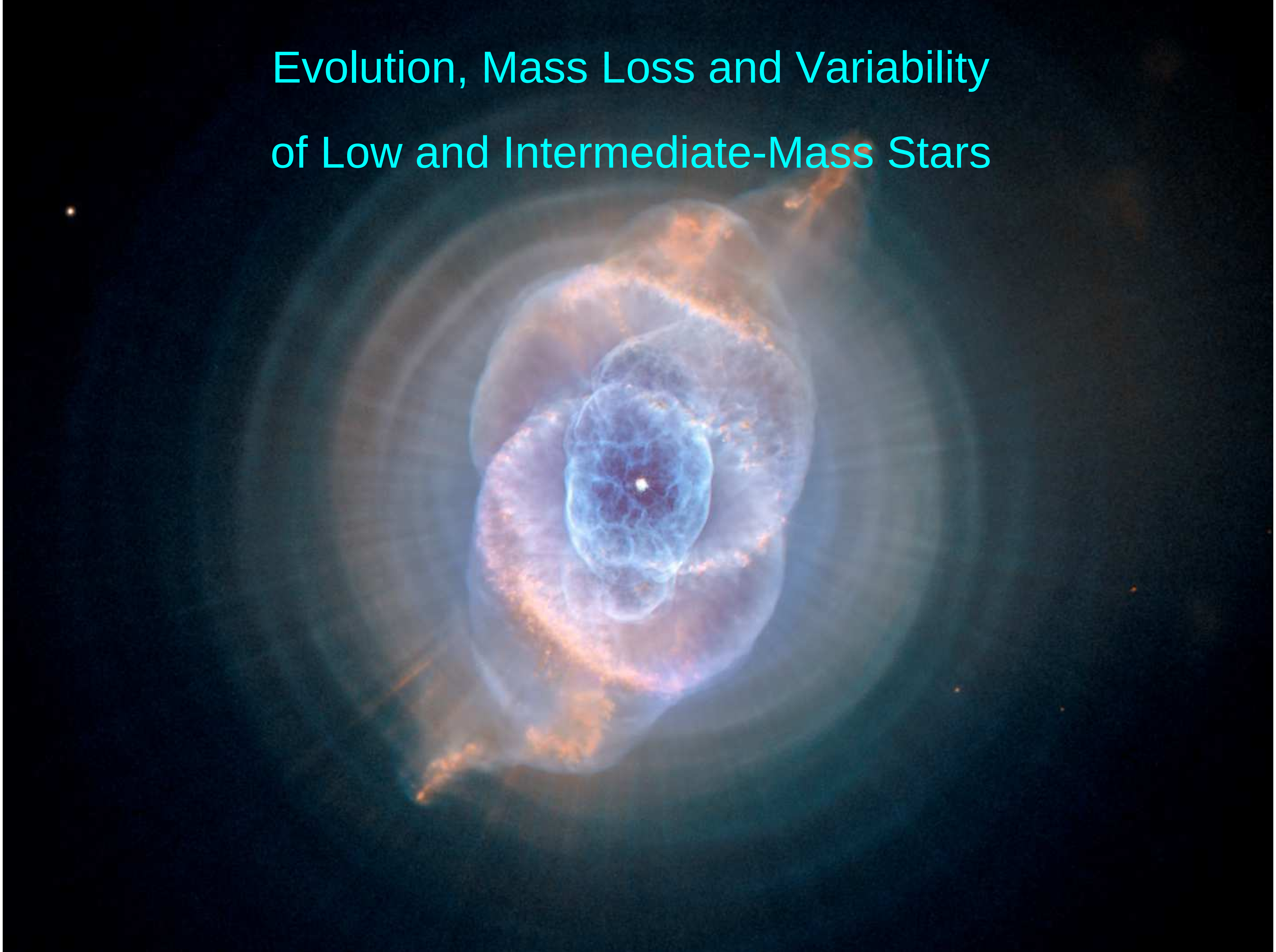
Evolution, Mass Loss and Variability of Low and Intermediate-Mass Stars



Mass Loss from Low and Intermediate Mass Stars

Significant mass loss occurs in two phases

1. In red giants before large amplitude (Mira) pulsation starts. These mass loss rates are slow (<10^{-8} Msun/year). This is the dominant form of mass loss in the lowest mass evolved stars – globular cluster stars. It occurs mostly on the RGB,also on the early-AGB.

2. In AGB stars with large amplitude pulsation. Rates can be as high as 10^{-4} Msun/year. These are known as Superwinds.

What causes mass to be lost on the Red Giant Branch?

Dissipation (by acoustic or magnetic waves) of mechanical energy generated in the convection zone??

In the absence of reliable theoretical models, most modellers use Reimers' Law for RGB mass loss (Reimers 1975):

Assume that the rate gravitational energy is carried away in the stellar wind is proportional to the stellar luminosity. Then the mass loss rate $\dot{M}$ is given by

$$L \propto \dot{M} * GM/R \Rightarrow \dot{M} = \eta LR/M$$

An improved, semi-empirical, modified Reimers' law
(Schröder & Cuntz 2005, 2007)

For the wind energy balance, we thus obtain

$$dE_{\rm wind} \simeq \frac{GM_* \dot{M}\, dt}{R_{\rm chr}} \propto F_M 4\pi R_*^2\, dt$$

where $\dot{M}$ is the mass-loss rate, R_*, M_* are the stellar radius and mass, respectively, F_M is the mechanical energy flux, and G is the gravitational constant.

R_{chr} is the radius of the chromosphere

Modelling of F_M (convective turbulence => magnetic+acoustic waves) suggests $F_M \propto T_{eff}^{7.5}$

Assume $(R_{chr} - R_*)/R_* \propto 1/g$

$$\dot{M} = \eta \cdot \frac{L_* R_*}{M_*} \cdot \left(\frac{T_{\rm eff}}{4000\ {\rm K}}\right)^{3.5} \cdot \left(1 + \frac{g_\odot}{4300 \cdot g_*}\right)$$

with $\eta = 8 \times 10^{-14}\ M_\odot\ {\rm yr}^{-1}$, $g_\odot$ as solar surface gravitational acceleration, and L_*, R_*, and M_* in solar units.

η set to give the correct globular cluster mass loss (total, ~0.2 Msun)

How do we know any mass is lost on the RGB?

Typical globular cluster turnoff mass is 0.85 Msun.
Masses of RR Lyrae stars (on the Horizontal Branch, following He core ignition at the tip of the First Giant Branch) is 0.65 Msun (from pulsation theory).
Hence, ~0.20 Msun is lost between the main-sequence and the Horizontal Branch.

But where? Maybe on the main-sequence? Maybe as a result of the He core flash?

Red variables in 47 Tuc

Use masses from pulsation theory to test if mass is lost along the FGB or just at the tip

Known distance	$(m\text{-}M)_V = 13.50$
Known reddening	$E(B\text{-}V) = 0.024$
Known metallicity	$[Fe/H] = -0.66$
Known turnoff mass	$0.9\ M_{sun}$

Calculation were done with two assumptions:

No mass loss models

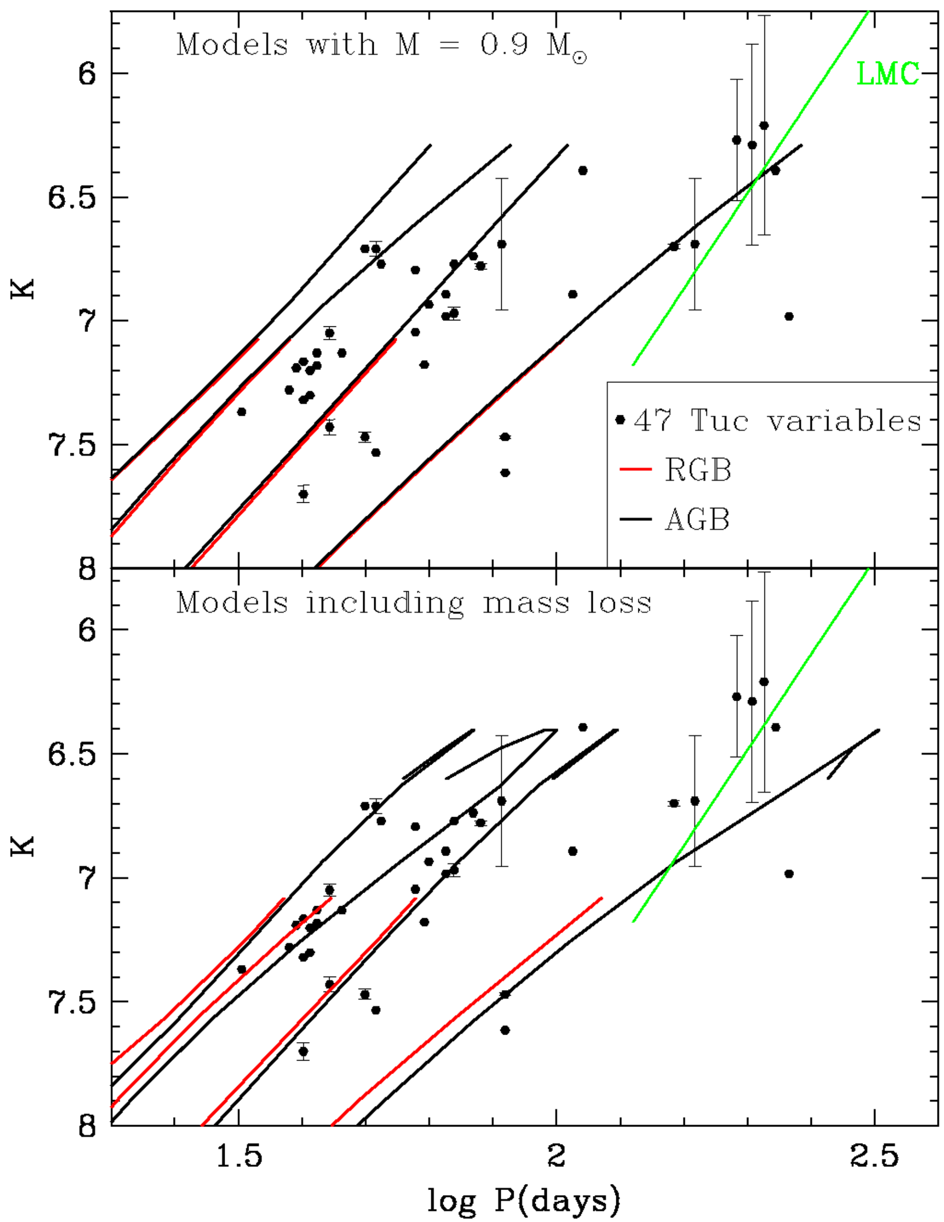
$M = 0.9\ M_{sun}$

Models with mass loss

Reimers' law $\dot{M}\ \alpha\ LR/M$

$M = 0.6\ M_{sun}$ at $L = 4000 L_{sun}$ (terminates the AGB at the observed L)

Period-luminosity relations



Models without mass loss give incorrect linear periods for small amplitude stars.

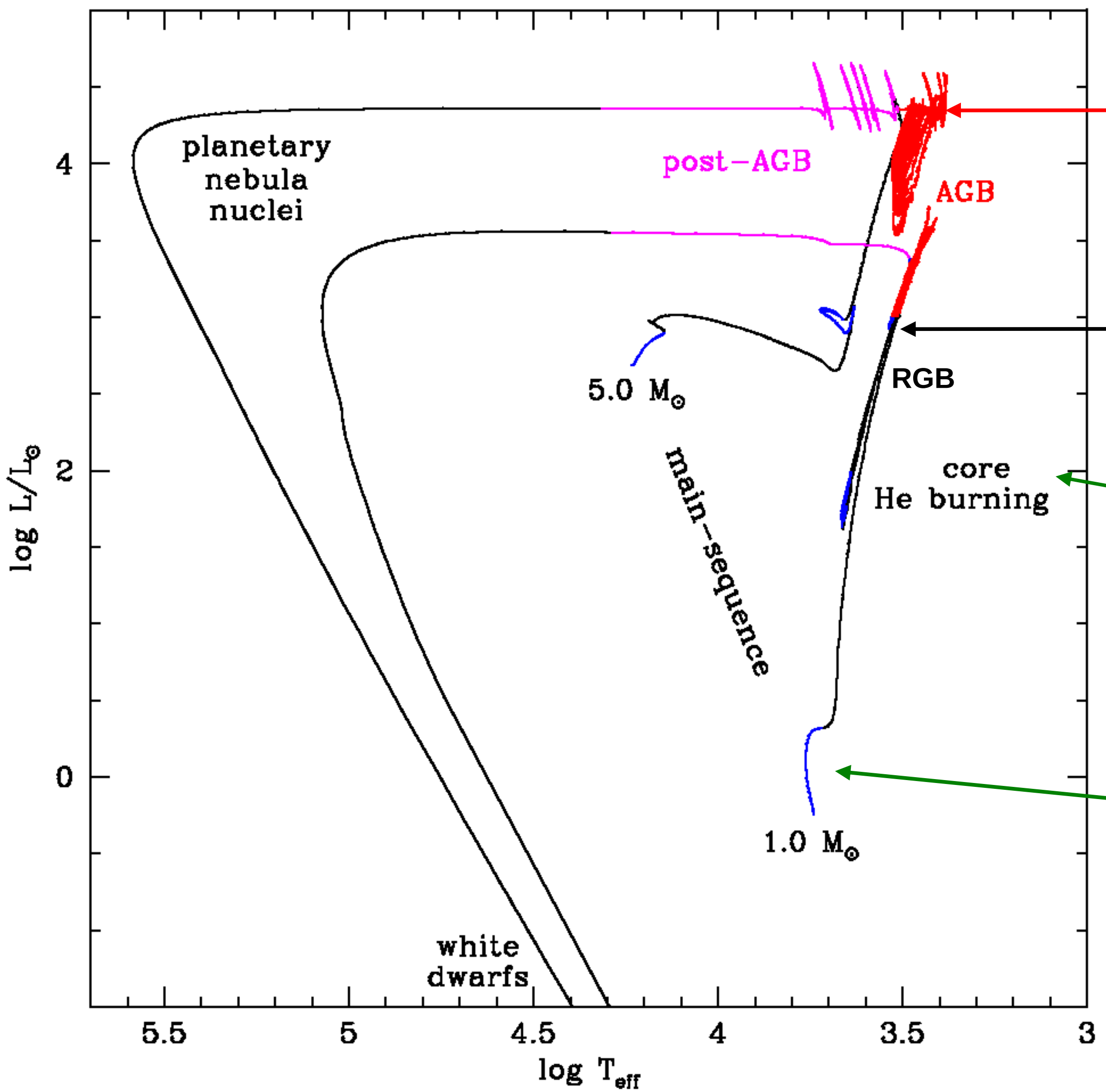
Models with mass loss give correct linear periods for small amplitude stars.

Total mass loss required is ~0.3Msun – over a range in luminosity.

Large amplitude Miras – periods affected by nonlinear effects.

Lebzelter and Wood (2005)

Mass loss during the AGB stage of low and intermediate-mass stars



The AGB
Surface enrichment
Pulsation
Mass loss

The RGB
Surface enrichment
Pulsation
Mass loss

About 10^8 years spent here

Most time spent on the main-sequence burning H in the core (~10^{10} years)

Low mass stars:
M < ~1.9 Msun

Intermediate mass stars:
~1.9 < M/Msun < ~7

The transition to a superwind:
Large amplitude pulsation - and dust + radiation pressure (large L)

Pulsating AGB star at base of wind

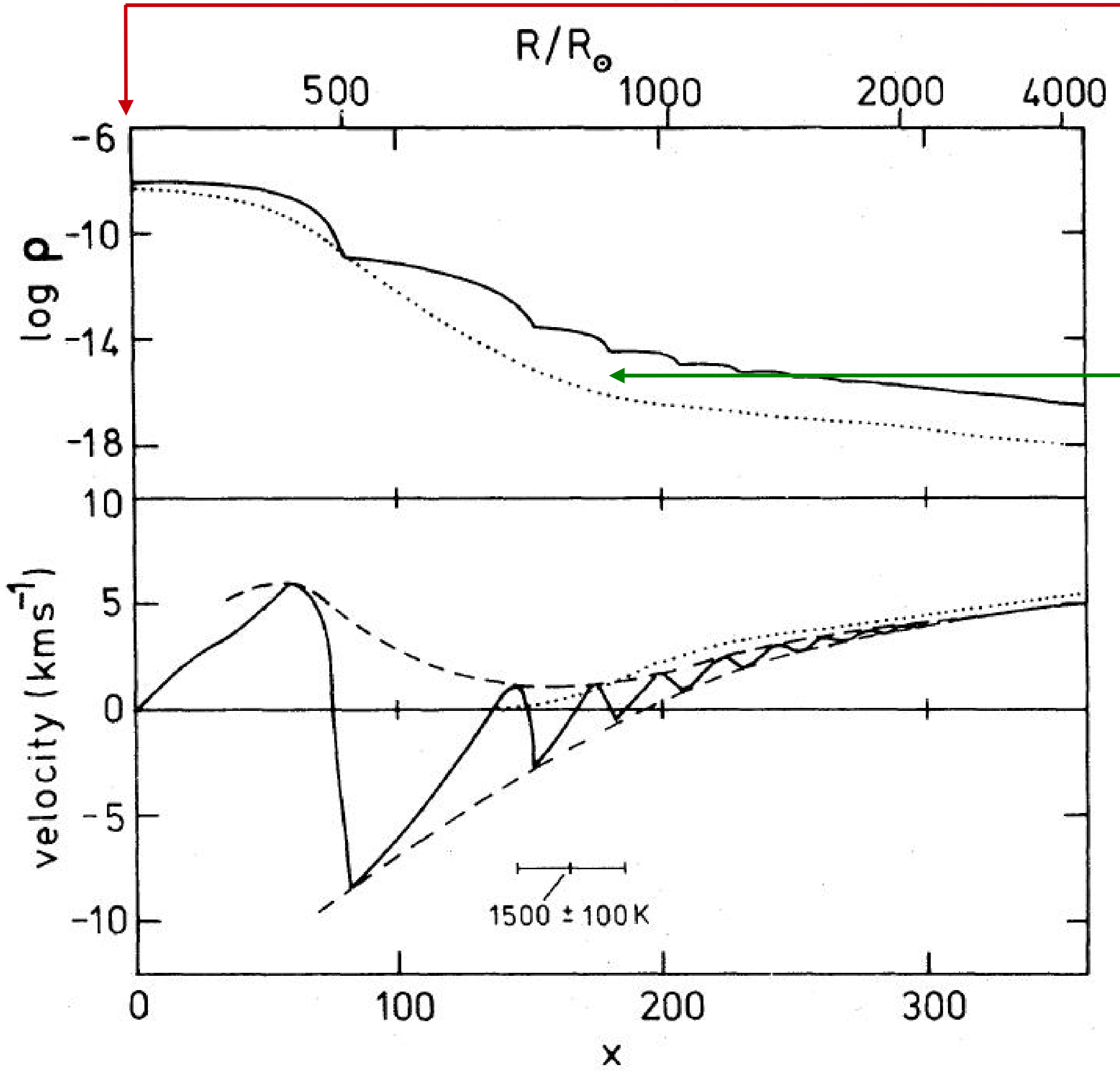


FIG. 12.—Density and velocity profiles at a single phase in the models which include a radiation pressure–induced mass flow as well as pulsation. Dotted lines show density and velocity profiles in the initial steady-state mass outflow model. The dashed curves are an envelope to the velocity profiles.

Pulsation enhances the density in the dust formation layer by a factor ~100. The mass loss rate is enhanced by a similar factor.

$\dot{M} = 4\pi r^2 \rho v$

<v> is unchanged at given r.

