Stellar End Products:
Grand Overview

- The impact of stellar evolution

- Mass loss and Initial-final mass relations
- Angular momentum and binary evolution
- Environment
- Presolar grains

Death by mass loss

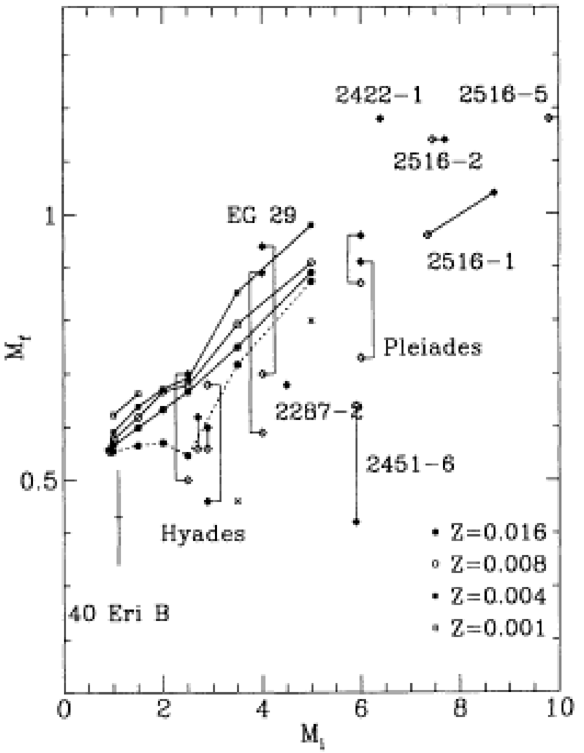
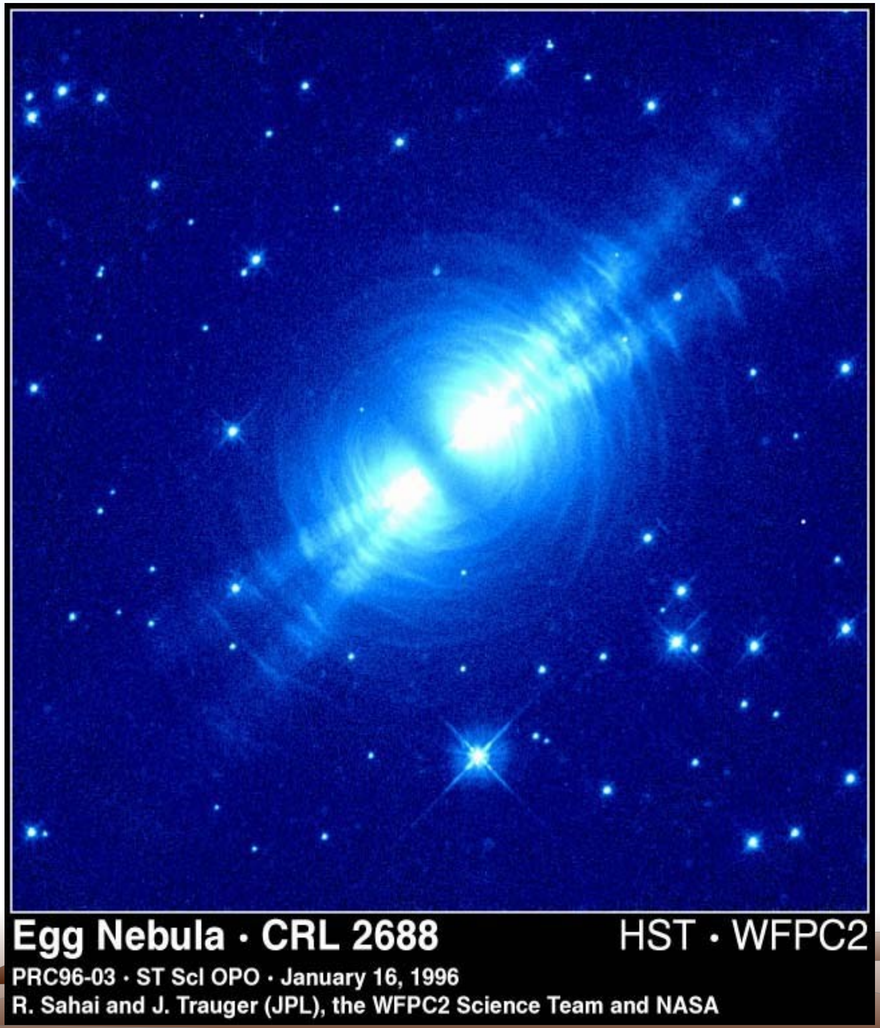
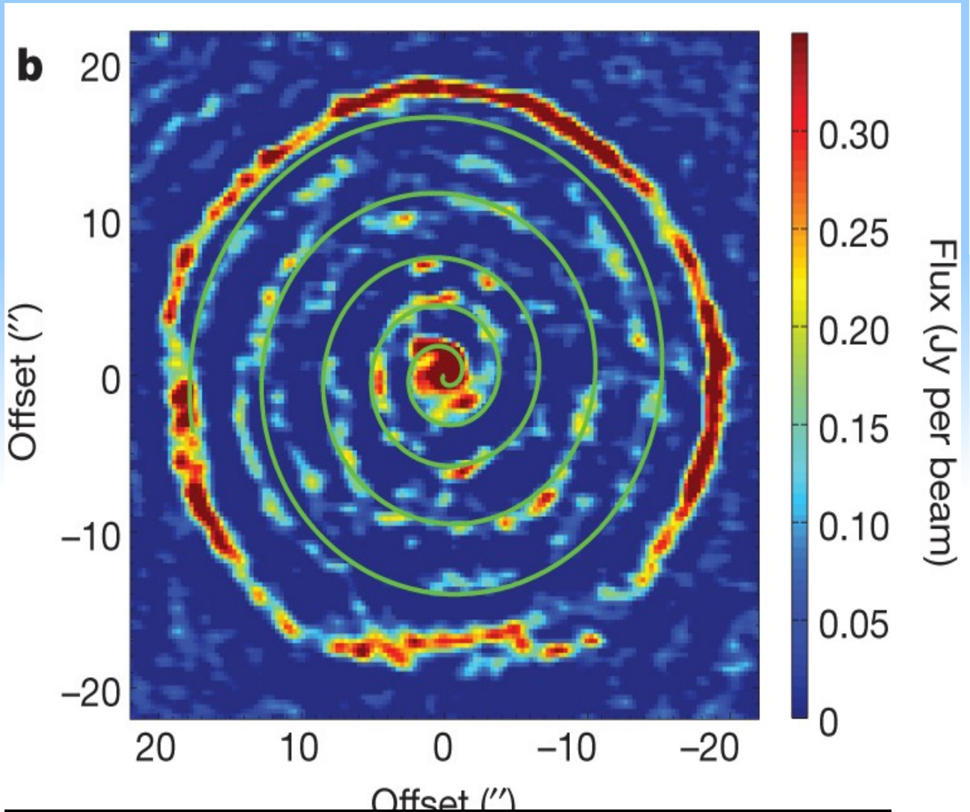


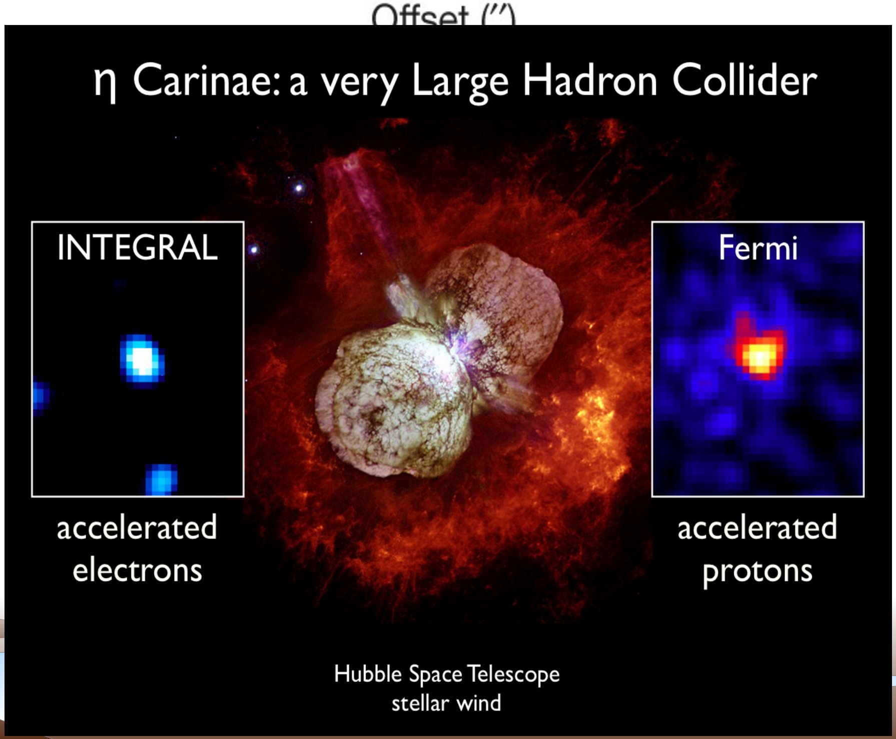
FIG. 21.—Final stellar remnant mass, after AGB mass loss, plotted as a function of the initial mass (*solid curves*). The dashed line represents the core mass at the first helium shell flash for the $Z = 0.016$ calculations. Observational points are taken from Weidemann (1987), and references therein. Annotation of the data points is similar to that presented in Fig. 1 of Weidemann & Koester (1983). Filled diamonds represent masses derived from log g, while open diamonds represent masses derived from the stellar radius. Mass determinations via log g and radius for the same object are joined by a line. The crosses represent the Sanduleak-Pesch binary (Greenstein, Dolez, & Vauclair 1983) where $M_f = 0.8$ was assumed for the primary.

- Between birth and death, stars lose 40%-80% of their mass
- Mostly through catastrophy winds
- Occurs during the red (super) giant phase of evolution

Reflecting on the past







Importance of the stellar end phase

Stellar remnants

- White dwarfs, SNe, degenerate binary systems

Galaxy evolution

- Baryonic and chemical evolution
- Dust

Planetary evolution

Astrophysics

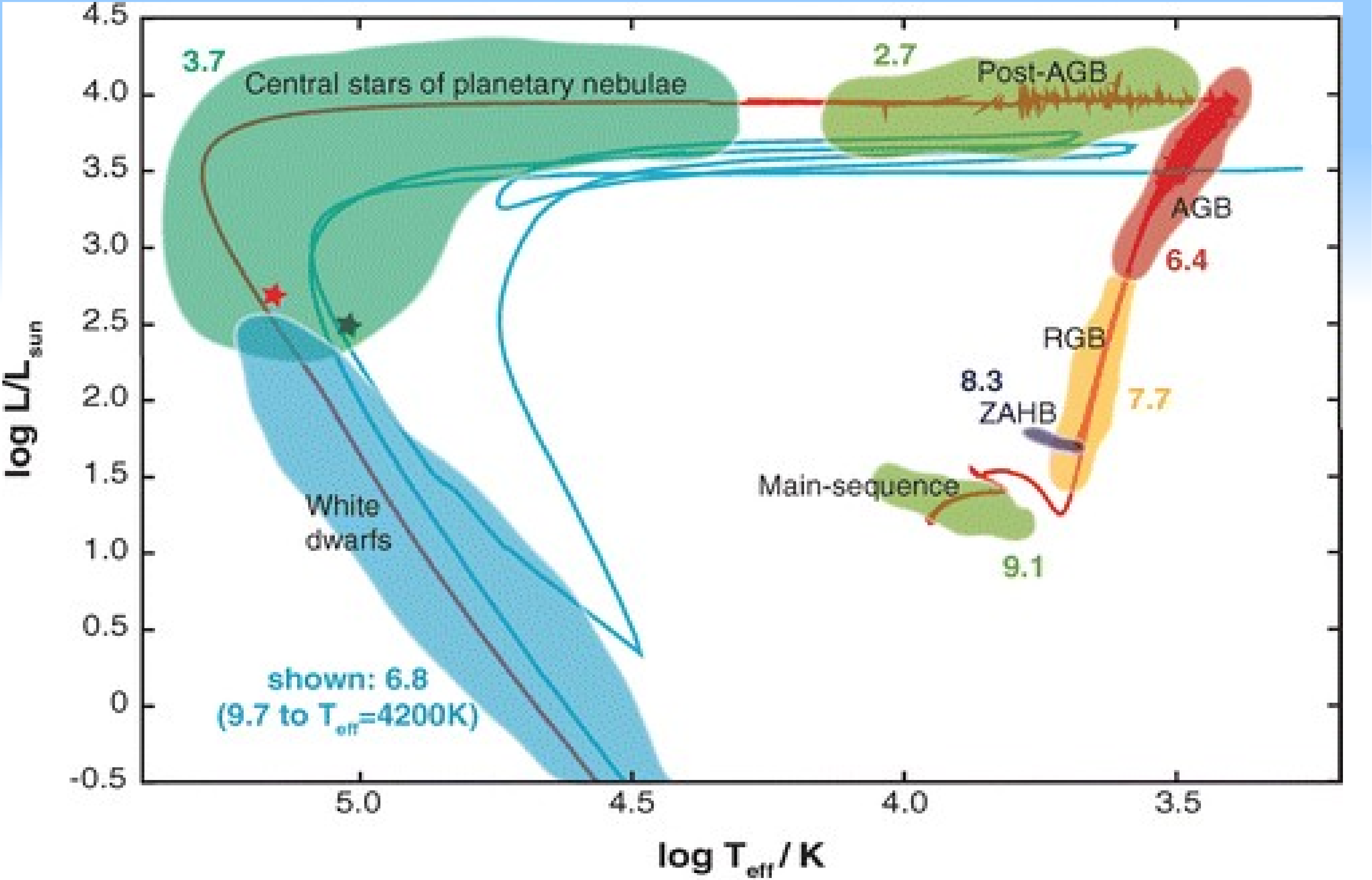
- Convection; Mass loss
- Hydrodynamics and Jet formation

