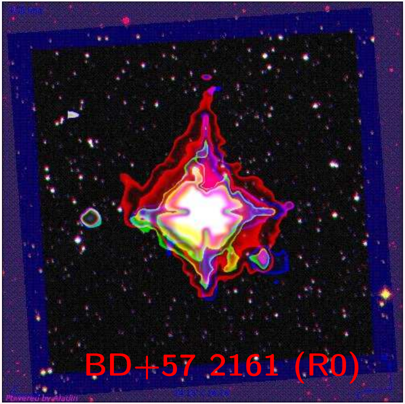
Solving the Century-Old R-Star Mystery



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John Lattanzio (Monash University)

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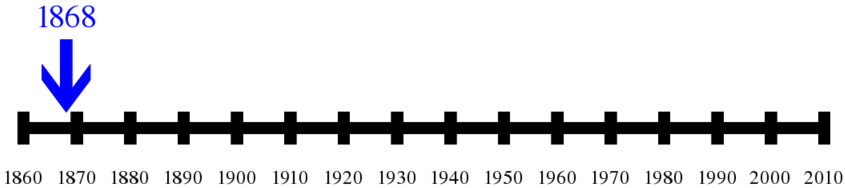
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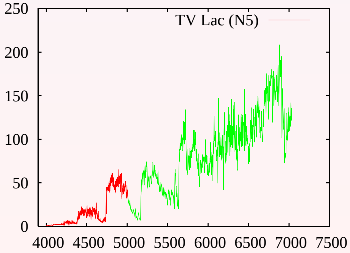
Father Secchi, 1868

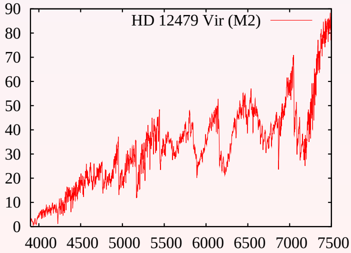
A Catalogue of Spectra of Red Stars: "You will see that there is a new type of stars. . . this classification is very curious indeed. I am, however, surprised to see some zones always at the same places; so that there is a great cosmical law about to come forth . . . You see, however, that the red stars make quite a family by themselves, which is very distinct."

His Discovery...

The Carbon Stars

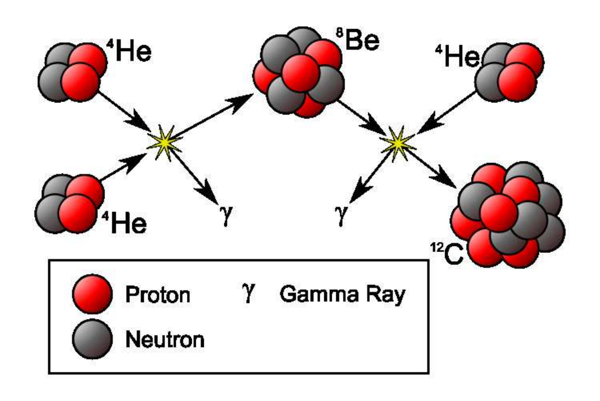
- Asymptotic Giant Branch Stars (H + He burning)
- $1 - 3\,M_\odot$, all Z, $L \gtrsim 10^3\,L_\odot$, $R \gtrsim 100\,R_\odot$, $T_{eff} \sim 3 \times 10^3$ K
- *Third Dredge Up* brings carbon to the surface
- Spectral "zones": C_2, CN, CH etc. absorption bands
- Spectral Type *N* = Spectral Type *M* with carbon

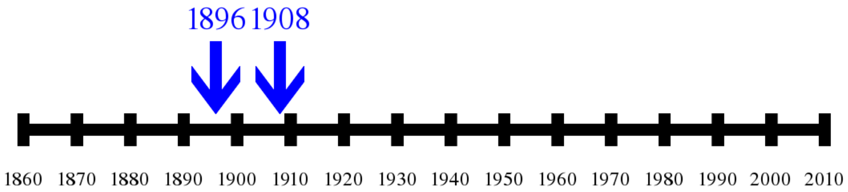




How To Make Carbon

- Carbon in stars must come from somewhere...
- Triple alpha reaction, $3\alpha \rightarrow^4$ He, in AGB and WR stars (SNe)

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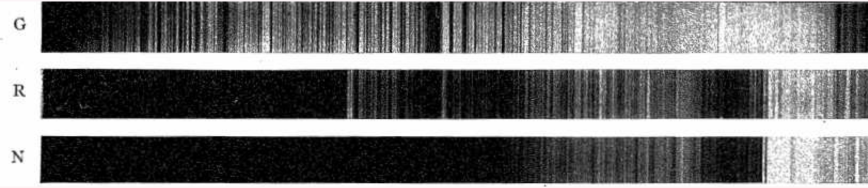
Fleming & Pickering, 1896/1908

Fleming & Pickering, 1896/1908

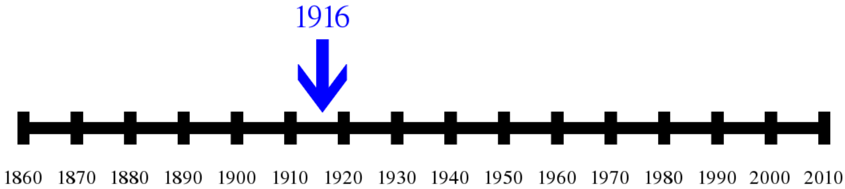
- Observations 1896 - Reclassification in 1908.
- In Fleming's classification, stars of the fourth type are red carbon stars (N stars)
- "Of the seven stars whose spectra are here announced as of Type IV ... <four> contain rays of much shorter wave length than ordinary fourth type stars"
- 

- "They are described as showing one or more dark bands" which "agree almost equally well with the dark band in spectra of the fourth type"

Fleming & Pickering, 1896/1908

- "These spectra cannot well be classed as fourth types since they contain so much blue light"
- "Why not assign a Class to them, if they are outside the Classes already known?"
- Definition of "Class R, to designate stars having this Class of spectrum".
- Fleming finds 51 stars which fall in this new Class R.

Class R stars are not rare!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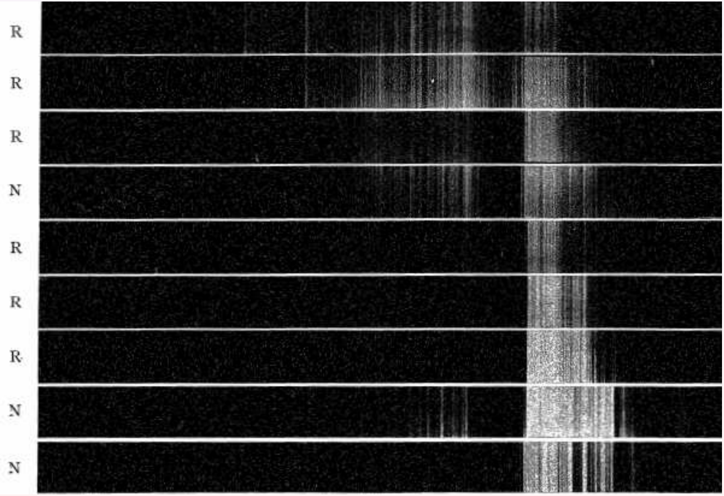
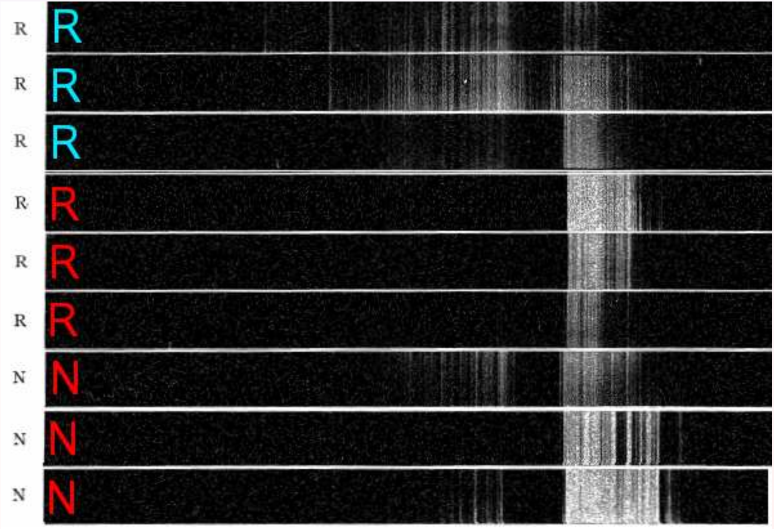
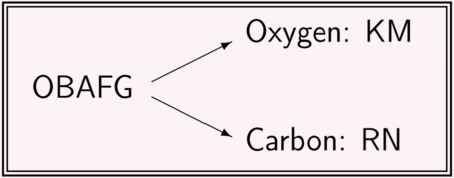
Rufus 1916

