Synthetic Binary Star Models: BSE Code

- SSE→BSE (Hurley et al 2002 MNRAS 329 897)
- Orbital algorithm
  - Orbital and stellar rotation
  - Angular momentum (transfer)
  - Tidal interactions
- Mass Transfer: RLOF and wind accretion
  - Common Envelope Evolution
  - Novae, Type Ia Supernovae
  - Stellar Mergers
- In Sverre Aarseth's `NBODY` Globular Cluster code
- Download `http://astronomy.swin.edu.au/~jhurley/`

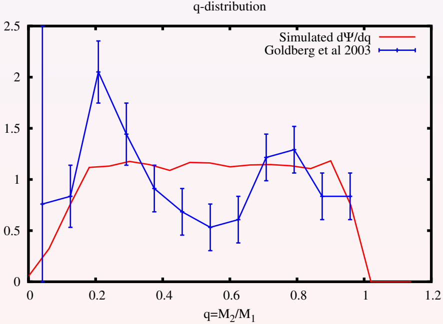
Motivation: Odd Stars In Binaries(/GCs)

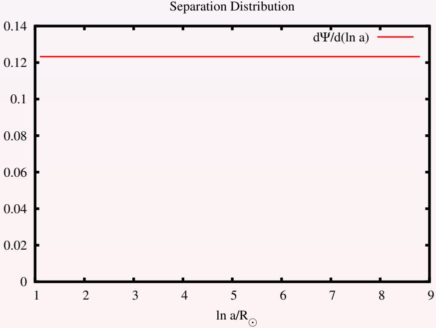
Some types of star or event occur predominantly or totally in binaries. These can be modelled with BSE:

- Wolf-Rayet stars (stripped massive stars)
- SNeIa (many types!), novae (accretion onto WDs)
- X-Ray binaries (accretion onto NS/BH)
- Contact/Semi-detached binaries (c.f. eclipsing binaries)
- Blue stragglers
- Double degenerate (WD-WD, WD-NS, NS-NS)
- Algols (accreting MS star)
- Symbiotic stars
- Cataclysmic Variables

Binary Parameter Space

- Five basic parameters: M_1, q (M_2), a (P), e, Z
- Assume $e = 0$, $Z = 0.02$: compute $n^3\times$ single stars
- IMF for M_1, For q , a





Parameters. . .

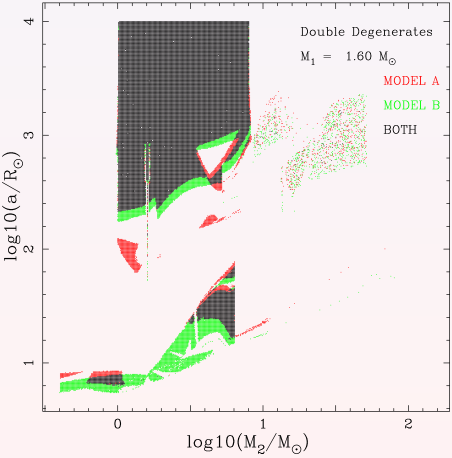
- Maximum evolution time $t_{\mathrm{max}} \sim 13.7\,\mathrm{Gyr}$
- Metallicity Z
- Eccentricity e (distribution)
- Mass-loss prescription
- Common envelope parameters α and λ
- Eddington limit for accretion?
- SN kick velocity dispersion
- Bondi-Hoyle accretion factor
- Fraction of matter retained in a nova explosion
- $M_{\mathrm{NS/BH}}(M_{\mathrm{CO}})$ prescription
- Angular momentum transfer in RLOF?
- Binary enhanced mass loss? (CRAP)

Binary Formation Rates

Hurley et al (2002) predicted the rates of different binary systems for seven parameter set choices

