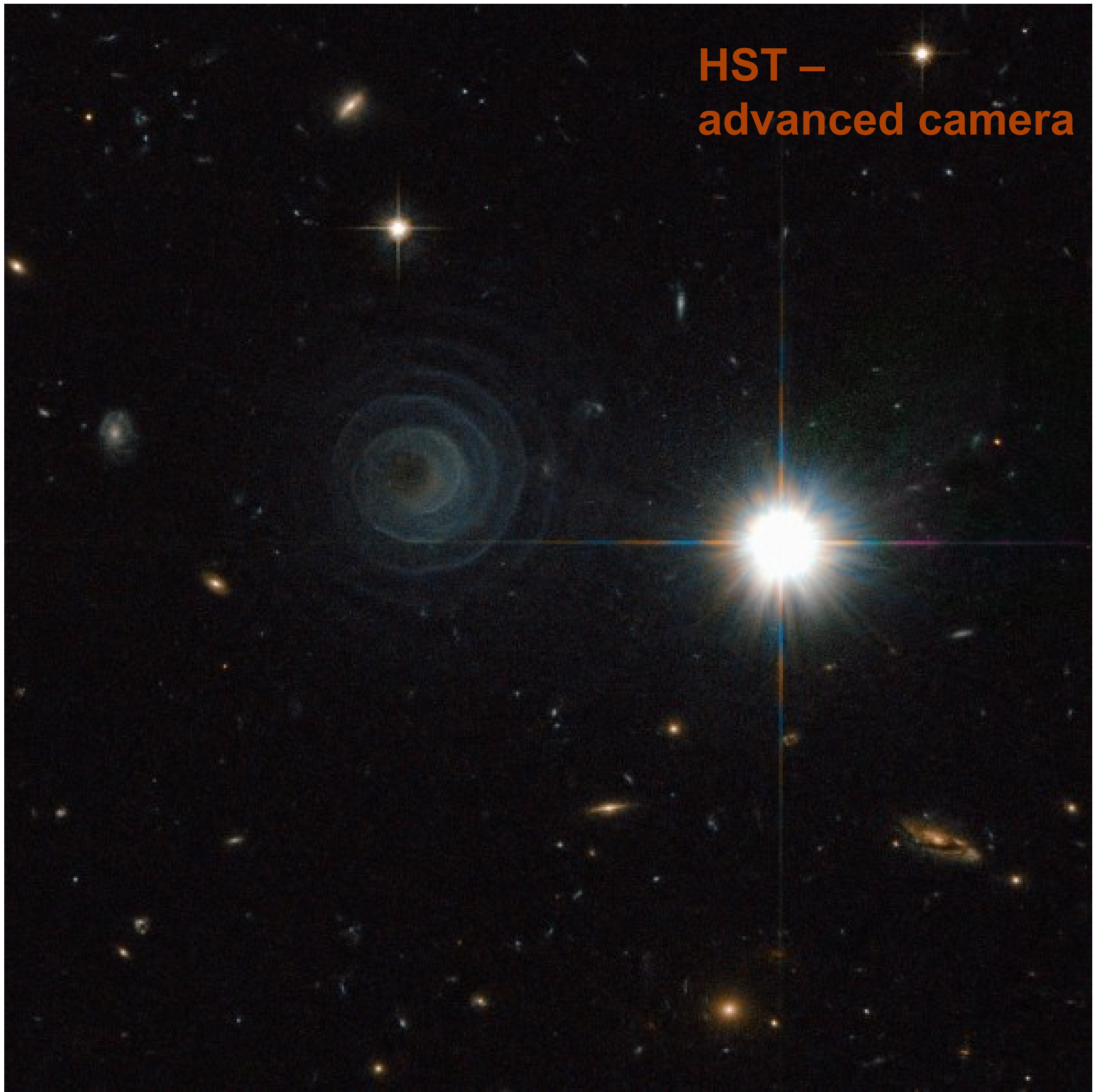
The brightest object on the sky at mid infrared wavelengths (except for the Sun)



Weigelt et al. 2002, Astronomy and Astrophysics 392, p.131-141

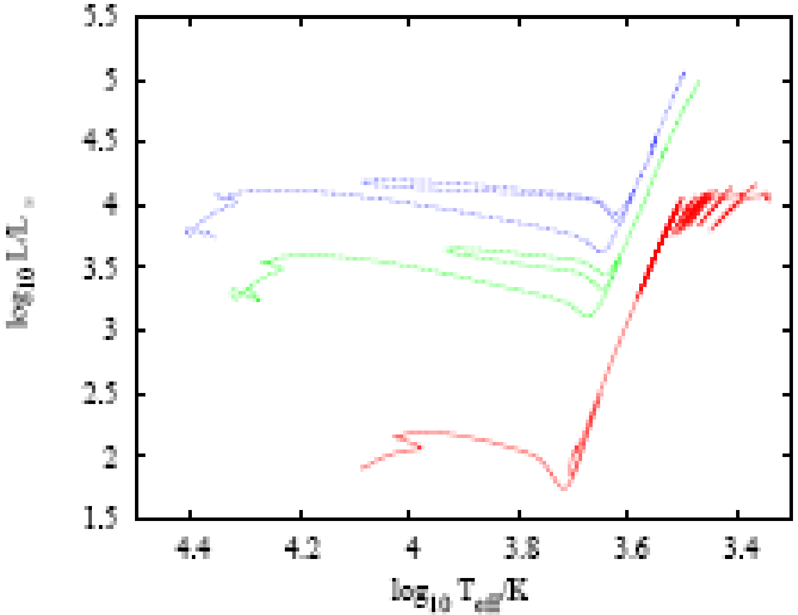
AGB stars are usually surrounded by large quantities of gas and dust which often has an irregular clumpy structure (which can change on timescales of only a few years).

Pre-planetary nebula Mass Loss from dusty carbon star in binary system



Super-AGB

- Super-AGB stars are the more massive counterparts of AGB stars
- They are massive enough to ignite carbon under partially degenerate conditions
- Do not proceed to further stages of nuclear burning
- Responsible for the production of ONe white dwarfs or may explode as SN



Stancliffe 2008

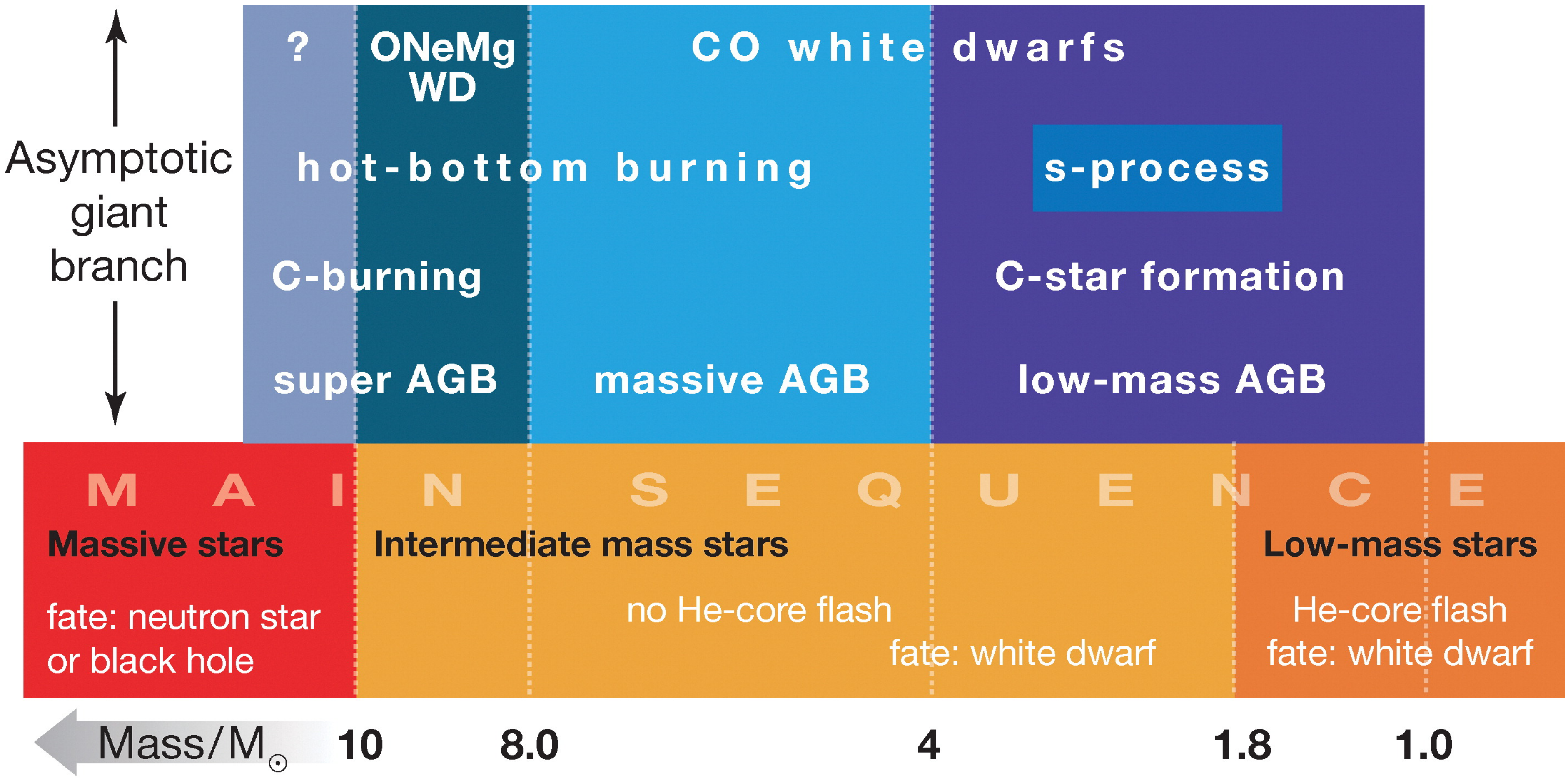
Super AGB - HBB

- C ignites in partially degenerate conditions
- Carbon flash, drives convective zone – high C abundance
- After 2^{nd} dredge-up, C burning slowly dies out
- H- and He-burning shells pushed close together
- Star enters a thermally pulsing phase just like a 'normal' AGB star
- Pulses are quite weak L_{He}^{max} around $10^6\,L_\odot$
- Base of convective envelope in H-burning shell – Hot Bottom Burning