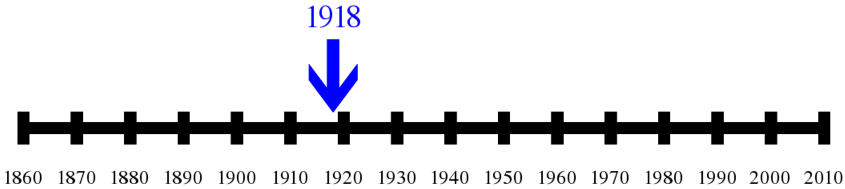
- Class R precedes class N ?
- 

Rufus 1916

- Class R precedes class N
- 

Rufus 1916

- Class R precedes class N
- First discussion of *carbon as the agent of the bands*
- Identifies R stars with K stars on the basis of colours, galactic distribution, radial velocities, variability, similarity of absorption lines, similar (cyanogen, hydrogen, 4227 etc) lines.
- ...and M with N stars
- 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Henry Draper Catalogue, 1918

Cannon and Pickering, 1918

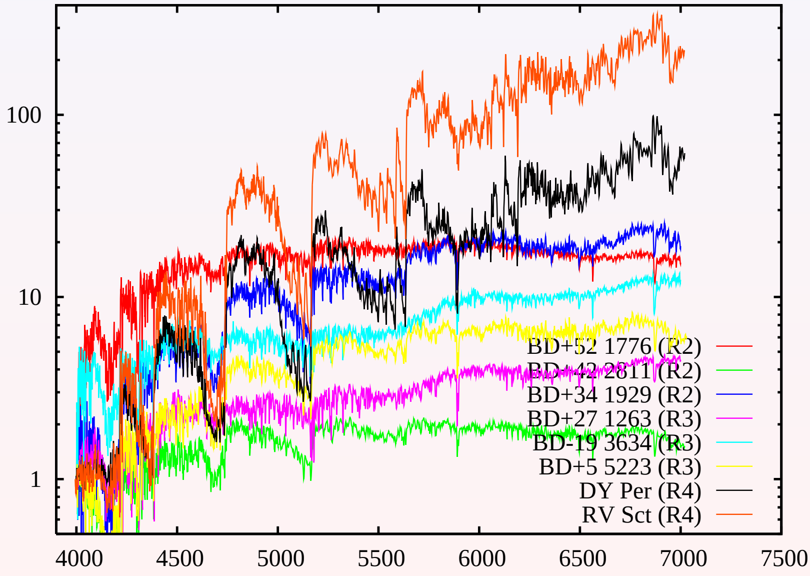
Henry Draper Catalogue, 1918

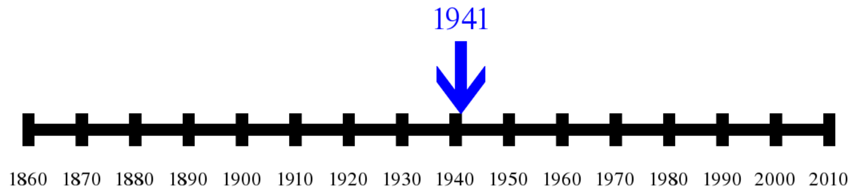
Cannon and Pickering, 1918

- Split Class R into R0 to R8, from bluest to reddest:
- R0: ~G5/K0, dark C-band at 4700. Some K-R0 intermediate spectra, H and K calcium bands visible.
- R3: As R0 with fainter H and K calcium lines.
- R5: Shorter than 4240 the continuous spectrum is barely visible.
- R8: Very faint shorter than 4240, hard to distinguish from Class N

Also updates due to Shane 1928, Wildt 1936:
Cyanogen lines in R stars, not in N stars

Spectra (Barnbaum et al. 1996)

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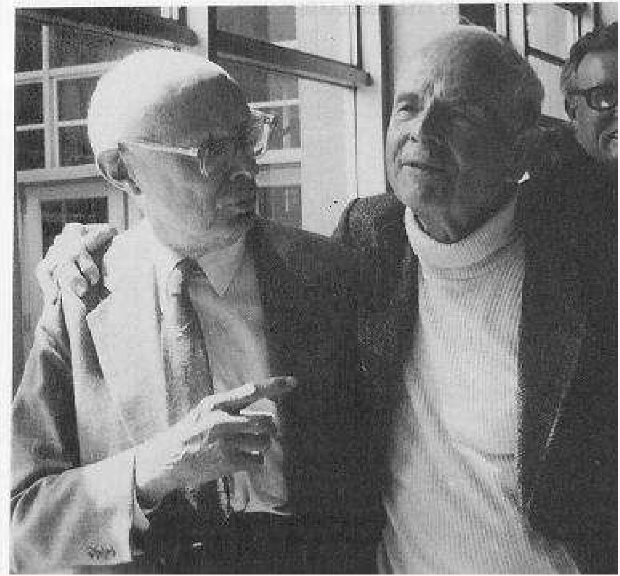
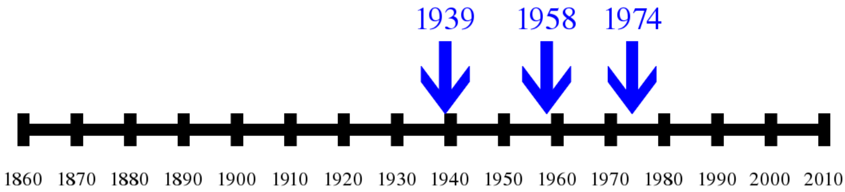
Keenan and Morgan, 1941



Keenan and Morgan, 1941

- Reclassification of R-N
- *Spectral classes R and N do not appear to represent a consistent progression in temperature.*
- New classes based on: atomic line ratios sensitive to temperature, sodium D lines, C_2 molecule etc.
- Class depends on stellar carbon abundance
-

First identification of high velocity *CH stars:* *Low metallicity dwarfs/giants which accreted carbon from an N-type AGB star*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Statistical Surveys

Wilson 1939, Sanford 1944, Vandervort 1958, Baumert 1974

- Magnitudes of (early) R stars:
  $1 - 2\,\text{mag}$ *dimmer* than N stars
- Early R stars are *Red Clump* stars?
  (magnitude about 0.5)

Sanford 1944, Vandervort 1958

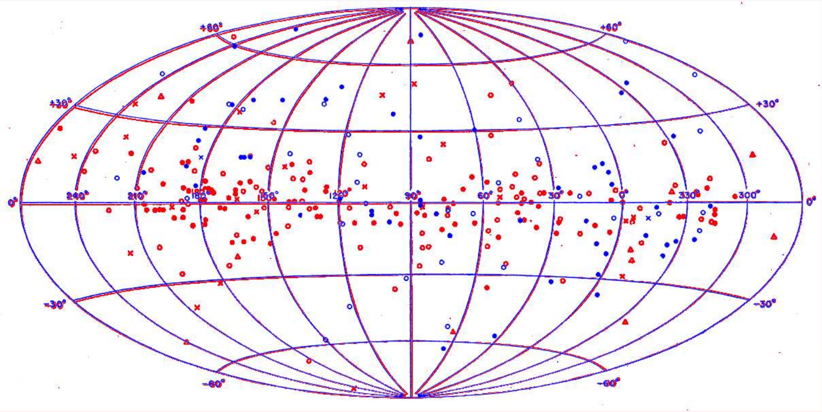
- Radial velocities:
  R stars faster (older) than N stars?