Model	A	B	C	D	E	F	G	%err
BSS	1.295×10^{-1}	1.138×10^{-1}	1.248×10^{-1}	5.049×10^{-2}	1.839×10^{-1}	1.181×10^{-1}	1.367×10^{-1}	0.31
CV class	1.987×10^{-2}	1.292×10^{-2}	2.120×10^{-2}	1.820×10^{-2}	3.080×10^{-2}	1.889×10^{-2}	3.973×10^{-2}	3.65
GK Per	1.398×10^{-2}	1.165×10^{-2}	1.671×10^{-2}	1.679×10^{-3}	3.709×10^{-2}	1.374×10^{-2}	3.460×10^{-3}	0.93
CV Symb	7.858×10^{-4}	1.423×10^{-4}	2.450×10^{-3}	1.898×10^{-4}	1.027×10^{-2}	8.527×10^{-4}	4.440×10^{-4}	2.73
sdB	1.135×10^{-2}	1.398×10^{-2}	2.189×10^{-3}	1.090×10^{-3}	1.729×10^{-2}	1.047×10^{-2}	1.125×10^{-2}	0.49
pre Algol	1.248×10^{-1}	1.040×10^{-1}	1.244×10^{-1}	8.807×10^{-2}	1.861×10^{-1}	1.112×10^{-1}	2.082×10^{-1}	0.07
MS Algol	2.861×10^{-2}	2.981×10^{-2}	2.864×10^{-2}	1.558×10^{-2}	2.784×10^{-2}	2.485×10^{-2}	1.077×10^{-2}	0.32
cold Algol	1.313×10^{-2}	1.145×10^{-2}	1.293×10^{-2}	7.007×10^{-3}	3.718×10^{-2}	1.222×10^{-2}	2.255×10^{-3}	1.11
hot Algol	4.910×10^{-2}	4.593×10^{-2}	4.458×10^{-2}	1.018×10^{-2}	9.049×10^{-2}	4.430×10^{-2}	2.780×10^{-2}	0.18
NS LMXBp	3.487×10^{-6}	1.362×10^{-7}	2.219×10^{-7}	5.481×10^{-6}	1.010×10^{-5}	1.071×10^{-6}	4.906×10^{-6}	37.56
BH LMXBp	3.601×10^{-6}	1.696×10^{-6}	1.561×10^{-6}	3.686×10^{-6}	2.563×10^{-5}	3.865×10^{-6}	5.349×10^{-5}	25.36
NS MXRBp	7.481×10^{-4}	5.014×10^{-4}	6.307×10^{-4}	1.434×10^{-5}	6.096×10^{-4}	7.214×10^{-4}	5.164×10^{-4}	1.37
BH MXRBp	1.057×10^{-4}	1.612×10^{-5}	1.092×10^{-4}	2.043×10^{-6}	2.425×10^{-4}	1.085×10^{-4}	1.132×10^{-4}	3.77
NS WDXBp	1.639×10^{-3}	2.028×10^{-3}	1.686×10^{-4}	8.393×10^{-5}	3.563×10^{-3}	1.426×10^{-3}	1.347×10^{-3}	0.55
BH WDXBp	2.764×10^{-4}	3.513×10^{-4}	2.885×10^{-5}	4.987×10^{-6}	4.951×10^{-4}	2.400×10^{-4}	2.085×10^{-4}	7.62
NS LMXBt	2.359×10^{-5}	5.640×10^{-6}	1.253×10^{-6}	2.537×10^{-5}	4.198×10^{-5}	9.087×10^{-6}	3.654×10^{-5}	21.27
BH LMXBt	9.172×10^{-6}	1.691×10^{-6}	4.854×10^{-6}	6.552×10^{-6}	2.323×10^{-5}	6.542×10^{-6}	2.283×10^{-5}	20.87
NS MXRBt	7.345×10^{-4}	8.048×10^{-4}	8.122×10^{-4}	1.823×10^{-5}	1.568×10^{-3}	7.149×10^{-4}	6.515×10^{-4}	1.41
BH MXRBt	5.447×10^{-5}	2.320×10^{-5}	8.706×10^{-5}	2.564×10^{-6}	2.560×10^{-4}	5.823×10^{-5}	4.471×10^{-5}	2.81
NS WDXBt	8.963×10^{-4}	1.088×10^{-3}	7.332×10^{-5}	7.325×10^{-5}	2.296×10^{-3}	7.753×10^{-4}	6.918×10^{-4}	0.29
BH WDXBt	6.531×10^{-4}	8.299×10^{-4}	8.357×10^{-5}	1.017×10^{-5}	1.237×10^{-3}	5.636×10^{-4}	5.784×10^{-4}	1.78
S-Symb	5.353×10^{-3}	5.091×10^{-3}	5.370×10^{-3}	2.712×10^{-4}	6.356×10^{-3}	4.100×10^{-3}	4.305×10^{-3}	1.79
D-Symb	4.322×10^{-2}	4.701×10^{-2}	4.302×10^{-2}	5.748×10^{-3}	3.782×10^{-2}	3.494×10^{-2}	3.763×10^{-2}	0.23
nHe MSC	6.441×10^{-3}	1.929×10^{-3}	2.160×10^{-3}	1.657×10^{-3}	1.649×10^{-2}	5.591×10^{-3}	5.059×10^{-3}	0.94
gnt MSC	3.366×10^{-3}	3.639×10^{-3}	3.432×10^{-3}	1.093×10^{-3}	4.809×10^{-3}	3.075×10^{-3}	8.166×10^{-4}	4.75
WDWD DD	1.131×10^{-1}	1.229×10^{-1}	7.572×10^{-2}	1.334×10^{-2}	2.290×10^{-1}	8.631×10^{-2}	7.902×10^{-2}	0.16
WDNS DD	8.577×10^{-4}	8.982×10^{-4}	5.265×10^{-4}	2.088×10^{-5}	2.842×10^{-3}	7.986×10^{-4}	7.537×10^{-4}	1.10
NSNS DD	7.384×10^{-5}	8.192×10^{-5}	2.785×10^{-5}	6.972×10^{-7}	1.604×10^{-4}	7.587×10^{-5}	7.295×10^{-5}	5.11

DD Parameter Parameter Space



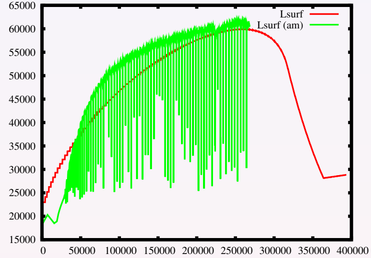
Other Odd Binaries

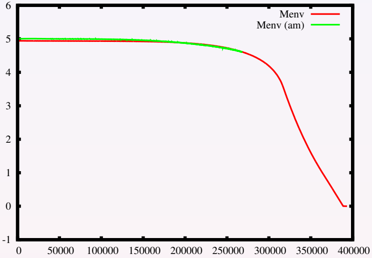
- Many types of stars look odd based on their chemical properties
- Tracers of stellar nucleosynthesis!
- Some examples:
  - Barium Stars
  - CH stars
  - CEMP stars
  - R stars (all single!)
  - J stars (binaries?)
  - Wolf-Rayet stars
- Would be good to model these!

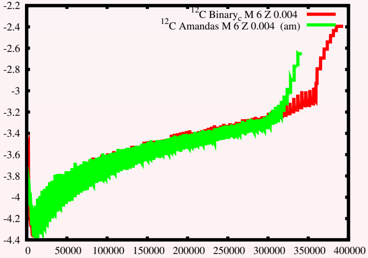
Binary Population Nucleosynthesis 1

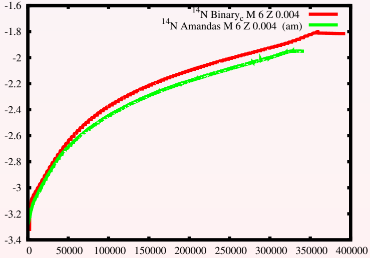
- Izzard et al 2004 (MNRAS 350 407) introduced nucleosynthesis into BSE:
- First, second, third dredge up, TPAGB based on Karakas models $0.004 \leqslant Z \leqslant 0.02$
- ...