Tip of the Super AGB

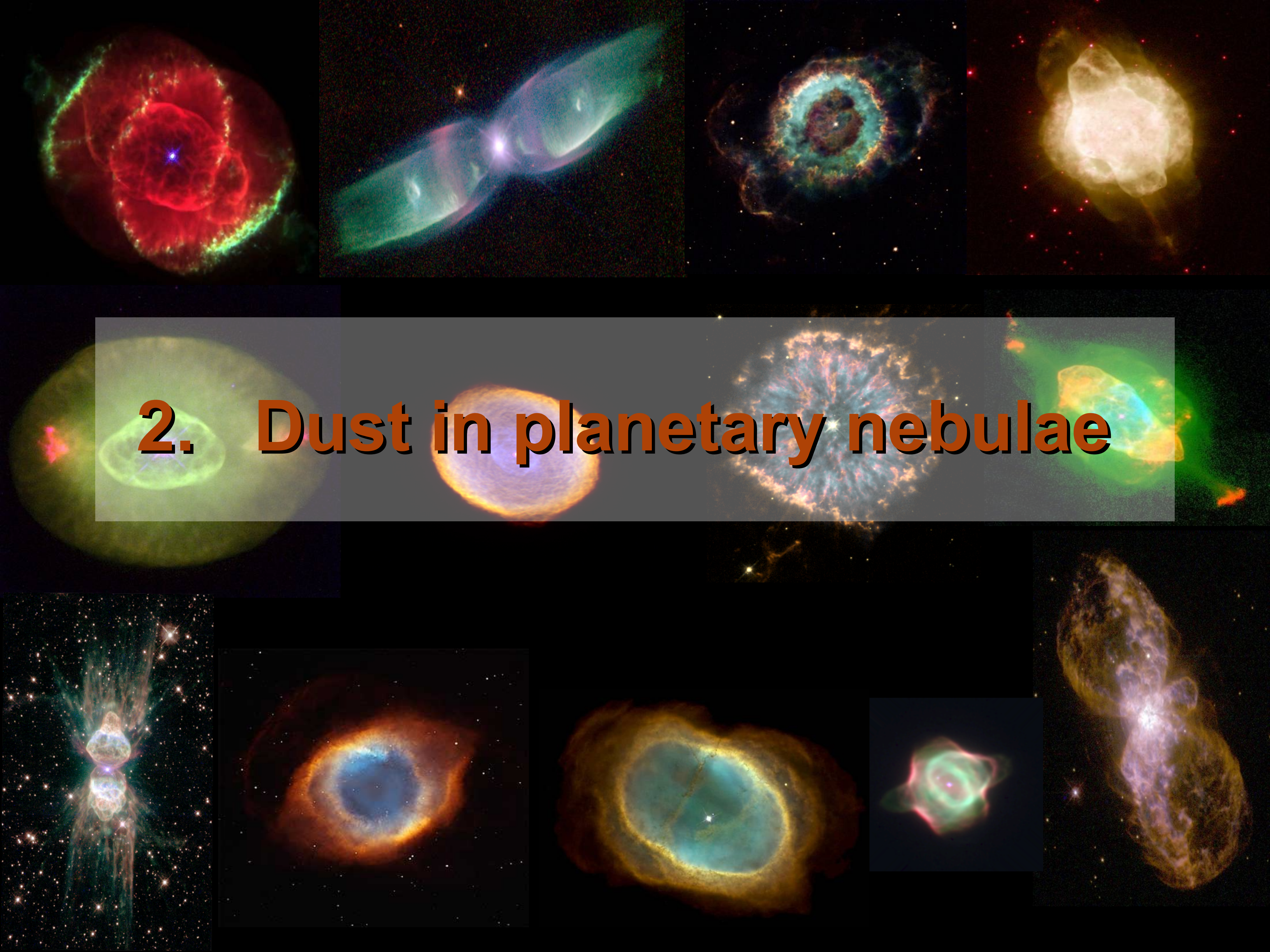
- TP-SAGB characterised by strong mass loss
- Core may grow to beyond the Chandresekhar mass
- Third dredge-up may inhibit core growth
- Competition between these processes determines final fate
- Either have a massive ONe white dwarf or an electron-capture super-nova

Stellar Evolution vs Mass



Herwig, F. 2005
Annu. Rev. Astron. Astrophys. 43: 435–79

2. Dust in planetary nebulae

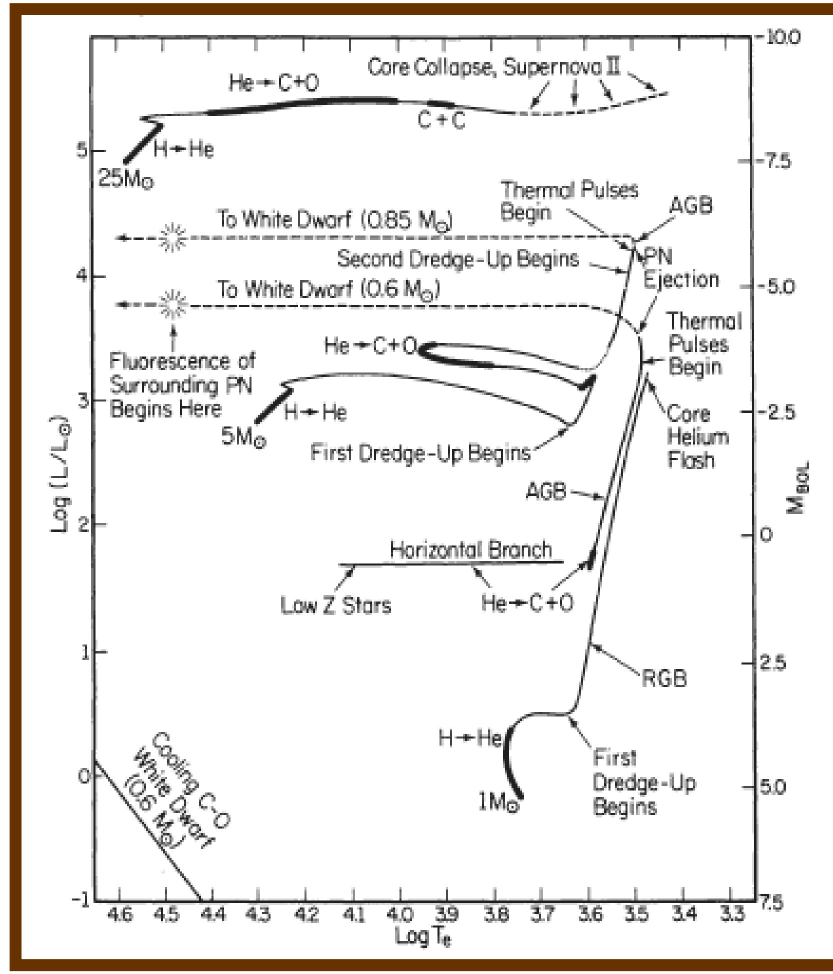


Planetary nebula stage

- After the AGB phase, 0.8-8 M⊙ stars pass through the **planetary nebula** phase before ending their lives as white dwarfs

- **Superwind** forming PNs is activated by radiation pressure on the **dust grains** (plus pulsation)

- Stars leave the AGB when the **strong mass loss stops** and then the future central star rapidly evolves towards **hotter effective temperatures** in the HR diagram
  → strong UV



- When the **ionization of the ejected gas** takes place, a new PN is formed

- The total amount of ionized gas is very small compared to the total mass previously ejected

- **Molecules are shielded from UV light by dust, H_2, CO**

An important fraction of this material remains neutral in the form of dust grains, molecules, or atoms, which can be easily detected in the infrared domain.