Astronomical Tracers

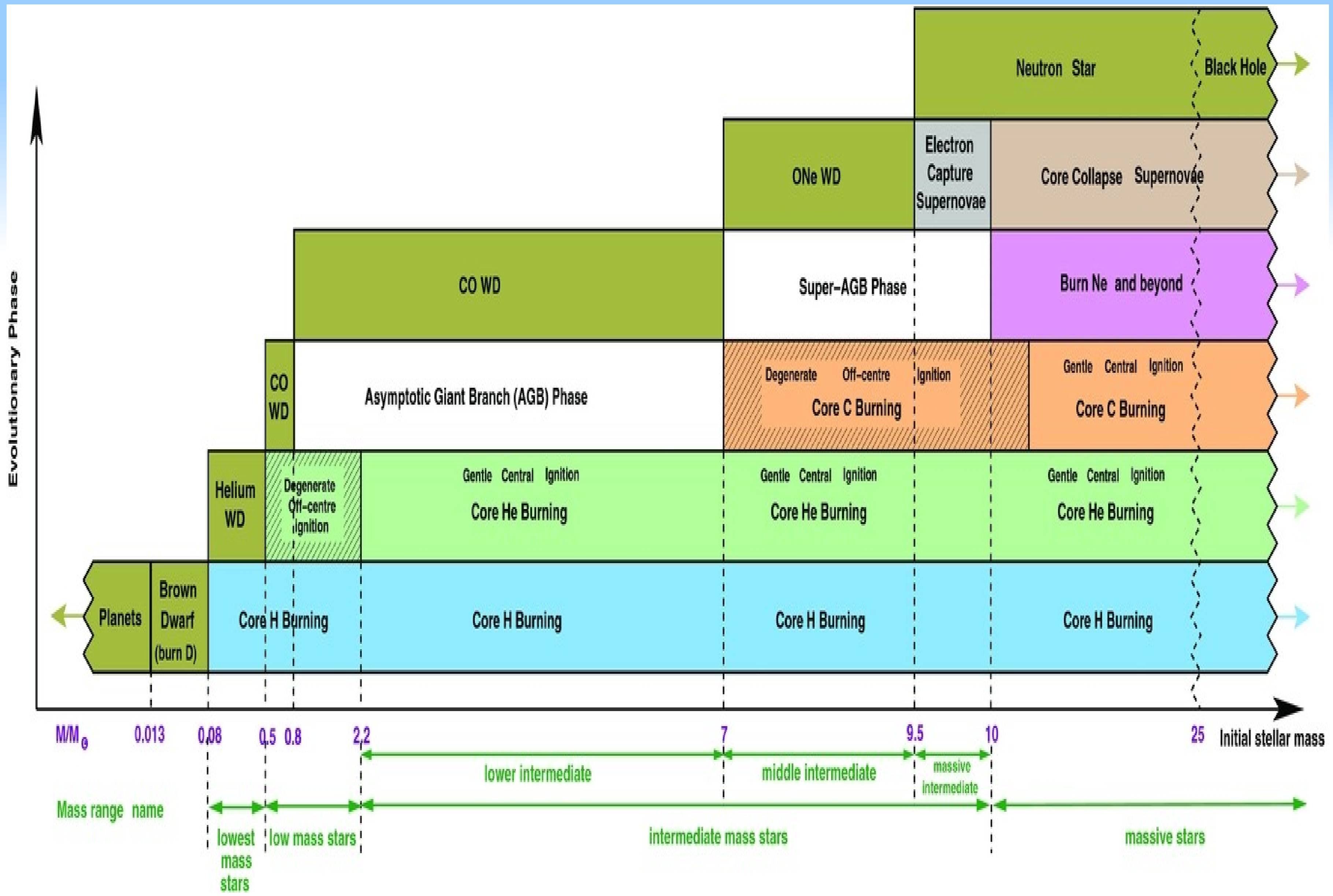
- Abundances; Distances; Kinematics

Cosmology

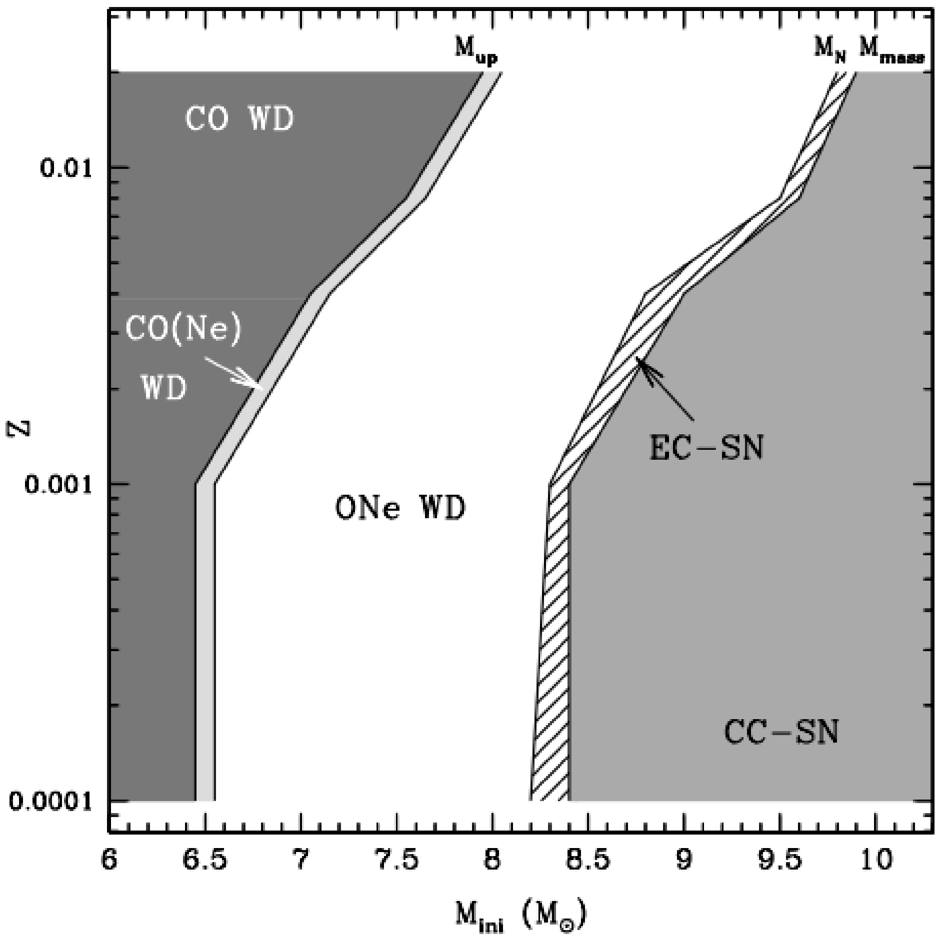
- Galaxy ages



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


Evolutionary Phase
Neutron Star
Black Hole
ONe WD
Electron Capture Supernovae
Core Collapse Supernovae
CO WD
Super-AGB Phase
Burn Ne and beyond
CO WD
Asymptotic Giant Branch (AGB) Phase
Degenerate Off-centre Ignition
Core C Burning
Gentle Central Ignition
Core C Burning
Helium WD
Degenerate Off-centre Ignition
Gentle Central Ignition
Core He Burning
Gentle Central Ignition
Core He Burning
Gentle Central Ignition
Core He Burning
Planets
Brown Dwarf (burn D)
Core H Burning
Core H Burning
Core H Burning
Core H Burning
M/M☉
0.013
0.08
0.5
0.8
2.2
7
9.5
10
25
Initial stellar mass
lower intermediate
middle intermediate
massive intermediate
Mass range name
lowest mass stars
low mass stars
intermediate mass stars
massive stars

The AGB/SN division



From Doherty et al. (2015)

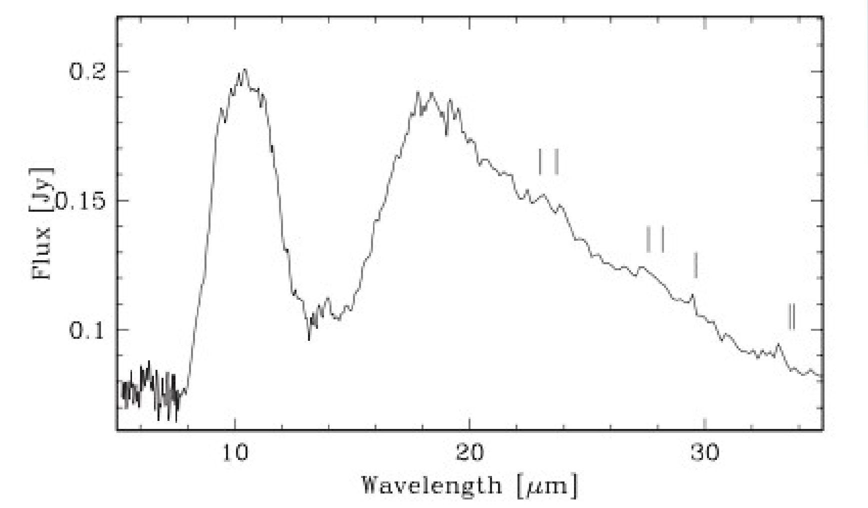
Mass loss through stellar winds

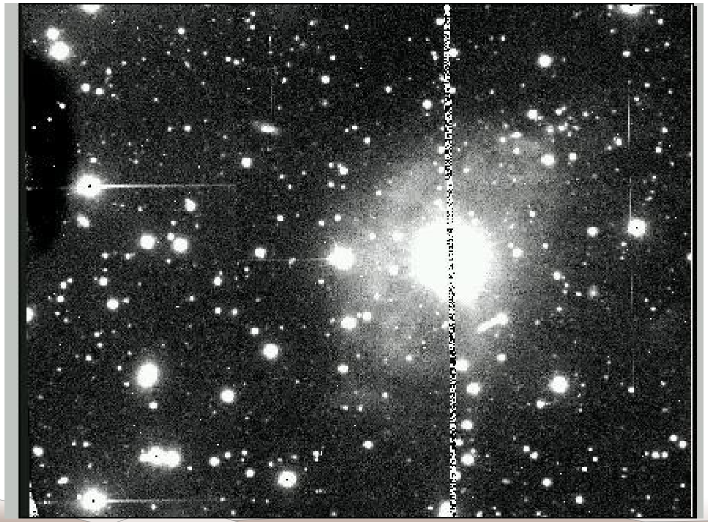
Dominant source of mass return to the ISM

Main questions

- Wind parameters (Mdot, Vexp, composition)
- Timing and evolution of the wind
  - Sets initial – final mass relations, yields
- Driving mechanisms
- Shaping and structure
  - Angular momentum, magnetic fields, gravity