Fits to Amanda's Models

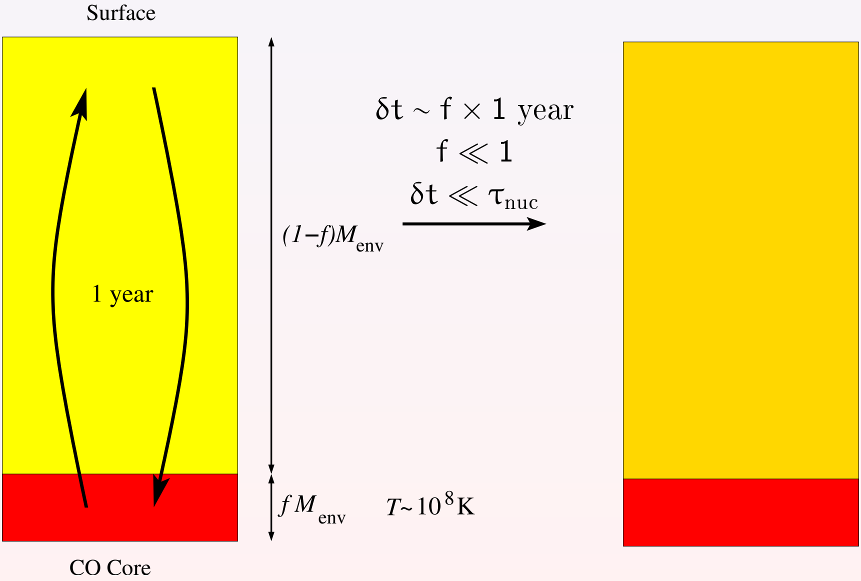








HBB 1



Surface

1 year

$(1-f)M_{\mathrm{env}}$

$\delta t \sim f \times 1$ year

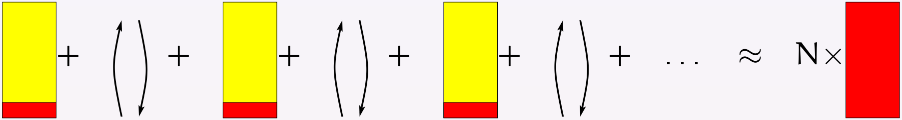
$f \ll 1$

$\delta t \ll \tau_{\mathrm{nuc}}$

$f\,M_{\mathrm{env}}$ $T \sim 10^{8}\,\mathrm{K}$

CO Core

HBB 2

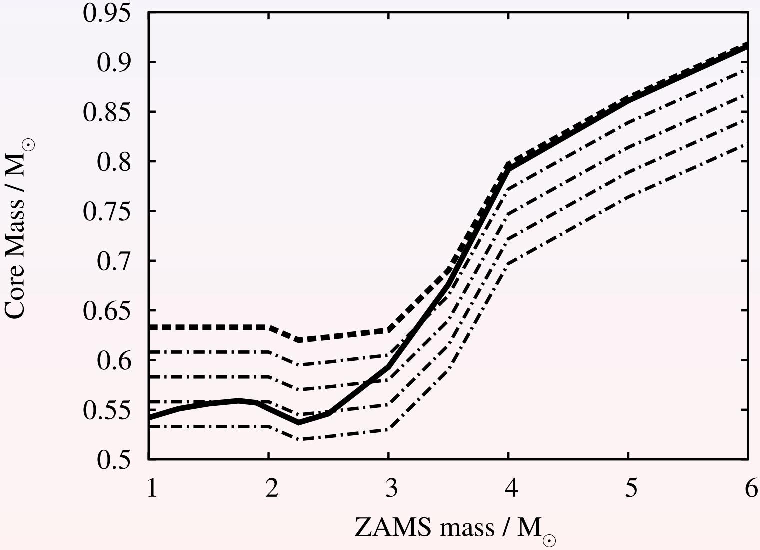


- N, T etc. from full stellar evolution models (Karakas 2002-2006…)
- Analytic nuclear network e.g. CN cycle

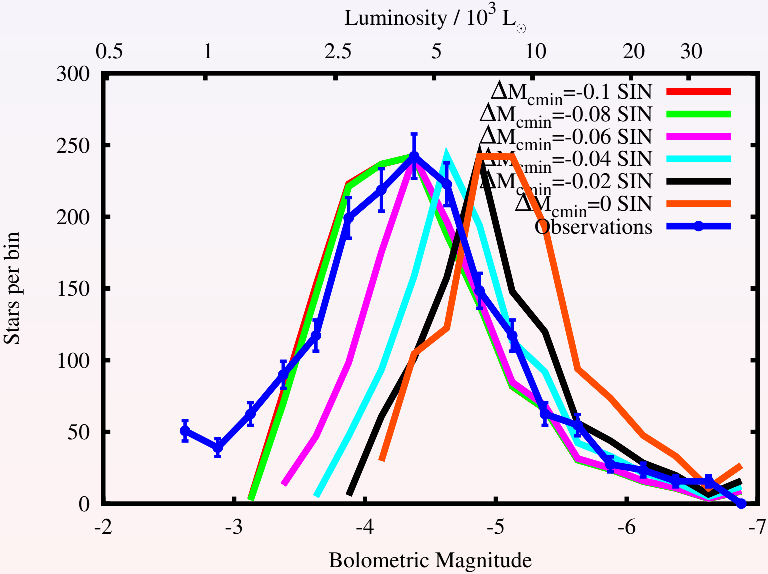
$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} {}^{12}\mathrm{C} \\ {}^{13}\mathrm{C} \\ {}^{14}\mathrm{N} \end{bmatrix} = \begin{bmatrix} -1/\tau_{12} & 0 & 1/\tau_{14} \\ 1/\tau_{12} & -1/\tau_{13} & 0 \\ 0 & 1/\tau_{13} & -1/\tau_{14} \end{bmatrix} \begin{bmatrix} {}^{12}\mathrm{C} \\ {}^{13}\mathrm{C} \\ {}^{14}\mathrm{N} \end{bmatrix}$$

- $\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{U} = \Lambda\mathbf{U}$: Eigenvalue problem, quickly solved