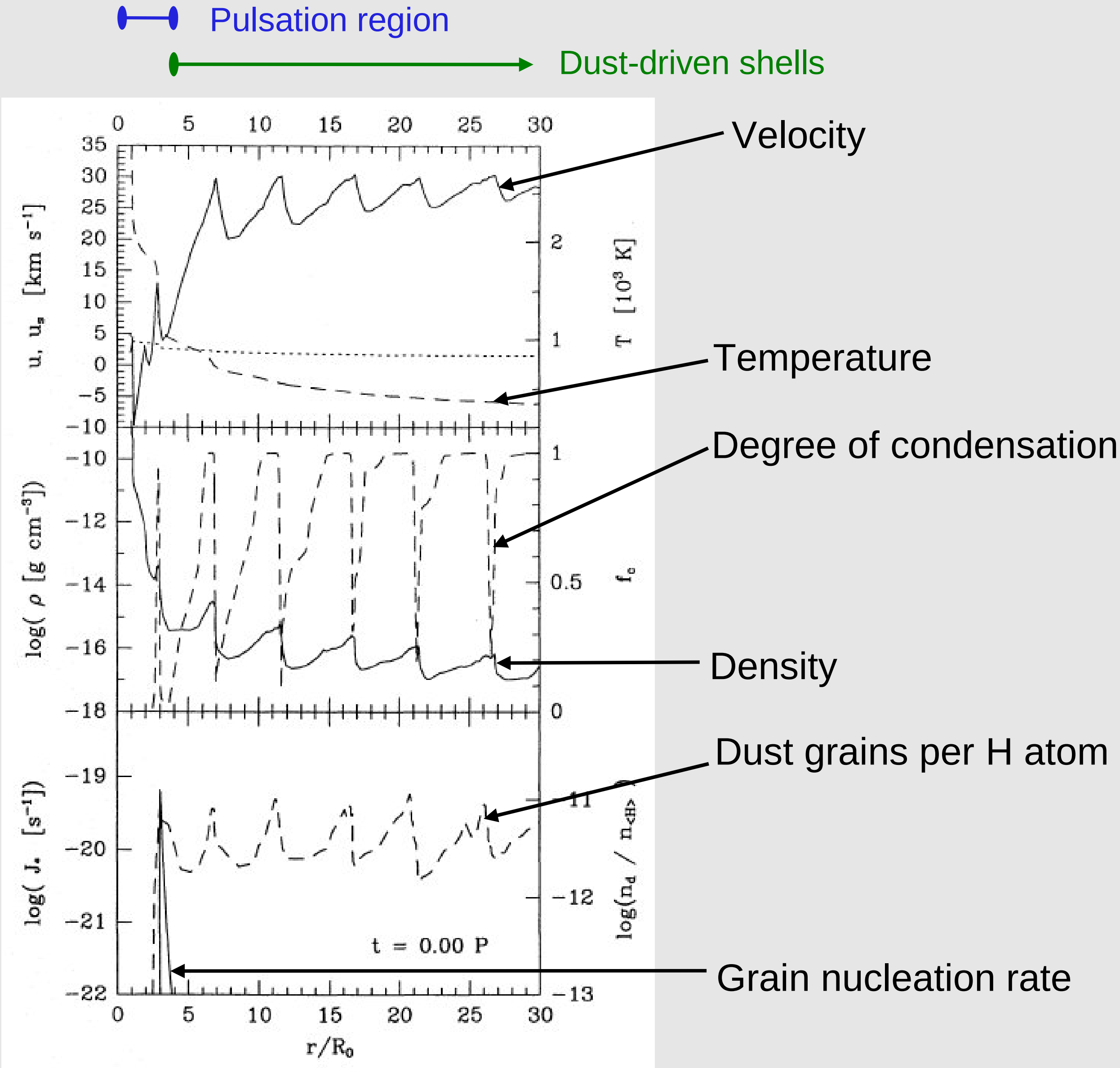
··········· Non-pulsating star with wind

——— Pulsating star with wind

Wood 1979

More detailed models - carbon star dust shell models

When grain growth and evaporation and radiative transfer in the dust is included, layered dust shells develop with a size and timescale longer than that of the driving pulsation (Winters et al . 1994, Höfner et al (1995).



Winters et al (1994)

Light curve prediction for carbon star mass loss models

Pulsation period + dust shell formation period

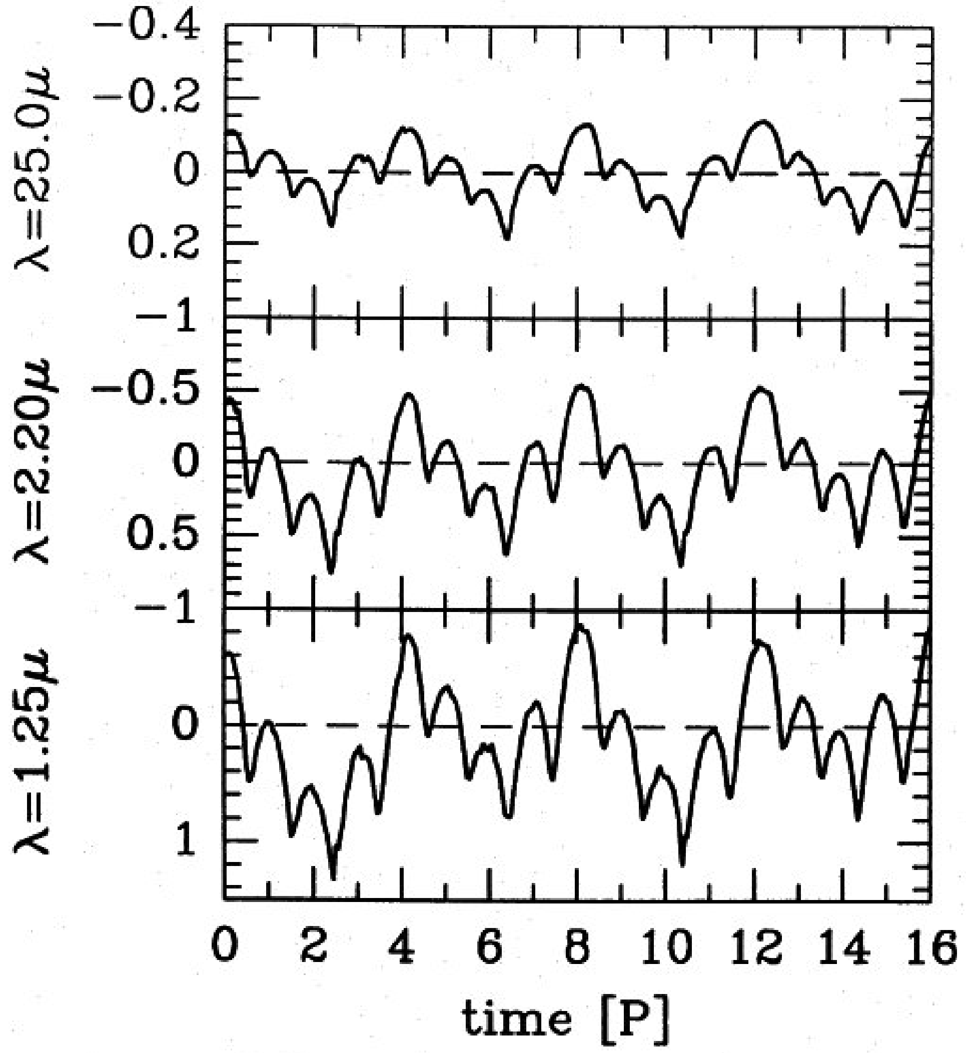


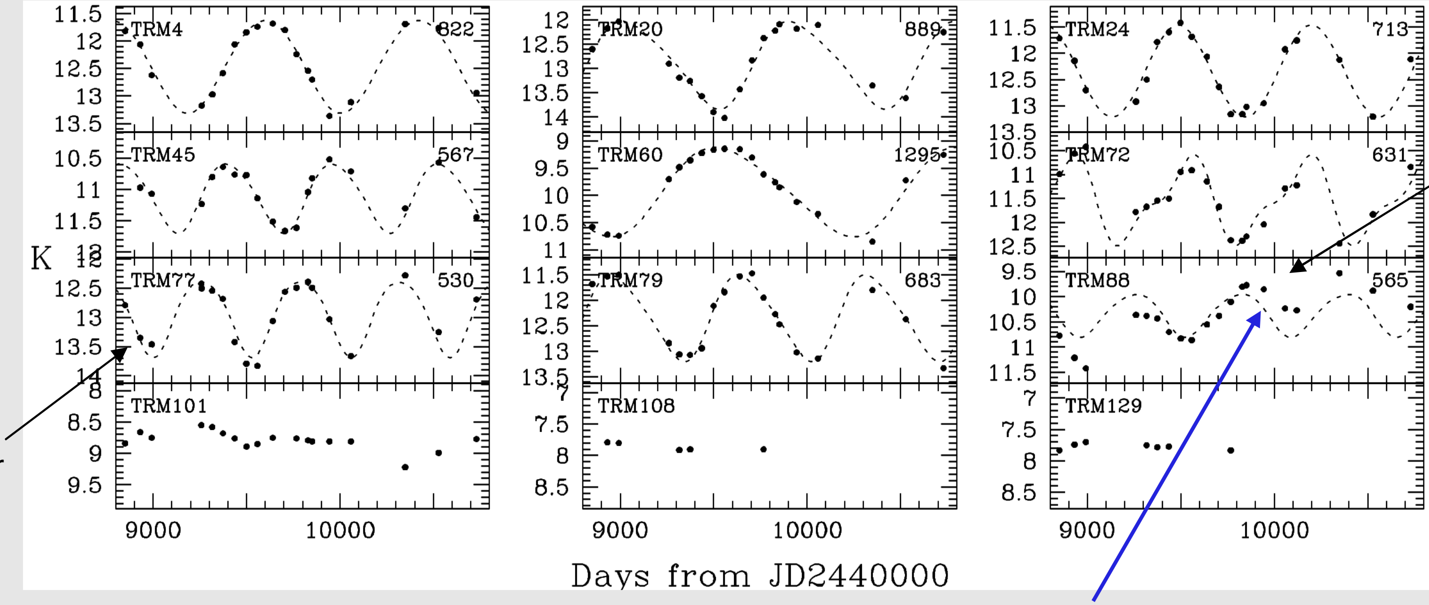
Fig. 6. Theoretical lightcurves (in magnitudes, relative to the mean magnitude) of Model B at different wavelengths. Note the different scaling of the ordinate at different wavelengths

A triumph of models!
This is commonly observed...

Winters et al. 1994:Astron. Astrophys. 290, 623

Observations of high mass loss rate AGB stars

- The dust-enshrouded AGB stars are all large amplitude pulsators.
- Suggests large amplitude pulsation is a vital part of the "superwind" mass loss process.

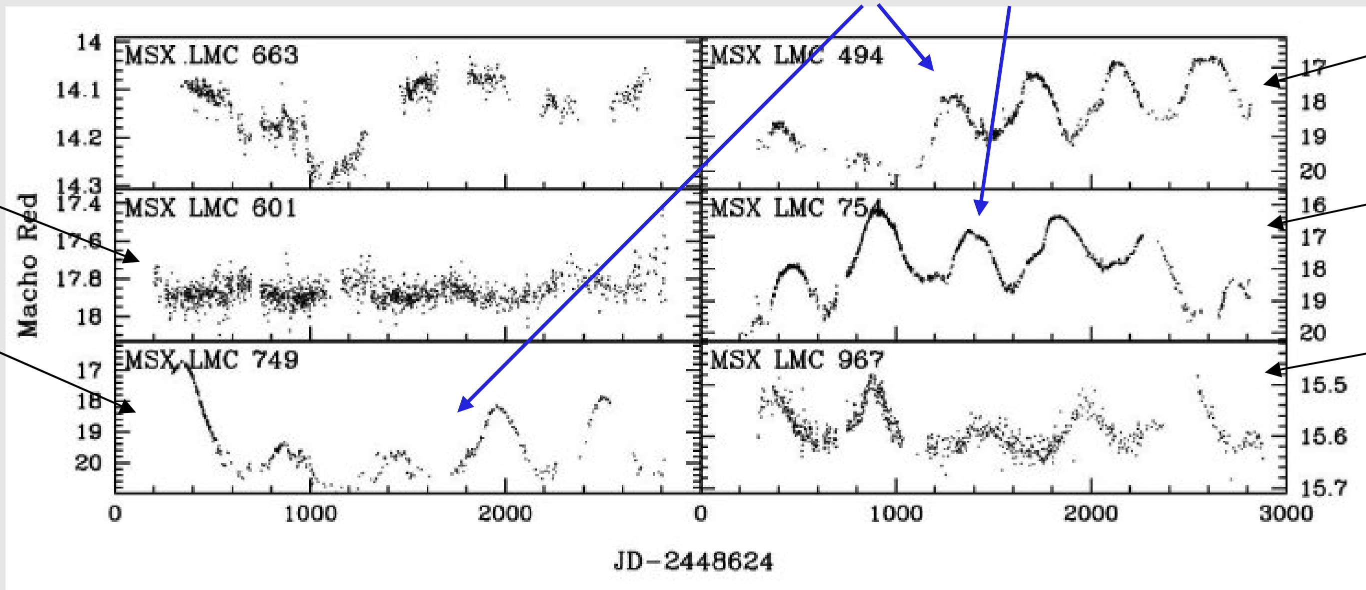


$\dot{M} = 3.3\times10^{-6}\ M_o$/yr

$\dot{M} = 5.8\times10^{-6}\ M_o$/yr

IRAS detections
Wood et al. (1998)

Dust shell modulation



$\dot{M} = 1.4\times10^{-6}\ M_o$/yr

$\dot{M} = 5.1\times10^{-6}\ M_o$/yr

$\dot{M} = 1.7\times10^{-6}\ M_o$/yr

$\dot{M} = 4.0\times10^{-6}\ M_o$/yr

$\dot{M} = 3.2\times10^{-6}\ M_o$/yr

MSX detections
Macho light curves

Wood et al, 2007: ASP Conference Series, 378, 251

Some estimates of the superwind mass loss rate

Vassiliadis & Wood (1993) [empirical, CO microwave estimates of Mdot, plotted against pulsation period]

Bowen (1988) and Bowen & Wilson (1991) [computed mass loss rates with simplistic energy loss mechanisms and grain opacities: gives an unrealistic chromosphere]

Blöcker (1995) [formula based on Bowen (1988)]

Groenewegen (1998) [C star mass loss rates in solar vicinity]

Wachter et al (2002) [C star pulsation/mass loss models]

Groenewegen et al (2007) [C star mass loss rates in the LMC and SMC from Spitzer observations]

Mattsson et al. (2010) [C star pulsation/mass loss models]

O-rich models lacking [see Jeong et al. (2003)]

Empirical mass loss rate from Vassiliadis & Wood (1993)

A very rapid rise in Mdot with P to "superwind" values.
Then a very slow increase.
No information on any mass dependence; large variation at a given P.

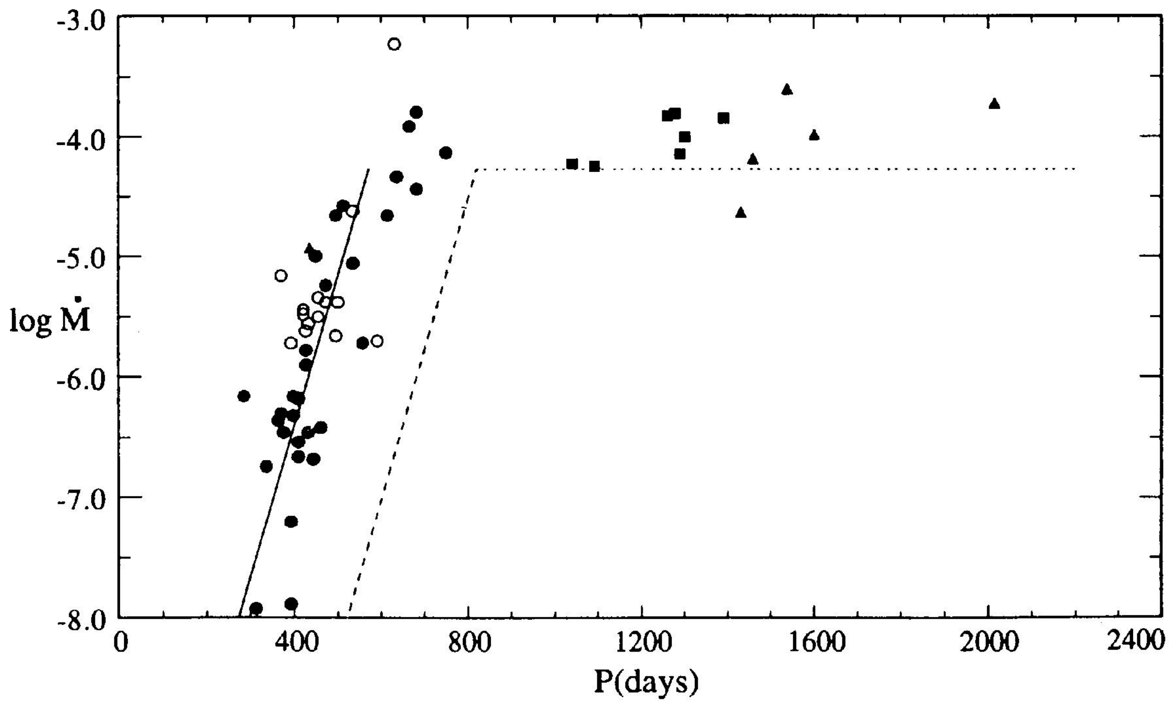


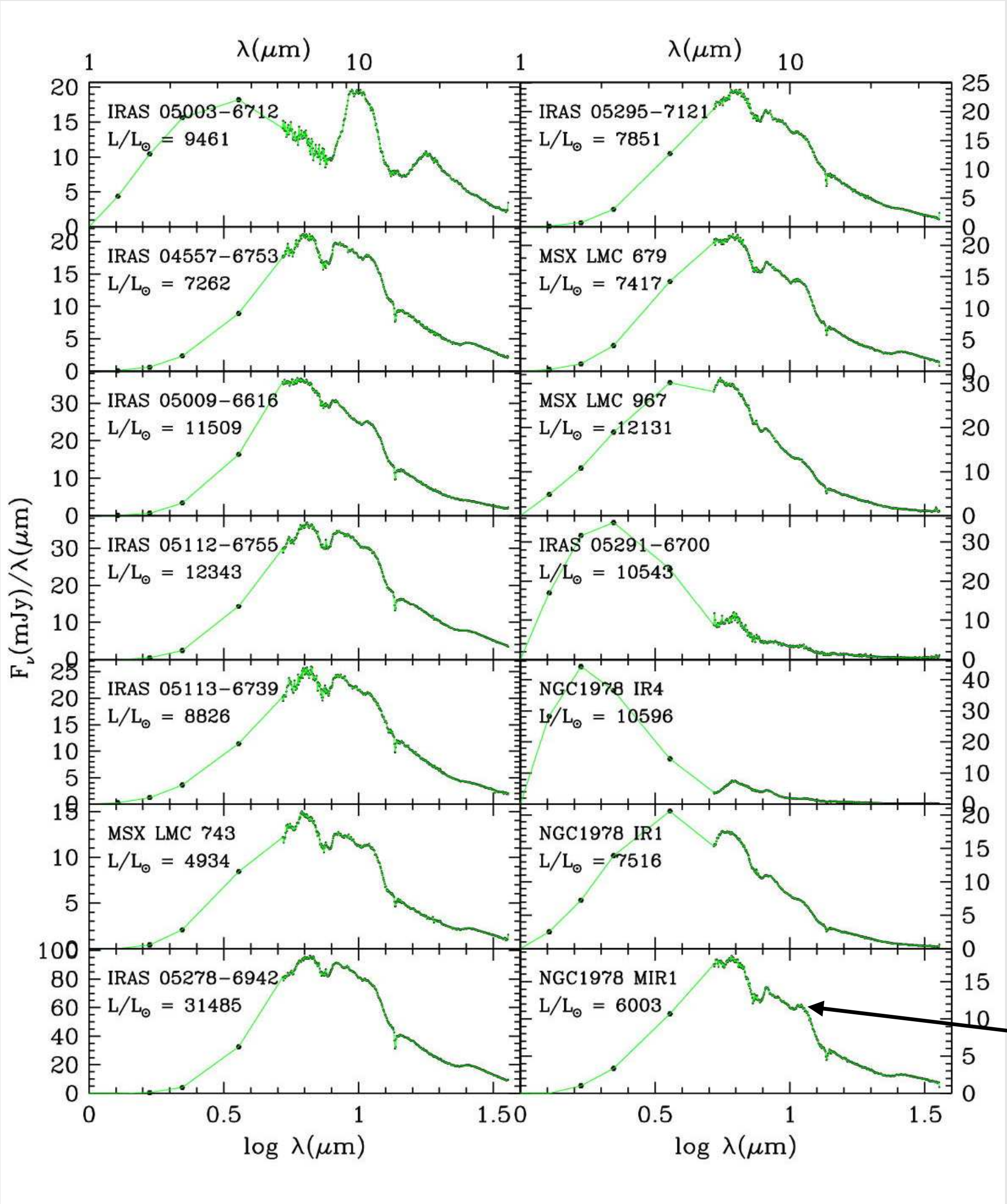
FIG. 1.—Mass-loss rate $\dot{M}(M_\odot\ yr^{-1})$ plotted against period for Galactic Mira variables of spectral type M and S (*filled circles*) and C (*open circles*), and for pulsating OH/IR stars in the Galaxy (*triangles*) and the LMC (*squares*). The solid line is the analytic fit used for low-mass ($M < 2.5\ M_\odot$) stars with the mass-loss rates less than the radiation-pressure-driven limit. The dashed line is the equivalent relation for a 5 $M_\odot$ star, while the dotted line corresponds to mass loss at the radiation-pressure-driven limit for a typical intermediate mass (5 $M_\odot$) LPV in the LMC with $M_{bol} = -6.5$ and $v_{exp} = 12$ km s^{-1}.