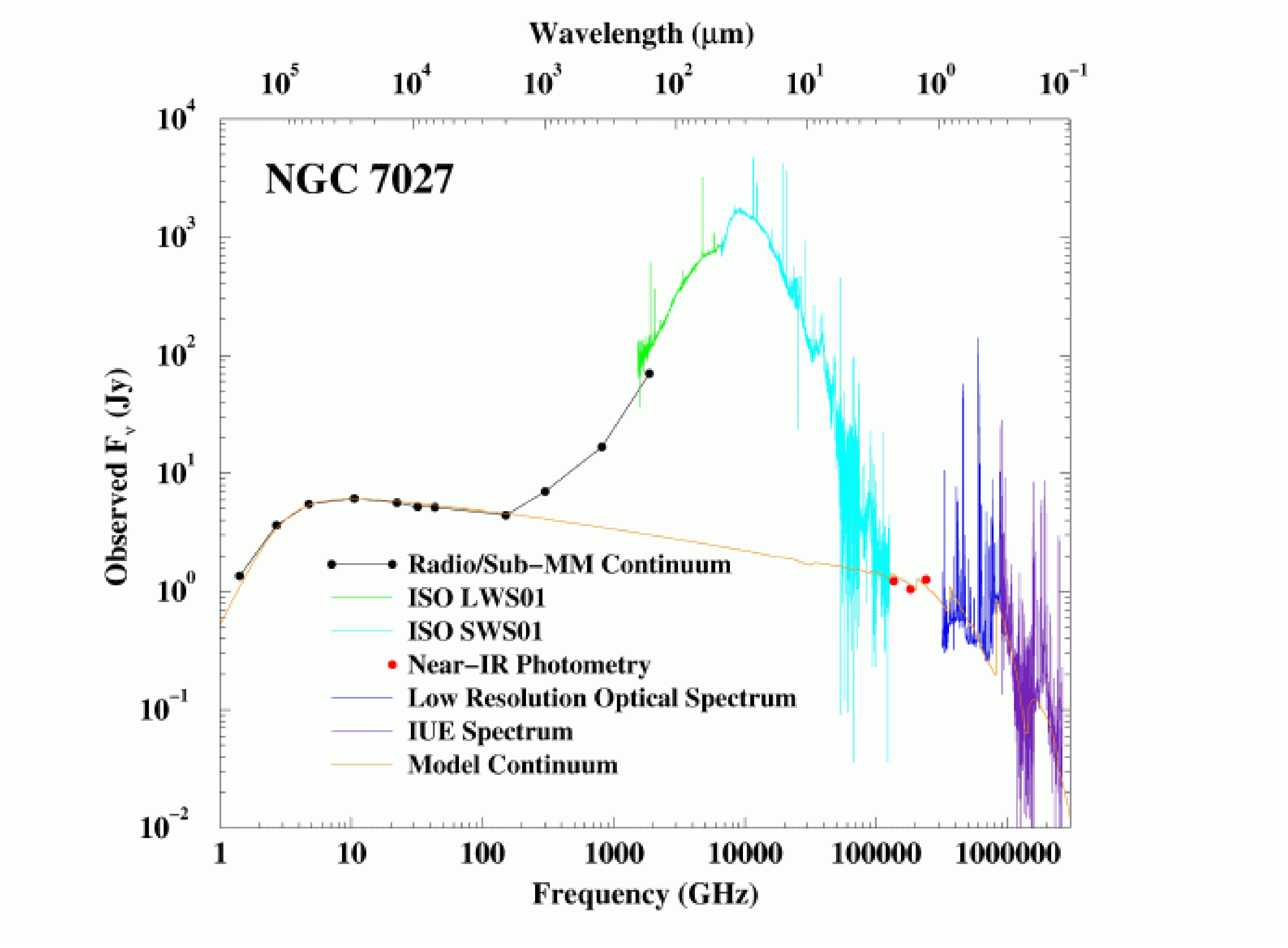
IR image of the Helix showing dust emission

From the Spitzer Space Telescope website

Dust Chemistry in Planetary nebulae

- In AGB CS stage (just before PN stage) the chemistry is dominated by molecules containing long carbon chains, silicon, and metals such as magnesium, sodium, and aluminum (quite different from what is found in molecular clouds)
- As these envelopes evolve into planetary nebulae with a hot, exposed central star, **synthesis of molecular ions** becomes important
- Numerous species such as **HCO**, **HCN**, and **CCH** are found in old planetary nebulae such as the Helix
- This "survivor" molecular material may be linked to the variety of compounds found recently in diffuse clouds
- Organic molecules in dense interstellar clouds may ultimately be traced back to carbon-rich fragments originally formed in circumstellar shells
- Infrared spectra of PNe show the presence of **large amounts of dust grains** (C-rich versus O-rich)
  - C-rich PNe: polycyclic aromatic hydrocarbons (PAHs)
    - ✓ Features at 3.3, 6.2, "7.7", 8.6, and 11.3μ
  - O-rich PNe: crystalline silicates
    - ✓ strong features centred on 23.5, 27.5 and 33.8 μ
  - dual-dust chemistry with simultaneous presence of both carbon-based dust (PAHs) and oxygen-based dust (crystalline silicates)

PN NGC 7027



Wavelength (μm)
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
NGC 7027
Observed F_ν (Jy)
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
Radio/Sub−MM Continuum
ISO LWS01
ISO SWS01
Near−IR Photometry
Low Resolution Optical Spectrum
IUE Spectrum
Model Continuum
1
10
100
1000
10000
100000
1000000
Frequency (GHz)

Gorny et al. 2010

Crystalline silicate

PAH's

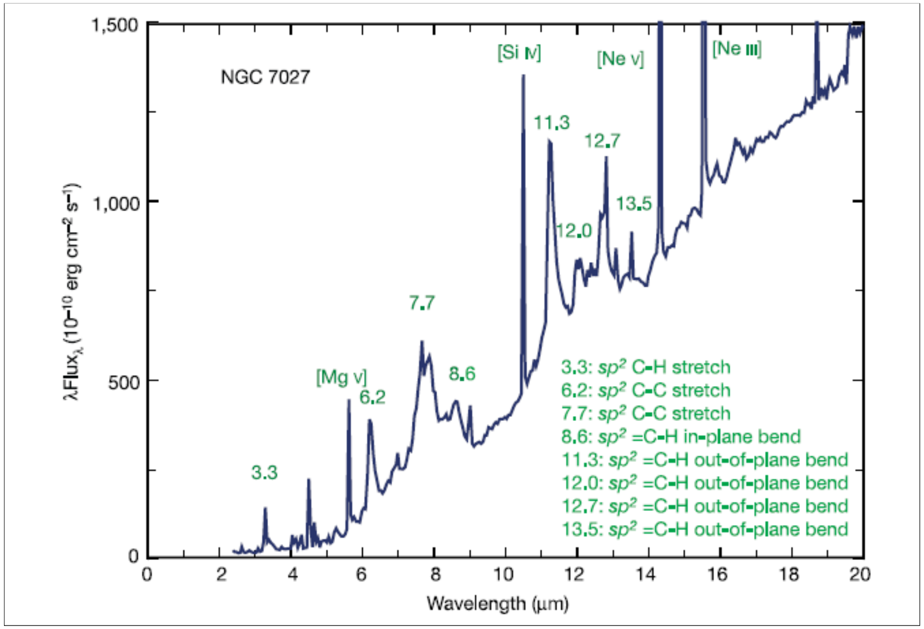
AMC

Fig. 1. Th 3-4 silicate

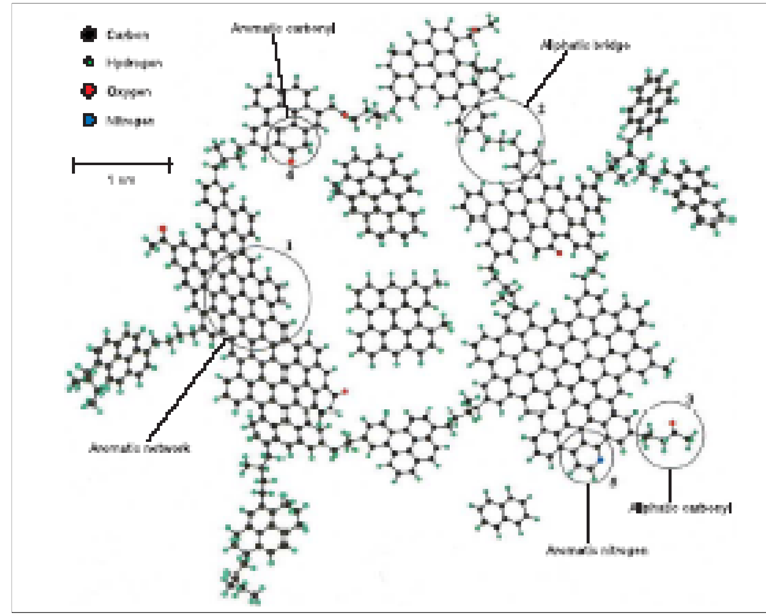
Spitzer/IRS spectra of PNe with different types of dust composition: DCcr, DCa+cr, OCa+cr

the top, stalline n (right

Aromatic Molecules in PNe



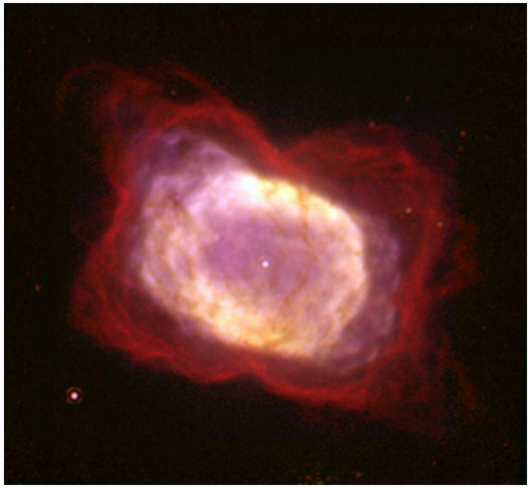
Aromatic Infrared Bands (AIBs) in a spectrum of the PNe NGC 7027 (from S. Kwok *Nature* **2004**)