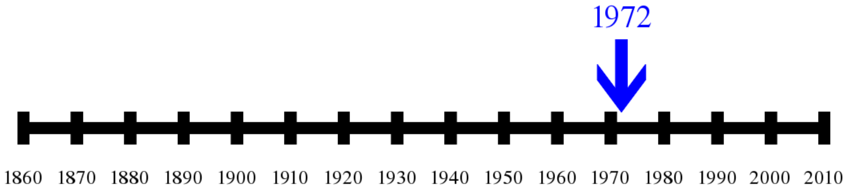
Statistical Surveys 2

Sanford 1944, Blanco 1965, Barbaro and Dallaporta 1974

- R-stars distributed over the sky,

  N stars show galactic concentration





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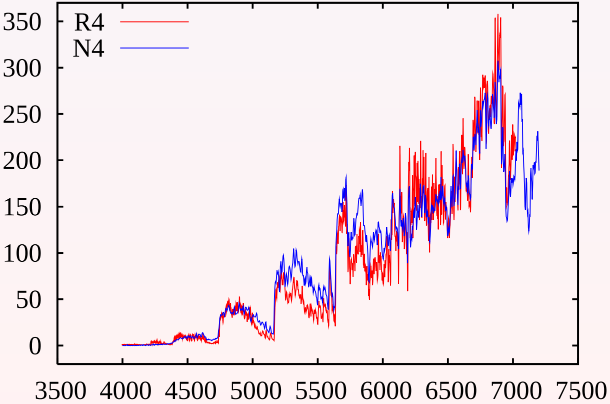
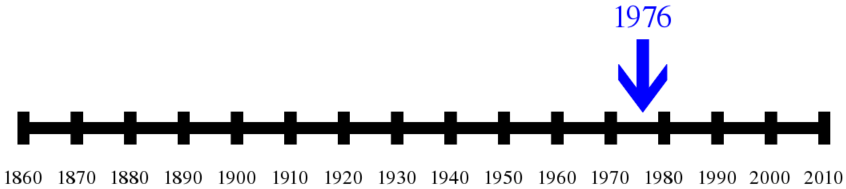
Eggen 1972

- Keenan and Morgan changes: *A Retrogressive Step*
- Some HD R5-R8 objects *reclassified* as type N!
- Only hot R0-R3 objects are true R stars
- **Late R stars are just misclassified N stars?**
-

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Scalo's HRD

Early R stars

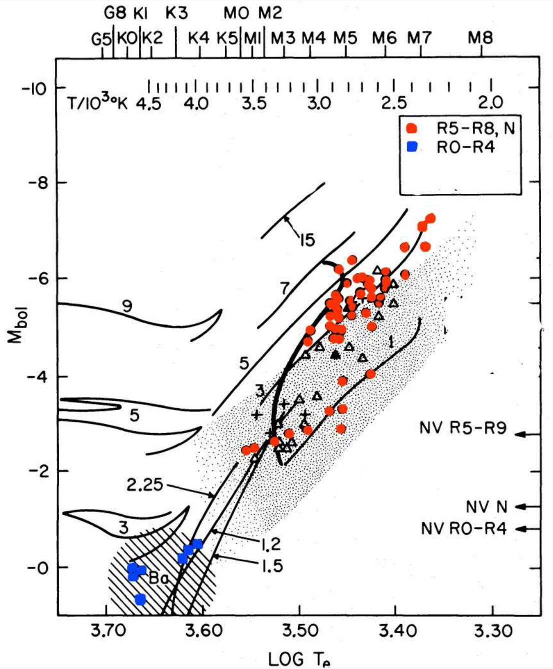
$L \sim 100\, L_\odot$

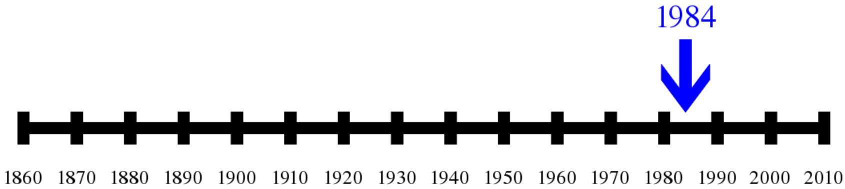
$\sim L_{clump}$

Late N stars

$L \sim 1000\, L_\odot$

$\sim L_{AGB}$

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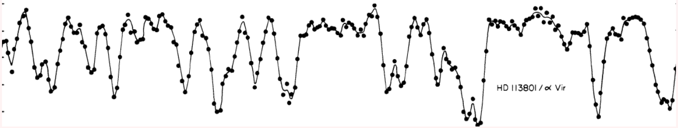
Dominy 1984

Modern hi-res spectra of *Early R stars* ($\Delta\lambda/\lambda = 30,000$)

- Carbon/Oxygen > 1 Helium burning
- $^{12}C/^{13}C < 10$: ^{13}C enhanced Hydrogen burning
- Nitrogen enhancement Hydrogen burning
- Oxygen and iron normal (~solar) Not too hot/much hydrogen burning, old disk population
- No lithium enhancement No AGB
- No odd Mg isotopes Not too much hydrogen burning
- No s-process No AGB



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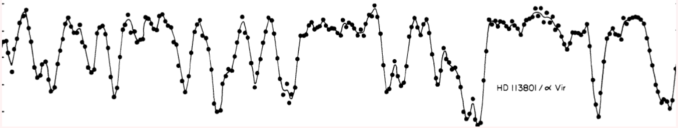

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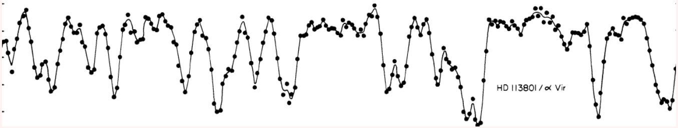

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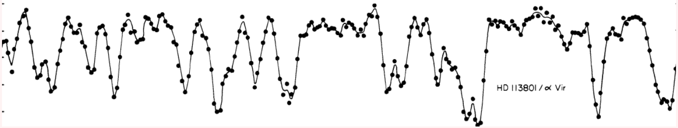

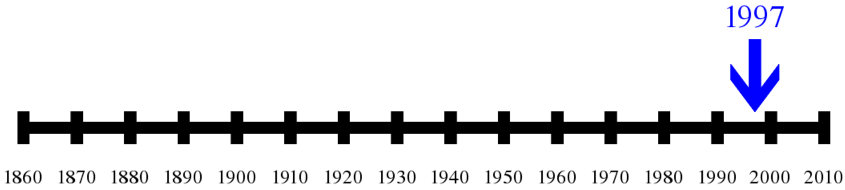
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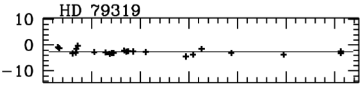
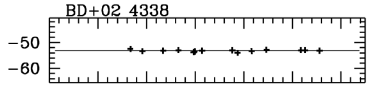
McClure 1997

- A key to the mystery! Observed 22 early R stars over 16 years . . .
- Early R Stars are

ALL SINGLE STARS

- Compare to:
- 20% binaries in late type giants
- 100% in Barium and CH stars (giants or dwarfs)





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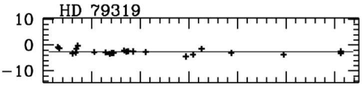