Mass loss evidence





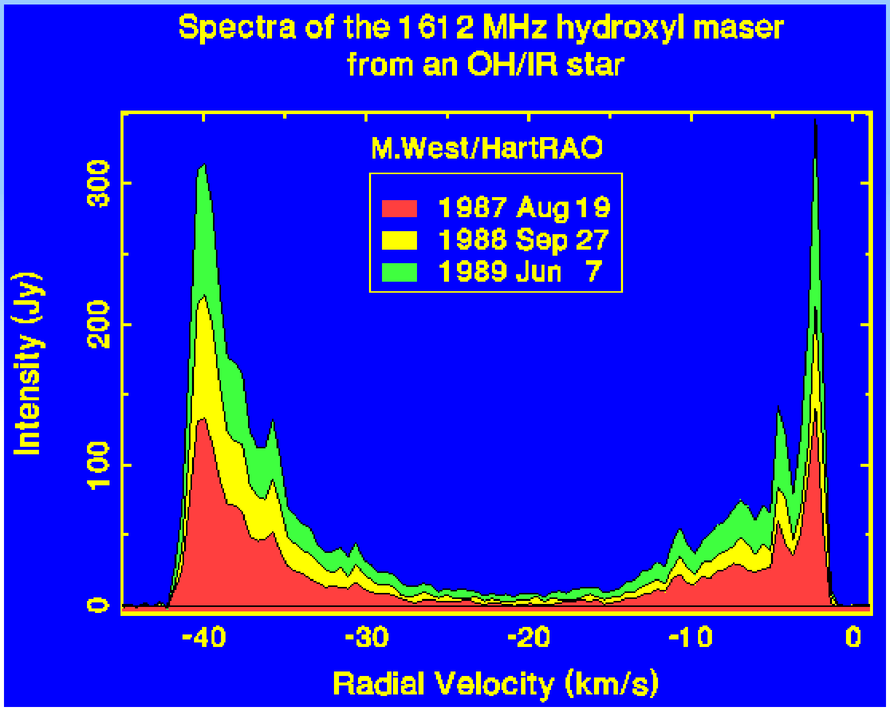
- Dust excess in stars

  IRAS, ..
- Molecular emission
  - OH masers
  - CO
- Reflection nebulae
  - RZ Sgr
- Absorption lines

Classical OH/IR stars

- Discovered 1968
- Optically obscured
- Long periods (2000 days)
- Baud (1981) ~ 20 stars with F>10Jy in northern plane

- High mass AGB stars



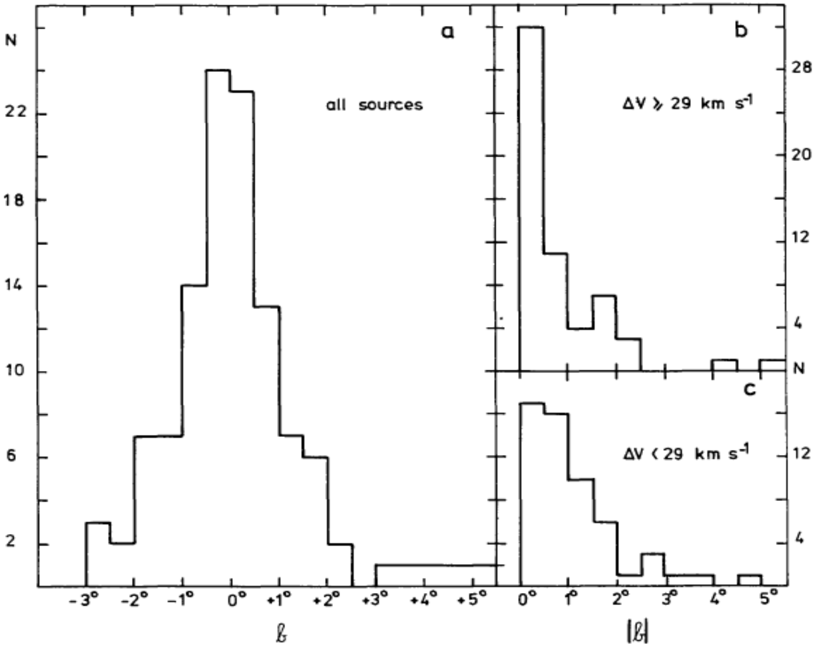
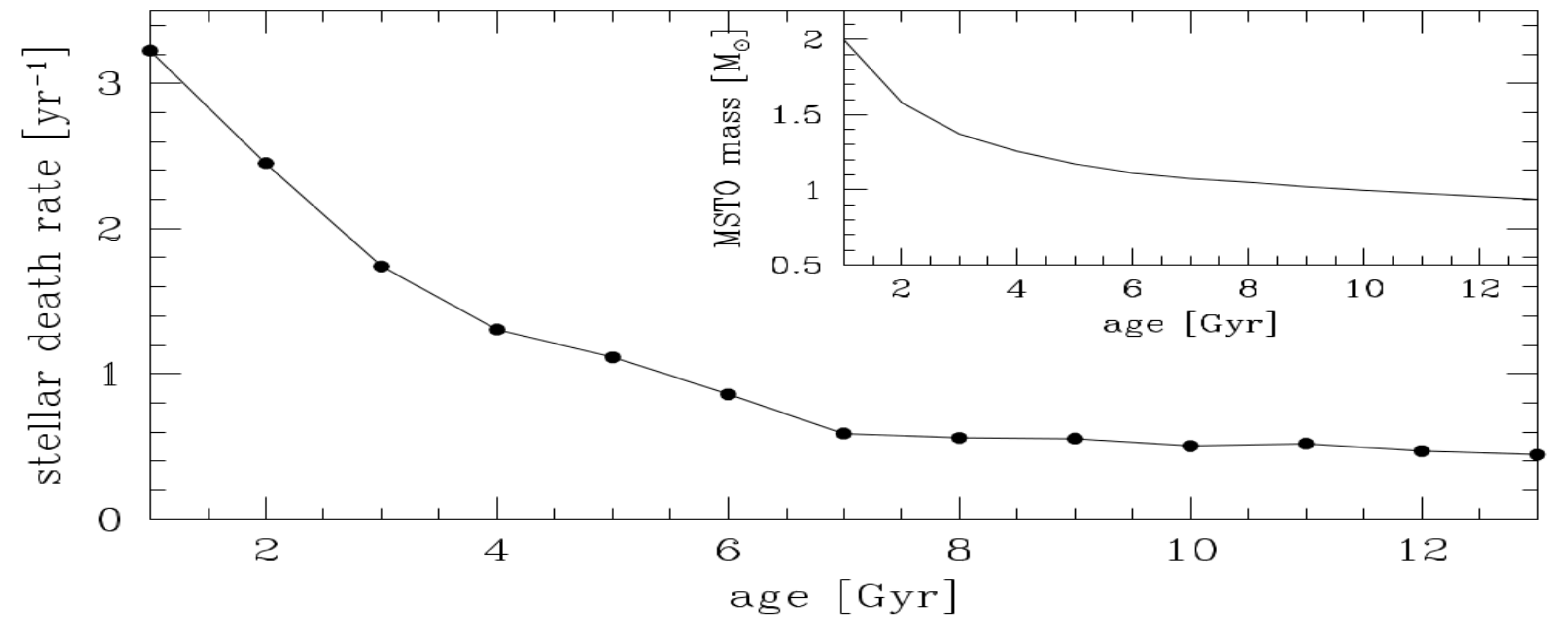


Fig. 5. **a** Latitude distribution of all OH/IR sources. **b** and **c** the distributions of sources with large and small ΔV as a function of absolute latitude, respectively

Stellar death rate



- Younger populations have higher death rates
- And longer lasting mass loss
- Samples can be biassed towards higher masses

Mass loss formalisms

Reimer's law (1975)

$$\dot{M}_{\mathrm{R}} = \eta_{\mathrm{R}}\, 4 \times 10^{-13} \frac{L}{gR} = \eta_{\mathrm{R}}\, 4 \times 10^{-13} \frac{LR}{M}$$

Schröder & Cuntz (2005)

$$\dot{M}_{\mathrm{SC}} = 0.2 \dot{M}_{\mathrm{R}} \left(\frac{T}{[4000\ \mathrm{K}]} \right)^{3.5} \frac{R_{ch}}{R}$$

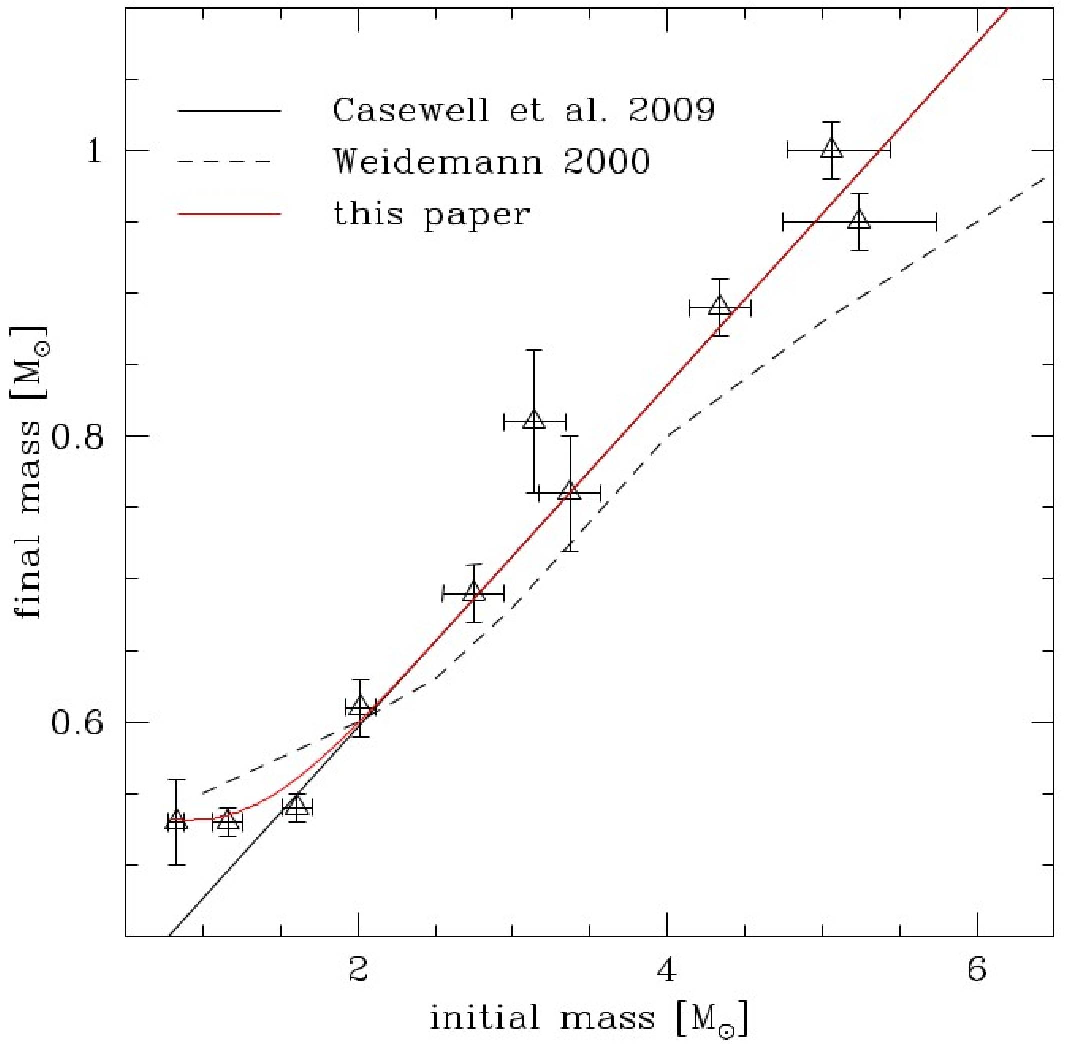
Blöcker (1995)

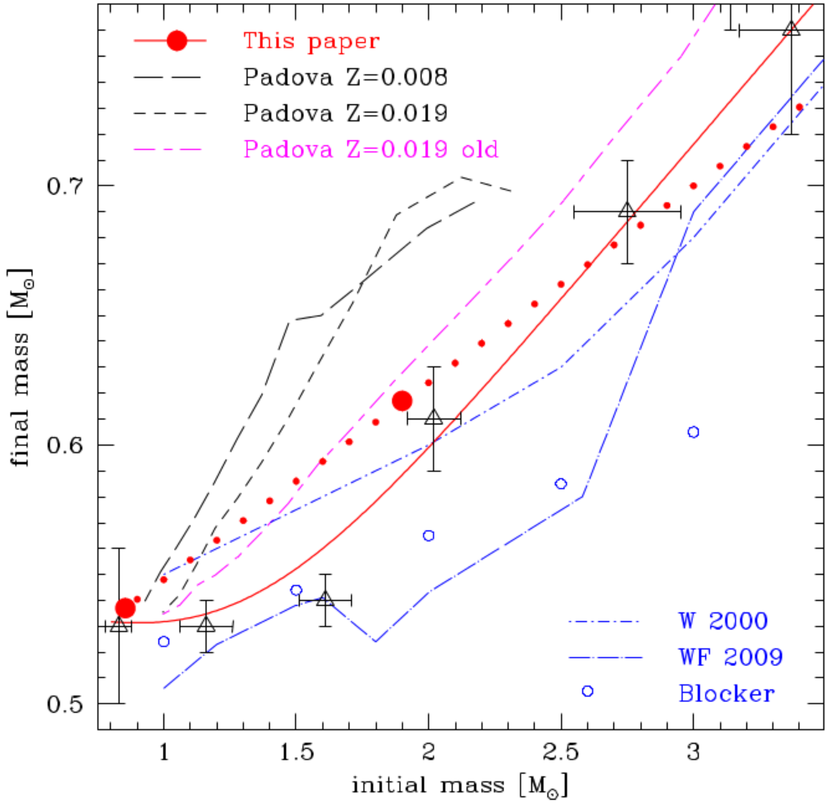
$$\dot{M}_{\mathrm{B}} = 4.83 \times 10^{-9} \dot{M}_{\mathrm{R}} \frac{L^{2.7}}{M^{-2.1}}$$