Possible structure corresponding to AIBs (from S. Kwok *Nature* **2004**)

Infrared emission corresponding to **vibrations of aromatic molecules** is detected in PNe

Chemical Evolution of PNe



NGC 7027, from HST & NICMOS

Helix PNe, from HST & Kitt Peak WIYN 0.9 m

Young PNe

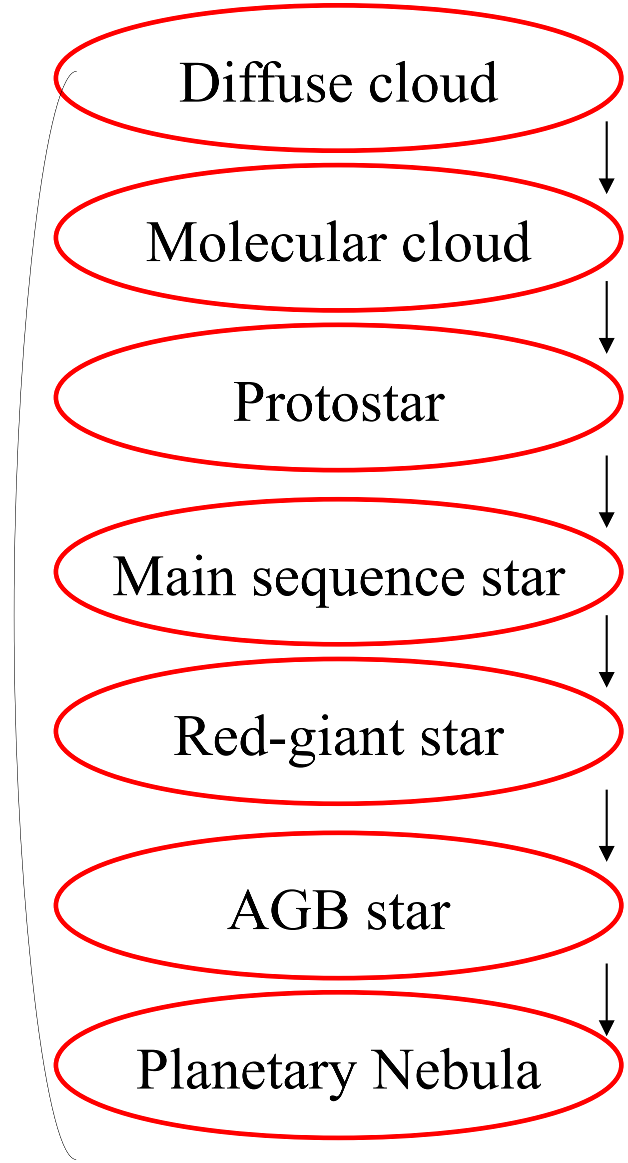
HCO^+	H_2	C_2H
CO^+	CO	$c\text{-}C_3H_2$
N_2H^+	CN	H_2CO
CH^+	CS	Large aromatic molecules
OH	HCN	
H_2O	HNC	

Evolved PNe
~12,000 yr

HCO^+	HCN
CO	HNC
H_2	Large aromatic molecules
CN	

Chemical Recycling in the ISM

- PNe gas disperses into diffuse clouds
- recycling/reprocessing of molecules in the ISM



3. Dust Production in red supergiants

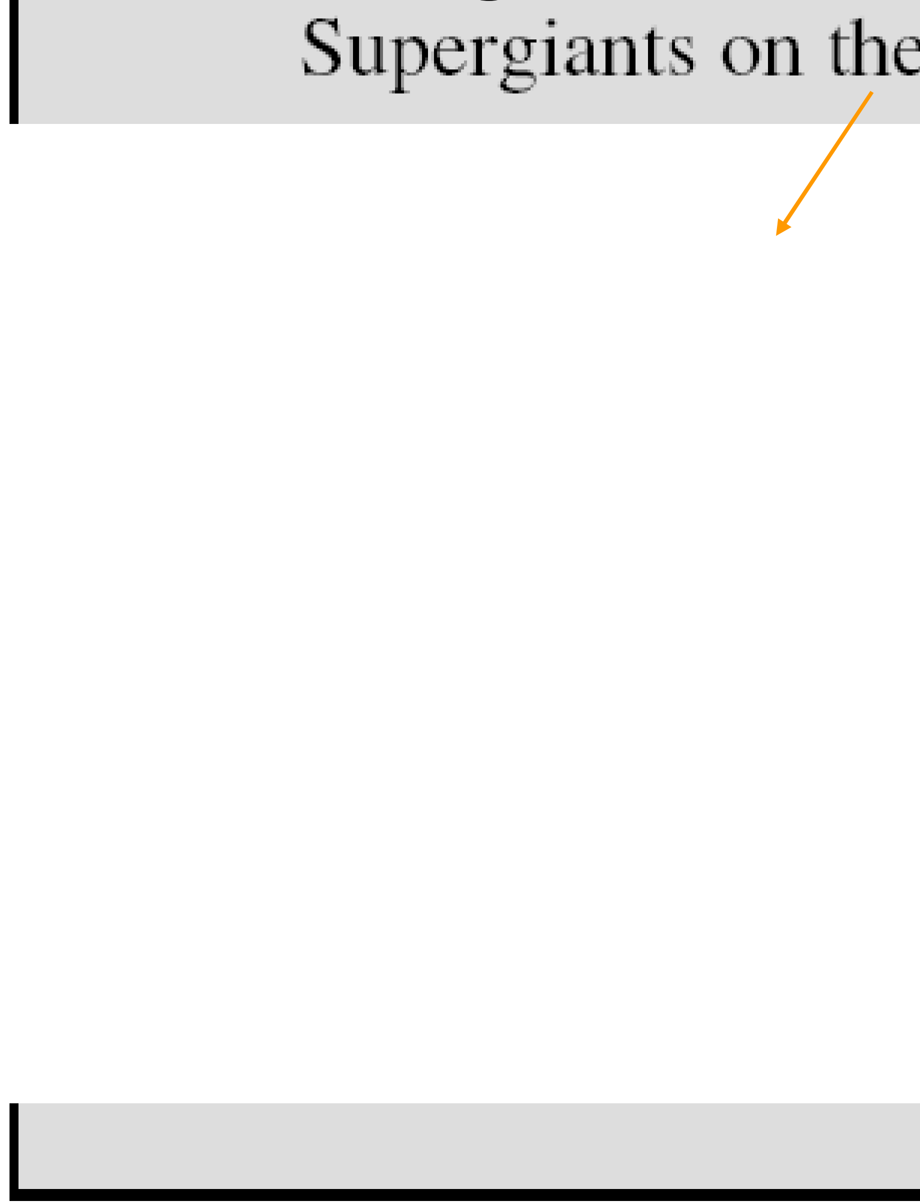
Red supergiants

❑As stars of initial mass ~8 ≤M_{init} ≤ 40$M_\odot$ evolve off the main sequence and reach the core helium-burning phase, they turn into red supergiant (RSG) stars

❑The terminal stage in the evolution of such massive stars is characterized by very short timescales (10^4 yr) and drastic changes in their immediate circumstellar environment

❑In the red supergiant phase, periods of large mass loss release a thick circumstellar envelope of molecular gas and dust

❑mass-loss processes from RSGs govern
- their evolution
- the structure of their surrounding envelope
- contribute to the enrichment of the ISM in dust and heavy elements



Dust in Red Supergiants

- Common dust properties with lower mass AGB stars

  - ✓ The dust has a high fraction of ”simple” dust species like metal-oxides
  - ✓ The winds have a relatively low abundance of silicates
  - ✓ The fraction of silicates correlates well with the mass-loss rate and/or the density and pressure at the base of the wind

- Differences:
  - ✓ RSGs show molecular bands only of di-atomic molecules (not H_2O, CO_2 or SO_2)
  - ✓ The general slope of the SED from near-IR to mid-IR wavelengths requires a source of continuous opacity which, in the case of RSG, could be due to **amorphous carbon**
  - ✓ PAHs are sometimes observed
  - ✓ strong influence by the chromospheric radiation field.