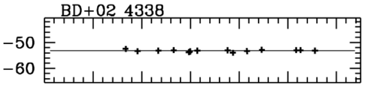

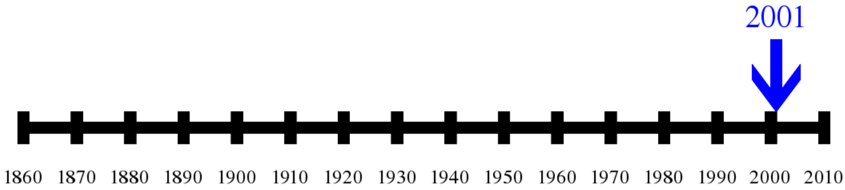
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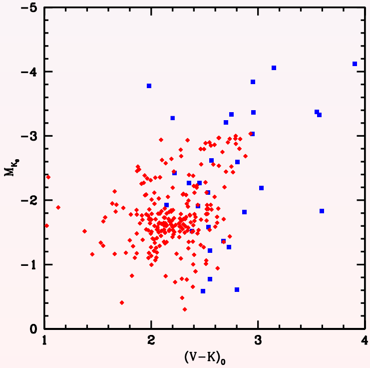
Knapp et al. 2001

- 317 Hipparcos cool carbon stars
- R0-3 $M_K = -2.0 \pm 1.0$ compared to -1.6 for red clump
- Late-R = N, Early-R: $0.04 - 0.14\%$ of red clump
- 

For a small fraction of the helium core burning stars, carbon produced in the interior is mixed (in)to the atmosphere in sufficient quantities to form a carbon star.

Evidence File Closed

But the question remains...

What are the R stars?

What Type of Star Can It (Not) Be?

"Whenever you have eliminated the impossible, whatever remains, however improbable, must be true."

Sherlock?

What Type of Star Can It (Not) Be?

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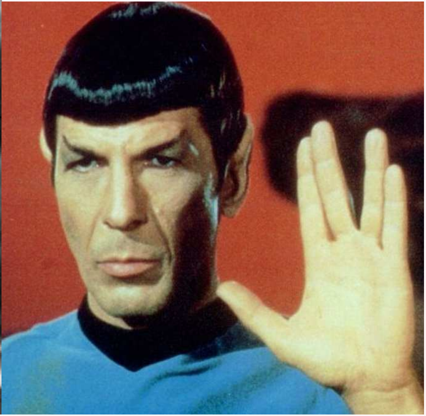

What Type of Star Can It (Not) Be?

Phase	Burning	Core	$L/L_\odot$
Main Sequence	H	H	$\gtrsim 1\,L_\odot$
Hertzsprung Gap or First GB	H	He	$100 - 200$
CHeB/Red Clump	He	He $\rightarrow$ CO	100
AGB	H/He	CO	$200 - 1000\,L_\odot$
Massive Star	H...	He...	$\gtrsim 100\,L_\odot$
Helium Star	He	CO	$\gtrsim 100\,L_\odot$
White Dwarf	-	He/CO/ONe	$L(t)$

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Phase	Burning	Core	$L/L_\odot$
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Helium Star	He	CO	$\gtrsim 100\,L_\odot$
White Dwarf	-	He/CO/ONe	$L(t)$

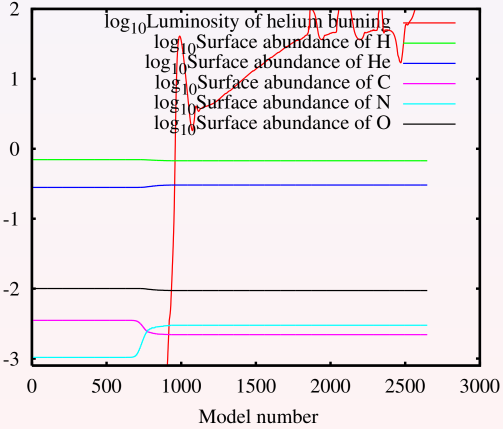
By elimination: CHeB star!

So What Are The R Stars?

- *Core Helium Burning* (red clump) giants
- Single stars
- Old disk stars
- Carbon, nitrogen rich
- Oxygen, iron, Mg, *s*-process: $\sim$solar
- $\mathrm{L} \sim 100\,\mathrm{L}_\odot$, $10\times$ dimmer than AGB
- $\mathrm{N_R/N_{clump}} \sim 0.1\%$ rare compared to clump
- $\mathrm{N_R/N_N} \gtrsim 10$ common compared to AGB

Helium Ignition

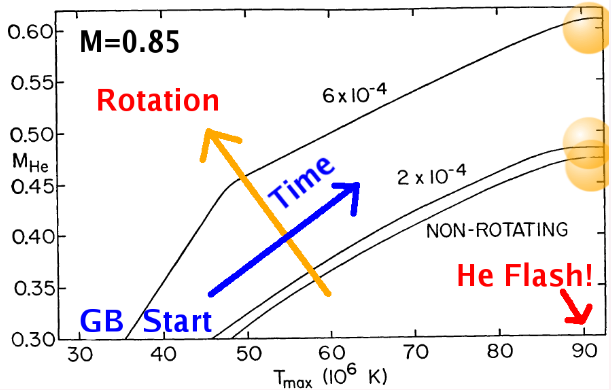
- Low mass stars: degenerate He flash
- Normal evolution: no extra carbon



- Is the helium flash different in R stars?

Promising 1D Models

- Mengel and Gross 1976: $0.85\,M_\odot$ rotating



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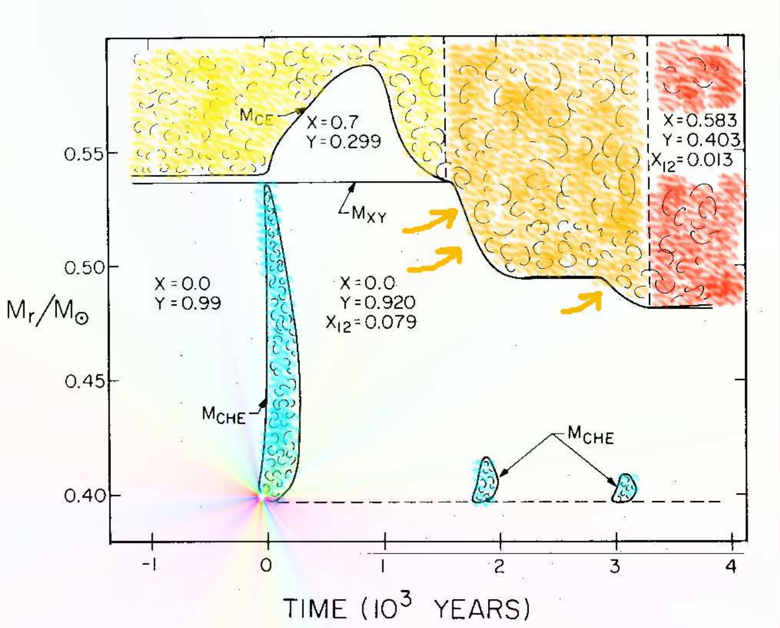
- Compared to zero rotation:
  - Fast-spinning cores develop on the giant branch
  - Helium ignites at a higher core mass
  - But: No pollution of the envelope

More 1D Models

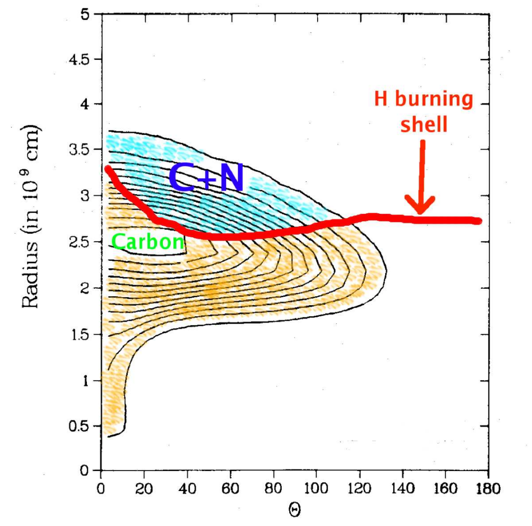
- Paczynski and Tremaine 1977: $0.8\,M_\odot$ Pop II star
- Variable helium ignition location
  - Possible for carbon to penetrate into envelope! (ignition at $0.4\,M_\odot$)
  - Final carbon abundance $X_{12} = 0.013$
  - *"We suggest that this process might explain the carbon overabundance in CH and R stars"*

Flash at 0.4 $M_\odot$



Speculative 2D Models

Deupree etc. 1980s/90s: Some C mixed.