Vassiliadis & Wood (1993)

$$\log M_{\mathrm{VW}} = -11.4 + 0.0123 \frac{P}{[\mathrm{days}]}$$

Initial final mass relations



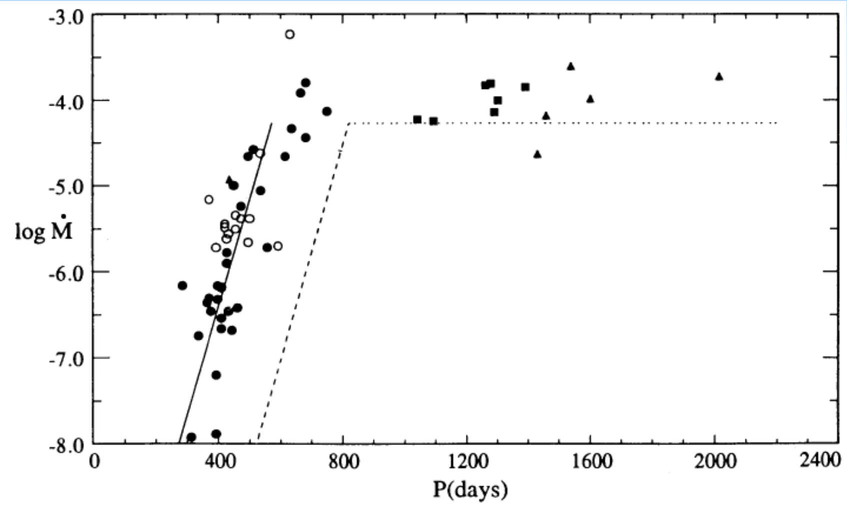


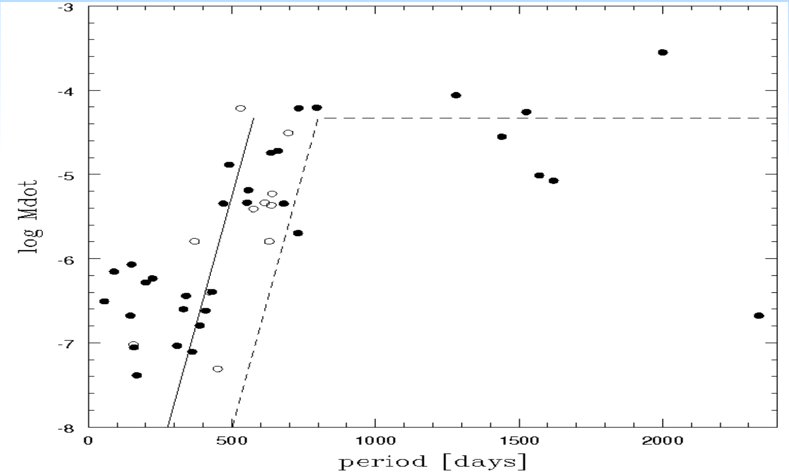
Casewell et al. 2009
Gesicki et al. 2014
Kalirai et al. 2015

mass los relations

- IFMR depends entirely on chosen mass loss formula
- All relations predict Z dependence
  - But eta is constant
- All predict higher Mdot for C stars
- Relations are poorly calibrated
- Scaling factors needed
- Bloecker has far too high mass loss
- VW93 is simplest, and works, but too good to be true?
  - Requires P~500 days

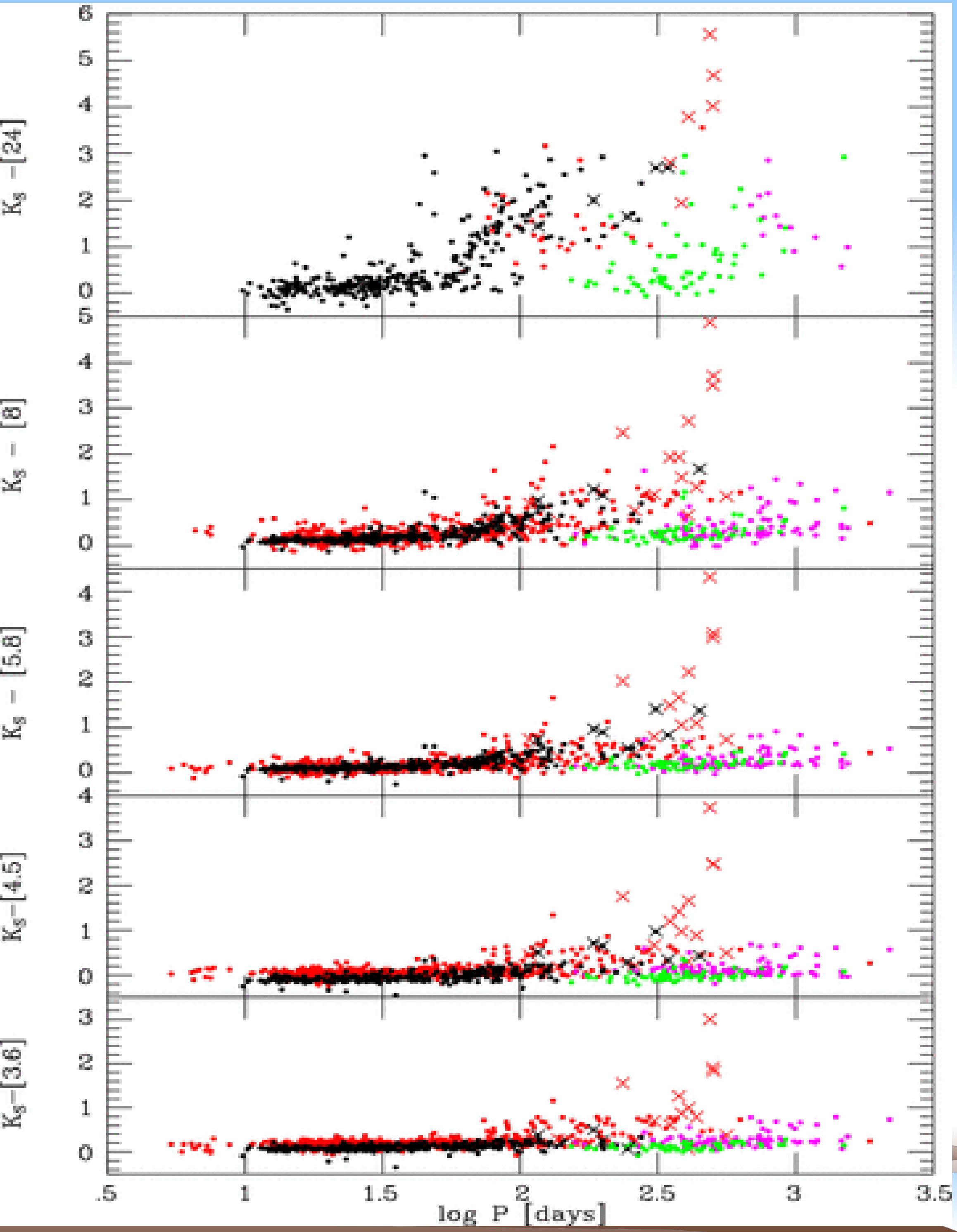
VW93 Pulsation formalism





- Mdot-period relation from VW93

- New mass loss rates from de Beck et al. 2010
- Yield shallower relation?



- Glass et al. 2009

  red/magenta: LMC

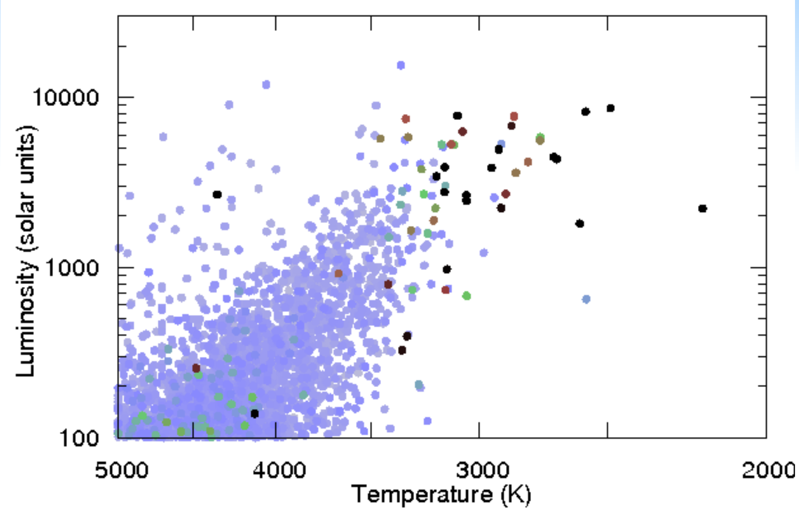
  black/green: Bulge

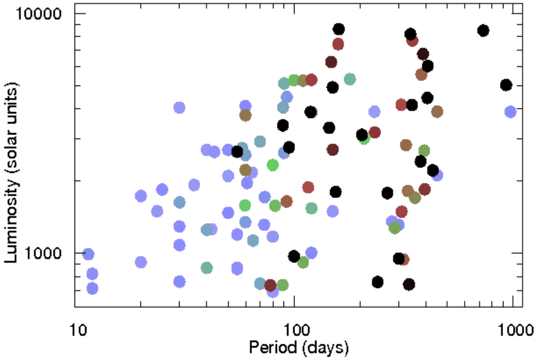
  Red/black: Miras

  Magenta/green: long secondary periods

- Dusty mass loss starts at P=65 days

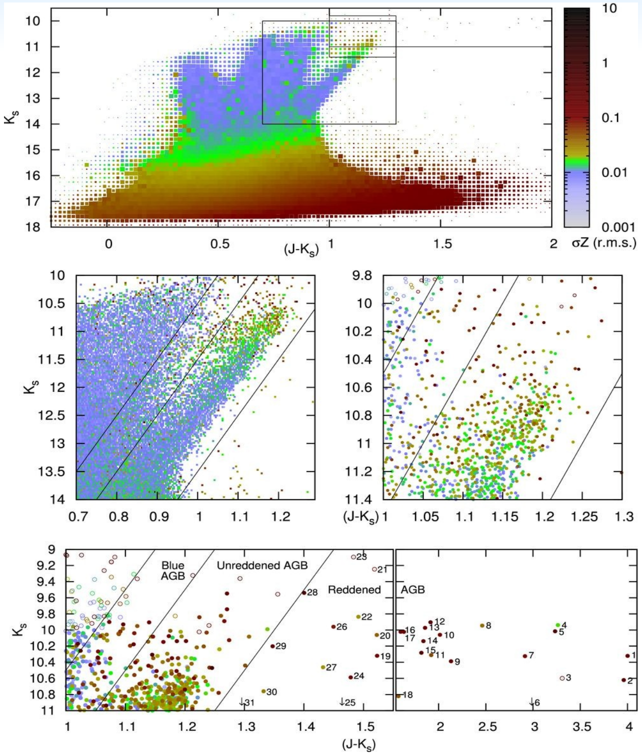
Nearby red giants



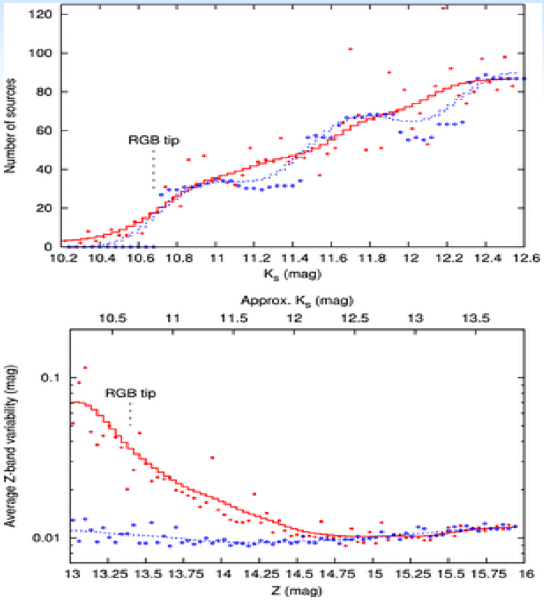


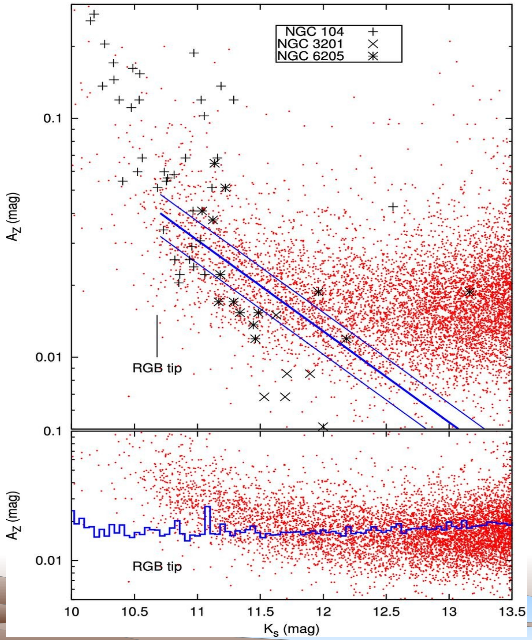
- Stars within 300 pc
  - McDonald et al. 2012
- Infrared excess seen when L>1000 Lsun
- Or P>70 days

RGB/AGB pulsation amplitudes



$$A_\lambda \propto \frac{L}{\lambda T_{\rm eff}^2 M},$$





McDonald et al. 2014

Driving the wind

- Chromospheric wind
    - Warmer stars
    - Lower luminosity
- Pulsation driven wind
    - Mira variables
- Radiation pressure on dust
    - TP-AGB
    - Tip RGB?