The luminosity of termination of AGB evolution (complete envelope ejection) is determined by the period (luminosity) at which Mdot rises rapidly to "superwind" values.

Based on observations of CO in the wind outflow.

Another way to estimate wind mass loss rates is via measurement of mid-infrared emission from dust in the stellar wind.

The Spitzer Space Telescope has recently provided many examples in the Large Magellanic Cloud, where the distance is known.



SEDs from Spitzer 5-35 micron spectra + simultaneous JHKL broadband photometry.

SED gives accurate L.

One O-rich star.
All others are C stars.

Higher mass loss rate moves the flux peak to longer wavelength.

Features due to SiC

Wood et al, 2007: ASP Conference Series, 378, 251

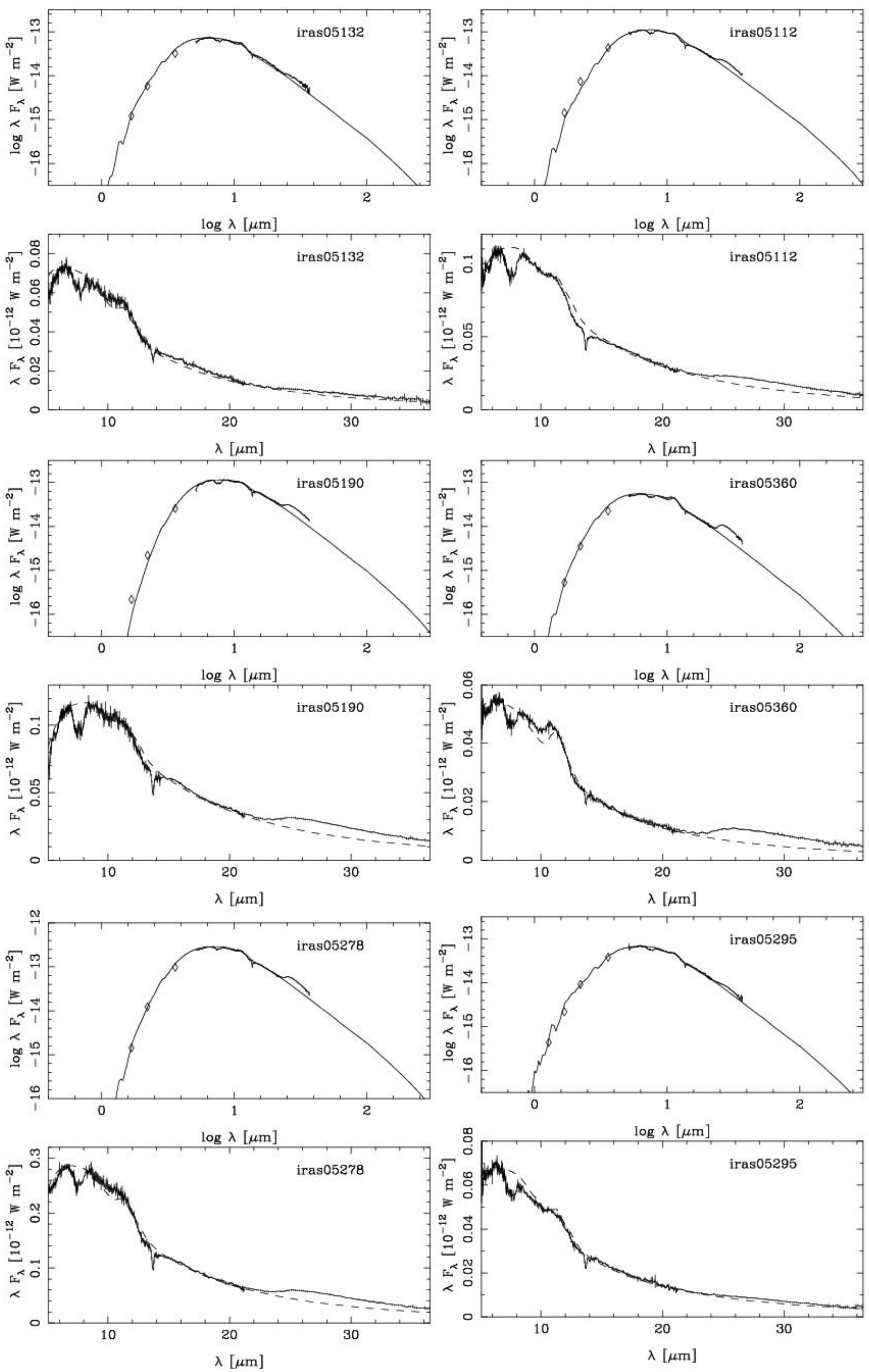


Figure 2. Fits to the SED in the top panel, and the IRS spectra in the bottom panel.

Groenewegen et al. (2007)

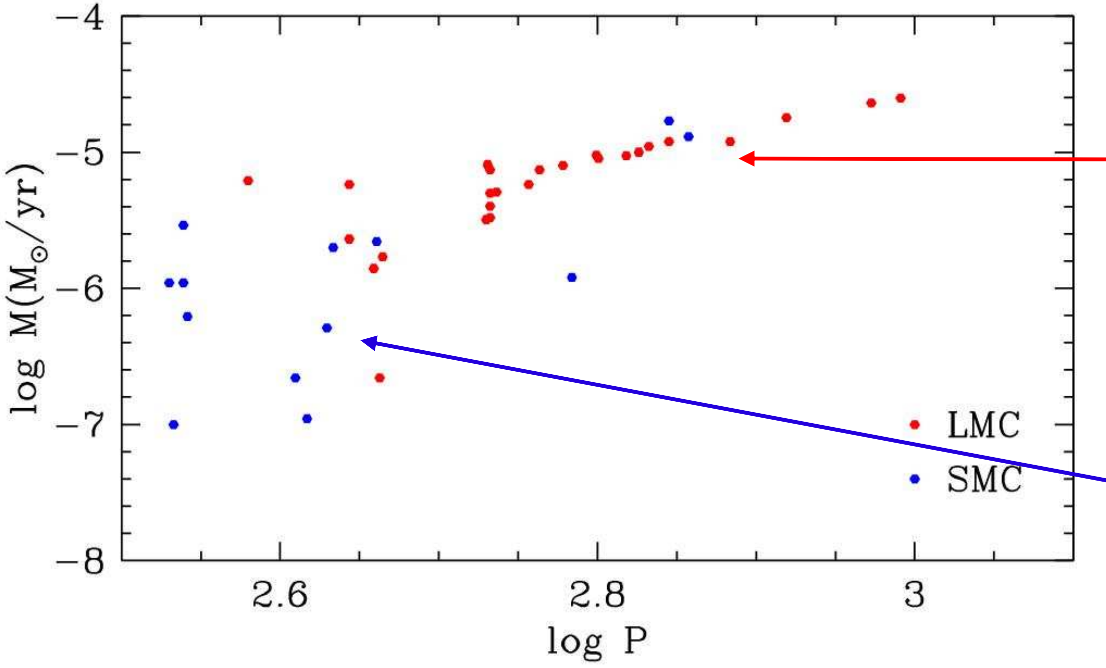
LMC AGB stars:
Mass loss rates were derived by fitting dust envelope models to the combined Spitzer spectra and simultaneous JHLK photometry.

Dust mass loss rate is derived directly.
Assume M(gas)/M(dust)=200 in the wind to get total mass loss rate.

If most C atoms not in CO end up in grains (mostly amorphous carbon), this corresponds to C/O ~ 2 in the LMC, and C/O ~ 3 in the SMC.

Typical mass ratio (SiC/Amorphous Carbon) = 2

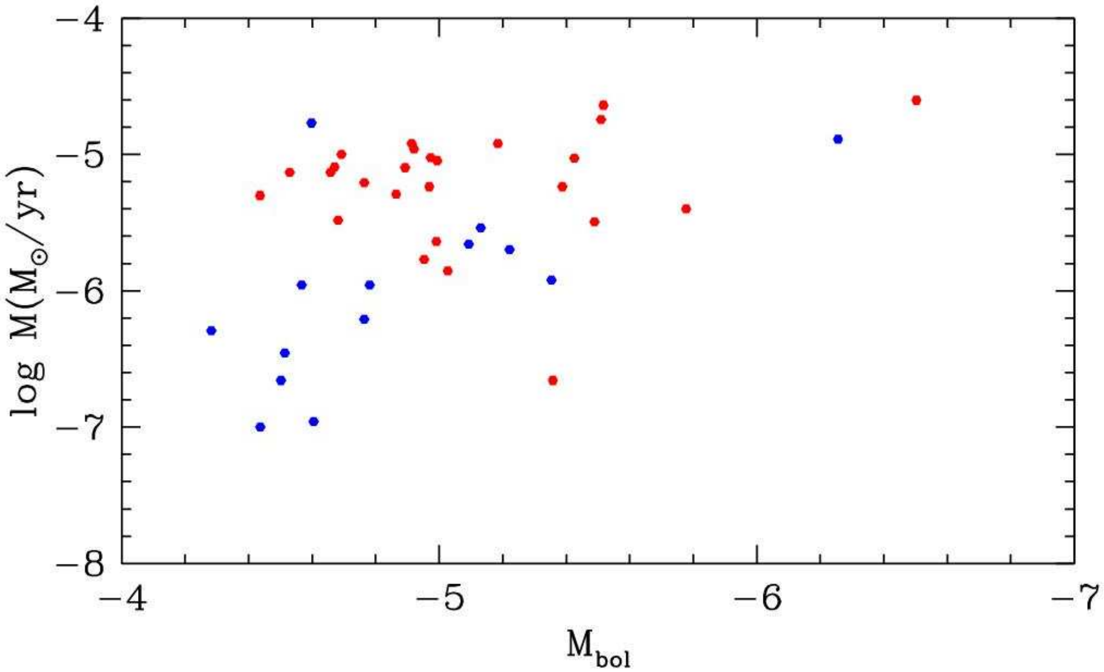
Spitzer mid-IR dust observations



There is a very tight correlation of mass loss rate with P for P>500 days.

Large range in L here (hence a range in mass).

Large scatter at shorter P. Onset of the superwind – why at different P?



A very weak correlation of mass loss rate with luminosity.

SMC stars have lower mass loss rates than LMC stars at the same luminosity (by a factor ~10).

Wood et al, 2007: ASP Conference Series, 378, 251

Is the mass loss rate (at given P) determined by stellar mass?

Deriving the stellar parameters

L - from SED (instantaneous, not <L>, can be corrected)

P - observed

M - from pulsation theory ($M_{current}$):

$P = P(M,R) = P(M,L,T_{eff})$ (using $L = 4\pi\sigma R^2 T_{eff}^4$)

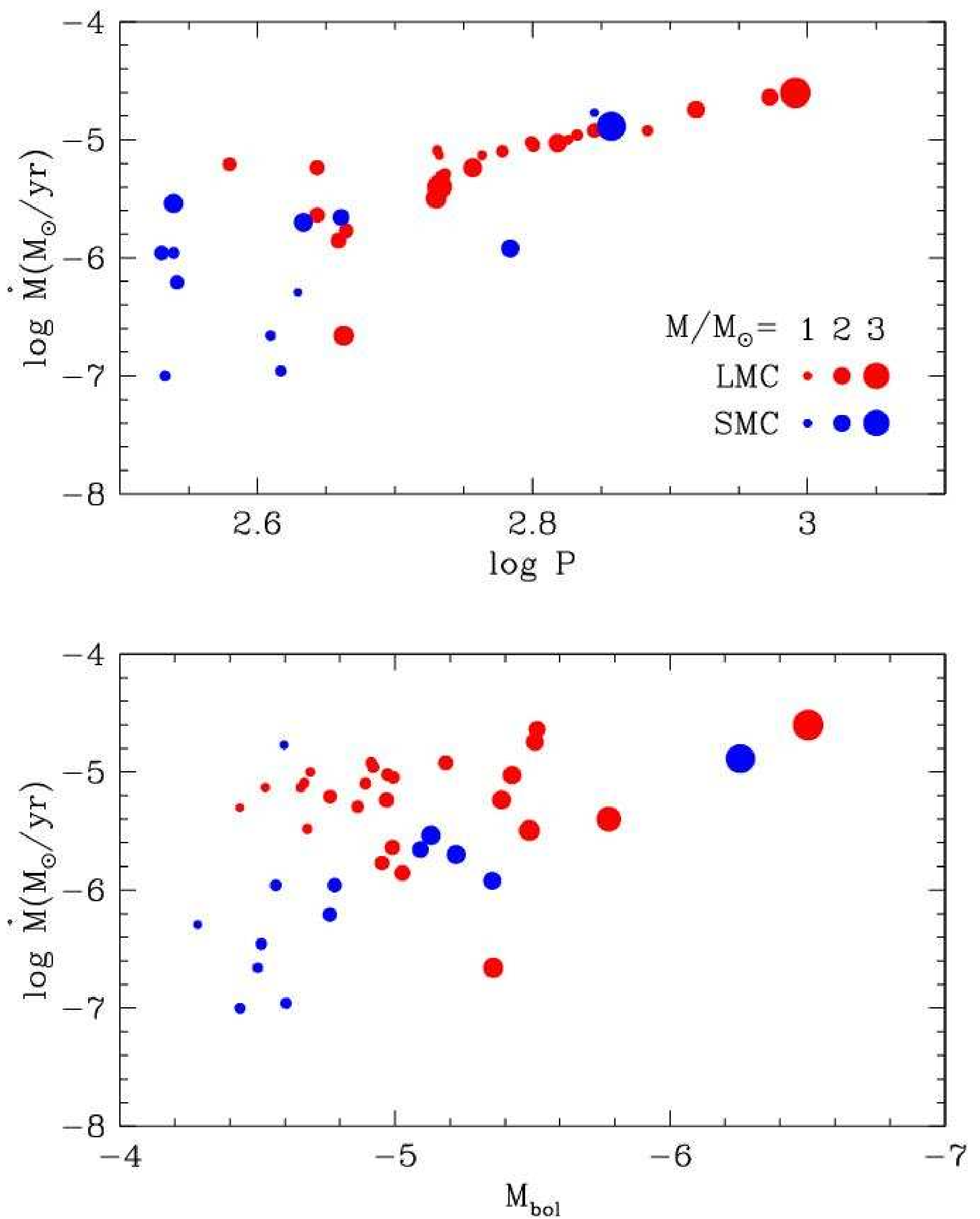
$T_{eff}=T_{eff}(L,M)$ (giant branch position)

$\Rightarrow P = P(M,L)$

$\Rightarrow M = M(P,L)$

X_i - abundances assumed

Pulsation masses (assuming Z=0.004 and C/O=1.4)



Wood, 2007:ASP Conference Series, 374, 47

- A tight correlation of mass with M_{bol} (only expected if mass loss speeds up rapidly)
- C stars with P > 500 days fall on a tight dM/dt-logP relation regardless of mass – surprising?
- For P < 500 days, there is no tight correlation between dM/dt and logP

C-star models (e.g. Wachter et al. 2002, Mattsson et al. 2010) should be able to reproduce these results.

In summary:

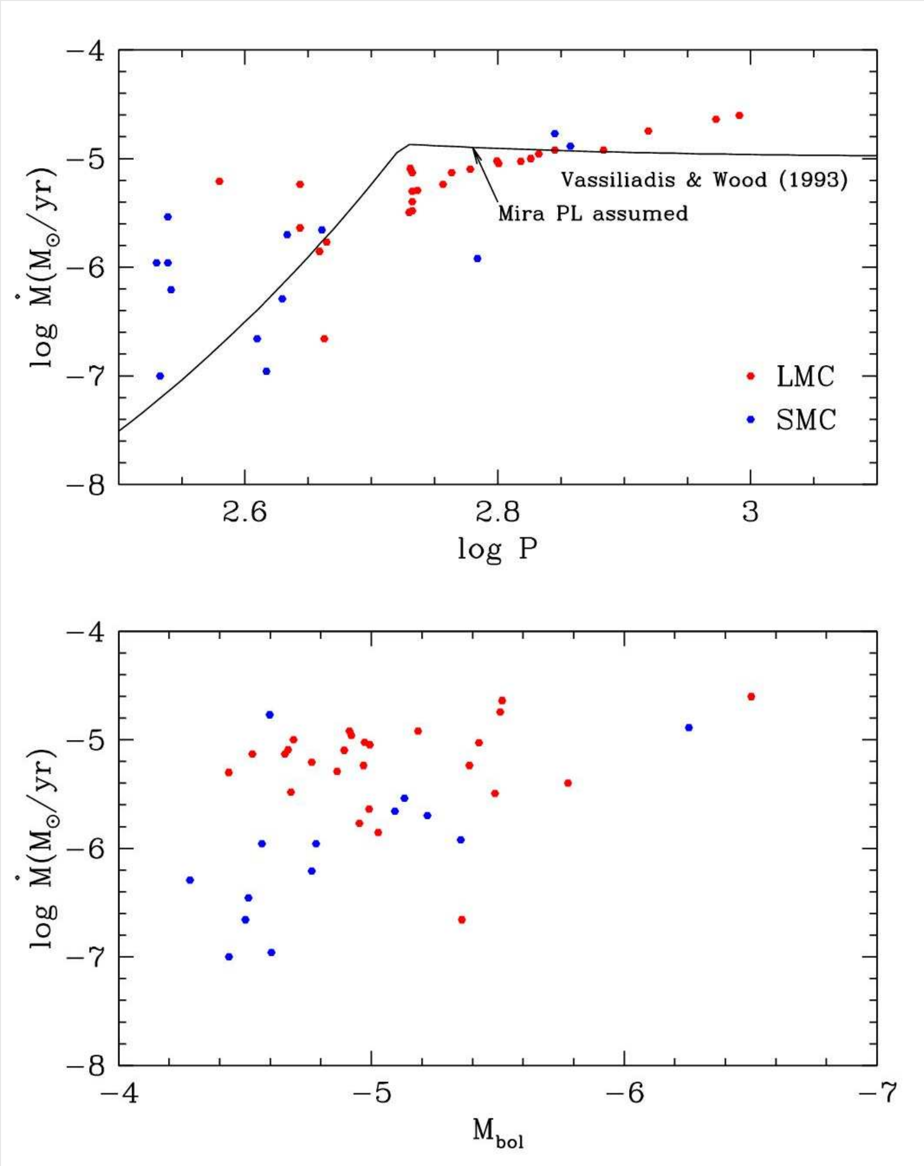
We still do not know what causes the sudden rise in mass loss rate at P ~ 300-500 days.

The pulsation amplitude?