R Star Recipe 1

1. Ignite a rapidly rotating helium core
2. Mix some carbon from 3α to the surface
3. Hydrogen shell burning $C \rightarrow N$
4. Voila! Your R Star
5. But why are they all *single stars?*
6. MERGERS

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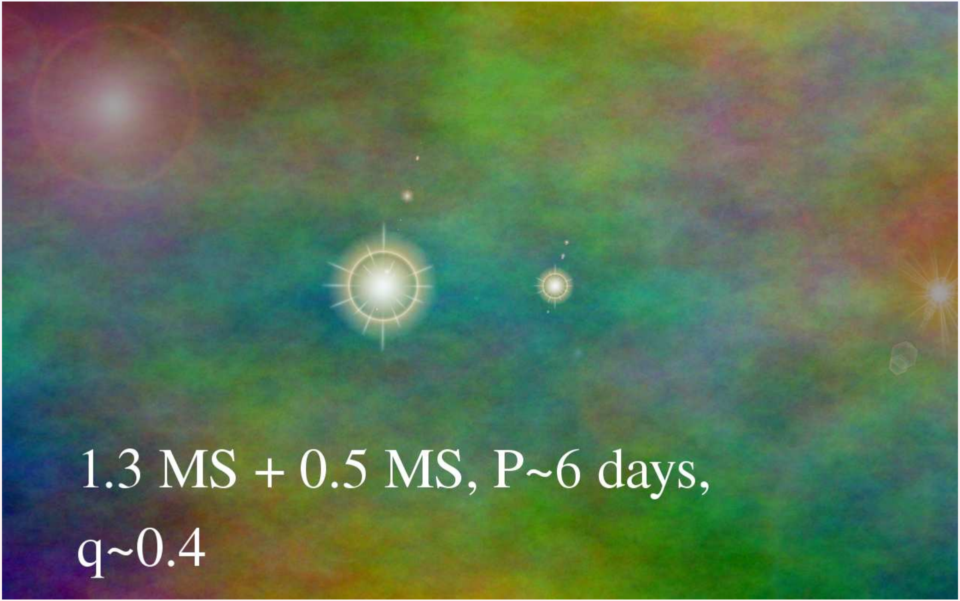
6. **MERGERS**

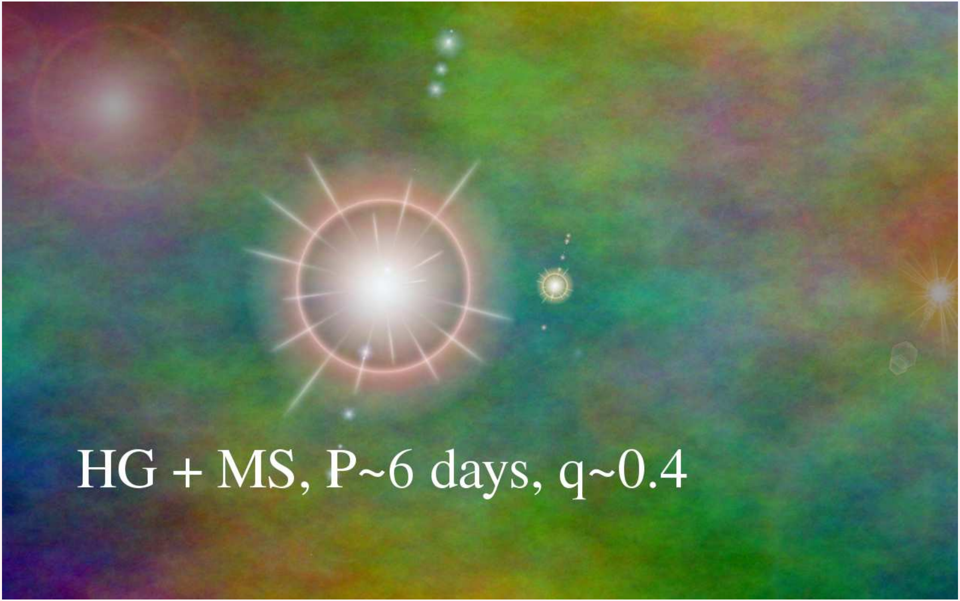
Evolutionary Scenario

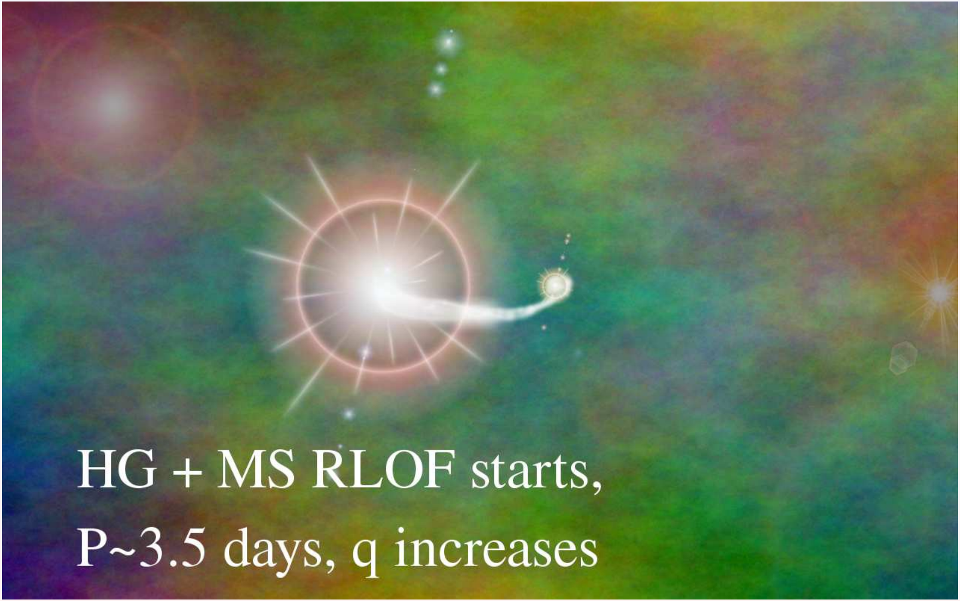
1. Merge two stars $\rightarrow$ rapidly rotating core
2. Ignite helium in core, mix to surface
3. *Single* R Star!

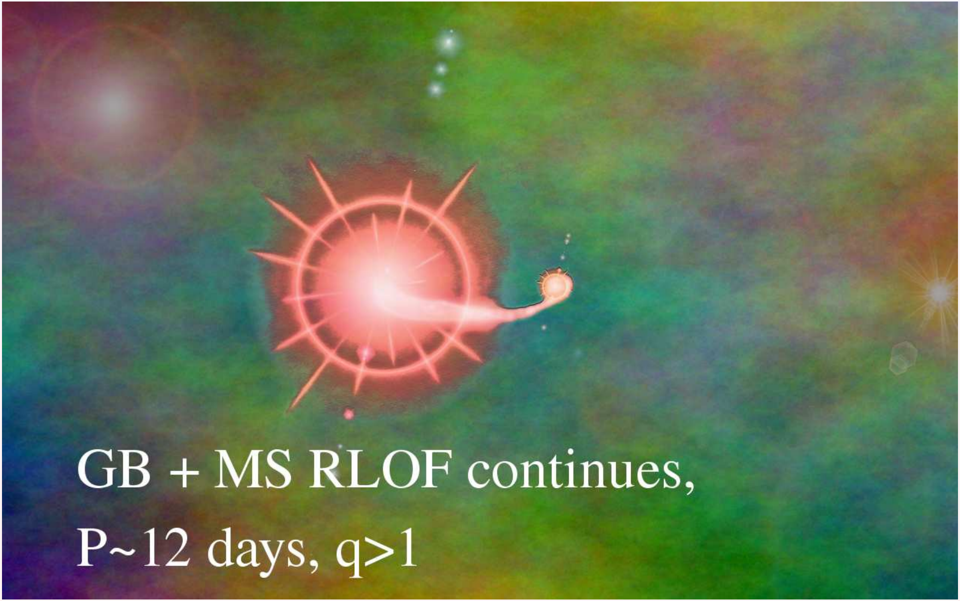
Constraints:

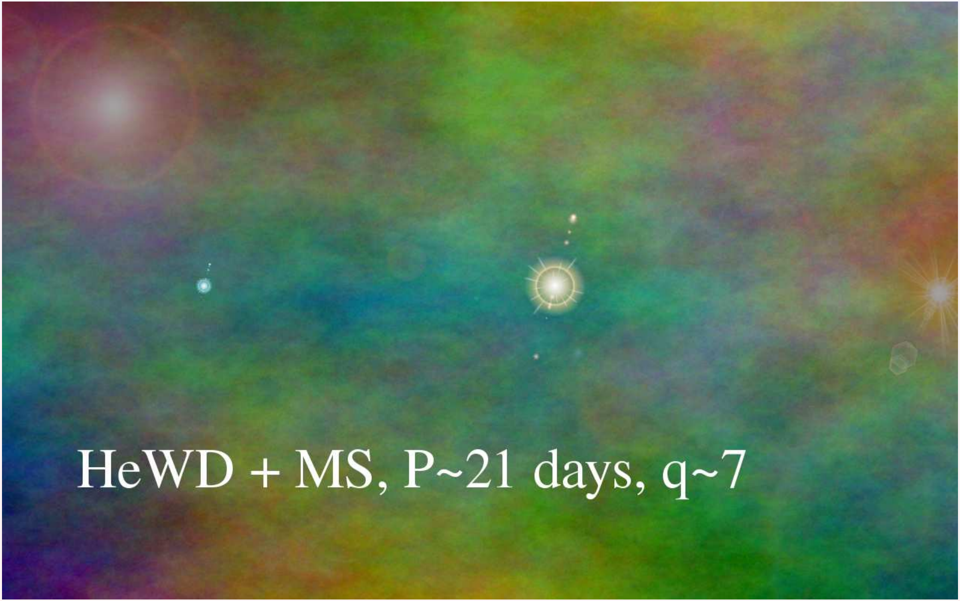
- Stars must be *before or during* He-burning phase
- Initial binary: low mass, close
- Merger: He $+$ He $\rightarrow$ ignition $\sim$ sdB stars