Dust issues

- Silicate dust lacks necessary opacity (Woitke)
- Dust may affect expansion velocity more than mass loss rate

Scattering wind

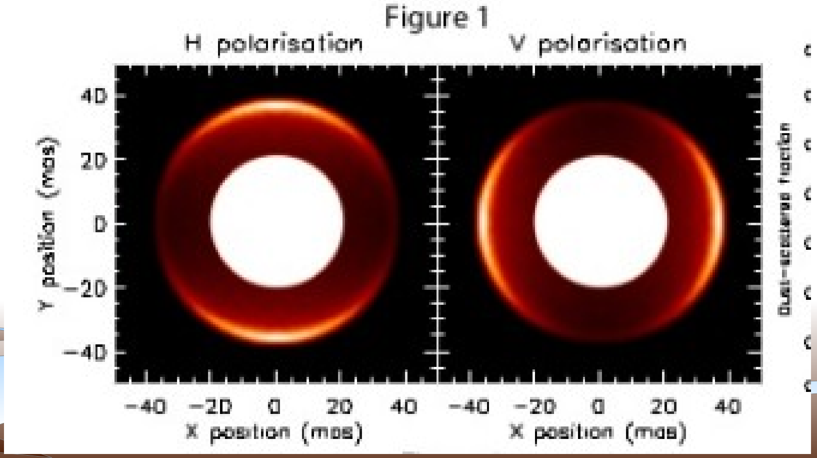
Silicate absorption

- Iron rich grains: too hot to exist close to the star
- Iron poor grains: don't absorb

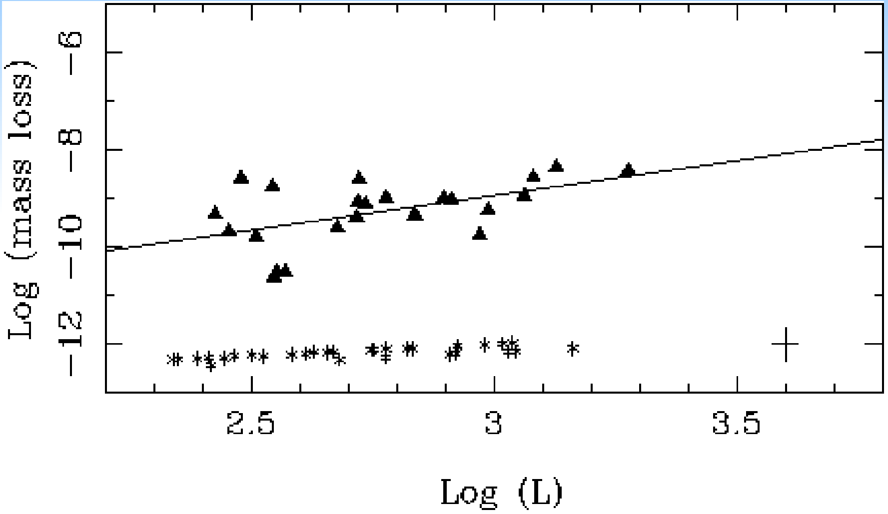
Neither can drive a wind

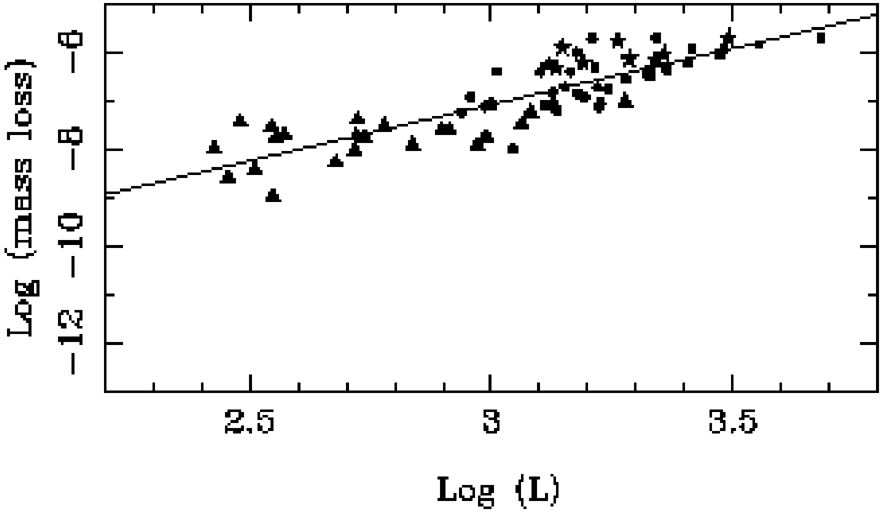
Scattering

- Hoefner wind
- Requires large grains (~micron)
- Confirmed by SAMPOL/VLT



RGB mass loss





Groenewegen 2012, McDonald et al 2012

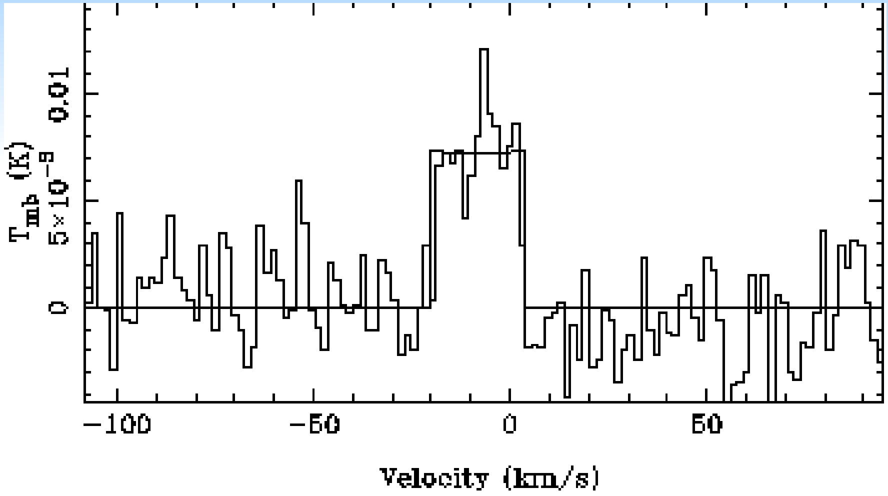
- Dominates over AGB for M<1Msun
- Strongest near tip of RGB
- Intermittent dusty mass loss? Unlikely.
- Vexp is crucial. DUSTY gives far too small values. Why? (Groenewegen 2014)

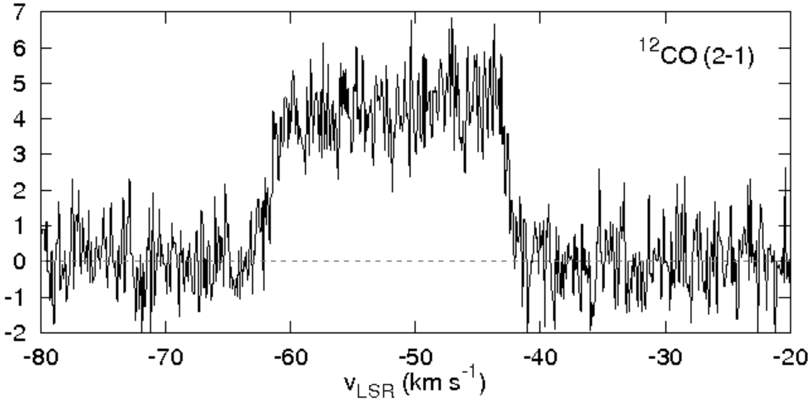
Expansion velocity

- Top: RGB star (Groenewegen 2014)
- Bottom: Low-Z star (McDonald, in prep)

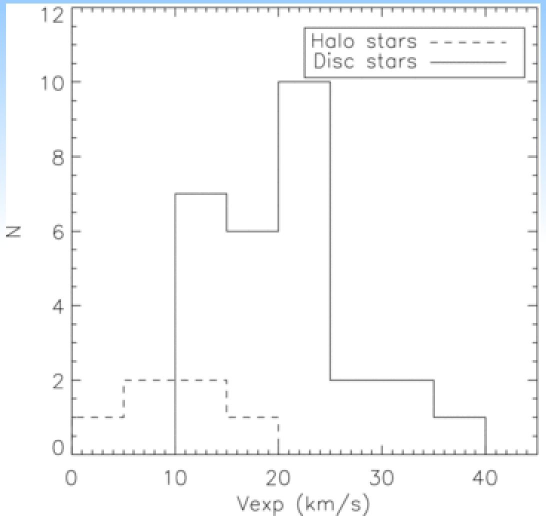
CO preferred

OH works best at high Mdot





Expansion velocity at low Z



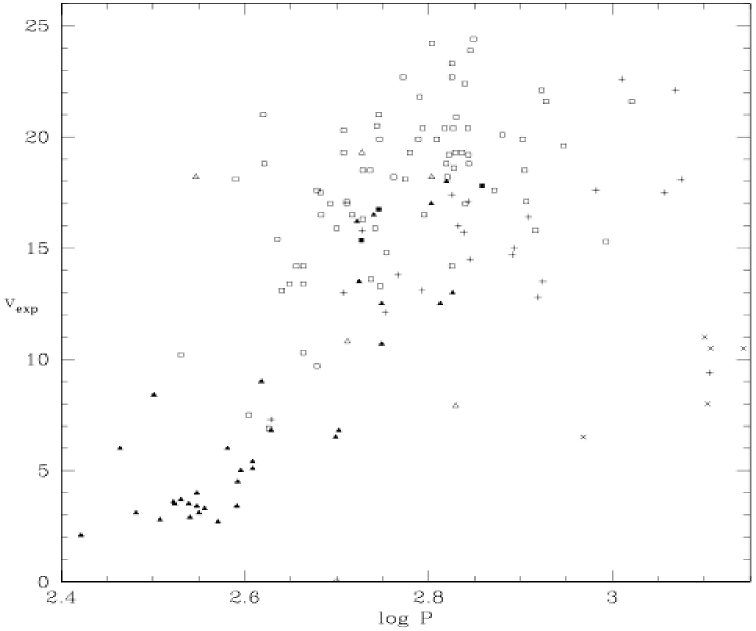


Fig. 13. The stellar wind expansion velocity plotted against period. The expansion velocities for the Galactic Center OH/IR stars are given by LWHM (open squares) and by Sjouwerman 1997 (open triangles). Also shown are local Miras (filled triangles), OH/IR stars near the Galactic plane (plus signs), OH/IR stars in the Galactic bulge (filled

- Carbon stars: evidence for lower Vexp
- Groenewegen et al. 1997
- Lagadec et al. 2010

- Oxygen stars: No significant relation?
- Marshall et al. 2004
- Wood et al. 1998

Wind structure: clumping

- Water masers found in Miras, SR, RSG
- Masers spots measure size of clumps
- Clump size ~ stellar radius