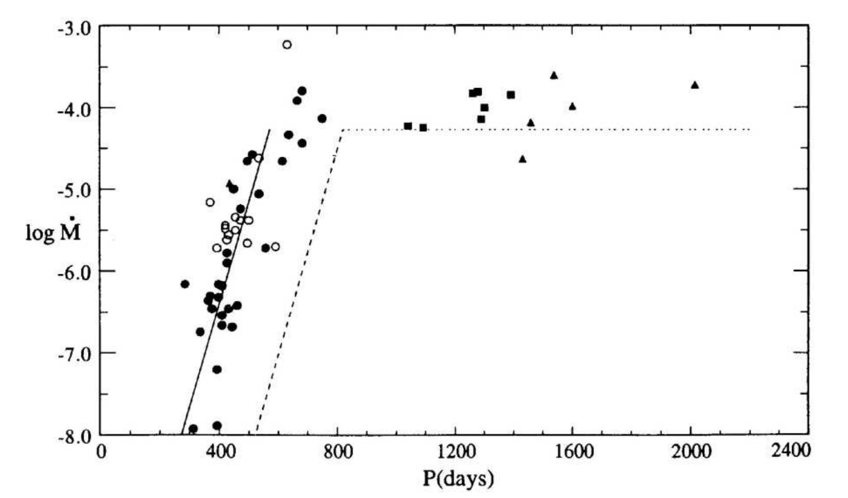
To model that would require nonlinear pulsation models with reliable driving. Convective uncertainties make this difficult and it has not been attempted.

The Vassiliadis & Wood empirical formula based on CO microwave observations is consistent with the dust-estimated mass loss rate on average.

Hence, evolution calculations done with this formula should give a fair picture of AGB evolution with mass loss.



Groenewegen et al. (2007)



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Vassiliadis and Wood (1993)

AGB evolution with mass loss

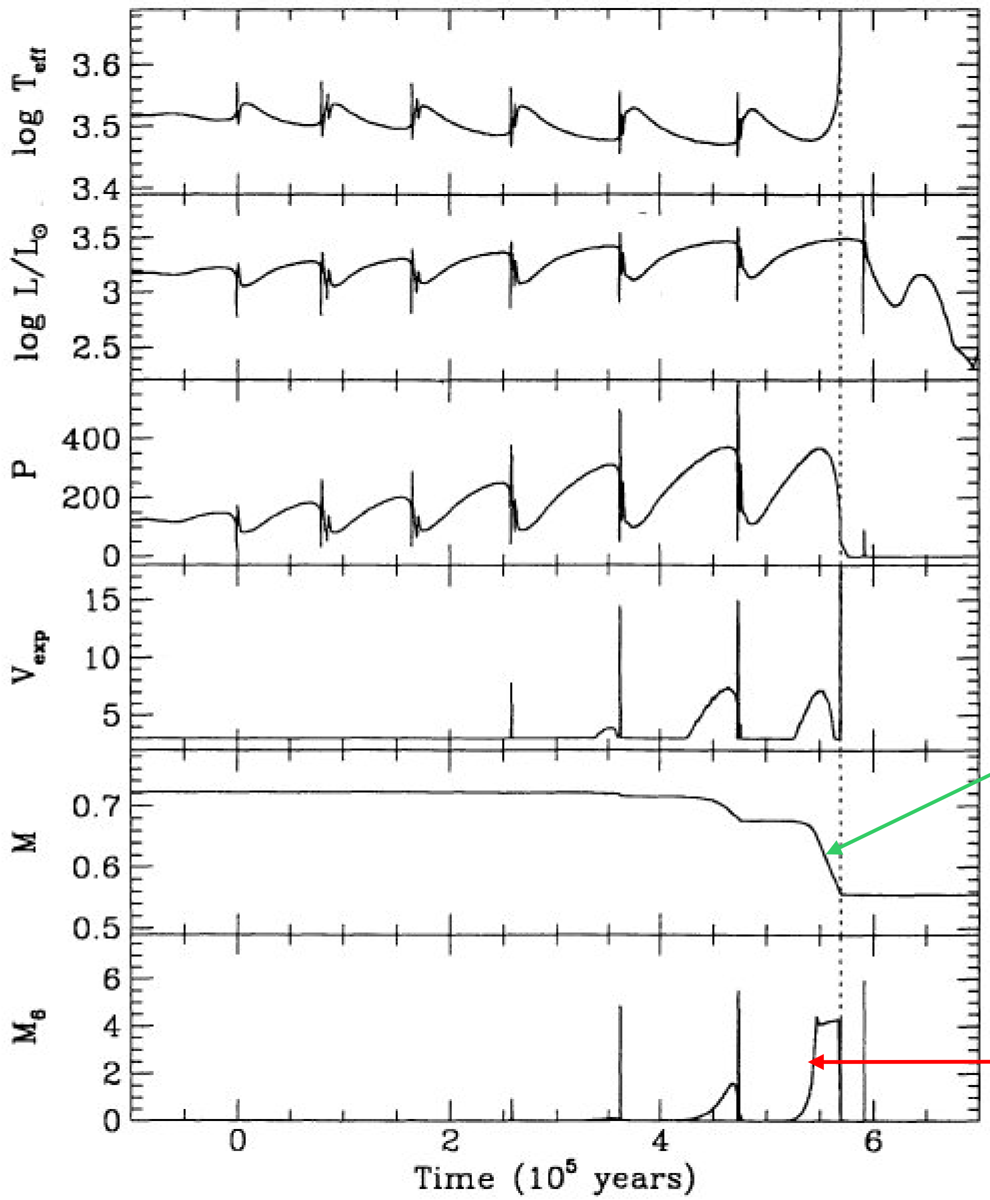


FIG. 3.—Time dependence of various quantities during the TP-AGB phase of a star with (M, Y, Z) = (0.945, 0.25, 0.008). The abscissa represents the time after the first major thermal pulse. The dotted vertical line at right represents the end of the AGB phase, as defined in the text. M_6 is the mass-loss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

Lose ~0.1 Msun over ~2x10^4 years, typical of Planetary Nebulae

Mass loss runs away quickly near maximum quiescent luminosity: lower M => lower T_{eff} => larger R

Larger R and lower M => longer P ($P \sim R^{3/2}M^{-1/2}$)

Vassiliadis & Wood (1993) $M_{initial}$ = 0.945 Msu

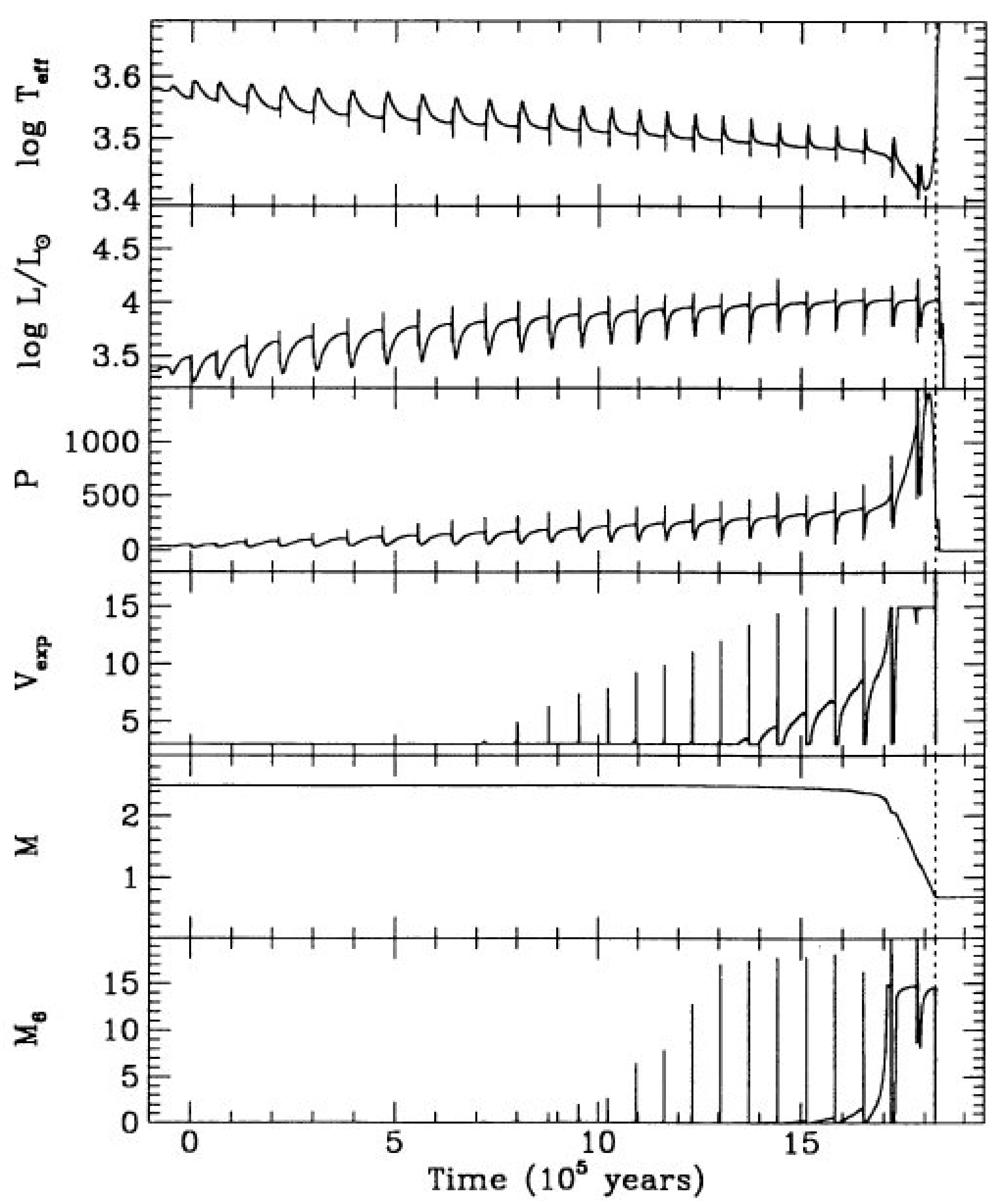


FIG. 7.—Same as Fig. 3, except for $(M, Y, Z) = (2.5, 0.25, 0.008)$

Higher mass => more flashes, higher mass loss rates, longer periods, more mass lost

VW1993 Mi = 2.5 Msun

Vassiliadis and Wood, 1993; Astrophysical Journal, 1-413-2, 641

L depends on M – the dependence solely on Mcore no longer holds in the presence of deep convection (Hot Bottom Burning)

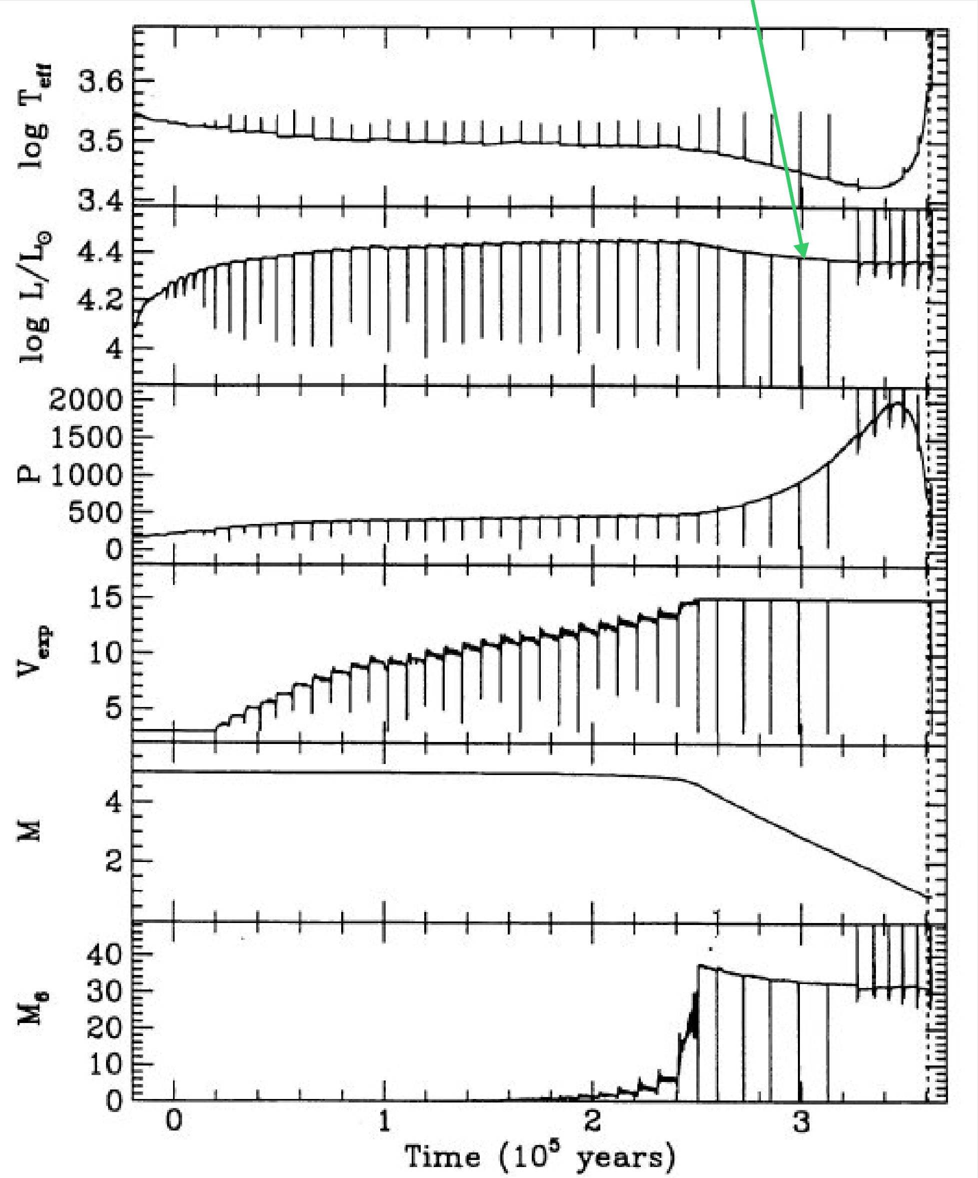


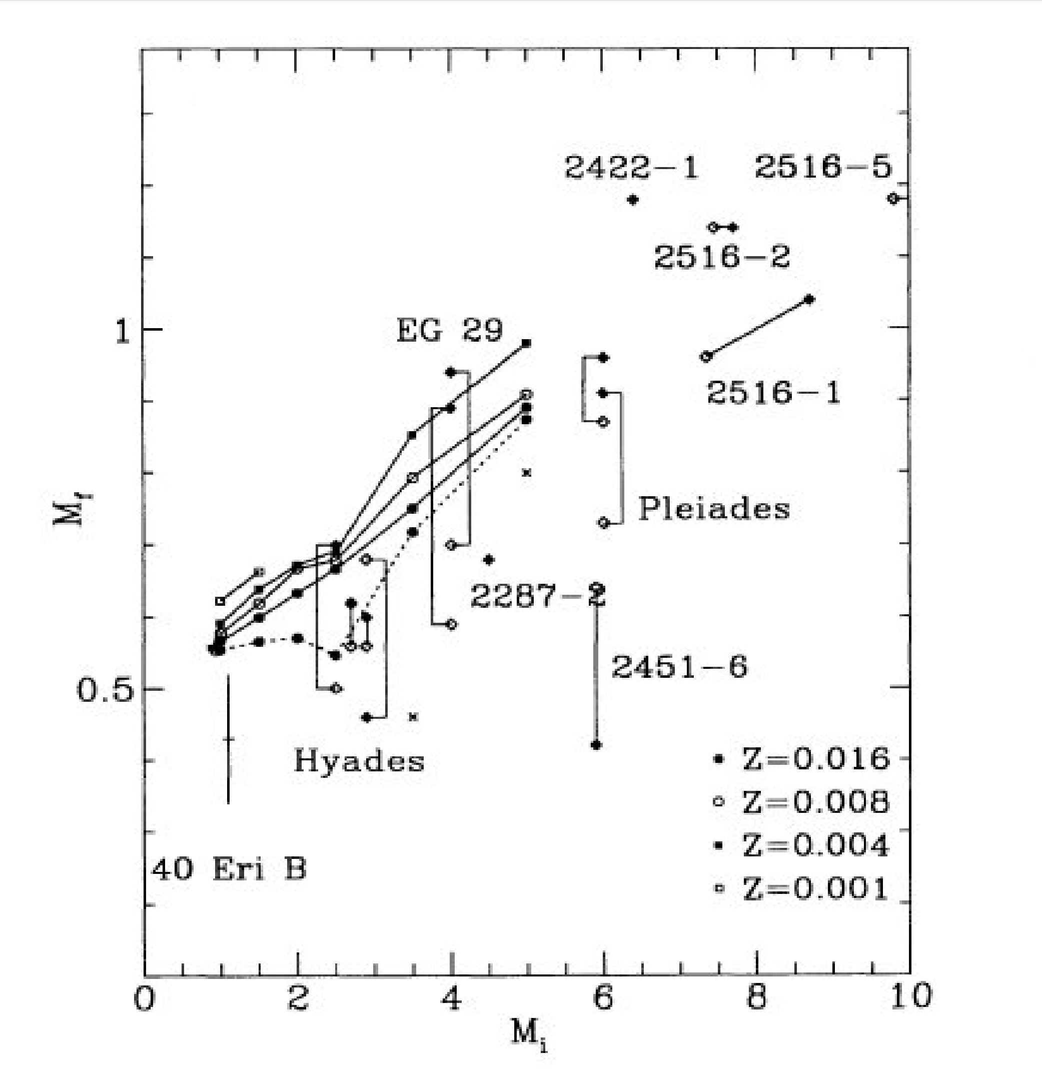
FIG. 9.—Same as Fig. 3, except for $(M, Y, Z) = (5.0, 0.25, 0.008)$

Vassiliadis and Wood, 1993; Astrophysical Journal, 1-413-2, 641

VW1993 Mi = 5 Msun

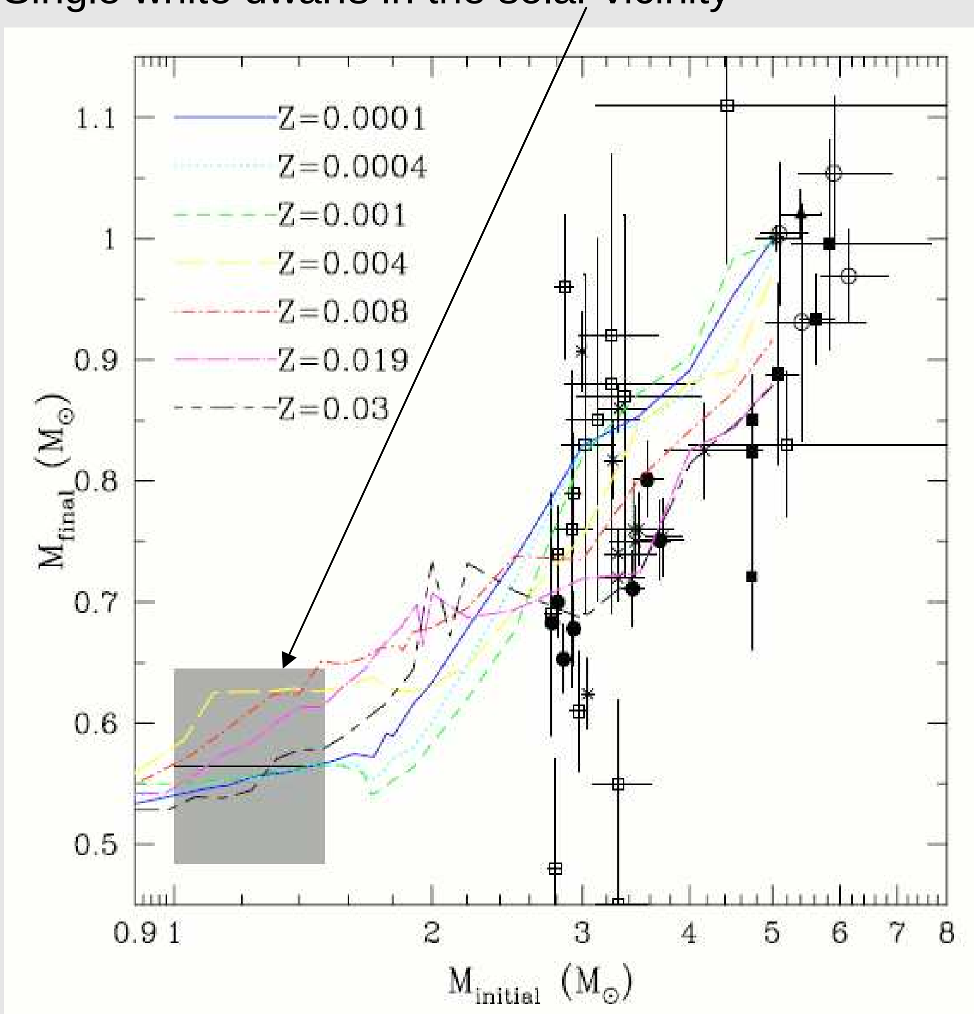
The relation between Initial Mass and Final Mass

It depends mostly on the superwind mass loss rate
(both the plots below use Vassiliadis & Wood mass loss rates).
Agreement with observations is reasonable.