Verhoelst et al. 2009

One of the brighest known red supergiants

VY CMa

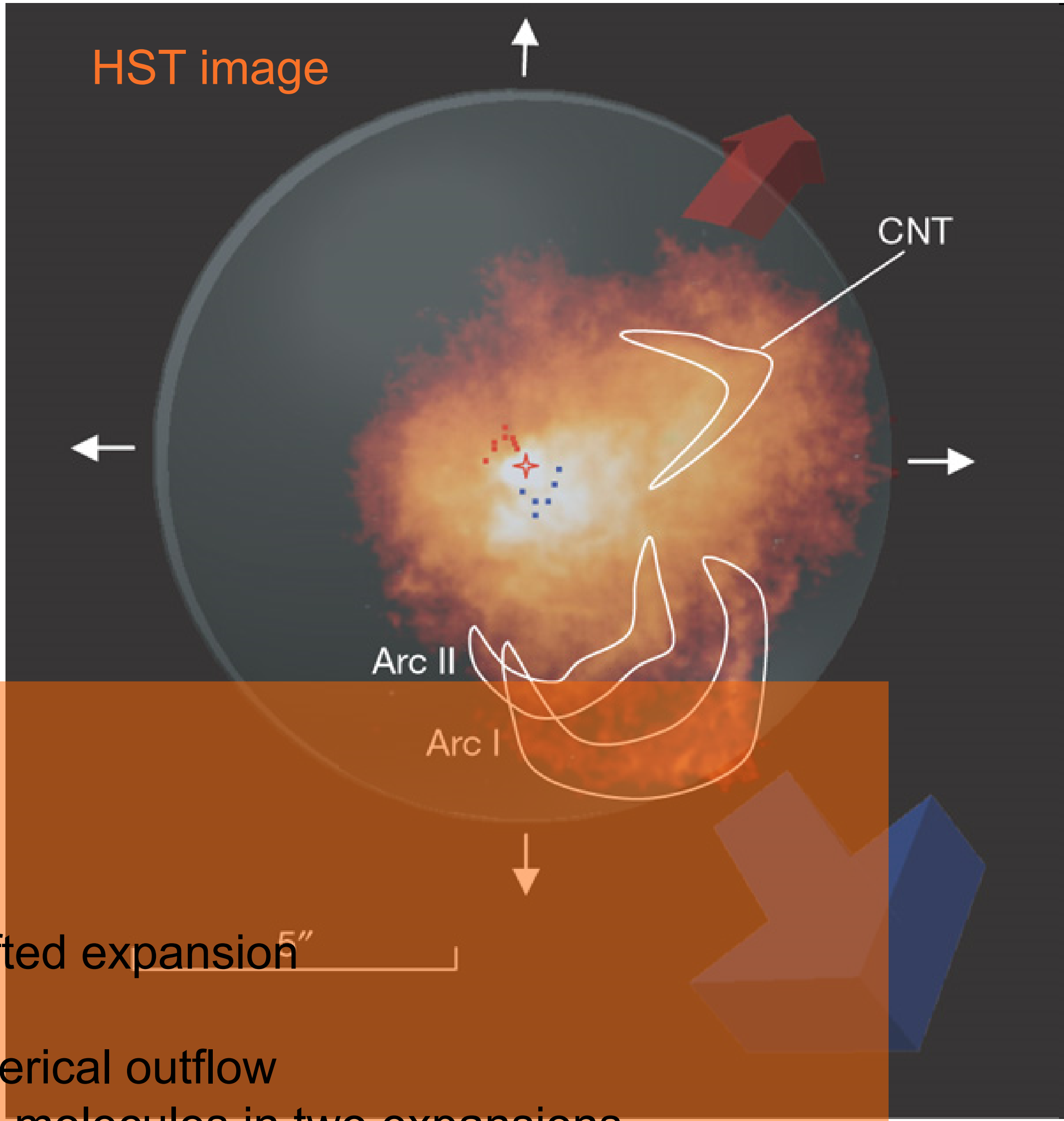
Basic Data of VY CMa

Parameter	Value	Reference
R.A. (J2000.0)	07 22 58.3315	1
Decl. (J2000.0)..........................	−25 46 03.174	1
Distance (kpc)	1.5	2
Angular scale	$1'' \sim 1500$ AU $\sim 2.25\ 10^{16}$ cm	
Luminosity L_* ($L_\odot$)....................	$\sim 2 \times 10^5$	3
Effective temperature $T_{\rm eff}$ (K)	2800	3
Stellar radius R_* (cm)	$1.2\ 10^{14}$	3
Stellar mass M_* ($M_\odot$)	≥ 15	
Mass-loss rate $\dot{M}$ ($M_\odot$ yr^{-1})........	$\sim(2–4) \times 10^{-4}$	4

Much of its visible light is absorbed by **a large, asymmetric cloud of dust** particles that has been ejected from the star in various outbursts over ~ 1,000 years.

The infrared emission from this dust cloud makes VY Can one of the brightest objects in the sky at wavelengths of 5–20 microns

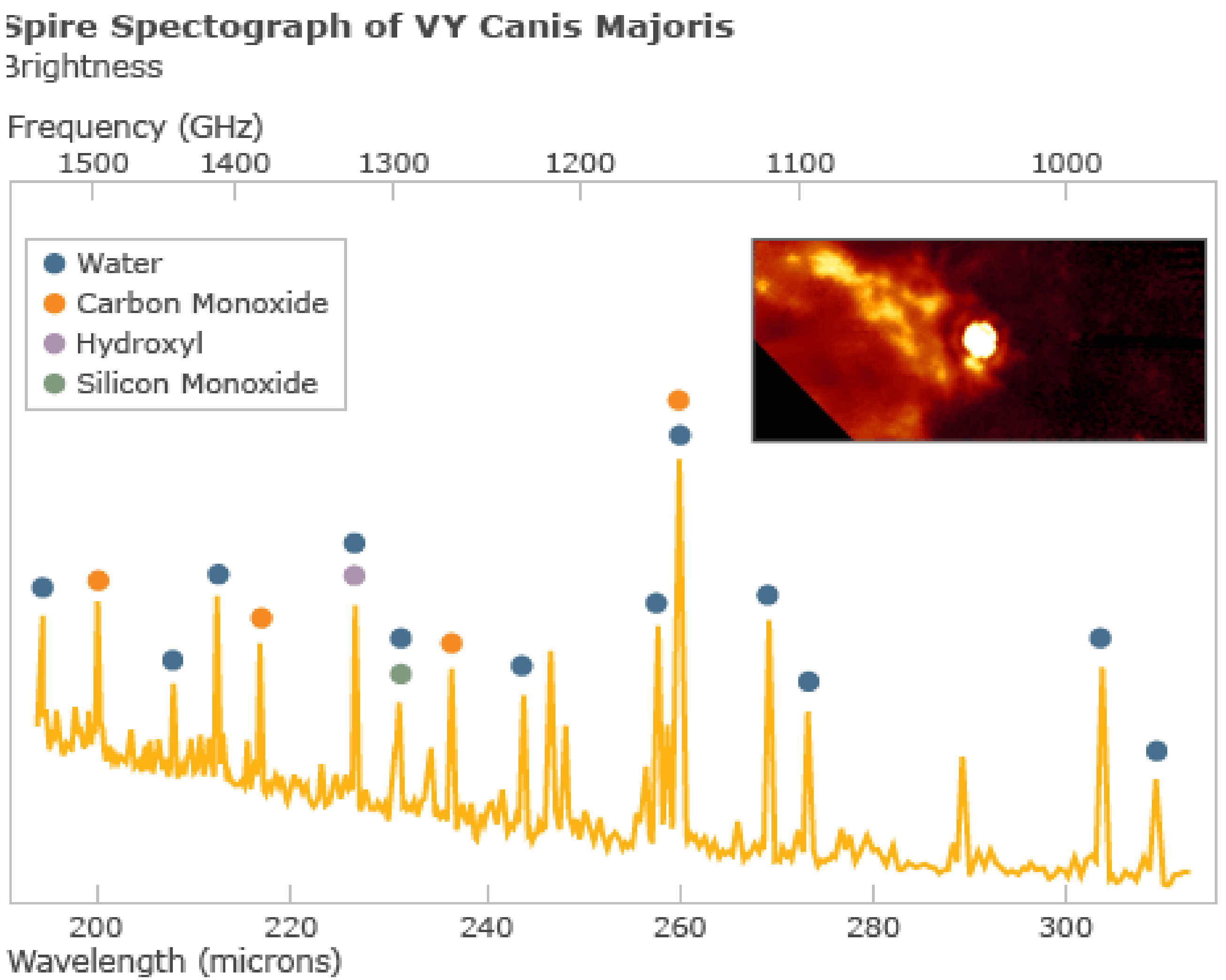
Chemical complexity in the wind of VY CMa