Fudged DUP to match L/SMC CSLF



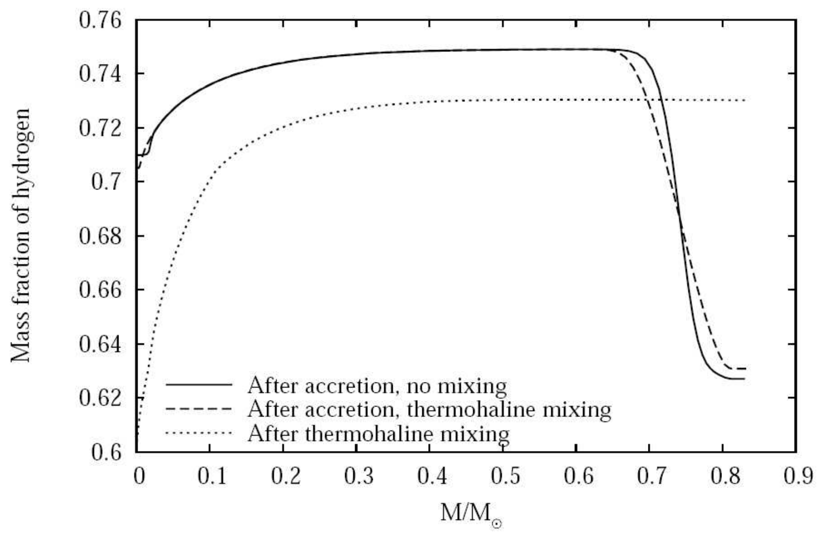
Fudged DUP to match L/SMC CSLF



Binary Population Nucleosynthesis 2

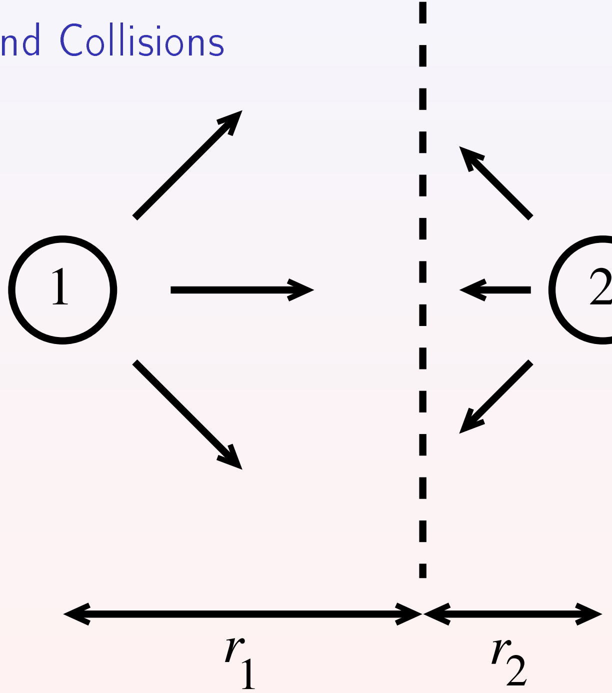
- Izzard et al. 2006 (A&A 460 565) extended this
    - Isotopes up to Fe, $Z = 10^{-4}$ models
    - HBB CNO, NeNa and MgAl (Karakas models)
    - s-process in AGB stars (Gallino's models )
    - Massive stars (Lynnette Dray's $\dot{M}$ models)
    - Supernovae (WW95, CL04 , SNe Ia)
    - Novae (José  & Hernanz 1998)
    - ...

Thermohaline Mixing



Stancliffe, Glebbeek, Izzard & Pols (2007?)

Wind Collisions



Rob Pauses for

Highlights of Population Nucleosynthesis

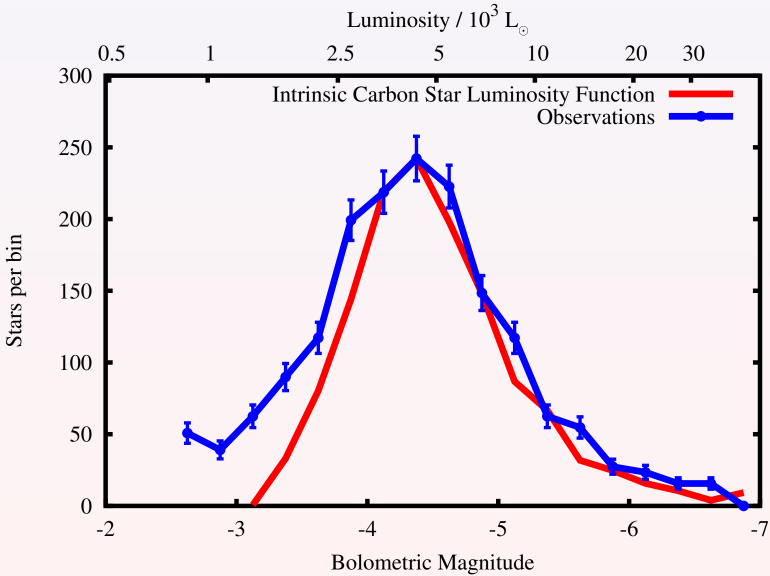
My non-exhaustive selection:

1. Carbon Stars and the Luminosity Function
2. NeNa and MgAl production with uncertain reaction rates
3. Constraining the s-process efficiency
4. Yields and Galactic Chemical Evolution
5. R stars
6. LIVE DEMO!

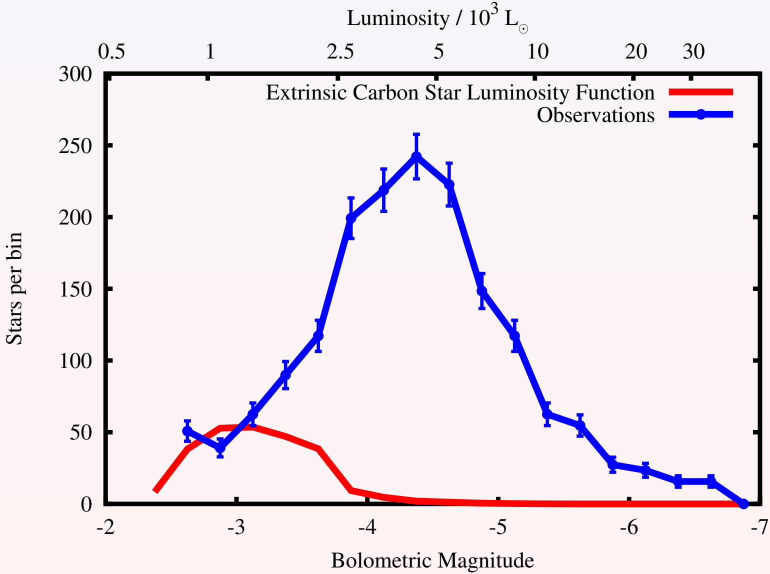
1: Carbon Star Luminosity Function

- Extra third DUP in synthetic models to replicate observed CSLF
- May not be necessary? (Observations misinterpreted? Guandalini/Busso 2006)
- Still does not explain "very low"-luminosity tail
- Idea: low-L stars due to accretion in binaries?