Vassiliadis & Wood (1993)

Single white dwarfs in the solar vicinity

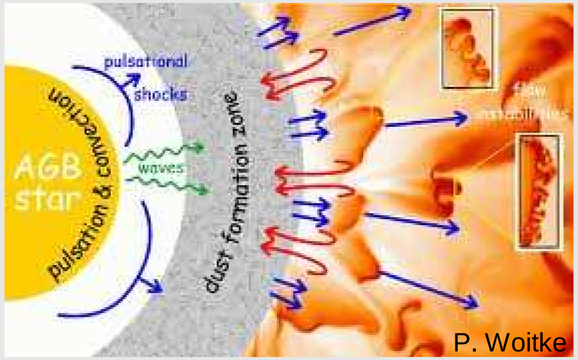


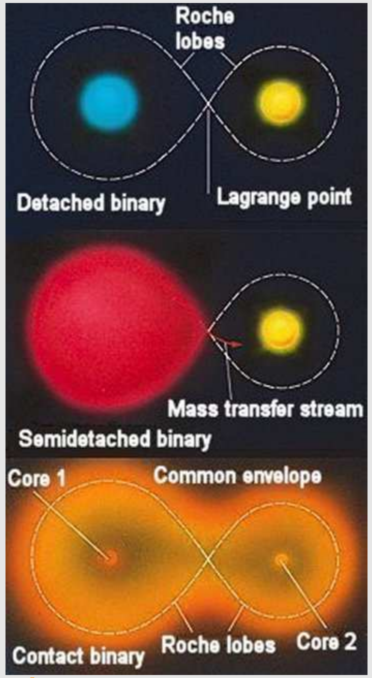
Marigo & Girardi (2007) [synthetic AGB]

The Binary Path to Terminating Red Giant Evolution

Single star - stellar wind
Pulsation + radiation pressure on grains

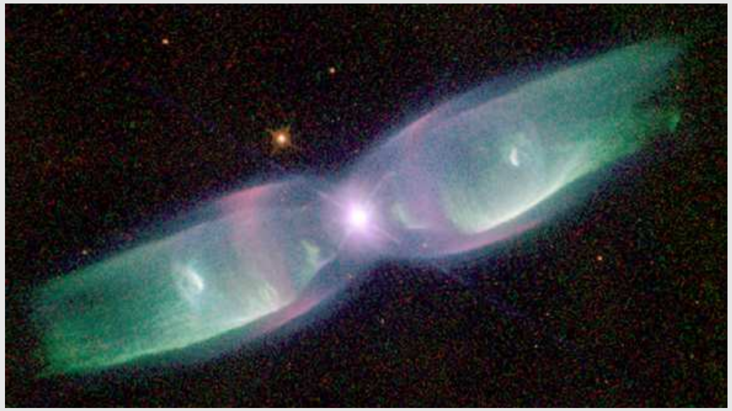
Binary star
Common envelope ejection
~10% of post-AGB births





Post-AGB phase

Post-AGB phase



http://hubblesite.org/gallery/

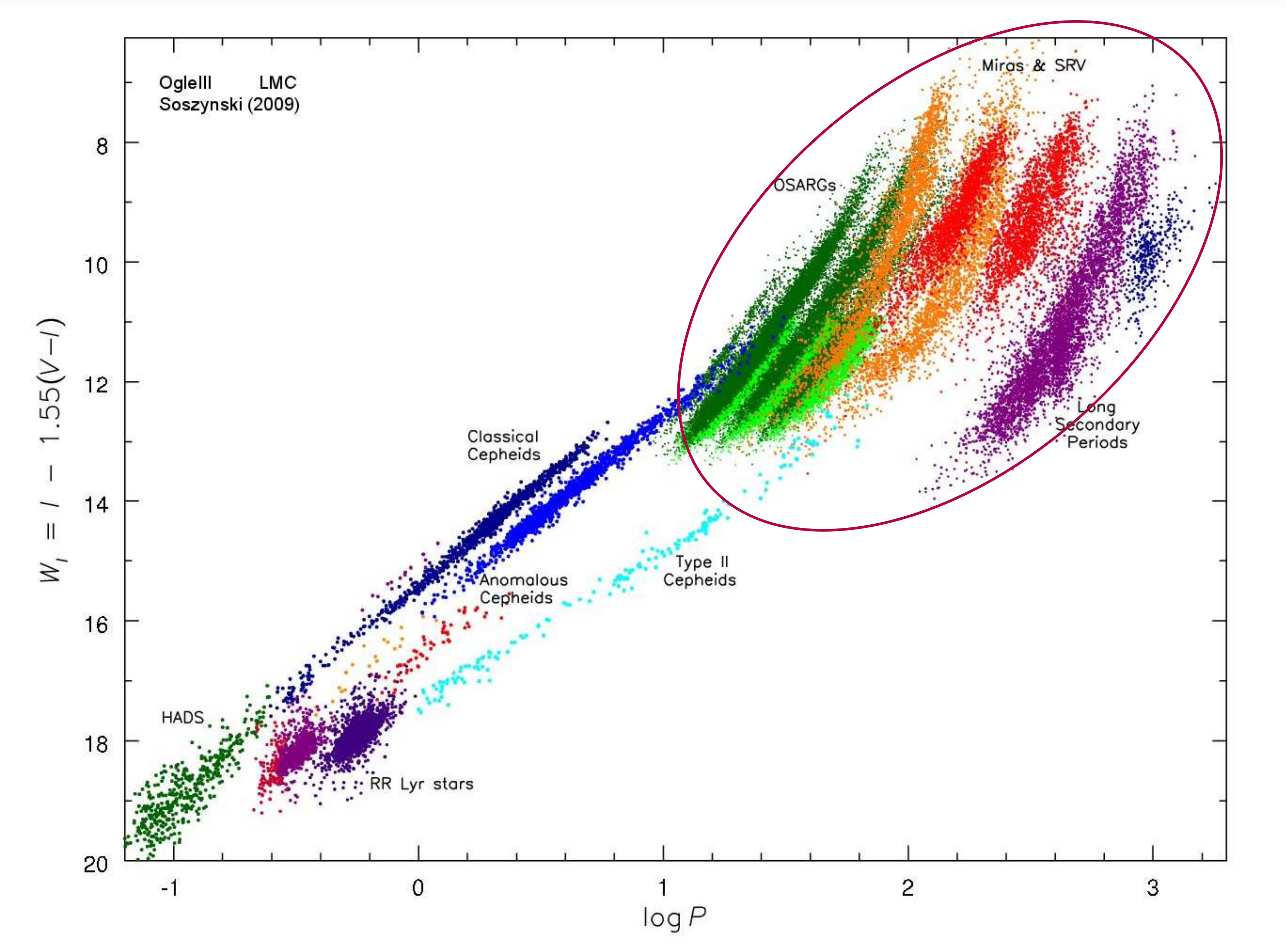
We've heard that pulsation is a key component in driving "superwind" mass loss.

Close binary red giants are variable.

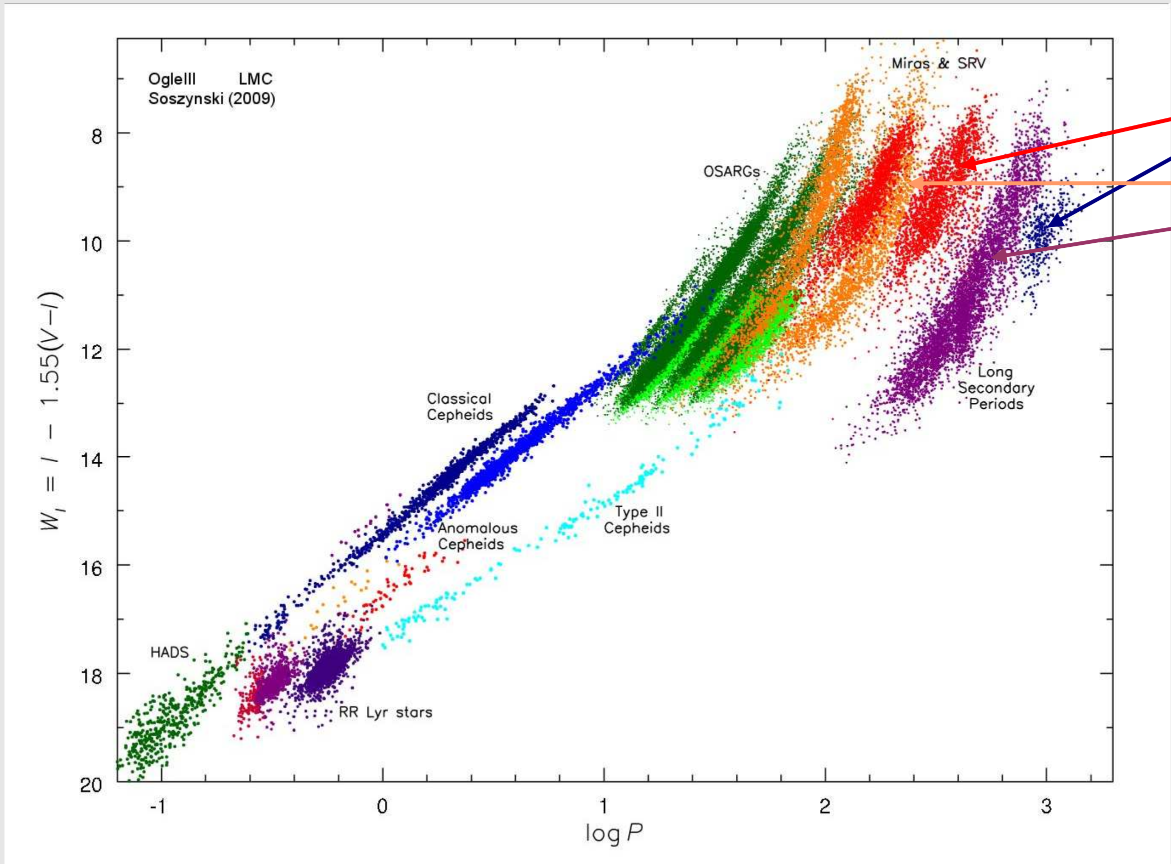
Other sorts of variable red giants lose mass.

So we need to look at the totality of red giant variability.

The Variable Low and Intermediate Mass Red Giants



W_I is a reddening-free **Weisenheit index**



The near-IR K magnitude is a much better luminosity
indicator for red giants than V or I or W_I.

- K is near the peak of the flux distribution
- both C and M stars have similar bolometric corrections to K
- K is less affected by interstellar extinction
- K is less affected by atmospheric molecular band absorption

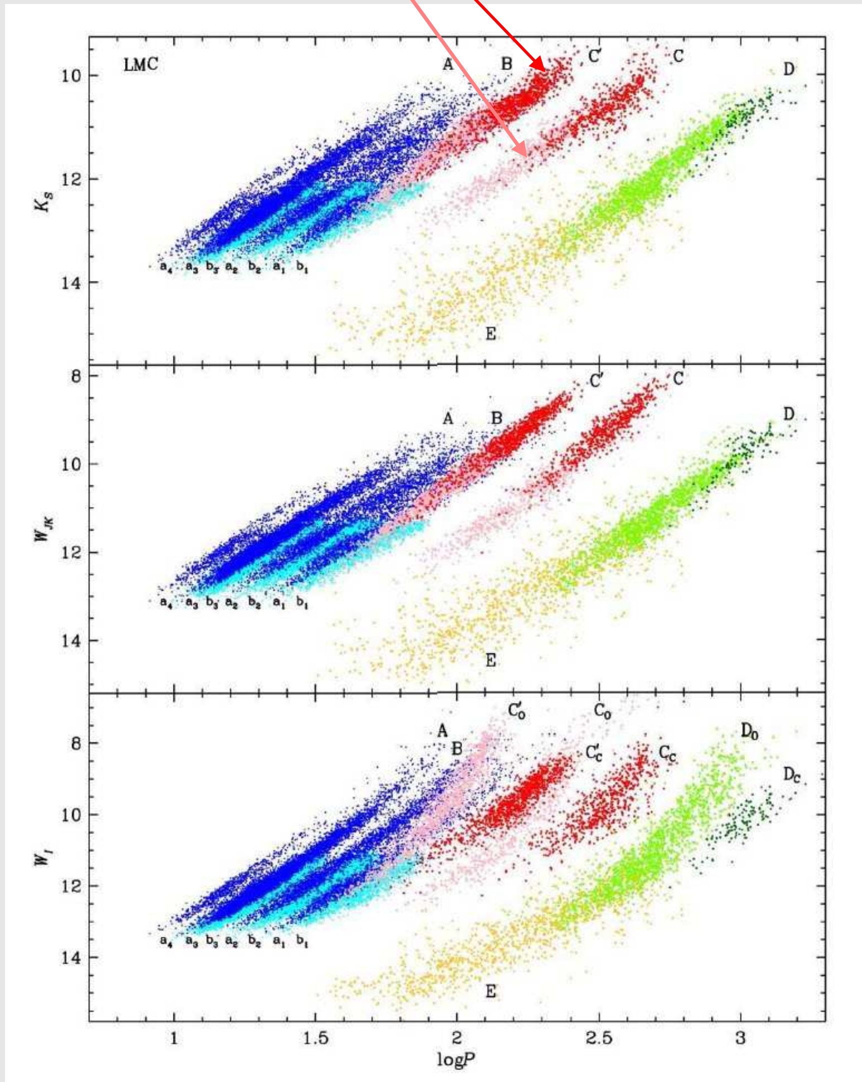
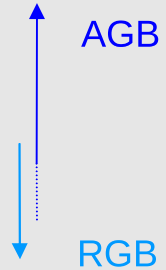


Fig. 1. Period–luminosity diagrams of variable red giants in the LMC. OSARG variables are shown as blue points (RGB as light blue, AGB as dark blue). Miras and SRVs are marked with pink (O-rich) and red (C-rich) points. Light and dark green points refer to O-rich and C-rich LSP variables, respectively. Yellow points indicate ellipsoidal red giants.

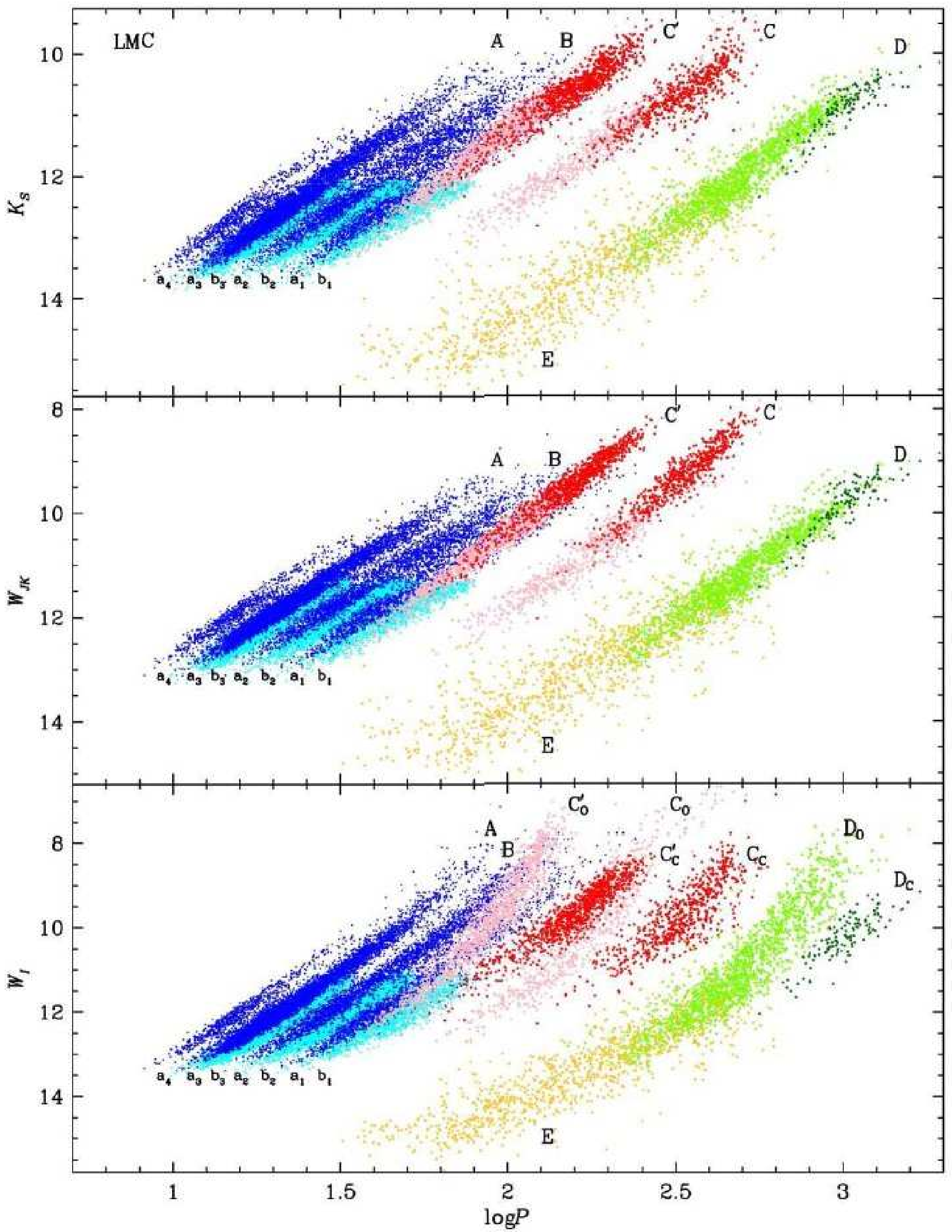
Soszynski et al. 2007: Acta Astronomica, 57, 201

AGB and RGB stars



RGB stars have slightly larger radii and smaller core masses => longer periods.

RGB stars do pulsate at low amplitude, with short periods (does this cause mass loss?).