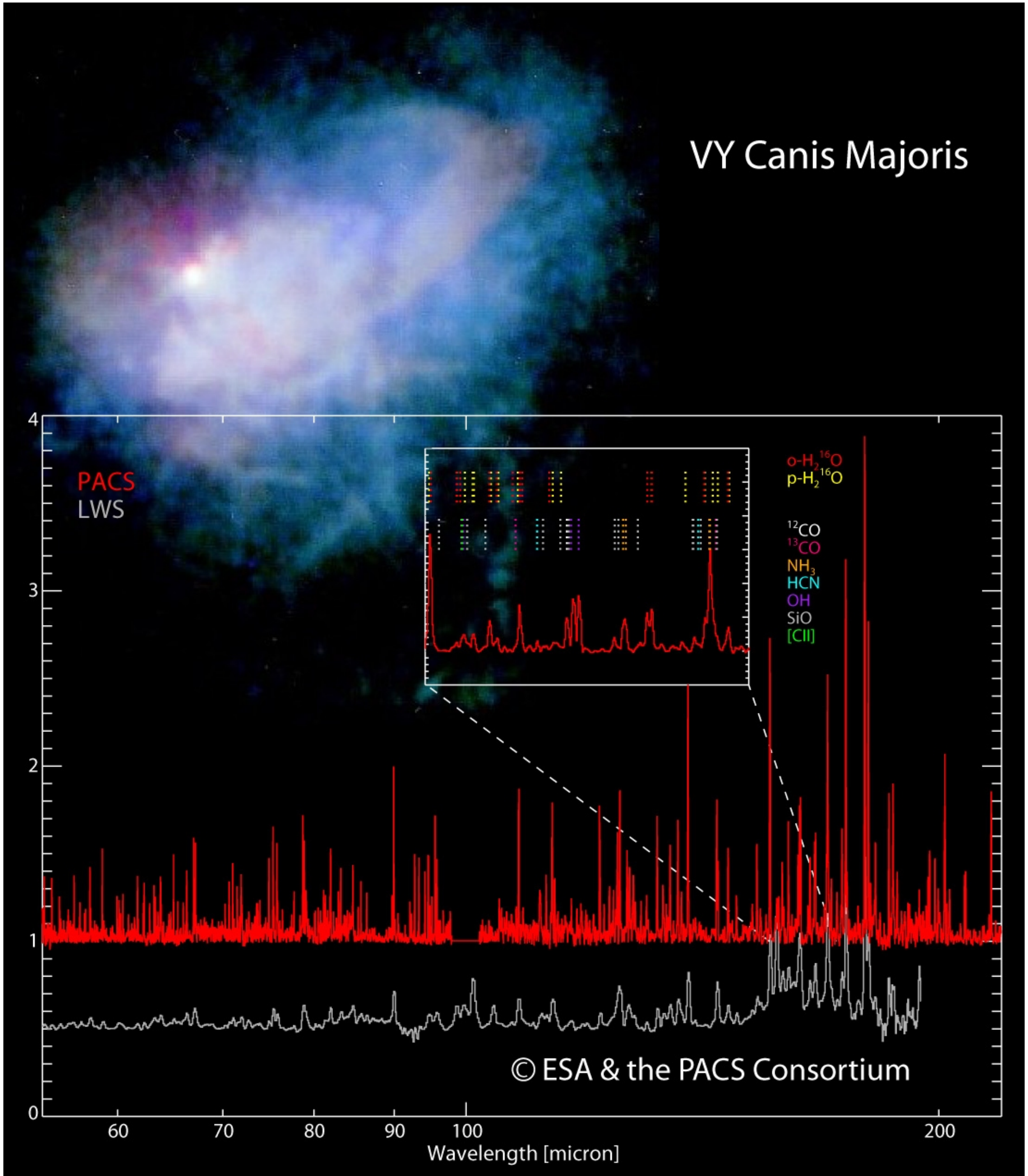
Ziurys et al. 2007, Nature
Sub-mm observations

- ❑ chemical compounds:
  NaCl, PN, HNC and HCO+.
- ❑ three distinct kinematic regions:
  - ✓ a spherical outflow
  - ✓ a tightly collimated, blue-shifted expansion
  - ✓ a directed, red-shifted flow
    - o SiO, PN and NaCl, in spherical outflow
    - o HNC and sulphur-bearing molecules in two expansions perhaps arising from shock waves.
    - o CO, HCN, CS and HCO+ exist in all three components.
- ❑ Despite the oxygen-rich environment, HCN seems to be as abundant as CO

Far Infrared spectrum of VY Canis Majoris

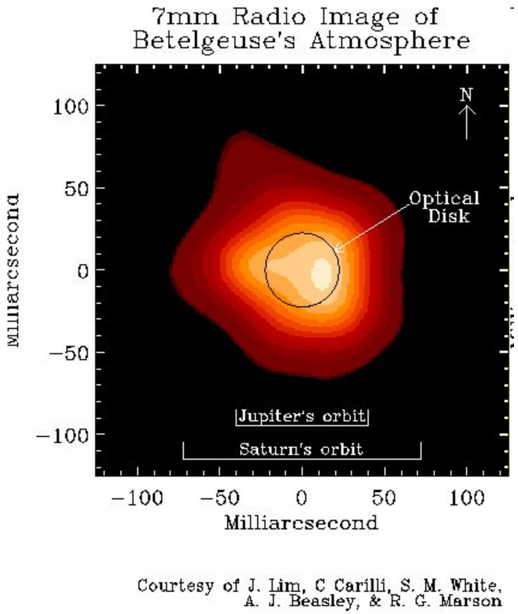


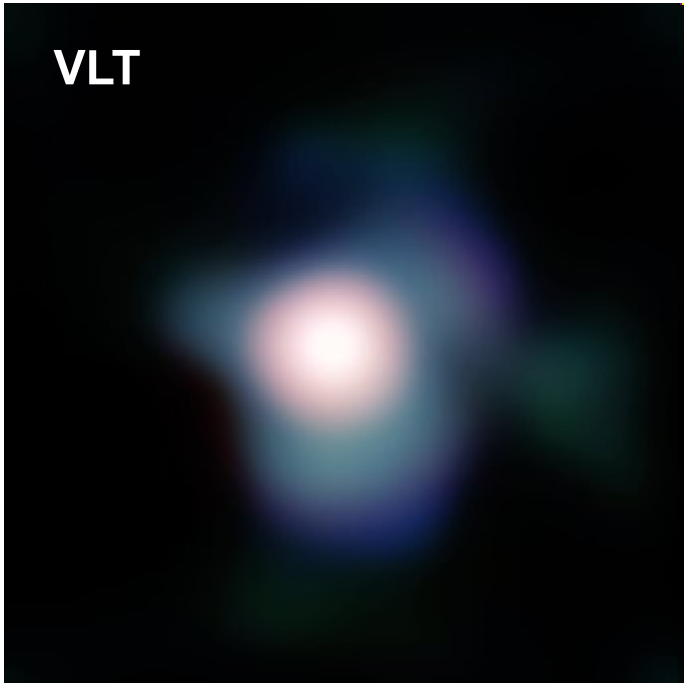
Source: ESA and the SPIRE consortium

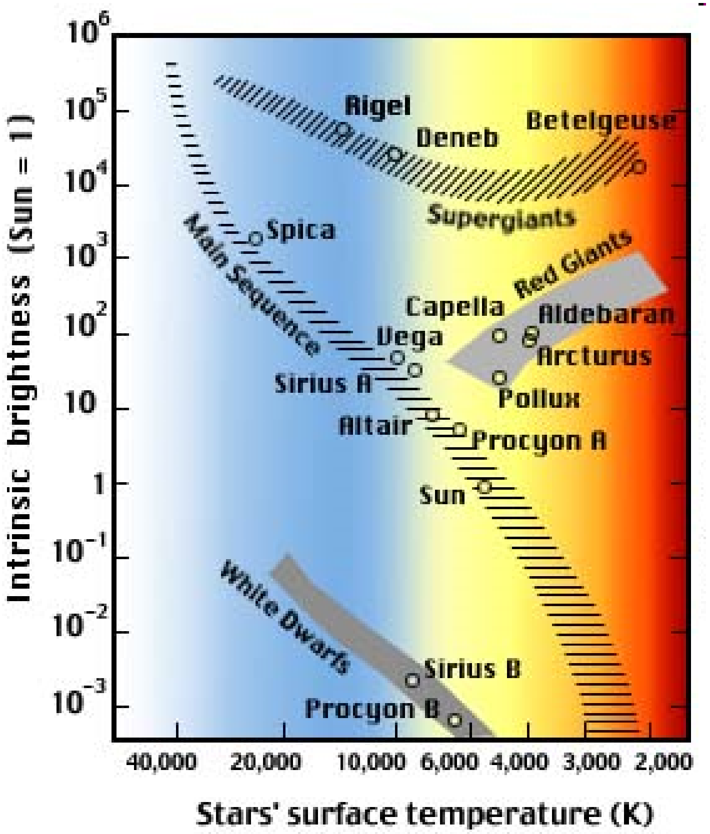


The shell of gas it has ejected displays a complex structure; the **circumstellar envelope** is among the most **remarkable chemical laboratories** known in the Universe, creating a rich set of **organic and inorganic molecules and dust species**