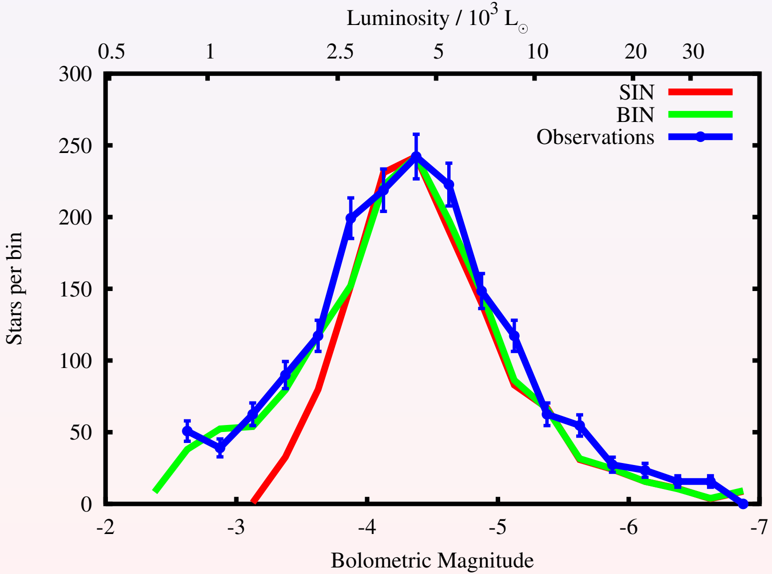
Intrinsic Stars Only (Traditional Approach)



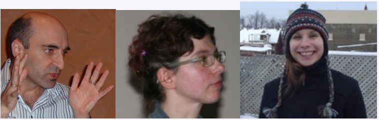
Extrinsic Stars Only

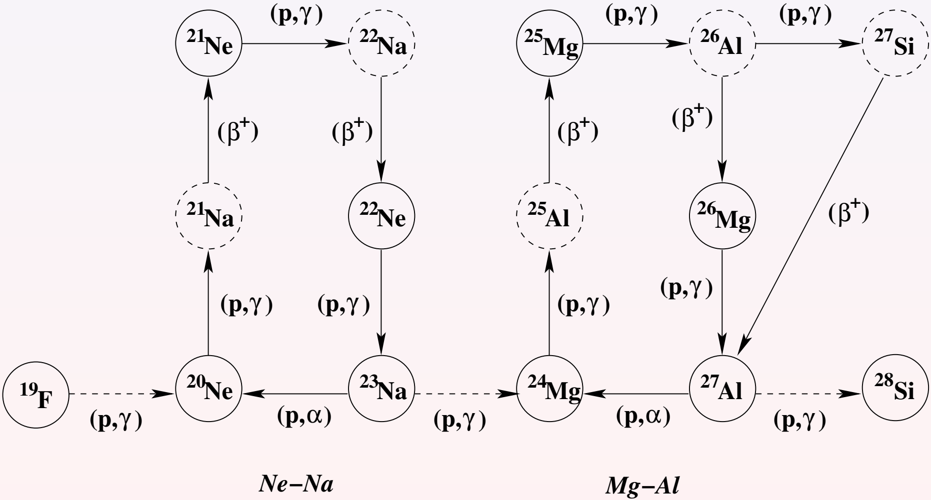


Intrinsic + Extrinsic

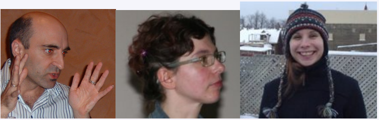


2: Rate Uncertainties



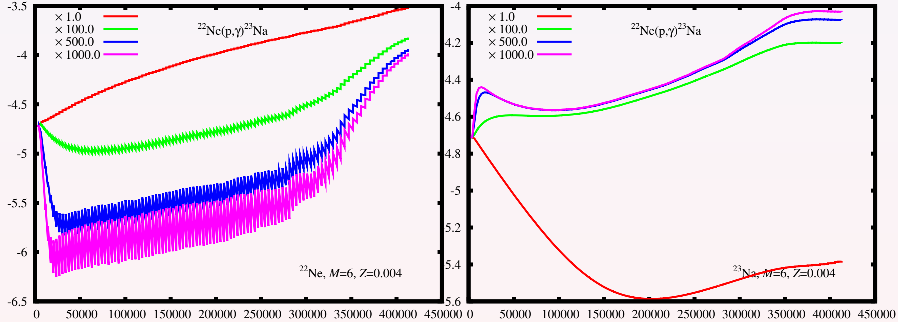


2: Rate Uncertainties

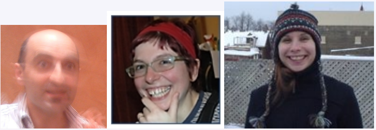


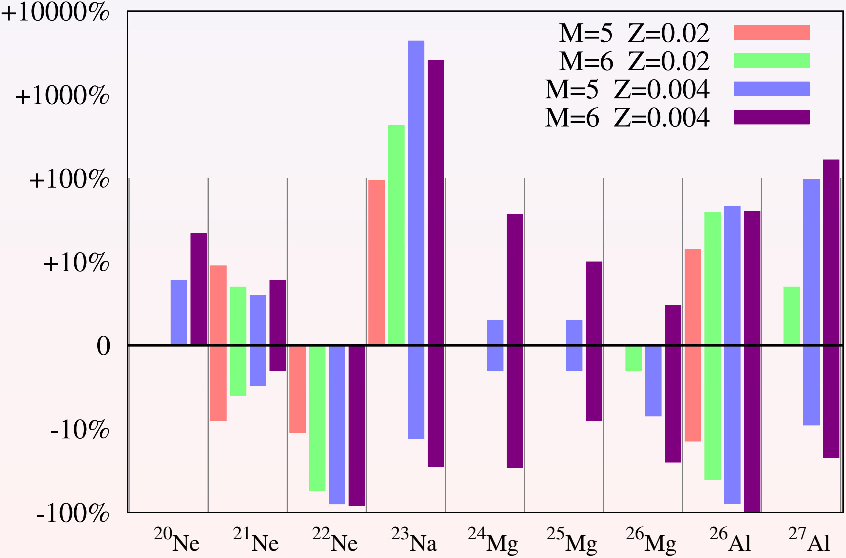
Rate			Source
$^{20}\mathrm{Ne}(p,\gamma)^{21}\mathrm{Na}(\beta^+)^{21}\mathrm{Ne}$	−50%	+50%	NACRE
$^{21}\mathrm{Ne}(p,\gamma)^{22}\mathrm{Na}(\beta^+)^{22}\mathrm{Ne}$	−20%	+20%	Iliadis et al. 2001
$^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$	−50%	×2000	Hale et al. 2001
$^{23}\mathrm{Na}(p,\alpha)^{20}\mathrm{Ne}$	−30%	+30%	Rowland et al. 2004
$^{23}\mathrm{Na}(p,\gamma)^{24}\mathrm{Mg}$	/40	×10	Rowland et al. 2004
$^{24}\mathrm{Mg}(p,\gamma)^{25}\mathrm{Al}(\beta^+)^{25}\mathrm{Mg}$	−17%	+20%	Powell et al. 1999
$^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}(\beta^+)^{26}\mathrm{Mg}$	−50%	×1.5	Iliadis et al. 2001
$^{26}\mathrm{Mg}(p,\gamma)^{27}\mathrm{Al}$	/4	×10	Iliadis et al. 2001
$^{26}\mathrm{Mg}(p,\gamma)^{27}\mathrm{Al}$	−25%	×3	Iliadis et al. 2001
$^{26}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$	/2	×600	Iliadis et al. 2001