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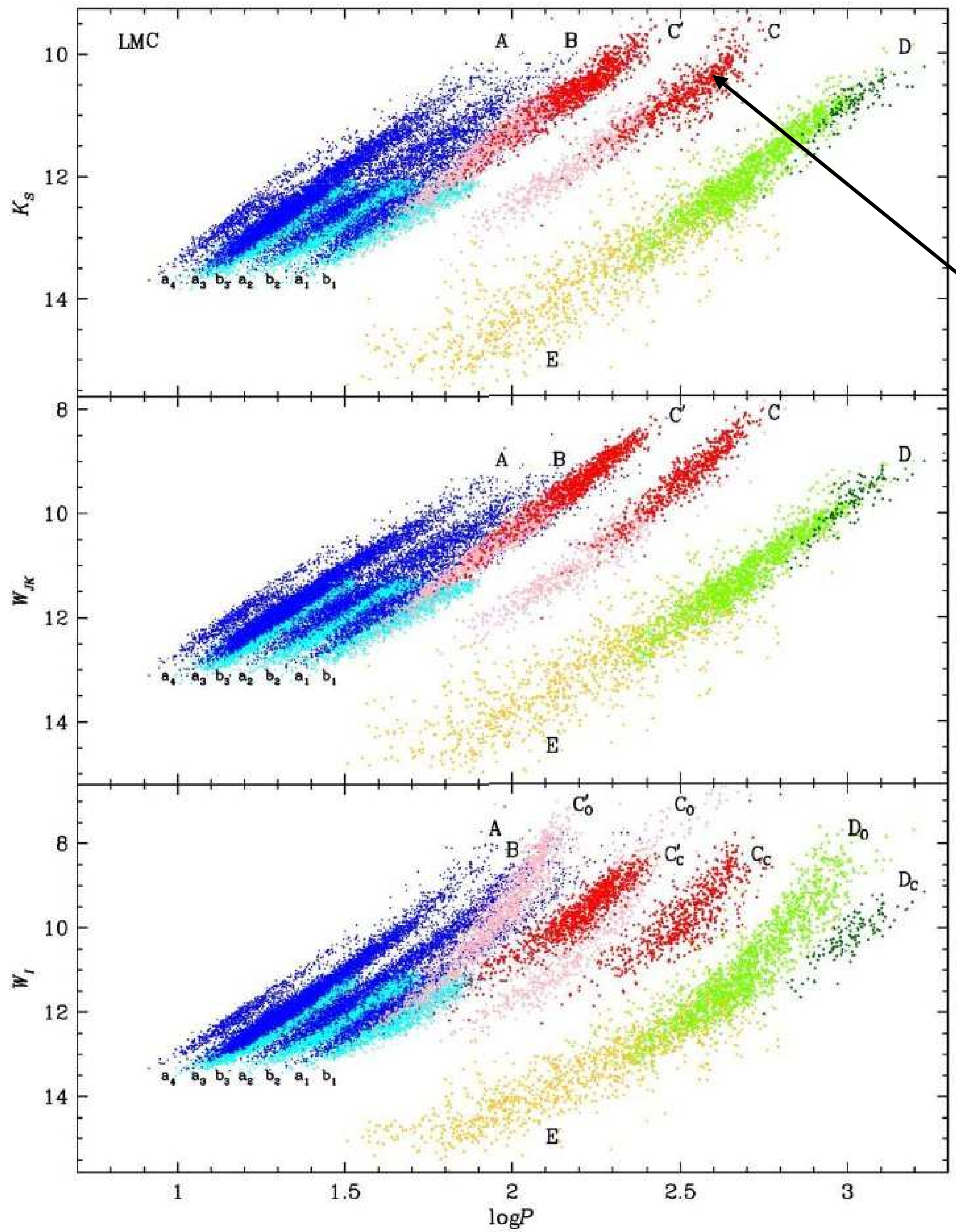
Soszynski et al. (2007)

The Pulsating AGB and RGB stars

Many of the period-luminosity sequences correspond to radial pulsation modes.

Large amplitude pulsators (Miras)



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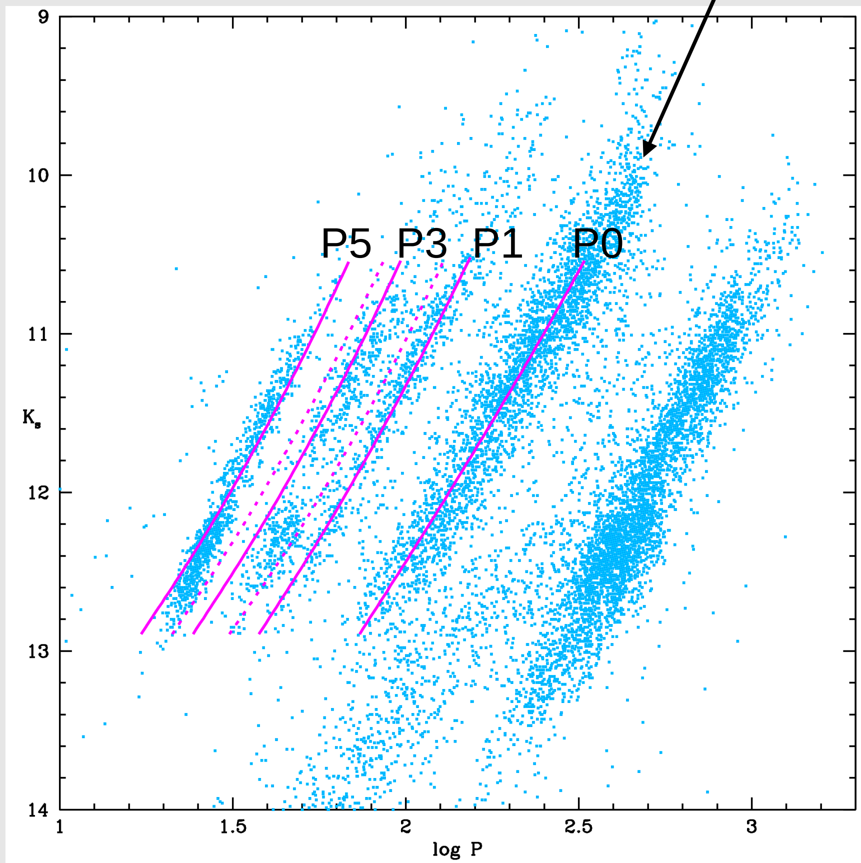
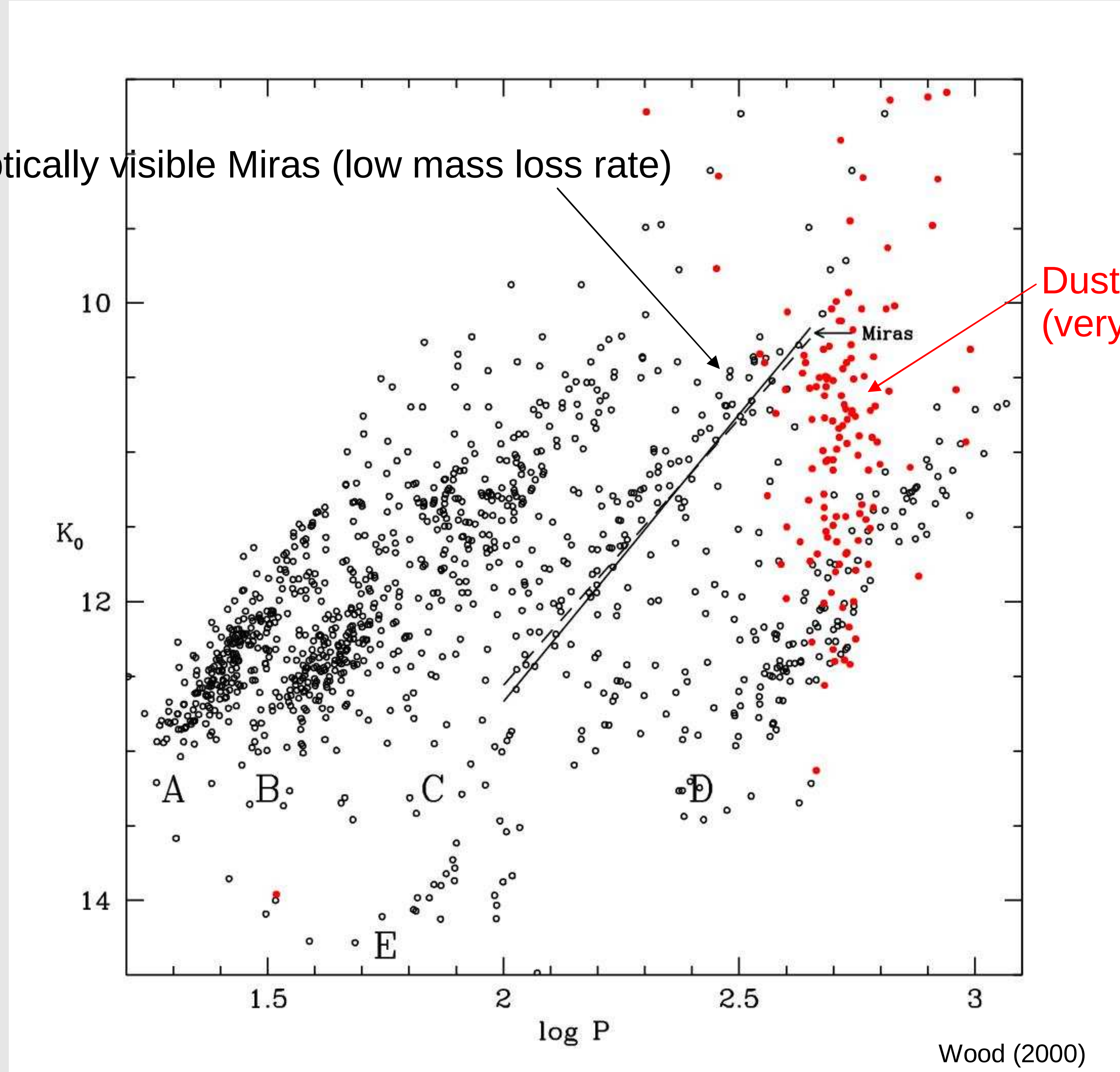


Wood and Arnett (2010)

Very high mass loss rate stars and the K-logP relation

Optically visible Miras (low mass loss rate)



Dusty Miras - mid-IR sources (very high mass loss rate)

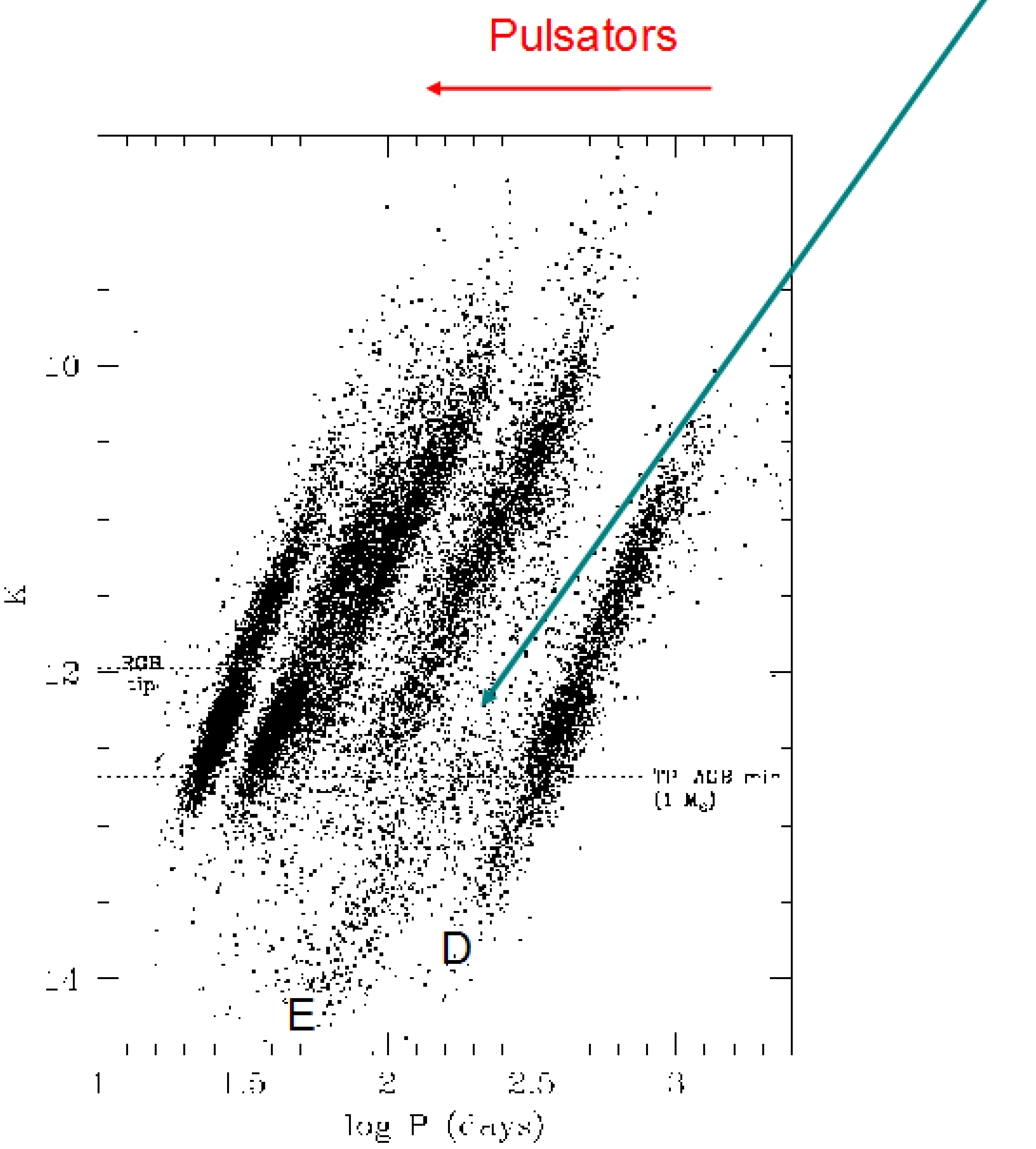
With very thick circumstellar shells, even K is reduced as the flux moves to the mid-IR.

But L is nearly constant...

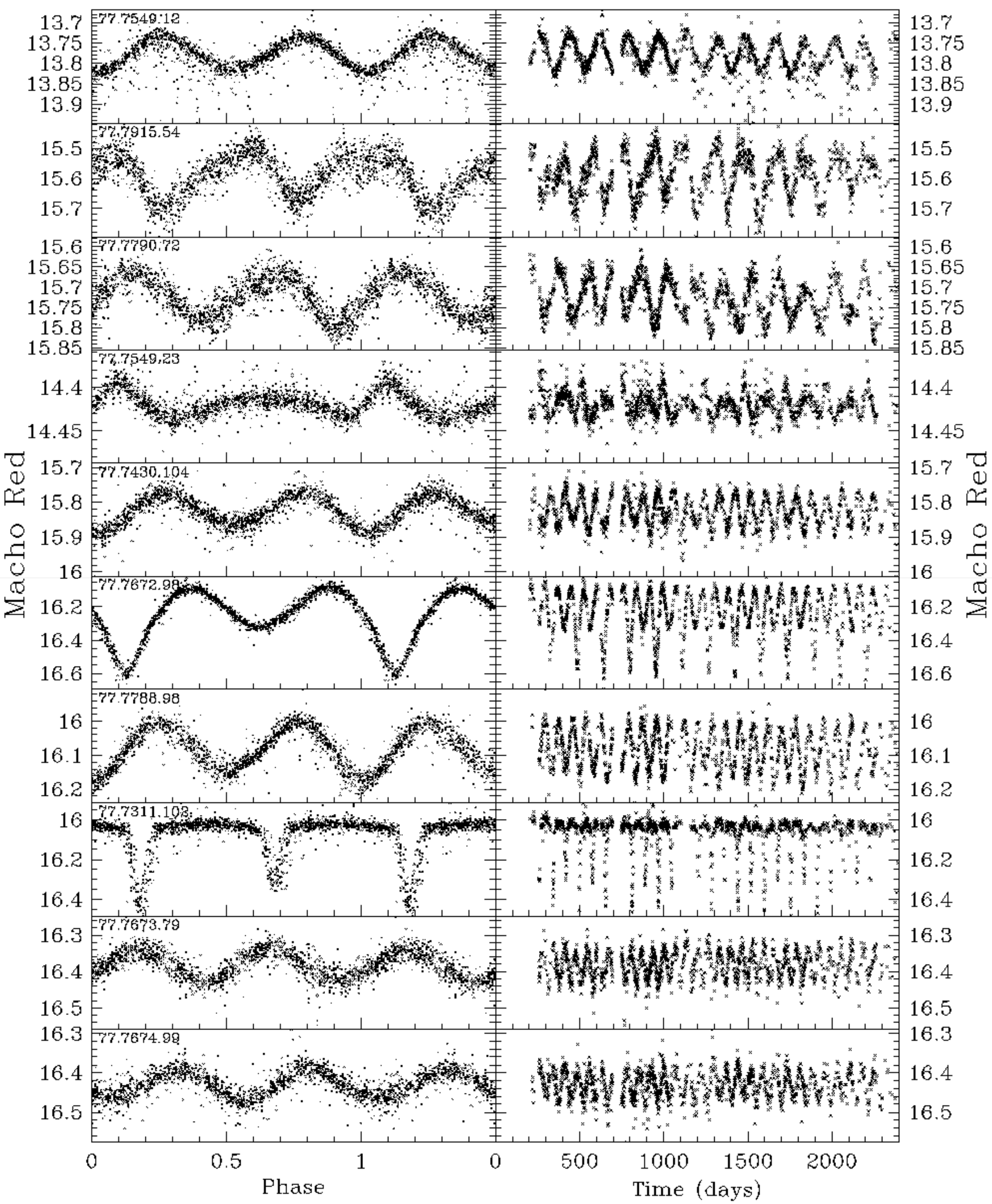
NON-PULSATING VARIABLE RED GIANTS

THE SEQUENCE-E STARS

About 1% of luminous red giants.
All along the giant branch.



Light curves of Sequence E stars



Wood, 2007:ASP Conference Series, 374, 47

There are very clearly eclipsing binaries in the group.

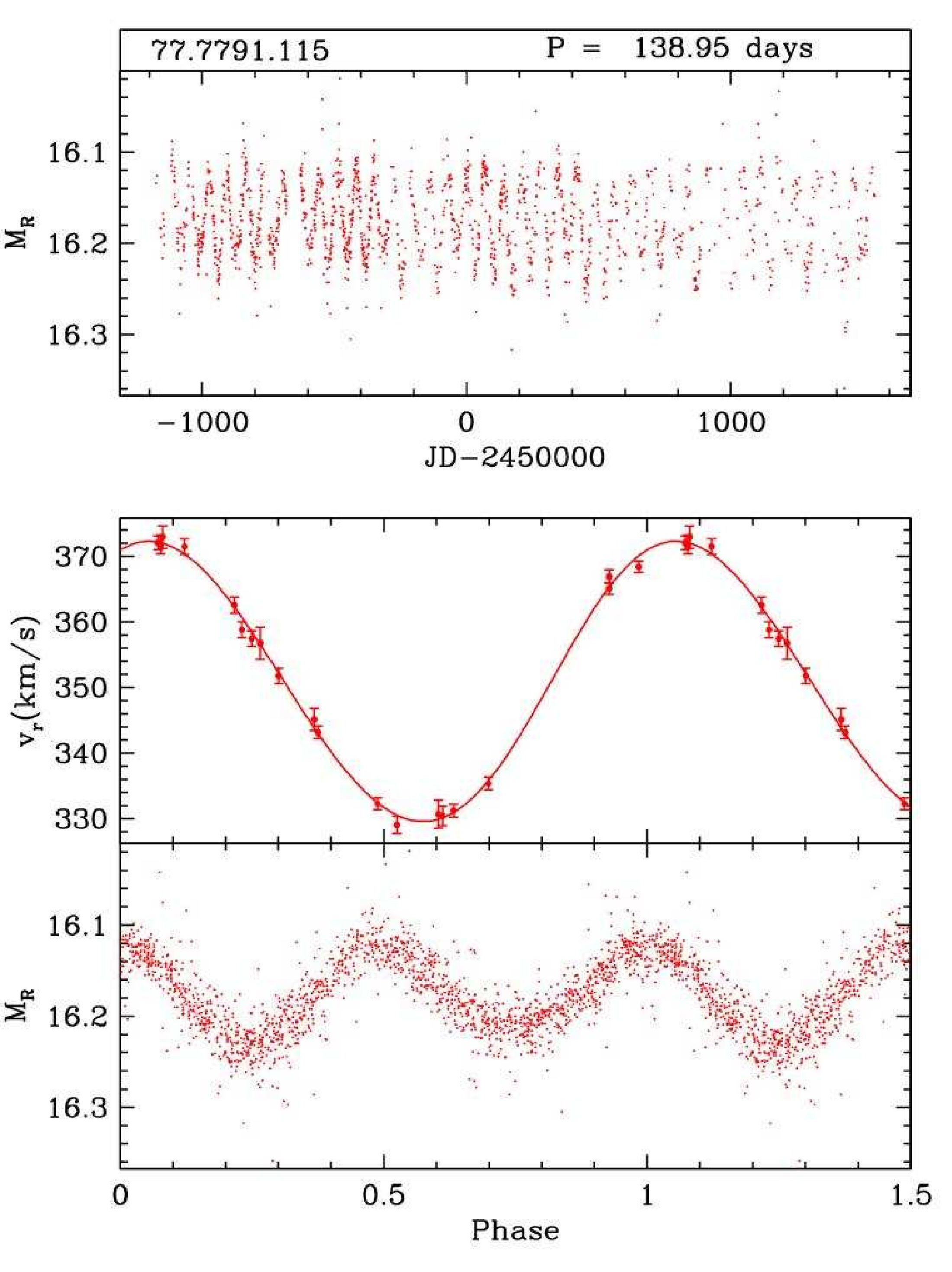
Most (~90%) are ellipsoidal variables – distorted red giants in binary systems with an invisible companion.