Closest red supergiant
Betelgeuse



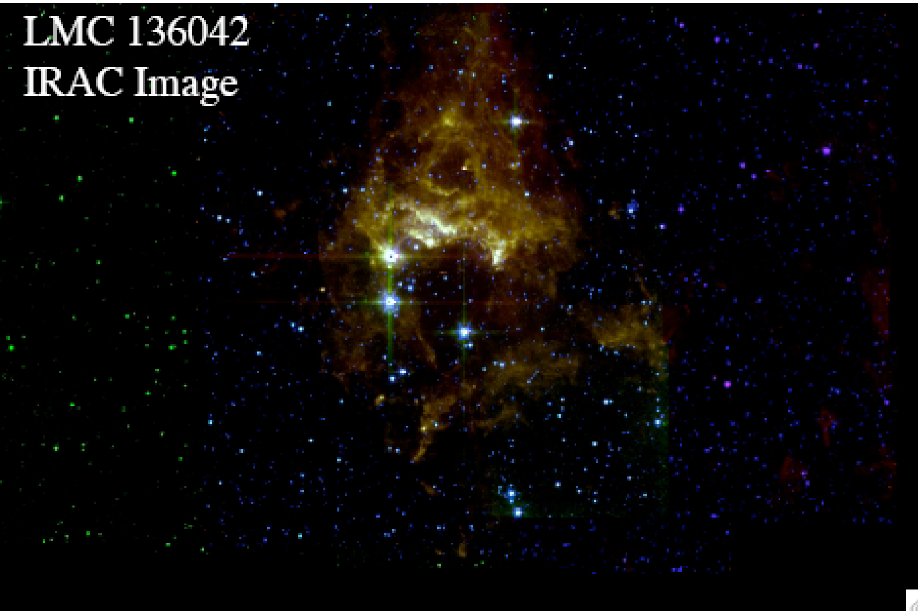


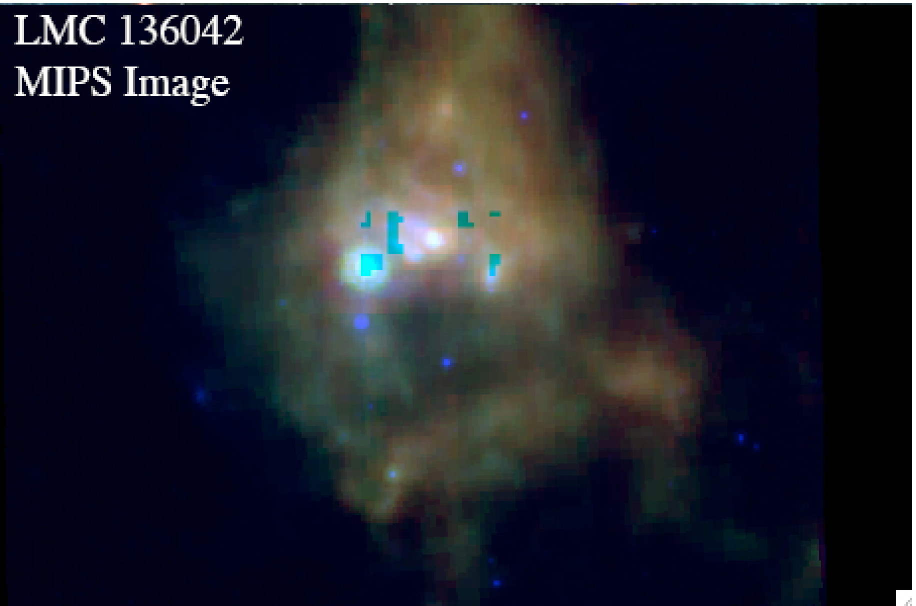


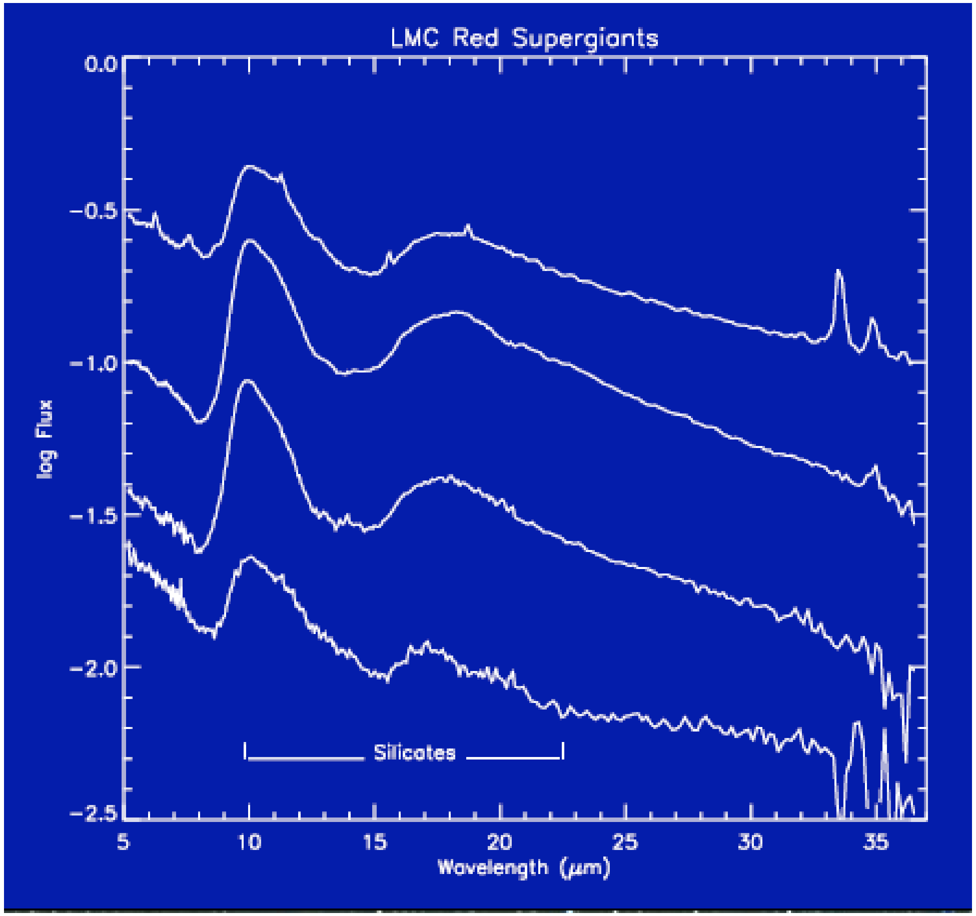
An Irregularly Pulsating, Red Supergiant

Spitzer images

Red Supergiant in the LMC

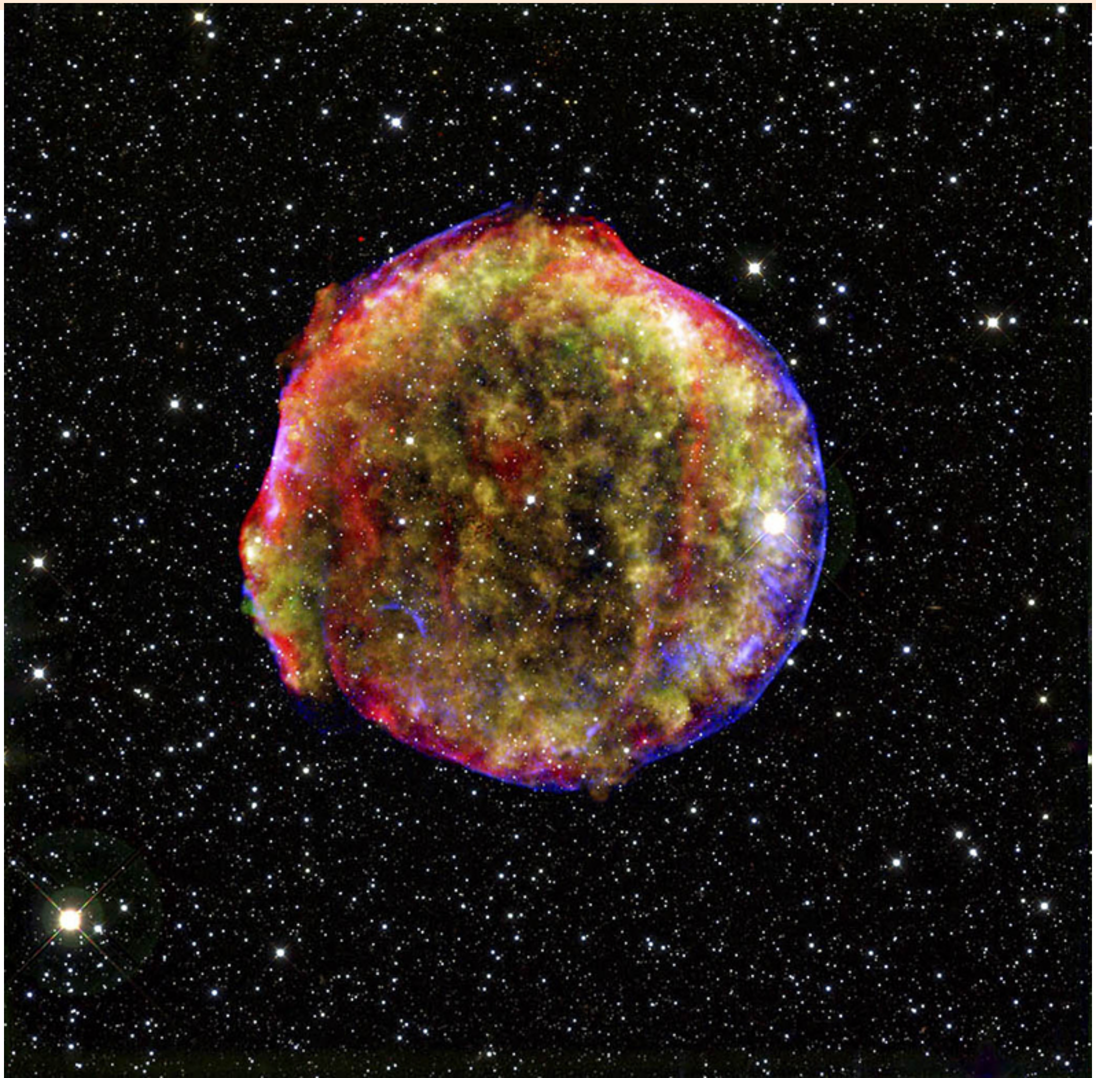






Clayton et al. 2006

4. Dust Production in core-collapse Supernovae



Dust production in CCSNe

- Are (were) core-collapse supernovae (CCSNe) major sources of dust in the universe?