Effect on Ne/Na

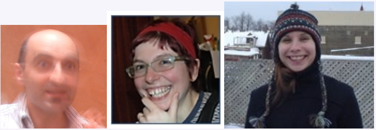


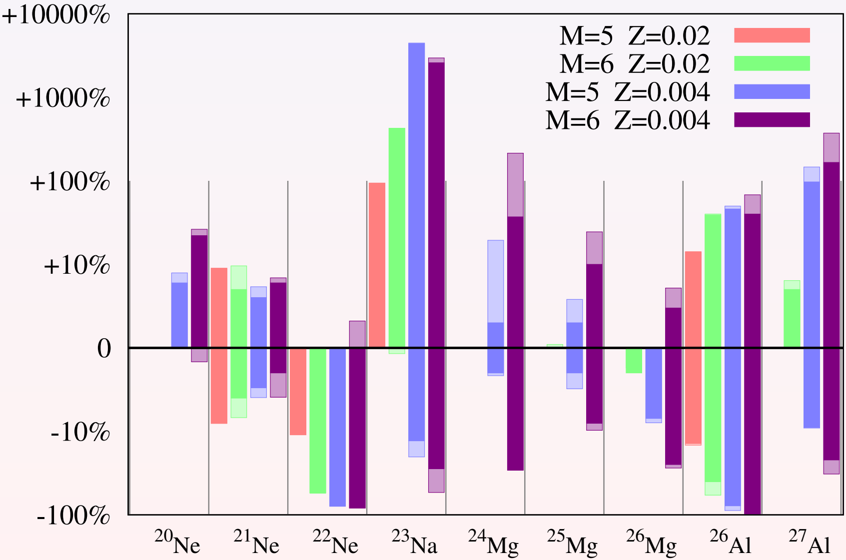
Yield differences





Yield differences



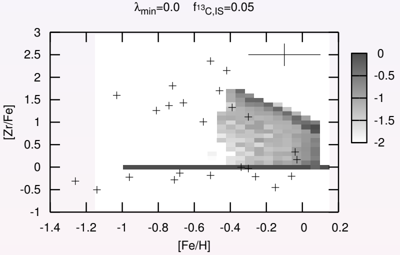


3: The *s*-process efficiency

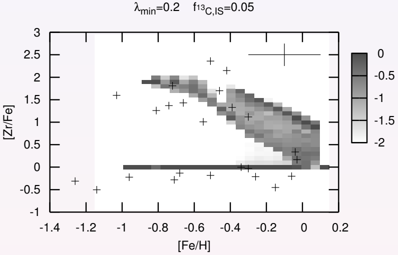
- *s*-process models from Italians
- Free parameter "^{13}C efficiency" $\zeta \sim$ neutron exposure in intershell
- Busso et al 2001 matched observations to a spread of 20 in ζ, but they considered only the 30th pulse
- Completely unrealistic:
  - 2nd-29th pulse have different abundances
  - A 1.5 $M_{\odot}$ star does not undergo 30 pulses!
- New work by Bonacic et al (2007)
- Agrees with work on isotopic ratios in pre-solar grains (Andy Davis etc.) which suggests $\zeta \sim 1$

e.g. Post-AGB abundances of Zr

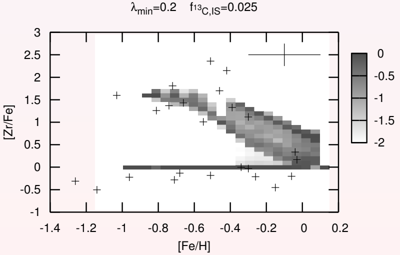
- Extra DUP to match obs (just like CSLF)



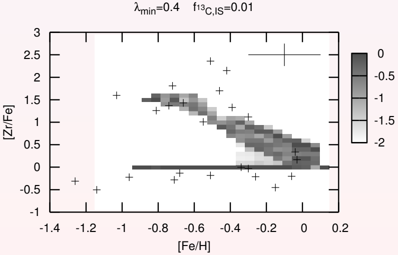
$\lambda_{min}=0.0$ $f_{^{13}C,IS}=0.05$



$\lambda_{min}=0.2$ $f_{^{13}C,IS}=0.05$



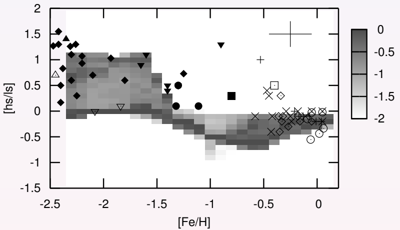
$\lambda_{min}=0.2$ $f_{^{13}C,IS}=0.025$



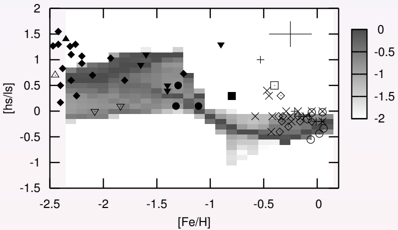
$\lambda_{min}=0.4$ $f_{^{13}C,IS}=0.01$

e.g. Extrinsic Ba,CH,C,N-rich,Pb... stars

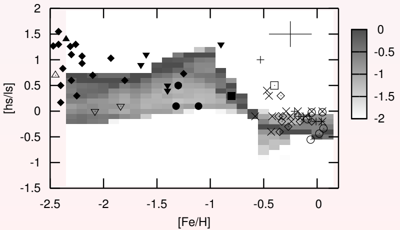
- $[\mathrm{Fe/H}] \geqslant 1$: $\frac{2}{3} \lesssim \zeta \lesssim \frac{4}{3}$ for *many types of stars*