An ellipsoidal red giant

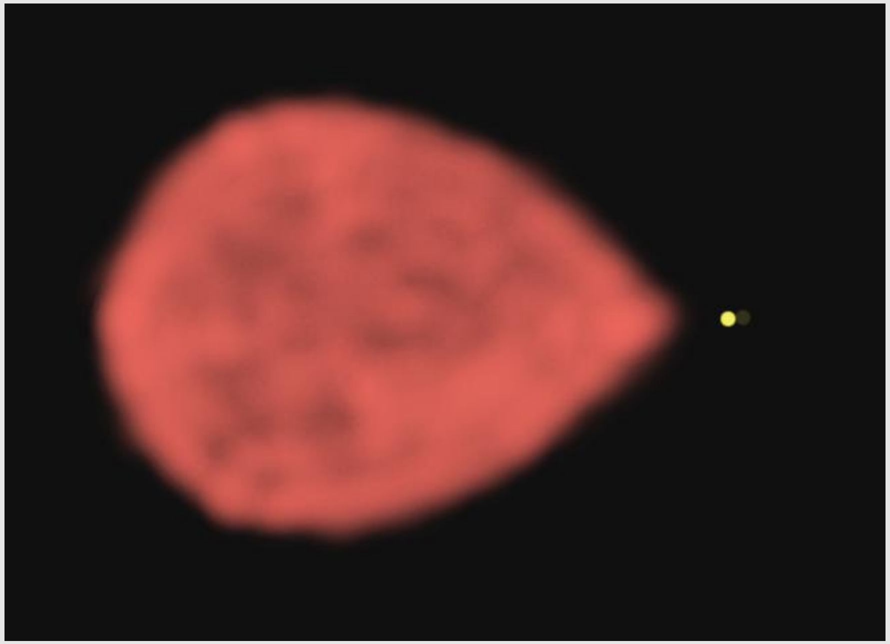
An <u>ellipsoidal variable</u> – we see a single distorted star in a binary

Velocity & light curves of a typical sequence-E binary.

Orbital period = twice light period.



Wood, 2007:ASP Conference Series, 374, 47



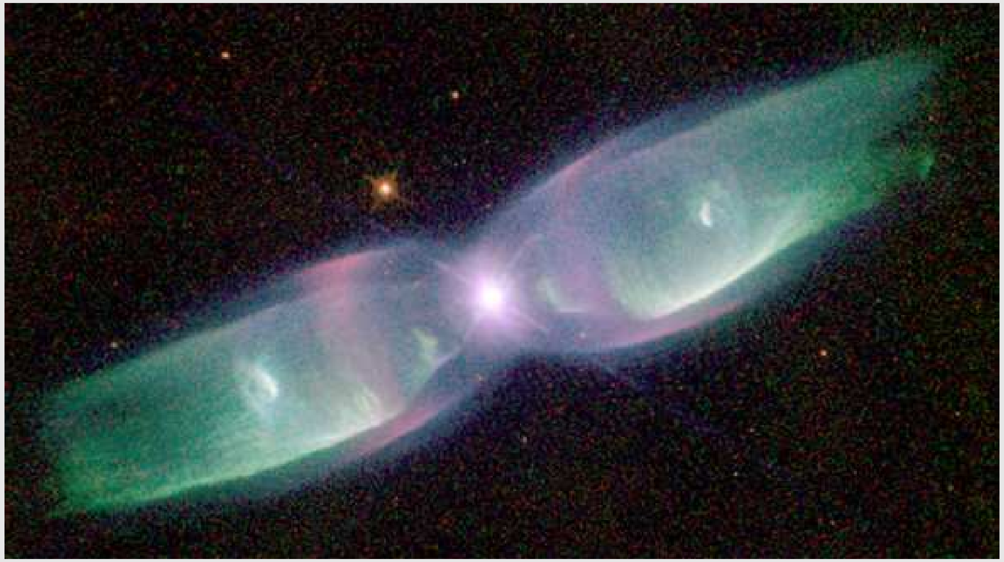
A red giant showing ellipsoidal variability must be close to filling its Roche Lobe.

Further evolution up the RGB or AGB will lead to the red giant filling its Roche Lobe.

The outcome will be a Common Envelope Event - the ejection of the entire red giant envelope giving a planetary nebula (probably bipolar, certainly asymmetric).
The central remnant star will be a close binary.

The observed fraction of red giants that show ellipsoidal variability, combined with models for ellipsoidal light curves can be used to estimate the fraction of planetary nebula central stars that come from termination of AGB evolution by a Common Envelope Event leaving a close binary central star. Nicholls and Wood (2010) estimated this fraction to be 8-13 %.

This is an alternative form of mass loss for ending the AGB.



Eccentric ellipsoidal binaries

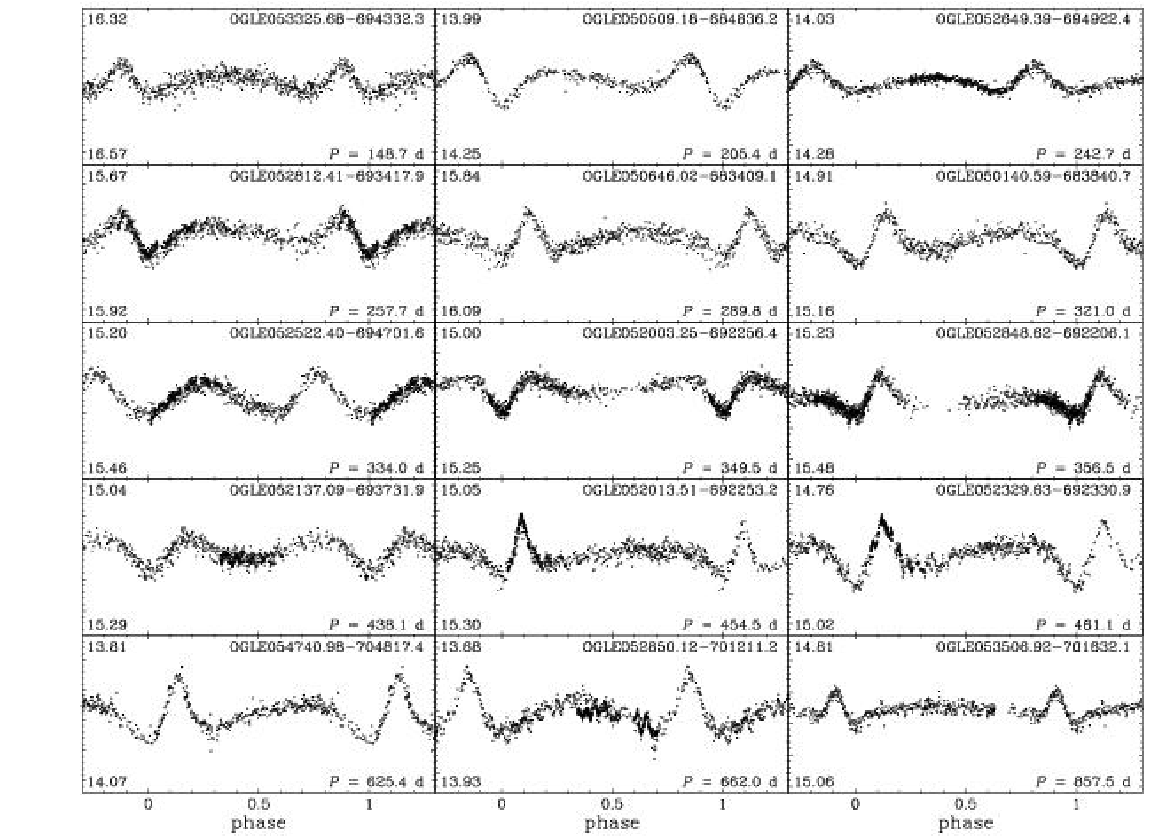
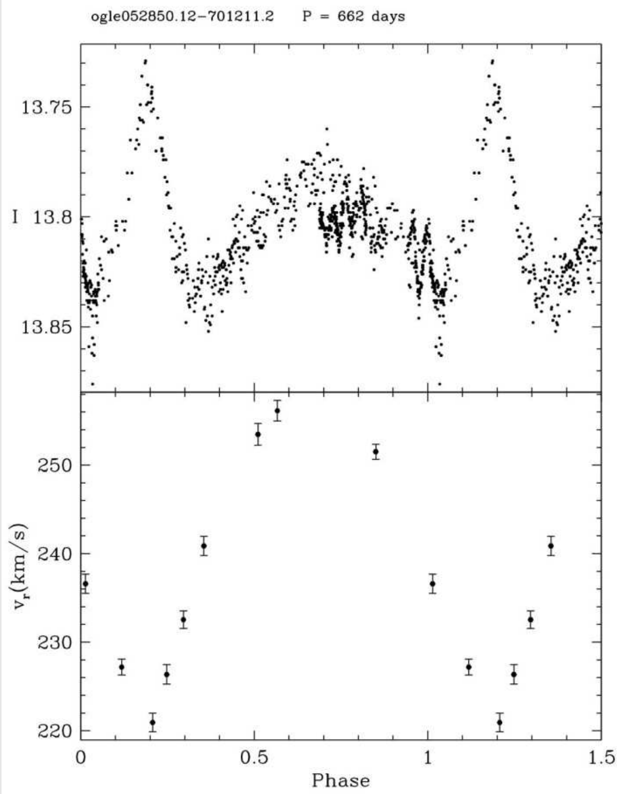


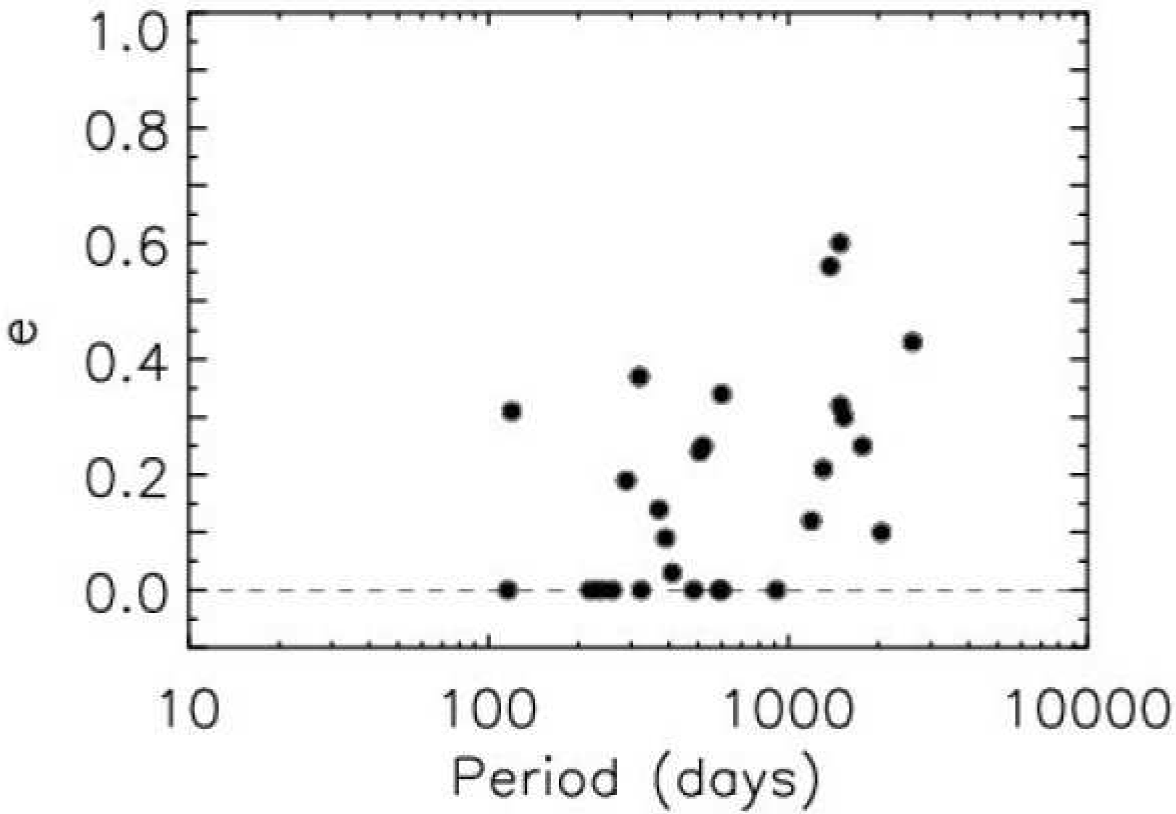
Fig. 7. Light curves of the exemplary ellipsoidal red giants with eccentric orbits.



Soszynski et al. (2004)

About 10% of red giant binaries have unusual shaped light curves.
These are eccentric binaries.

e-log(P) diagram: post-AGB stars: 28 orbits



Periods AND high eccentricities are NOT expected !

Phase of strong binary interaction in the past.

Now all objects are within the Roche lobes

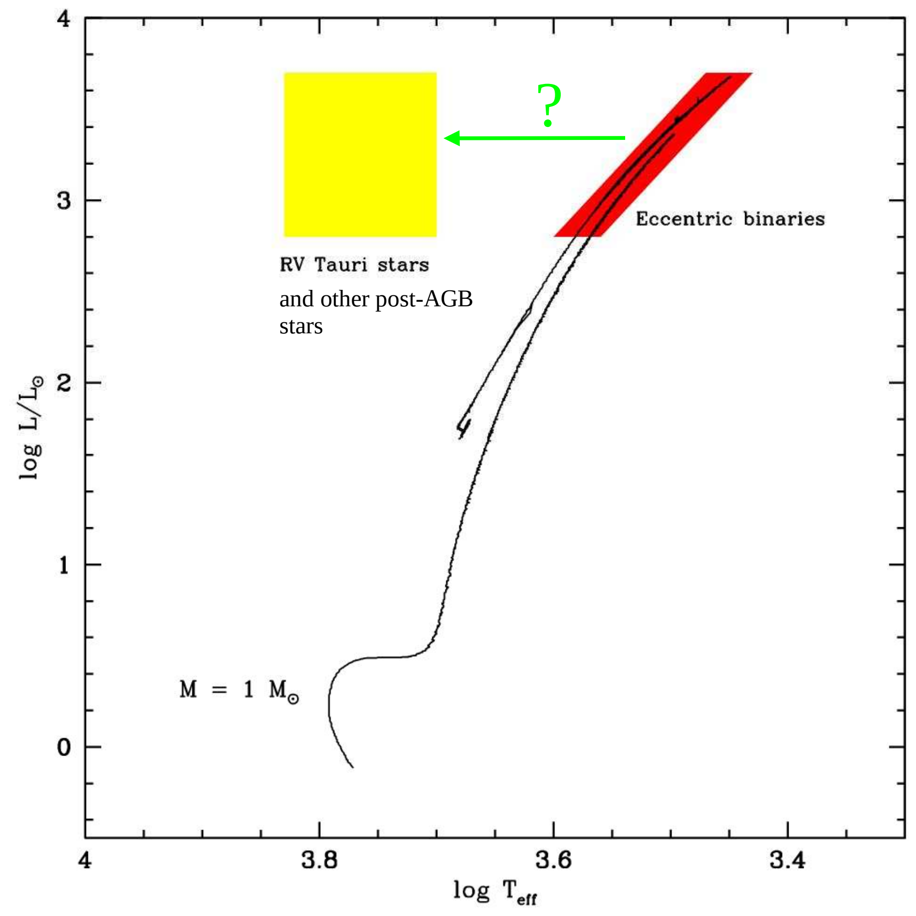
From Hans Van Winckel

Post-AGB stars (many are RV Tauri variables) have the periods and eccentricities similar to the eccentric sequence-E stars.

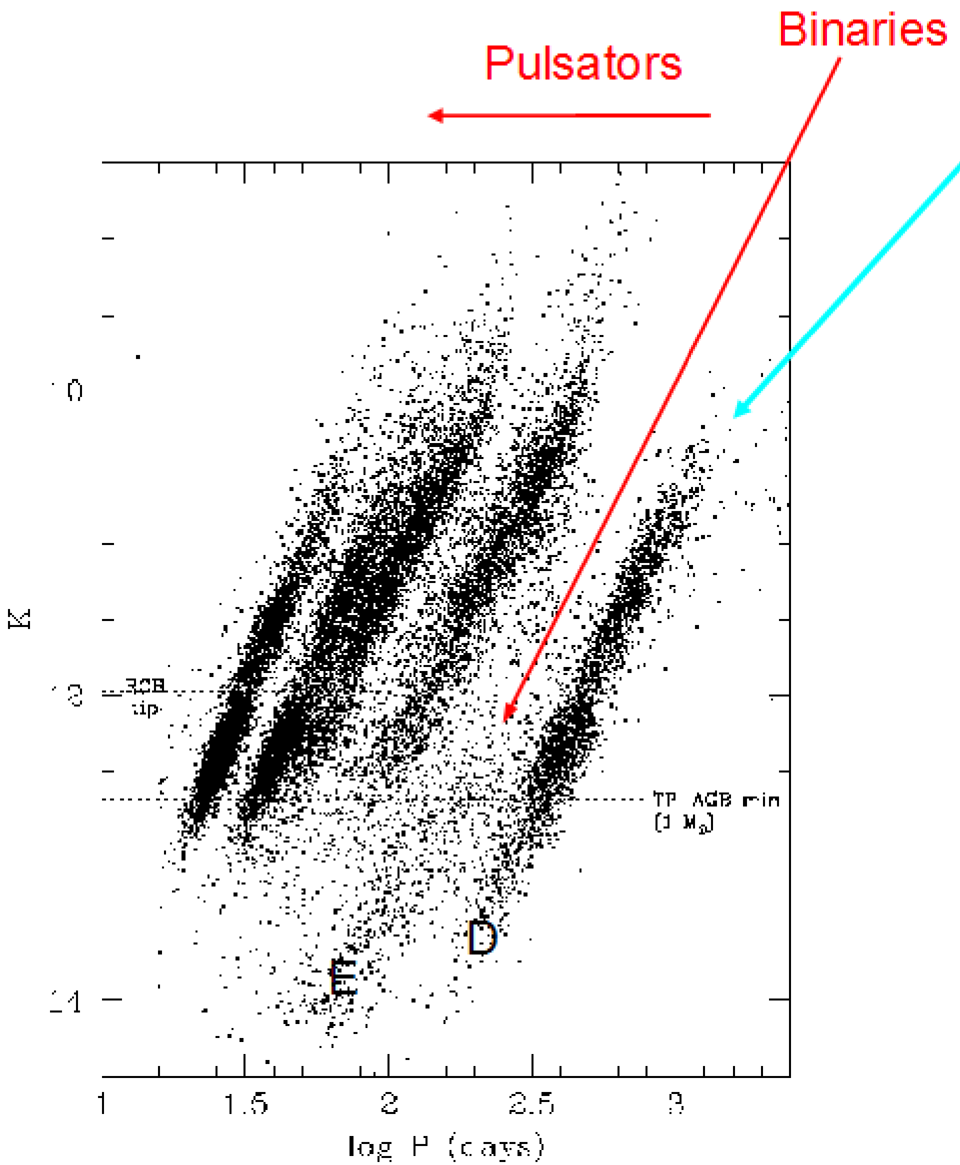
Do the eccentric sequence-E red giants have their envelopes stripped gradually by mass loss/transfer at periastron, without a CE event?