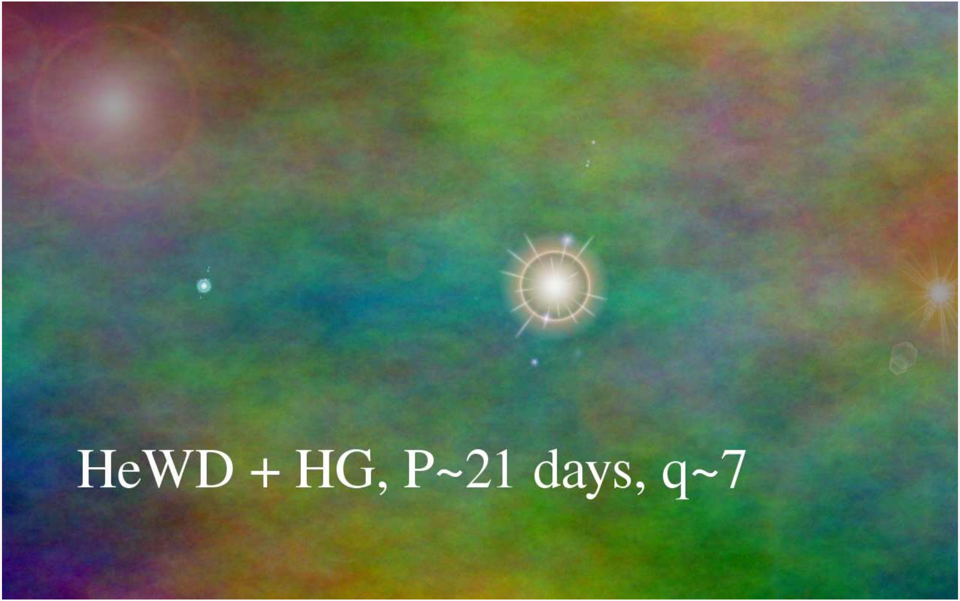

1.3 MS + 0.5 MS, P~6 days,
q~0.4


HG + MS, P~6 days, q~0.4

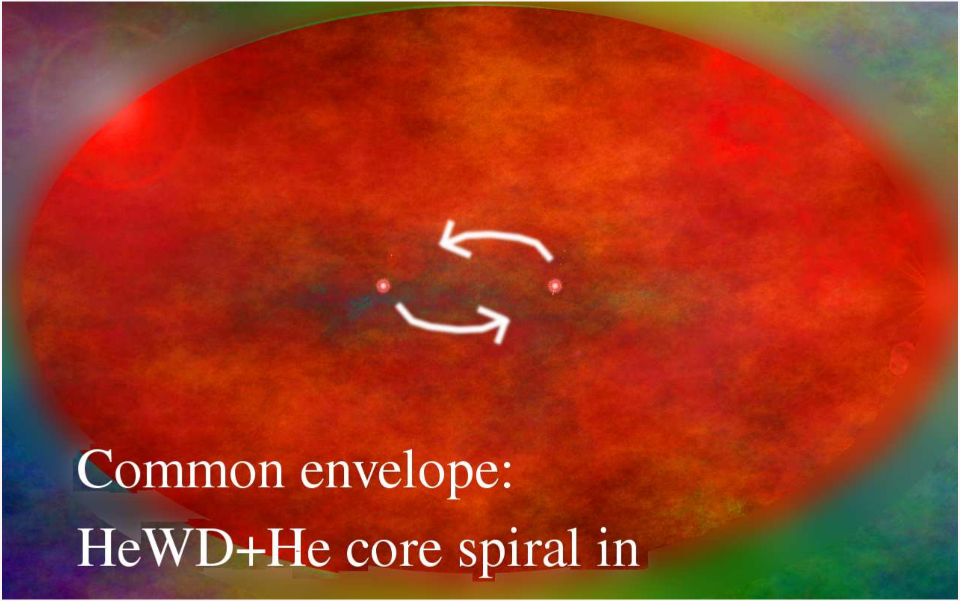

HG + MS RLOF starts,
P~3.5 days, q increases

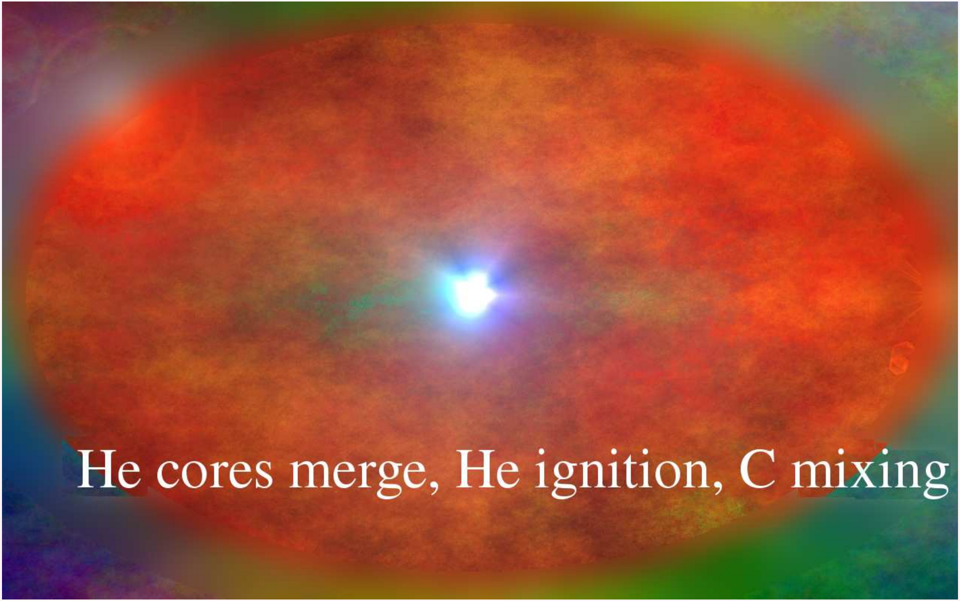

GB + MS RLOF continues,
P~12 days, q>1

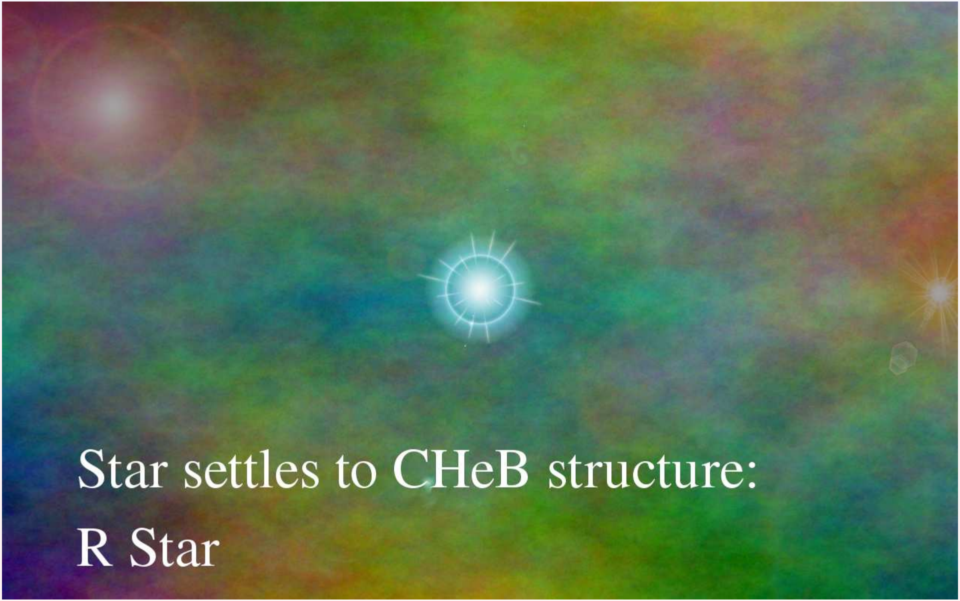

HeWD + MS, P~21 days, q~7


HeWD + HG, P~21 days, q~7


HeWD + GB RLOF starts


Common envelope:
HeWD+He core spiral in


He cores merge, He ignition, C mixing


Star settles to CHeB structure:
R Star

An R-Star Population Model

R stars are HeWD-GB mergers?

- Use our Binary Population Nucleosynthesis code* to analyse numbers and abundances
- Follows stellar evolution and nucleosynthesis in single and binary stars
- Runs about 10^7 times faster than typical stellar evolution code
- Great for exploring parameter space!
- Tag HeWD-GB mergers, follow them during subsequent CHeB phase
- Other channels: *extrinsic* (CH-star in CHeB phase), WR(C)?, HeWD-CHeB
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* Izzard et al. 2006 A&A 460 565

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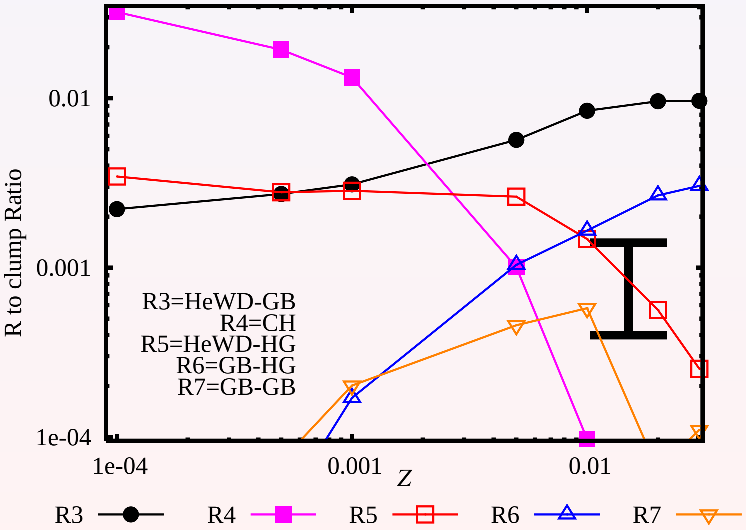
Results

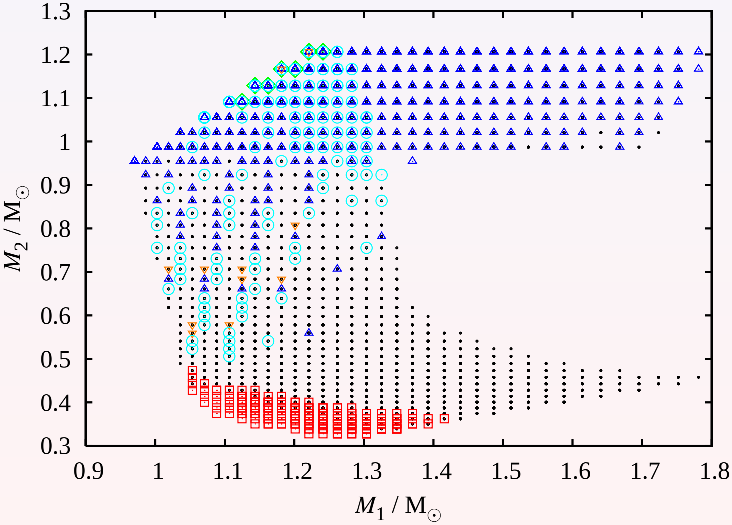
- R to Clump ratio
- Initial Distributions
- Common envelope entry conditions
- Zero-age R stars

Nucleosynthesis

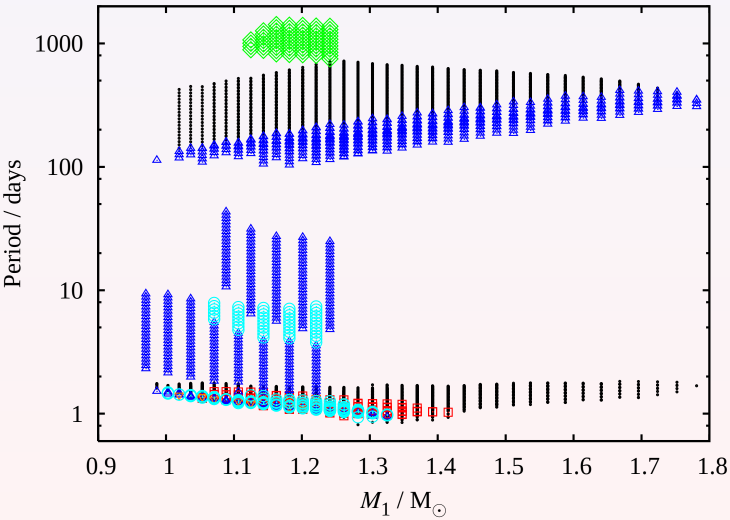
Results: R:CHeB ratio



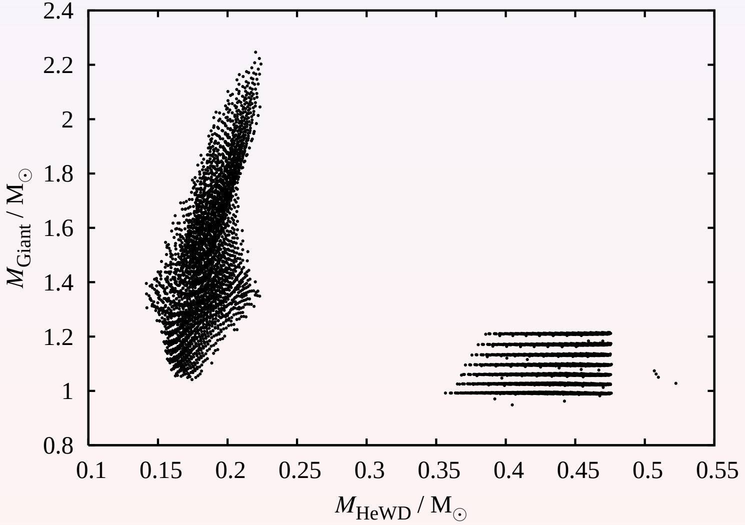
Results: Initial Distributions M_2 vs M_1