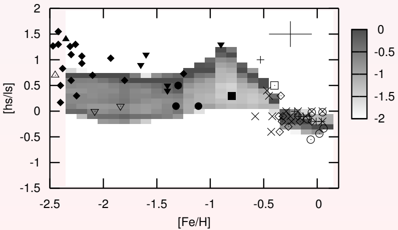
Extrinsic stars ($C13_{eff0}$=1/6)



Extrinsic stars ($C13_{eff}$=1/3)



Extrinsic stars ($C13_{eff}$=2/3)



Extrinsic stars ($C13_{eff}$=4/3)

4: Yields and Galactic Chemical Evolution

- Chemical yield (strictly *time-integrated ejecta*) for a given Z and other parameter set:
- Single Stars:

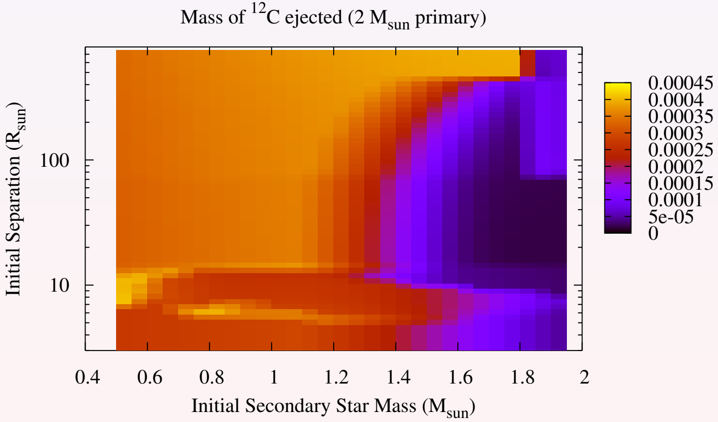
$$\text{Yield of isotope}\, i \;=\; \int_{\text{time}} \int_{M=0.1}^{100} \Delta M_i \, \psi(M) \, dM \, dt$$

- Binary Stars: $\text{Yield of isotope}\, i =$

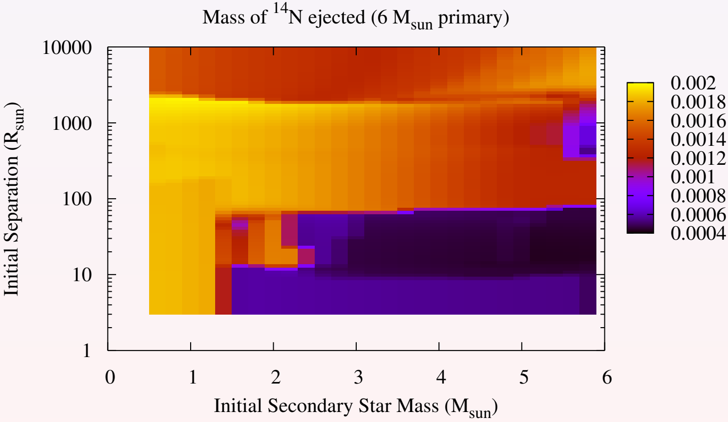
$$\int_{\text{time}} \int_{M_1=0.1}^{100} \int_{M_2=0.1}^{M_1} \int_{a=3\,R_\odot}^{10{,}000\,R_\odot} \Delta M_i \, \psi(M_1, M_2, a) \, dM_1 \, dM_2 \, da \, dt$$

- Integrate over M_2, a : average yield in binary with primary M_1

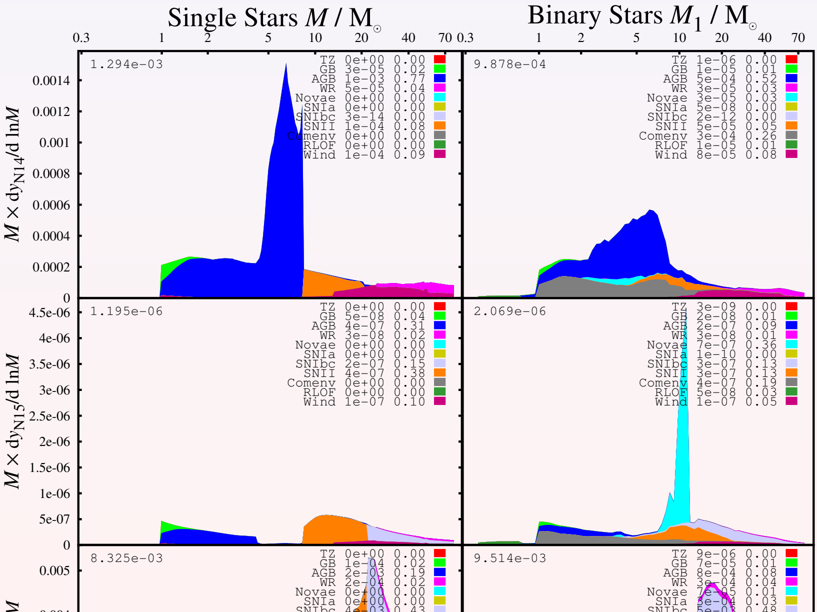
Binary Yield ($M_1 = 2\,\mathrm{M}_\odot$, $Z = 0.004$)



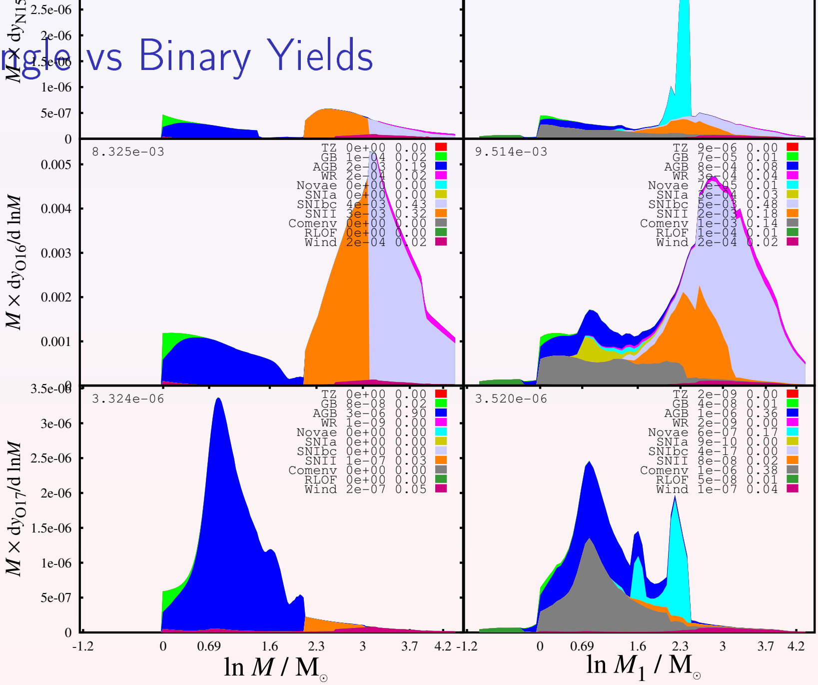
Binary Yield ($M_1 = 6\,\mathrm{M}_\odot$, $Z = 0.004$)