The RV Tauri stars are known to have circumbinary disks, and similar luminosities to the eccentric binaries, and many (if not all) are eccentric binaries.

Yet another mode of mass loss to terminate the AGB?



FINALLY... THE SEQUENCE-D STARS

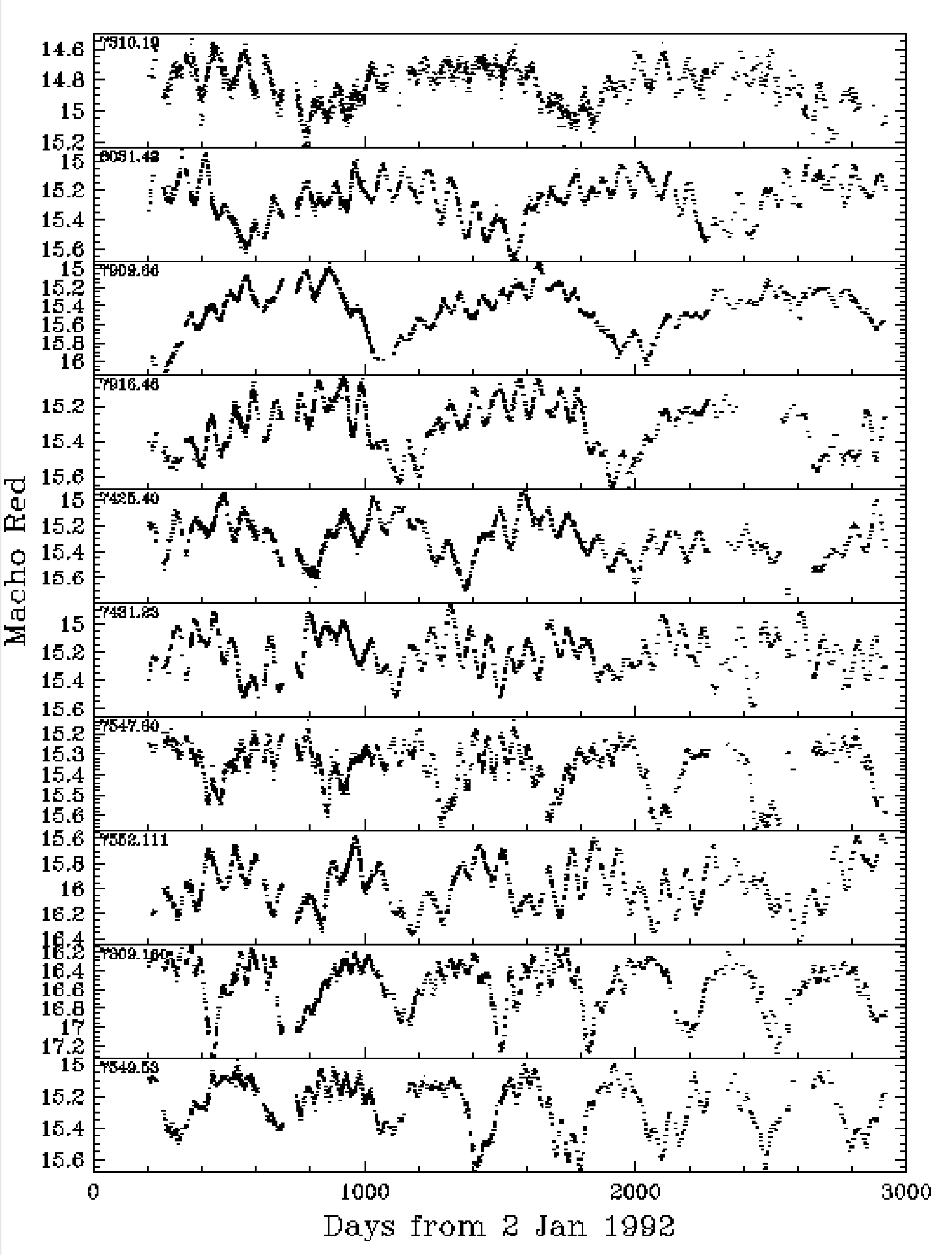


What are the Sequence D stars?

~30% of all luminous red giants!

They can not be normal-mode radial pulsators since P is longer than the fundamental mode.

STARS WITH LONG SECONDARY PERIODS (LSPs)



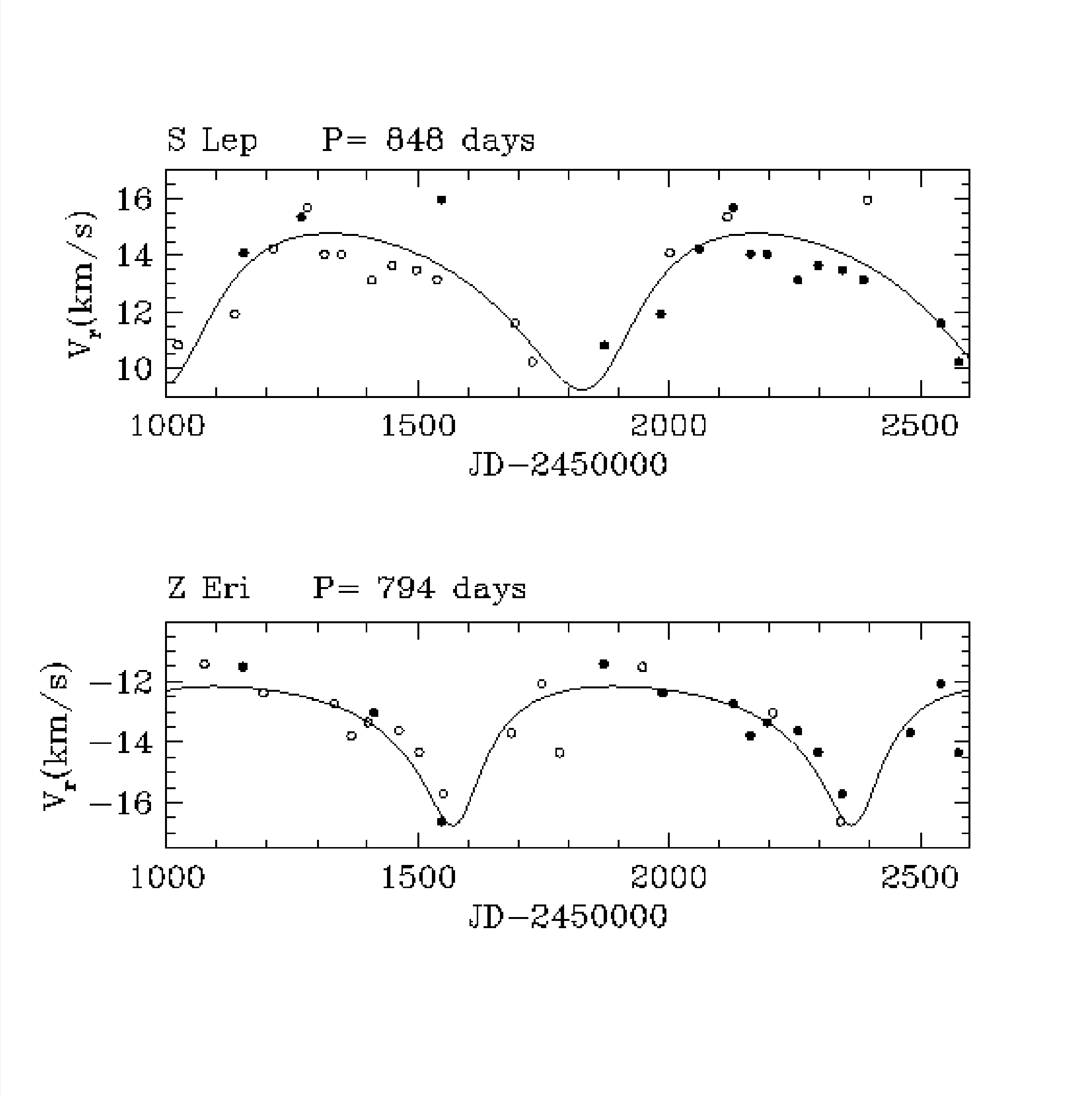
The LSPs lie on sequence D.

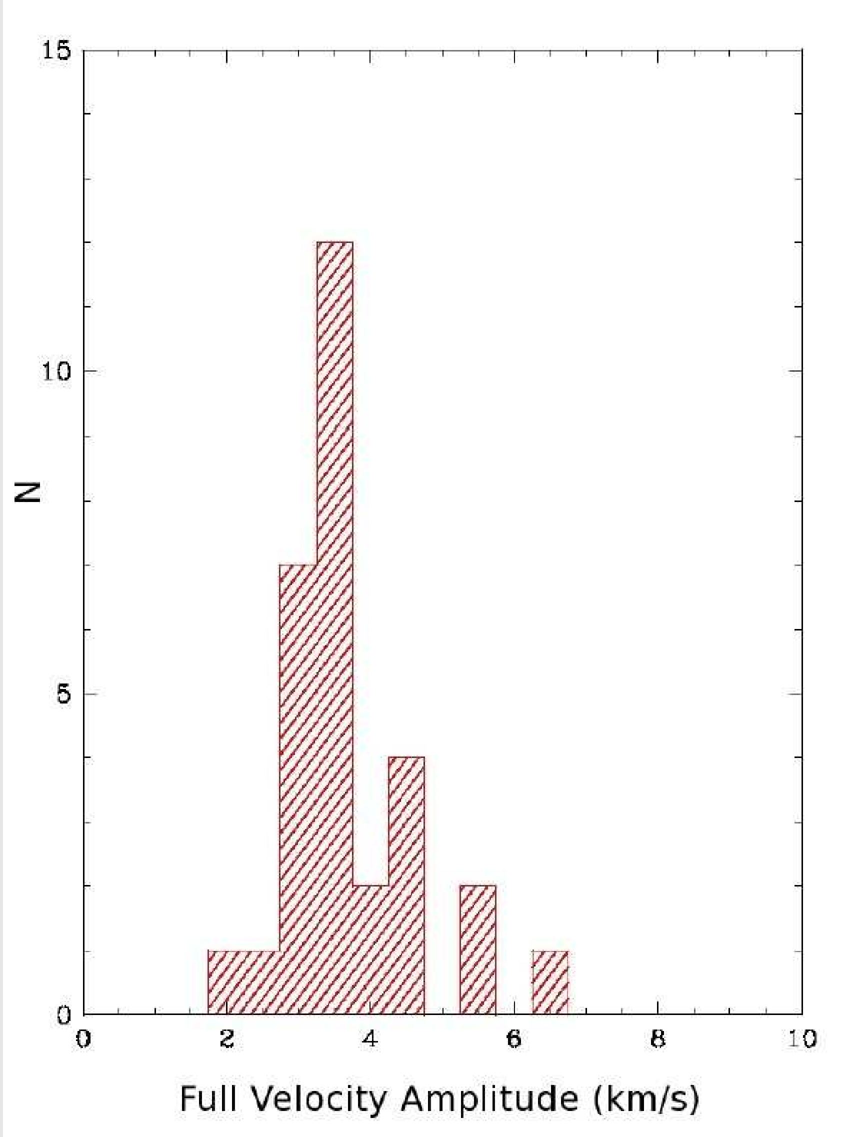
Primary period is sequence B (or A or C occasionally)

Amplitudes up to 1 mag.

Variation is not regular.

They have radial velocity amplitudes ~ 3.5 km/s.

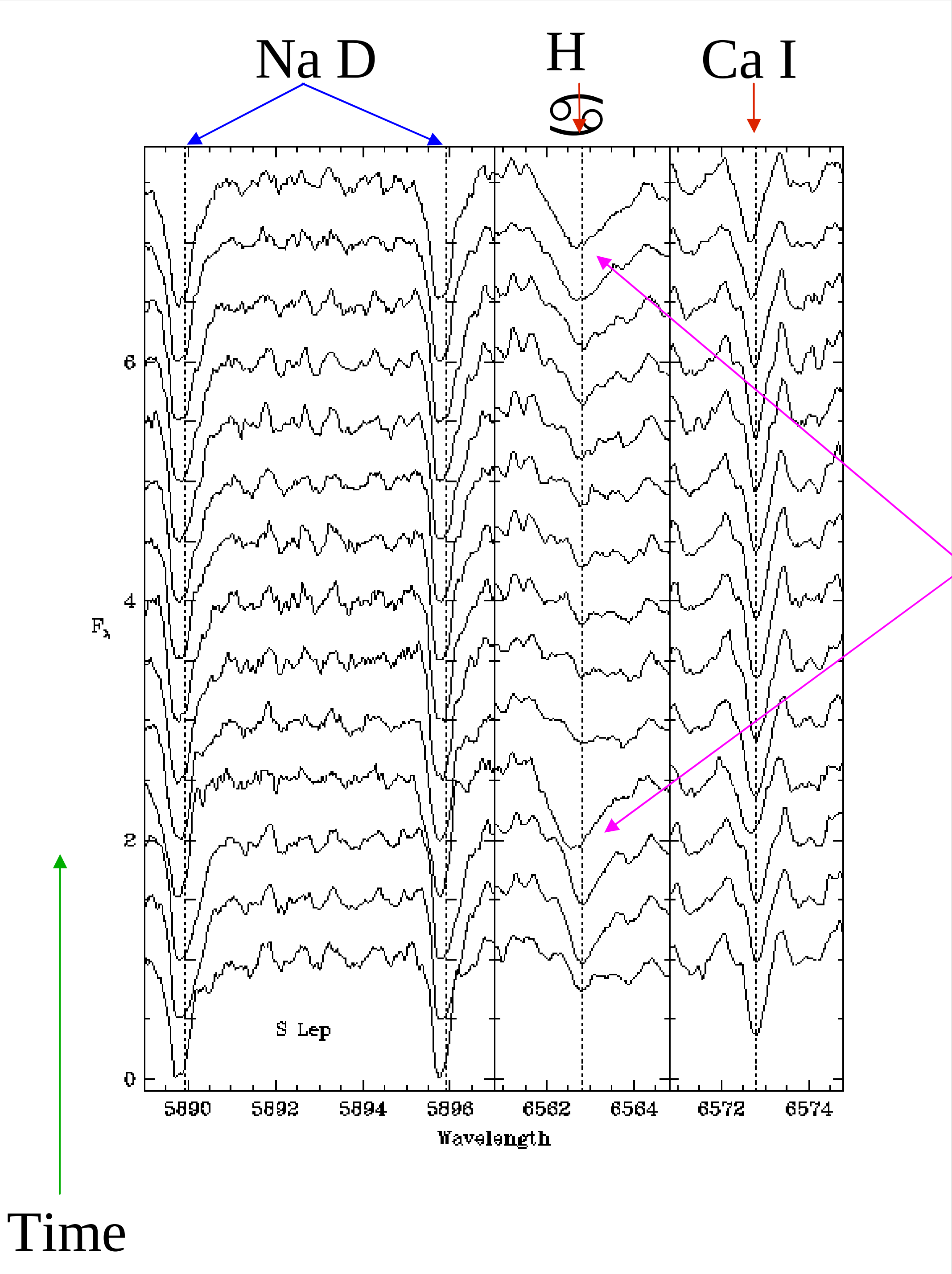




Wood, Olivier and Kawaler (2004)

Nicholls et al. (2009)

Another property - chromospheres



Wood, Olivier & Kawaler (2004)

Spectra of S Lep

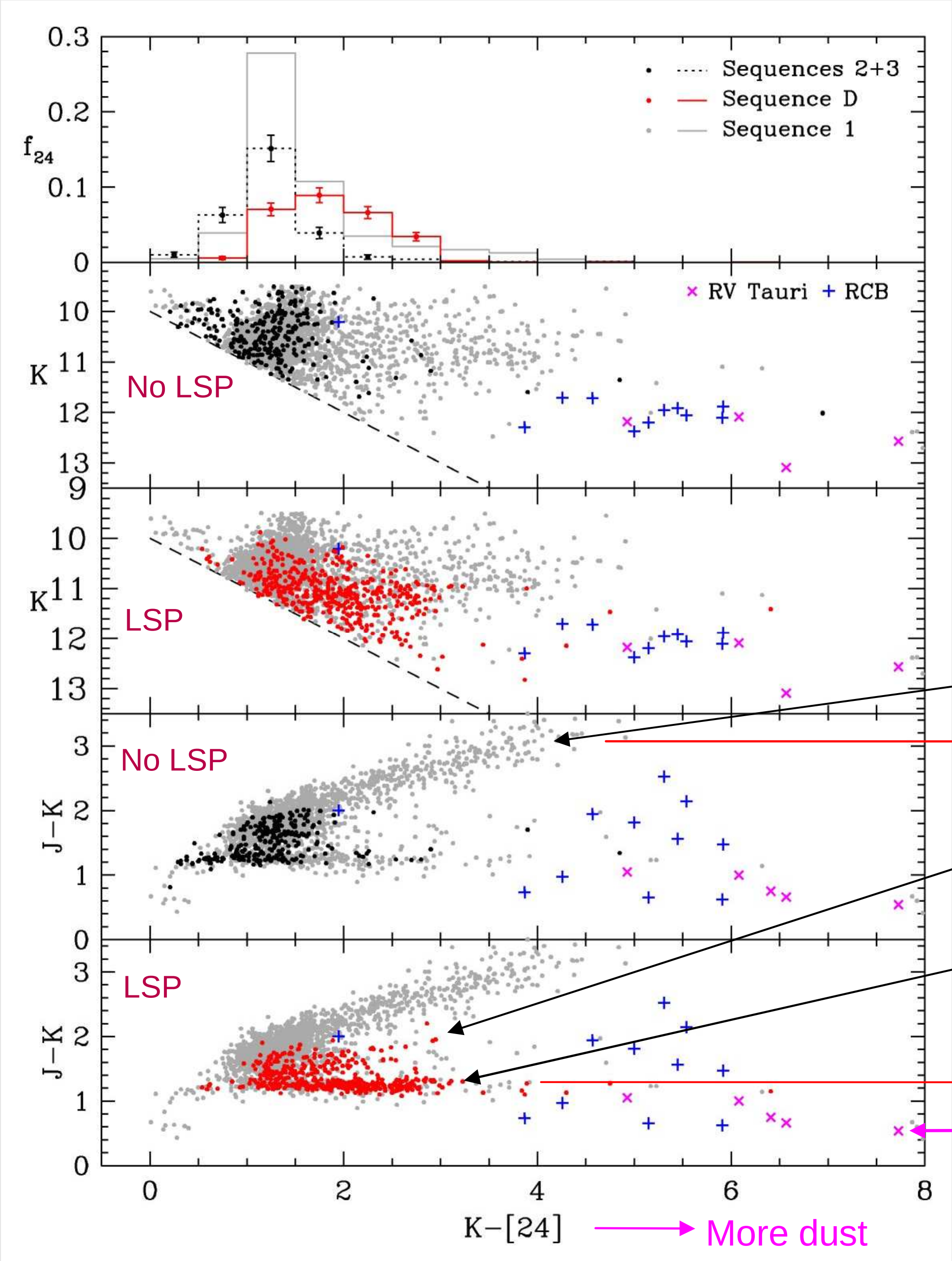
Hα is chromospheric in these stars (T_{eff} ~ 3200K).

Central line depth ~50%.

At least 50% of the stellar surface must be covered by a chromosphere periodically.

Need T~8000K in gas absorbing Hα. Hα is produced by the n=2 to n=3 transition in hydrogen.

And they have a stronger mid-IR excess than non-LSP stars => Mass ejection is caused by the LSP



- Stars with LSPs have larger K-[24] colours => mass ejection and dust formation associated with the LSP
- The low J-K colour indicates that the dust is in a disk (or other non-spherical distribution)
- The first steps to a bipolar nebula?

C stars with spherical mass loss shells

C stars

M stars

?

RV Tauri stars with disks

Wood & Nicholls (2009)

But we still have no firm idea what causes the sequence-D variations!

It has been spectulated that resonance between orbiting planets and unstable nonradial modes is the cause....

THE END (Mass loss and pulsation)

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