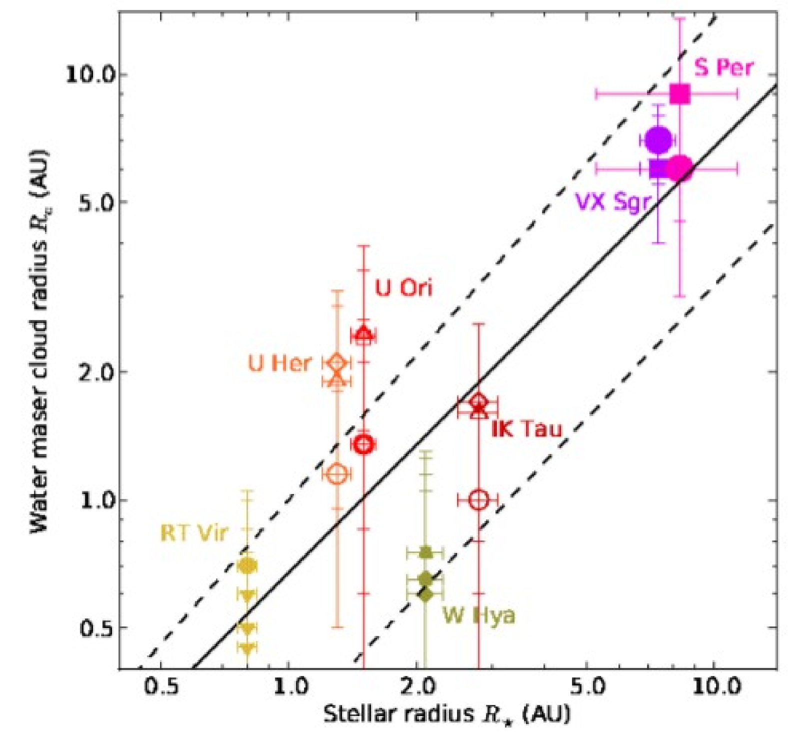
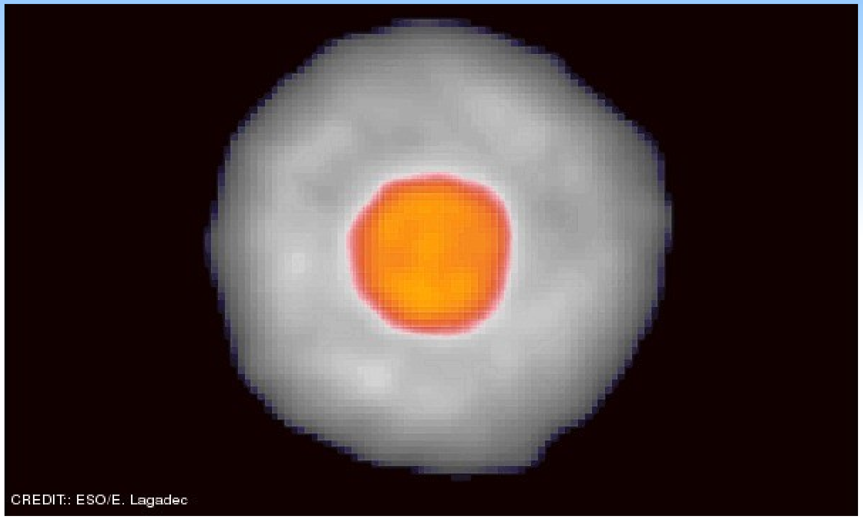


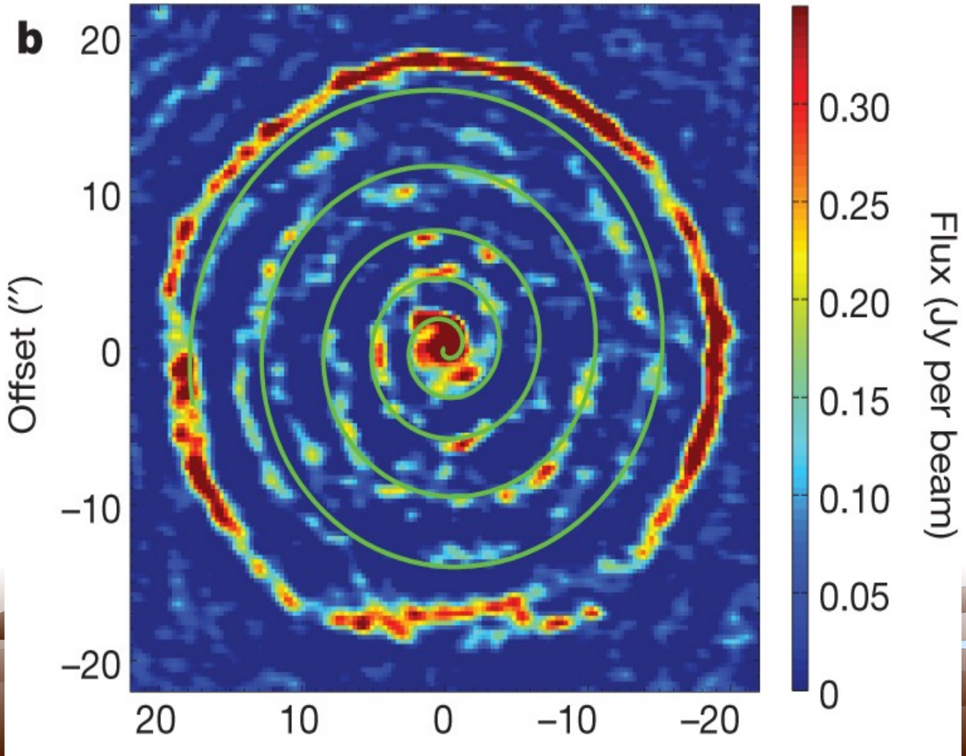
Fig. 62. Water maser cloud radius R_c as a function of $R_\star$. The different epochs are shown by different symbol shapes as in Fig. 44. RSG, Miras and SRb are shown by large, hollow and small symbols, respectively. The solid and dashed lines show the slope of an error-weighted fit to the relationship between R_c and $R_\star$, and the dispersion in the relationship.

Richards et al. 2012

Episodic winds



CREDIT:: ESO/E. Lagadec



- Supergiants tend to show multiple shells
  - HR excursions
- AGB stars show rings
  - Thermal pulse related
- Where is the border line?

Wind shaping

Shaping mechanisms

- Angular momentum or magnetic fields

  Closely related!

- Stronger shaping for low mass objects
- Suggest determinant: angular momentum per ejecta mass

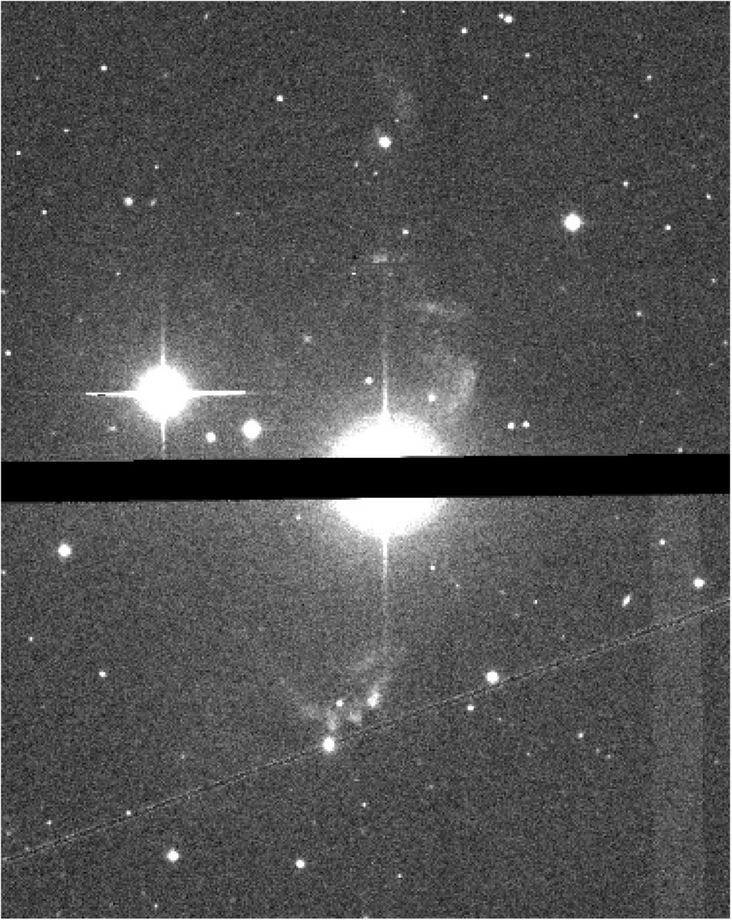
Specific

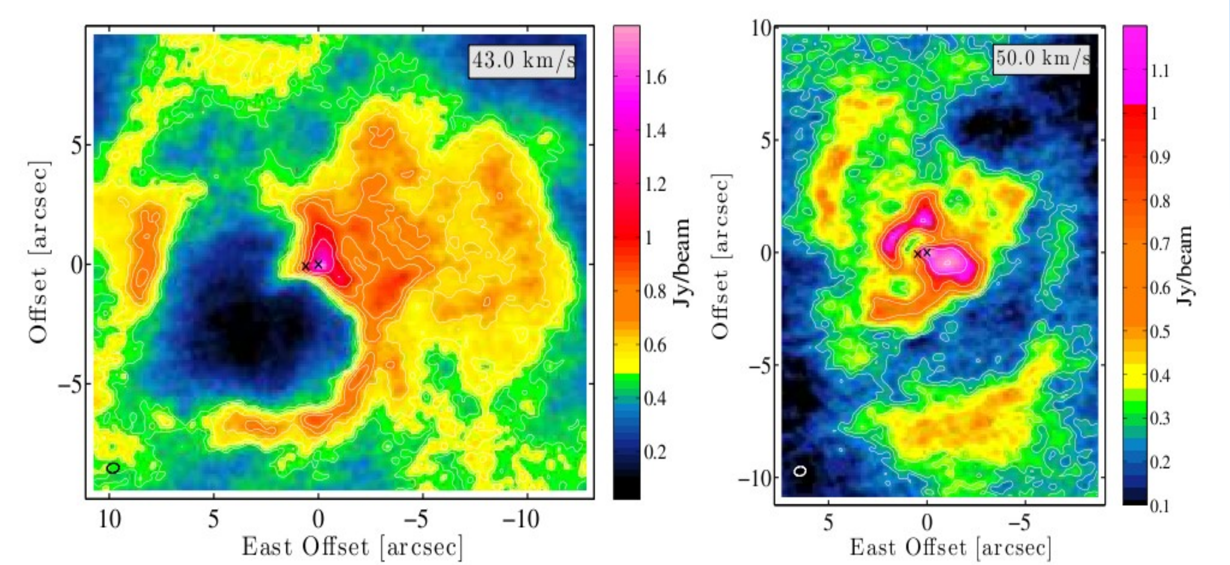
- Interacting winds
  - Ejected at different times
  - Or by different stars
- Jet shaping
  - Accretion disk around companion