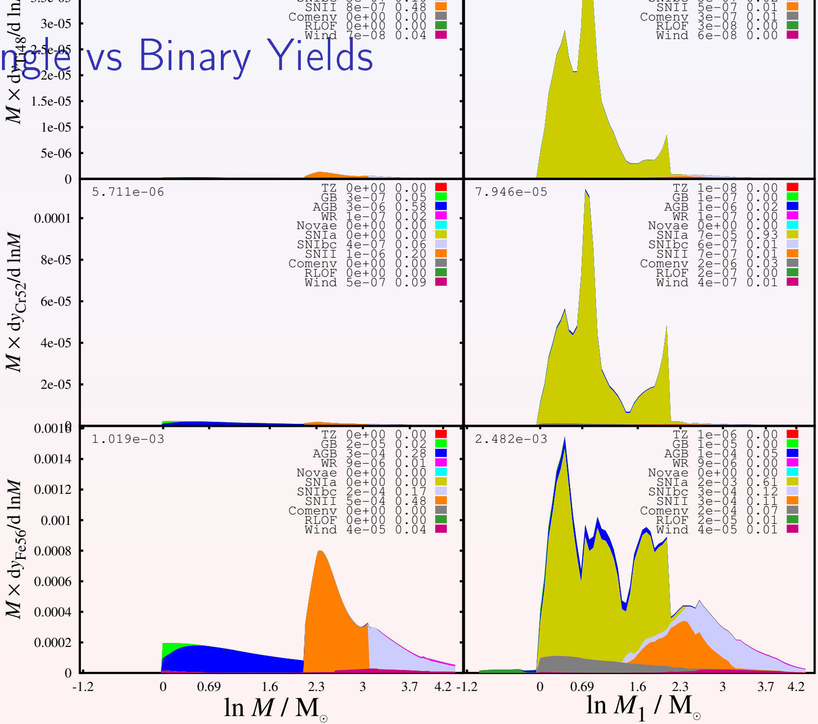
Single vs Binary Yields



Single vs Binary Yields



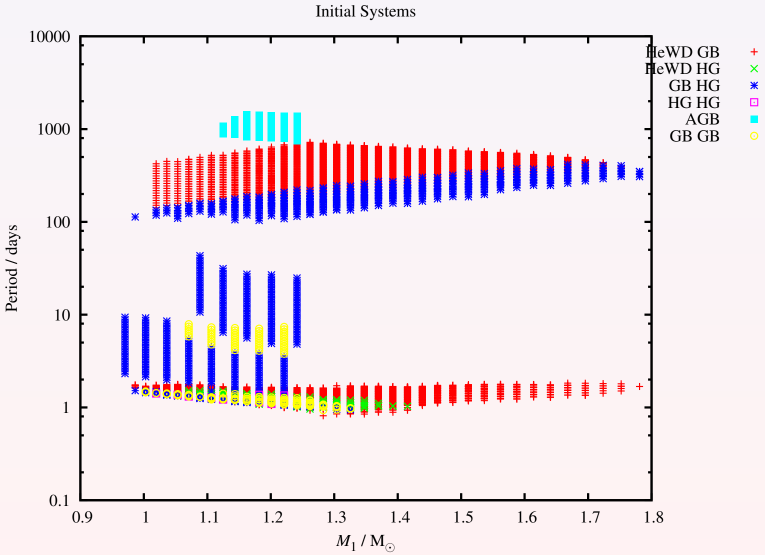
Single vs Binary Yields



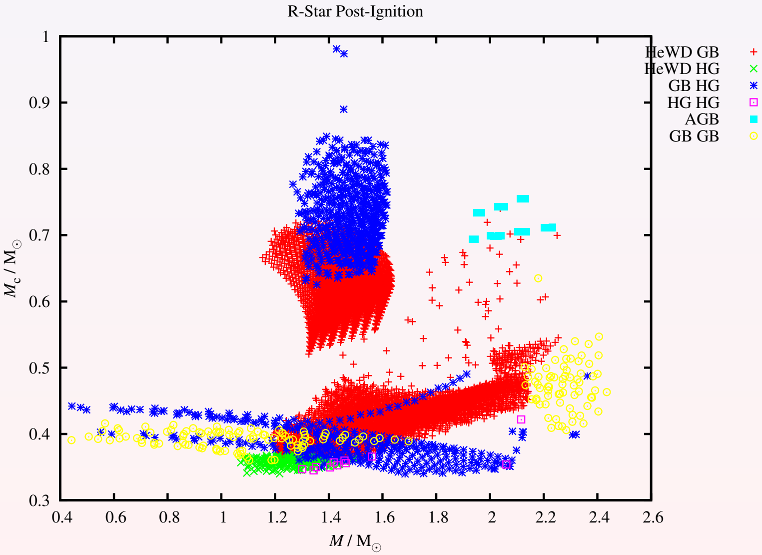
5: The R Stars (whole talk!)

- R stars are single, carbon-rich K-type stars
- They should not have carbon!
- We think they are mergers of degenerate helium cores which ignite and mix He-burnt material to the surface
- Use population synthesis to find channels for these mergers
- Compare to observations: R to CHeB ratio in model is $>$ observed by Hipparcos (good sign)
- Use formation channel information as input for detailed code

5: Predicted R star $P - M_1$



5: Predicted R star M, M_c



End of Talk. . .

Beginning of demonstration!

Try it yourself at

http://www.astro.uu.nl/~izzard/