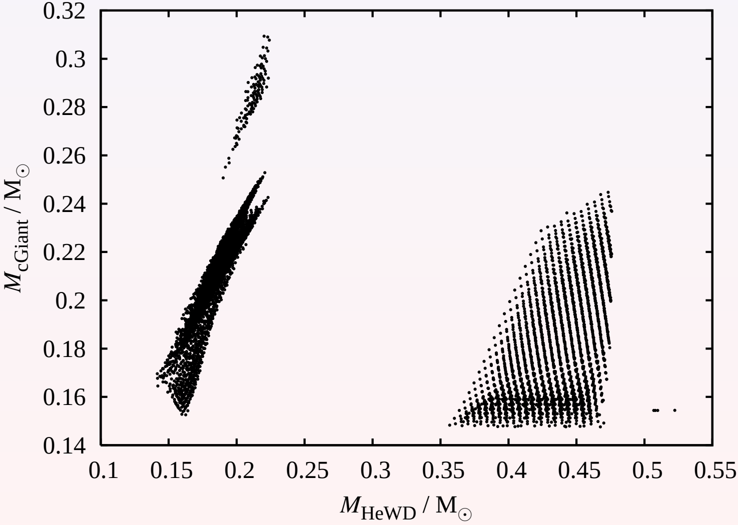
Results: Initial Distributions P vs M_1



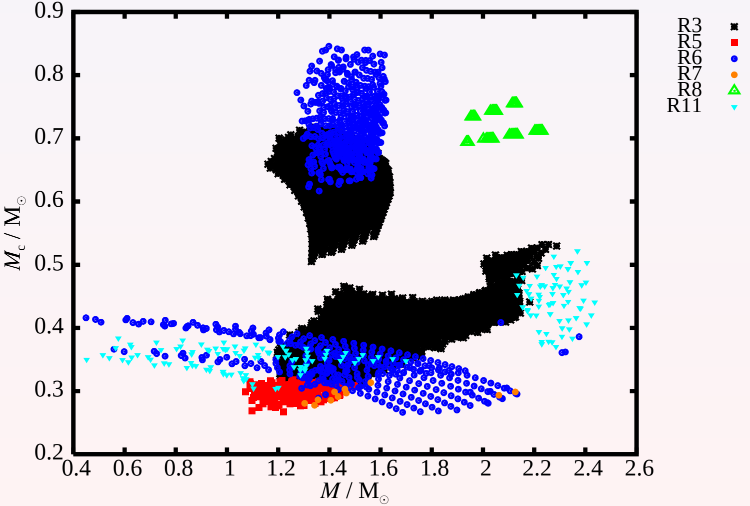
Results: Pre-CE $M_{1,2}$ (Ch. R3)



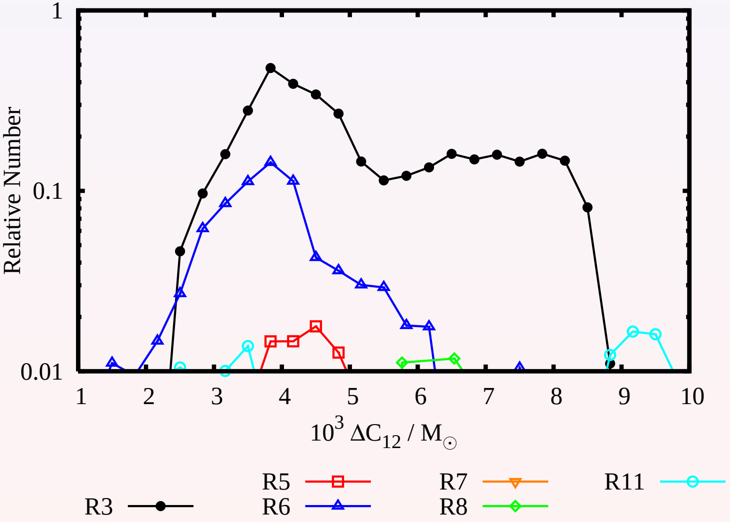
Results: Pre-CE Core $M_{c1,2}$ (R3)



Results: Post-Merger Stars



Results: How Much Carbon for C/O > 1?



R Star Checklist

L	OK	^{16}O	OK
T_{eff}	OK	$Z \sim Z_{\odot}$	OK
^{12}C	OK	Single stars	OK
$^{12}C/^{13}C$	OK	N_R/N_{Clump} ratio	OK
^{14}N	OK	Flash Mixing Mechanism	???

Early R stars are mergers

Late R stars are really N stars

Unanswered Questions

- Does the star/core retain its angular momentum?
  No!
- Can we model this in 1D?
  ...Or is it a 3D-hydro problem?
- How is carbon mixed to the surface?
- What about nitrogen? Other isotopes?
- Are there other channels we have failed to consider?
  Triples? Worse?! Planets?
- Post-1st-RLOF system is HeWD + Blue Straggler:
  observed?

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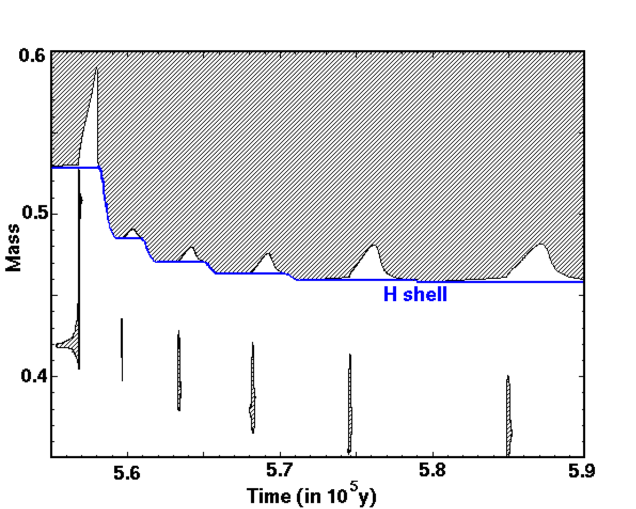
Latest models: Angelou & Lattanzio 2008



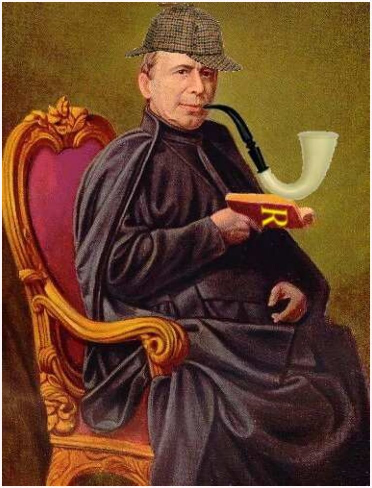
Latest Observations: Zamora et al 2009

23 R stars, hot and cool

- late-R = N
- Same results as Dominy 1984
- Large Li abundances in early-R?
- Dismissive of merger channel based on unpublished SPH models... ?!

Conclusions

- Our merger model is compatible with all current *reliable* observations (need more!)
- It naturally predicts the correct number and properties of *single*, $Z \sim Z_{\odot}$ R stars
- HeWD-He-core merger in common envelope is poorly understood but our results may be *telling us what happens*
- R stars are a key to understanding stellar mergers!
- Theoretical modelling of mergers, 1D rotating, 3D, SPH etc.



"Life is infinitely stranger than anything which the mind of man could invent." ... The End.