    Huarte-Espinoza et al. 2012

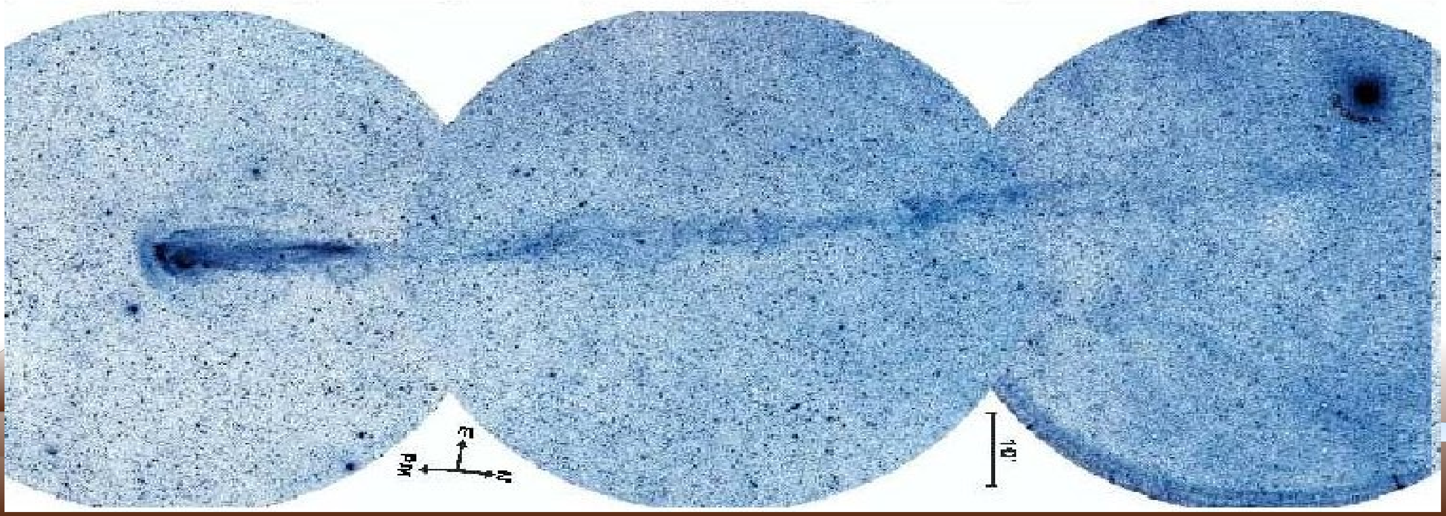
Shapes of Mira

Halpha:
INT



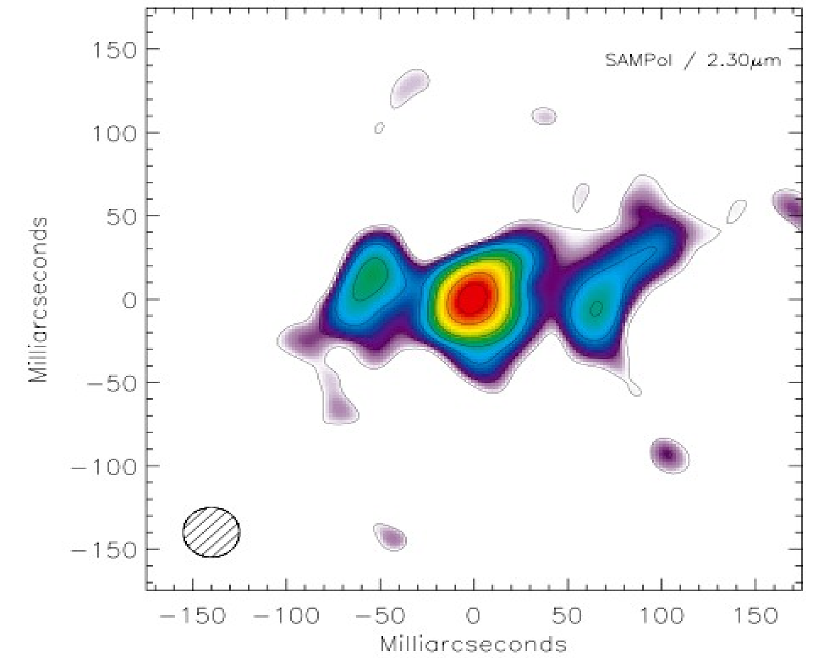


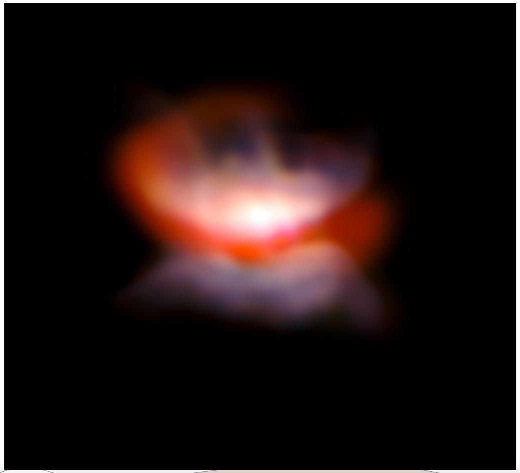
CO: ALMA



UV: Galex

Origin of asymmetries





Old view:

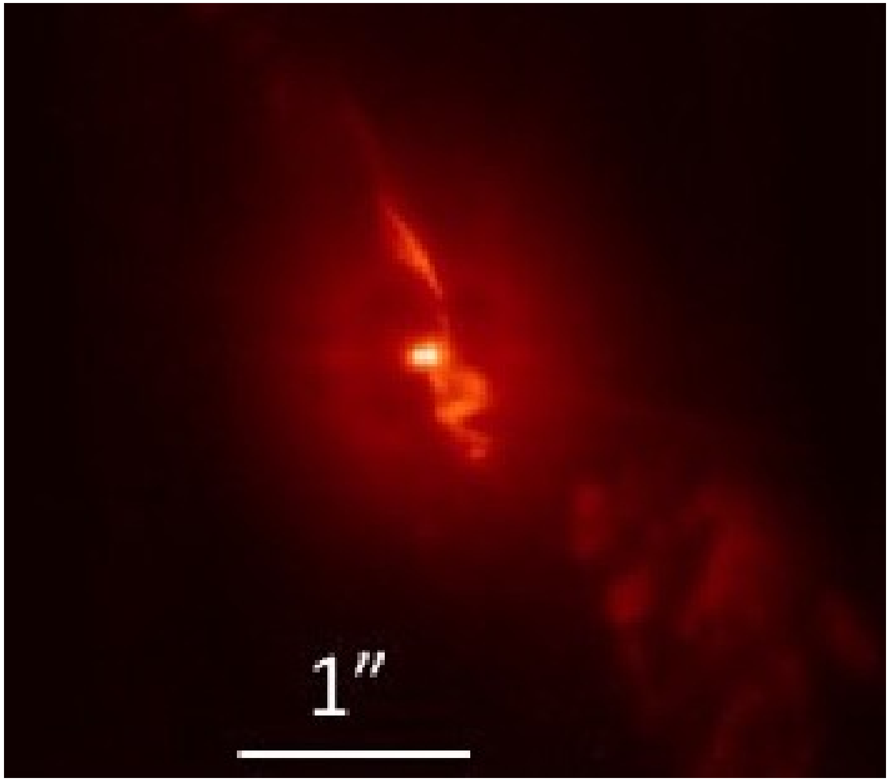
- AGB winds spherical
- Asymmetry forms during post-AGB

New view

- It is all AGB bias

Binary interactions

R Aqr - Sphere



Angular momentum

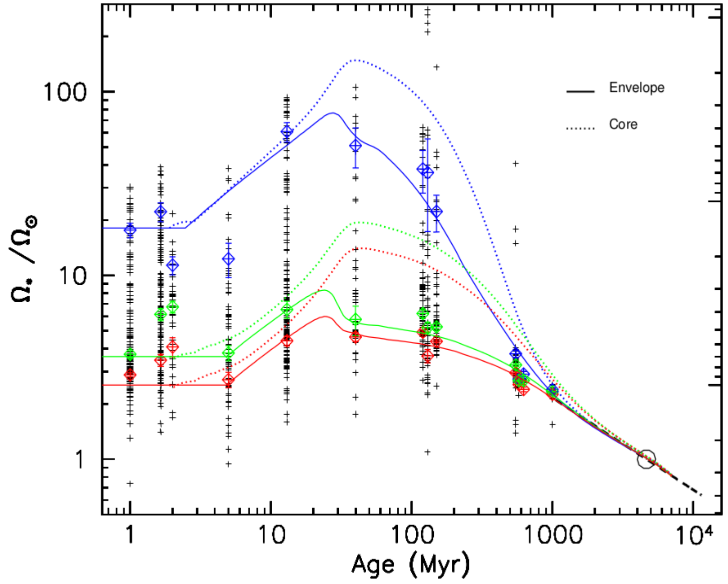


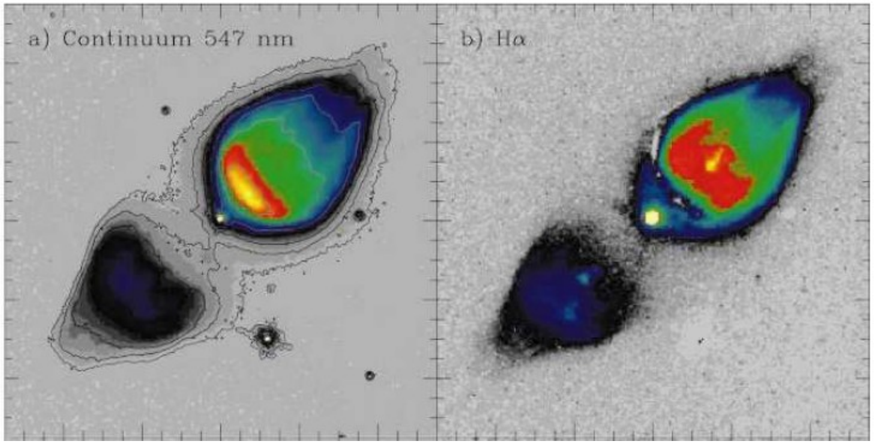
Fig. 3. Angular velocity of the radiative core (dashed lines) and of the convective envelope (solid lines) is shown as a function of time for fast (blue), median (green), and slow (red) rotator models. The angular velocity is scaled to the angular velocity of the present Sun. The blue, red, and green tilted squares and associated error bars represent the 90th percentile, the 25th percentile, and the median, respectively, of the rotational distributions of solar-type stars in star forming regions and young open clusters obtained with the rejection sampling method (see text). The open circle is the angular velocity of the present Sun and the dashed black line illustrates the Skumanich relationship, $\Omega \propto t^{-1/2}$.

Gallier & Bouvier 2013

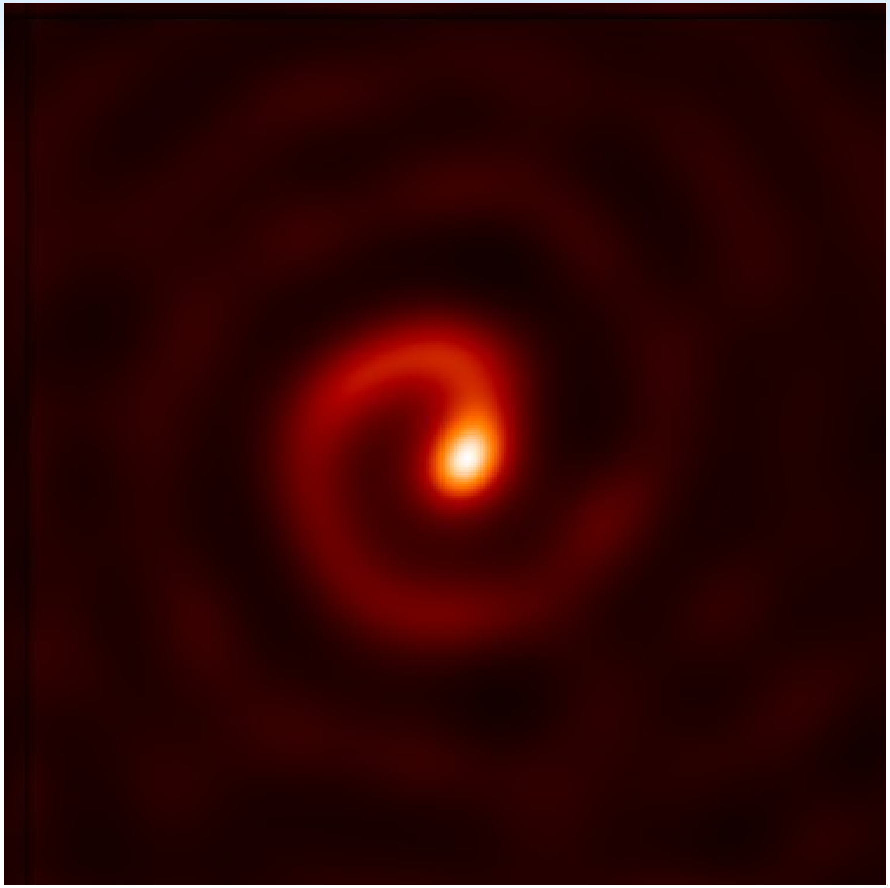
- Stellar rotation decays as $P \sim t^{0.5}$ after t~10^8 yr
- Low-mass AGB stars: slow rotators
- High-mass stars retain more angular momentum

Angular momentum

- Higher mass stars
  - Stellar rotation
  - Binary orbit
- Low mass stars
  - Orbital motion only
  - 'Cold storage'



High mass binaries



- WR104
- 8-month binary period
- Dust formation occurs in wind collision region
- Start of spiral