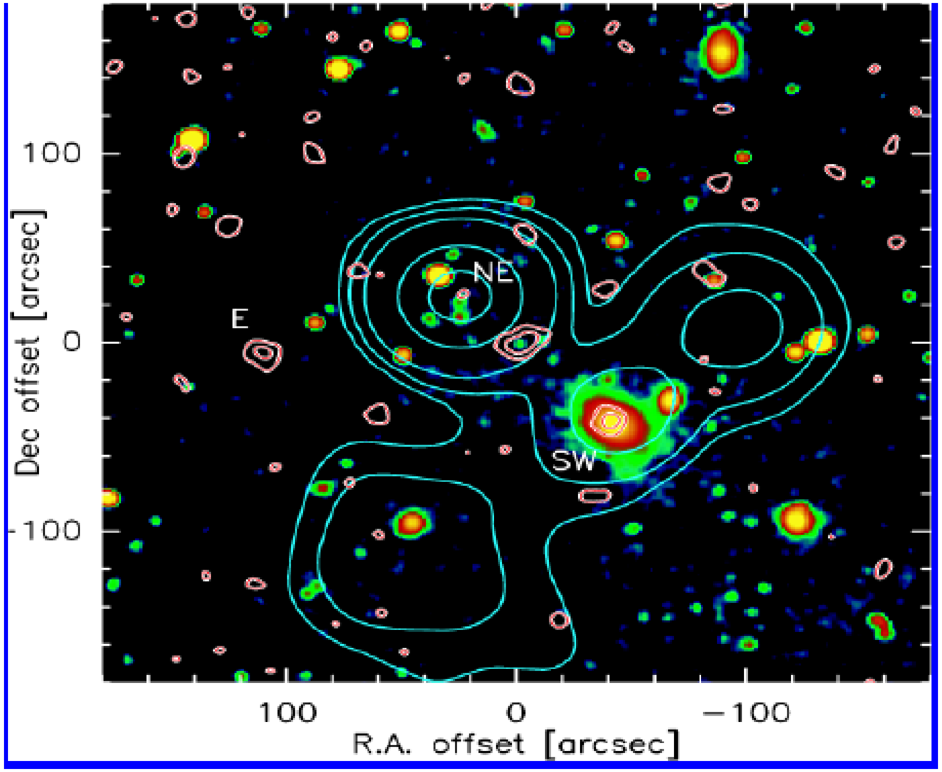
- The physical conditions in the expanding ejecta of CCSNe can result in the **condensation of large masses of dust grains**

- Interest in CCSNe as dust producers has increased due to the problem of accounting for the presence of **dust at high redshifts** since in these eras much less dust production from novae and asymptotic giant branch stars is expected as fewer stars will have evolved past the main-sequence phase (BUT evidence for dust production in low matallicity CS)

- CCSNe from Pop III stars have been proposed as the main early-universe source of dust.

- **Models of dust formation in CCSNe** have succeeded in producing large amounts of dust (~ 0.1 – 1 solar mass) even in the low-metallicity environments at high redshifts, enough to account for the quantity of dust seen at high redshifts.

Dust found in early galaxies



250GHz contours of a z=6.4 QSO
(Bertoldi et al. 2003, CO map)
The age of z~6.4 galaxy = 840Myr

- 10^8 Msun dust formed within ~1 Gyr
- candidate of dust producers in galaxies

Type II SN

Lifetime ~10 Myr

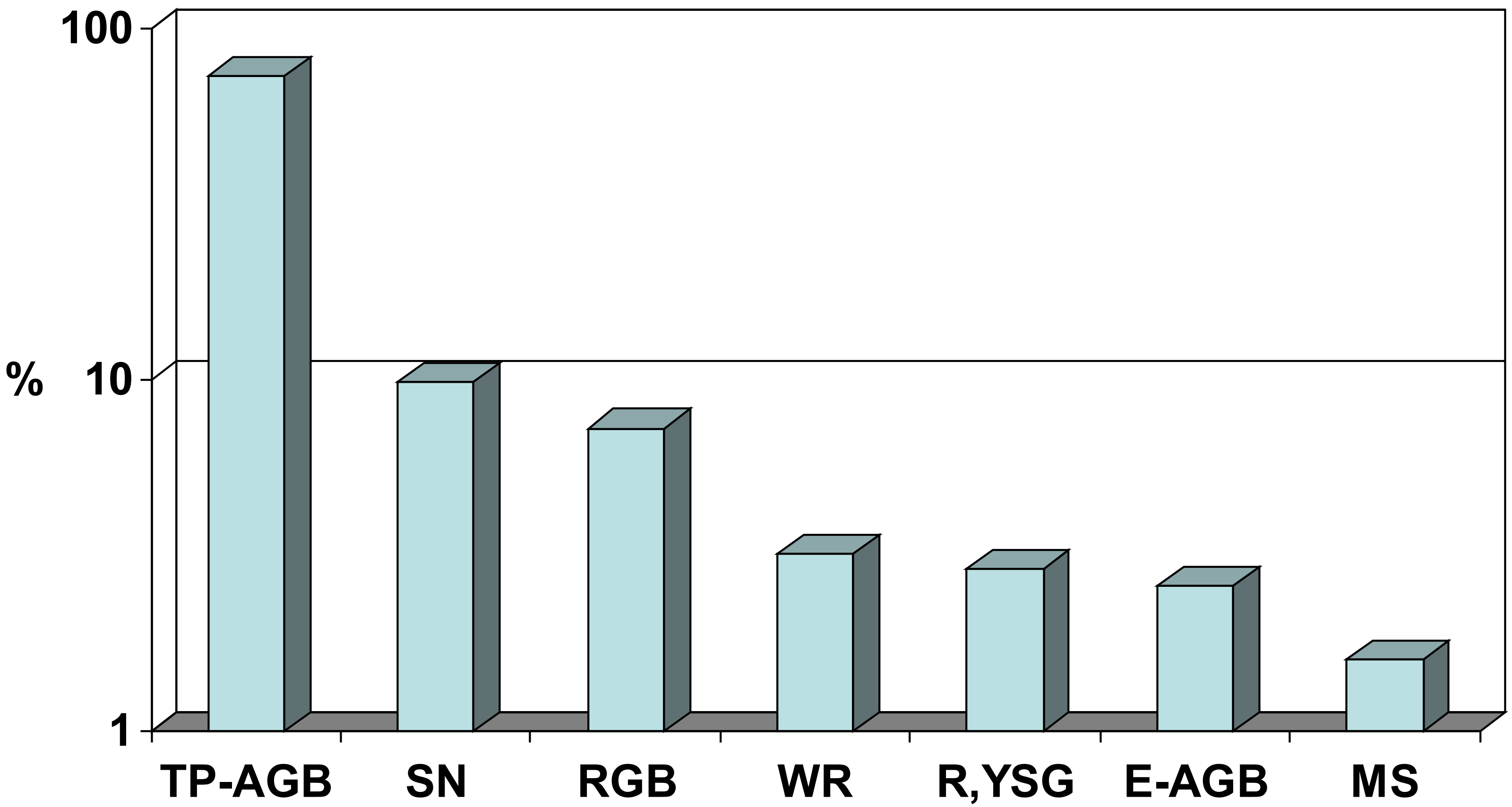
AGB stars

Lifetime ~1 Gyr

Perhaps, Type II SNe are main dust producers,

although > 0.1 Msun per a SNe (Dwek 2007, etc)

Contributions to the ISM
The Local Universe - picture



Sedlmayr 1994

Relative contribution of SNe and CS in dust in the early universe

- The relative contributions of SNe and AGB stars to dust in the early universe is a problem of great interest.
- Core-collapse SNe appear well before the first carbon stars, whereas type Ia SNe require white dwarfs, which appear only after AGB stars have evolved.
- Core-collapse SNe can produce both silicates and carbonaceous dust; it is difficult to determine which would dominate
- Current measurements of the dust around observed SNe fall short of what is needed to account for the dust observed at high redshifts but we lack direct observations of SNe at low metallicity.
- A recent study of dust extinction at a redshift of 6.2 found evidence for carbonaceous dust.
- The presence of such dust could be explained, at least in part, by the mass loss from carbon stars in the early universe.

Light from a stellar explosion echoing off dust surrounding the red variable V838 Monocerotis