Low mass binaries

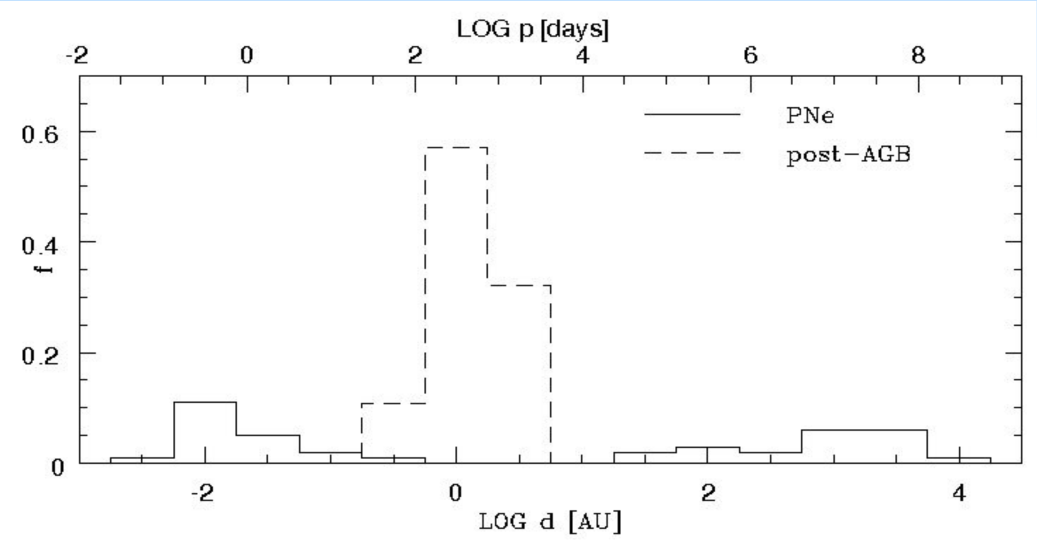
- Distant companions: evolve as two single stars
- Closer companions:
  - Enhanced mass loss; Mass transfer

    Symbiotic stars
- Closest: common envelope, interacting binaries

    Novae, CVs, ..
- Challenge 1: find the AGB binaries

Challenge 2: Connect the dots

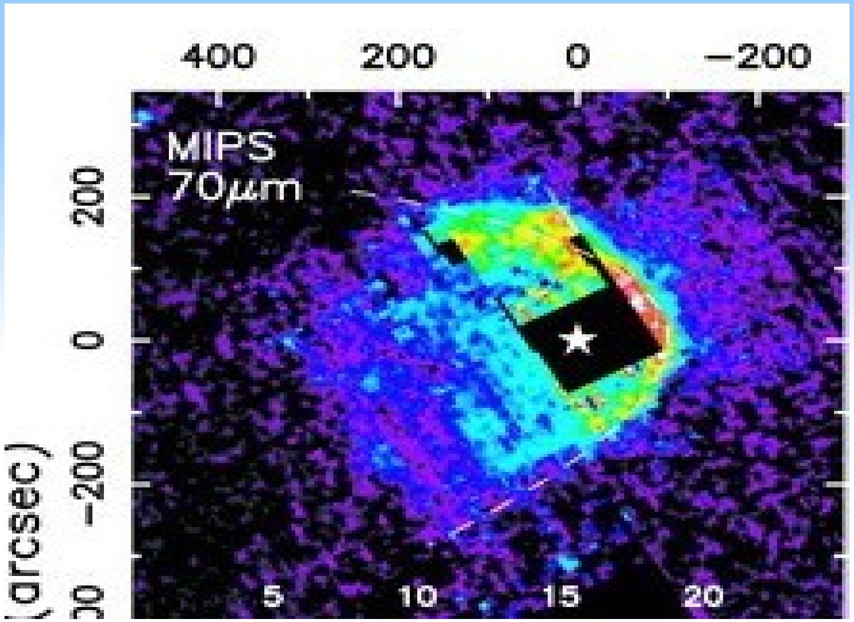
- Many binary systems known in different phases of evolution
- But evolutionary sequences are far from clear



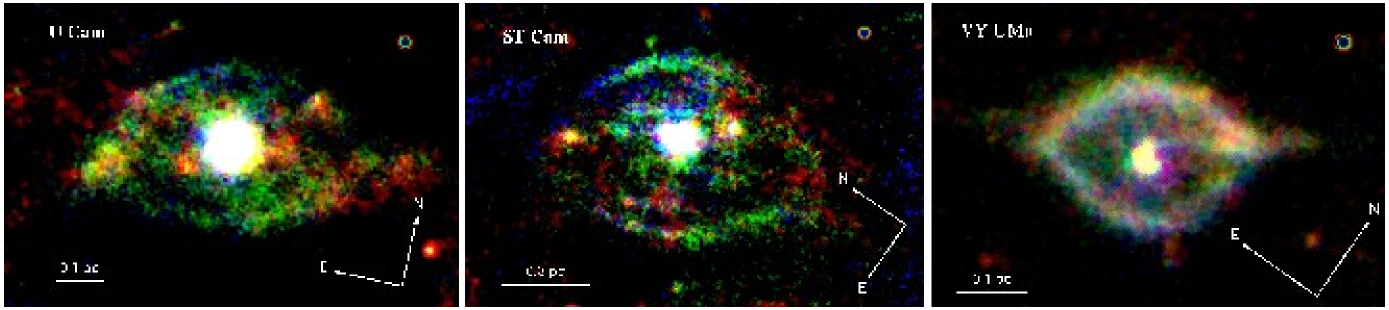
Environment

Wind interacts with environment

- ISM sweep up
- IS magnetic fields
- IS radiation fields

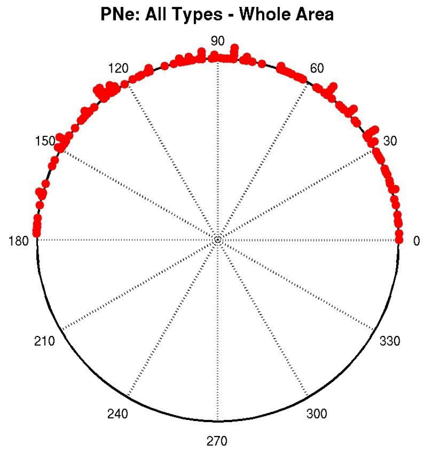


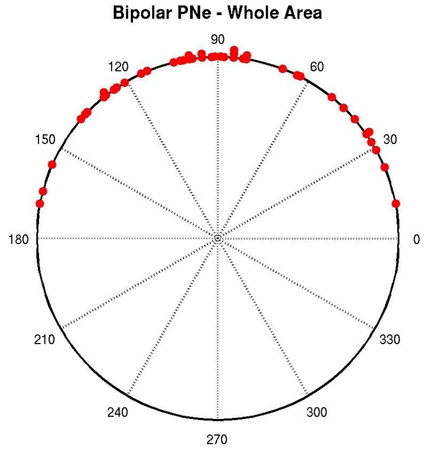
R Hya
Ueta et al 2006



Van Marle et al. 2014

Example: PN alignment


PNe: All Types - Whole Area


Bipolar PNe - Whole Area

- Bulge PNe show alignment of major axes
- Explained by interstellar magnetic fields stronger then 100 microG

Rees & Zijlstra 2013

Falceta-Gonçalves & Monteiro 2014

Interstellar radiation fields

- Globular clusters
- Hot post-AGB stars/WDs ionize wind and dissociate CO

McDonald & Zijlstra 2015

- Open clusters
- O,B stars ionize the AGB winds

Half of massive OH/IR stars will be in such clusters

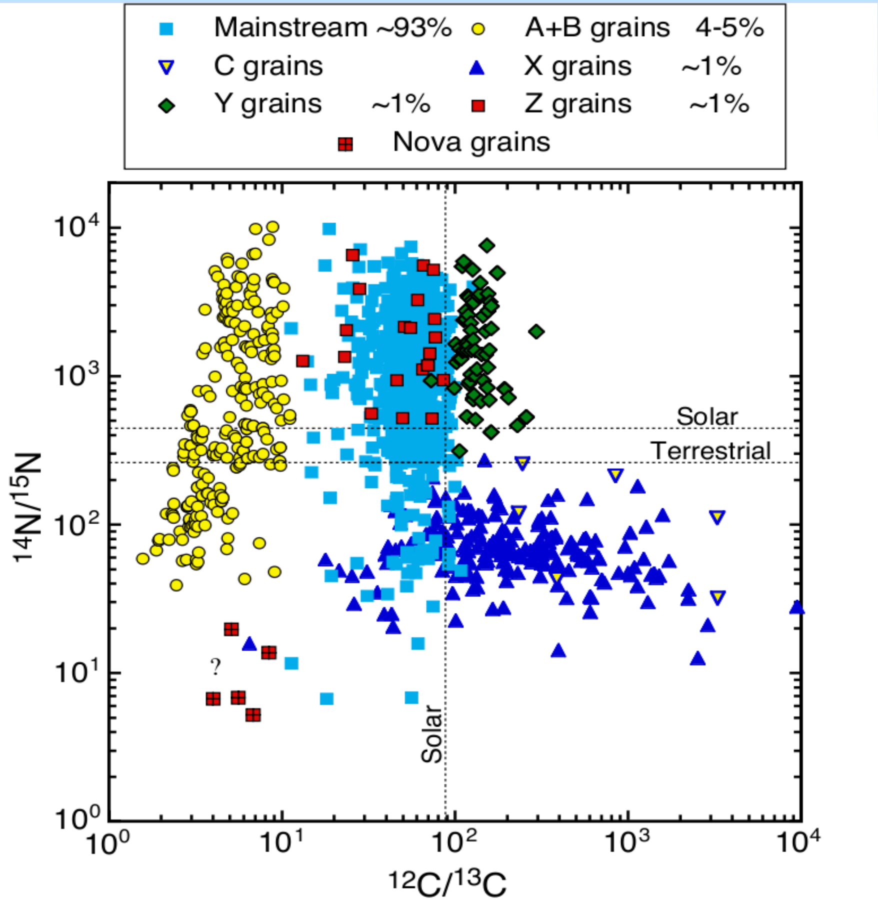
Zhukovska et al. Subm.

Presolar grains

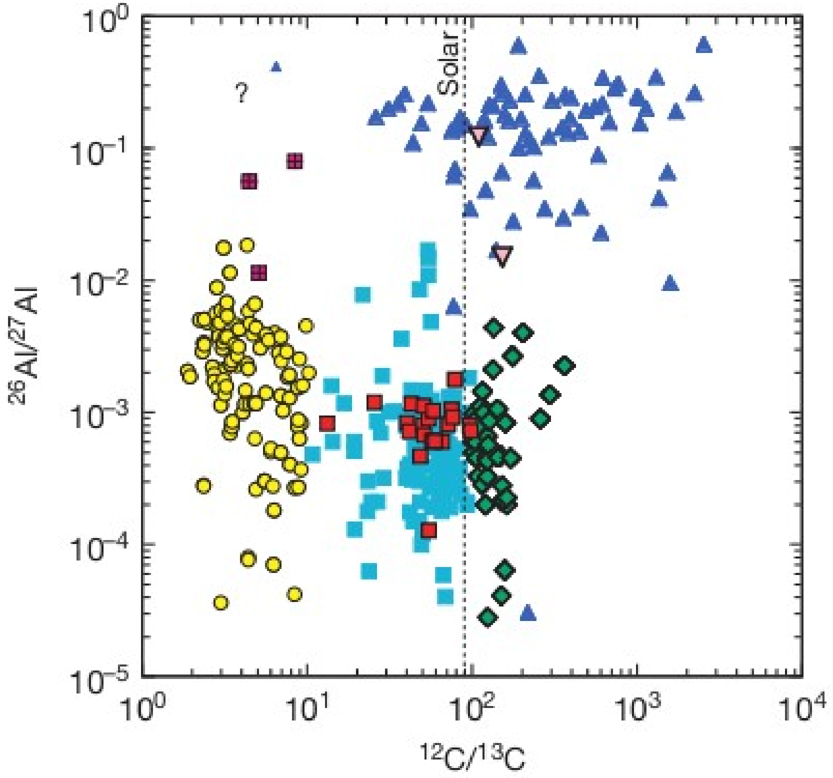
- Inclusions in meteorites

  Pre-date the solar system

- Direct measurement of isotopic abundances in stellar ejecta



Presolar grains



- Constrain nuclear reaction rates
- Dredge up
- Exotic dust producers
  - Novae, R Cor Bor stars (Karakas, 2015)
- Mystery of A/B grains

Big needs and questions

Data

- Distances and abundances!
- A mass loss tracer which works
- 3d wind structure
- AGB binaries

Can we

- get accurate mass loss formalisms?
- Explain the magic 13C pocket?
- Understand dust formation? (Iron !)
- Model binary interactions and jet formation?

Observing the future

- Wealth of new facilities
  - ESO VLT & ELT
  - ALMA
  - GAIA
  - JWST
  - LSST, TESS & PLATO

  - Require projects which are well designed and prepared

What to do

- Need for surveys
  - Large teams, integrated science
  - Complementing individual observing projects

- Piggyback science
  - e.g. Asteroseismology from Planet finders

Finally

- Late stages of stellar evolution are becoming frontier science
- Mass loss is crucial to many areas, from the evolution of the Universe to the formation of habitable planets
- We have a good understanding of the problems
- Learn from related areas, and be ambitious