Binary Stars – Lecture 10

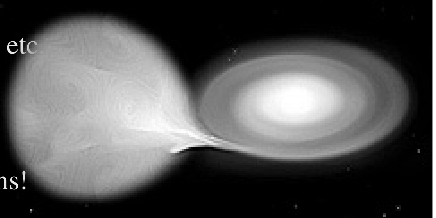
Astro 8501
6944

Argelander Institut für Astronomie

Cataclysmic Variables

- White Dwarf +
- Low mass star
- WD accreting:
- Disc, outbursts etc
- WD $M \uparrow$
- Sometimes...

  … Explosions!



Argelander Institut für Astronomie

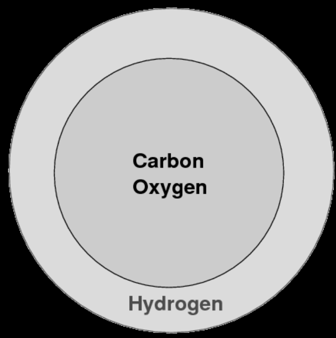
Accretion Rates onto a WD

$\dot{M} < 10^{-7}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$	Thermonuclear Novae
$1.03 < 10^{7}\,\dot{M} < 2.71$	Steady burning
$\dot{M} > 2.7 \times 10^{-7}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$	Giant envelope

See e.g. Warner's book (1995)
Remember the Eddington limit!

Argelander Institut für Astronomie

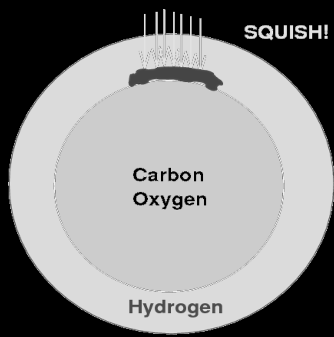
Classical Nova I



Michael Richmond
http://spiff.rit.edu/richmond/asras/sn_bh/sn_bh.html

Argelander Institut für Astronomie

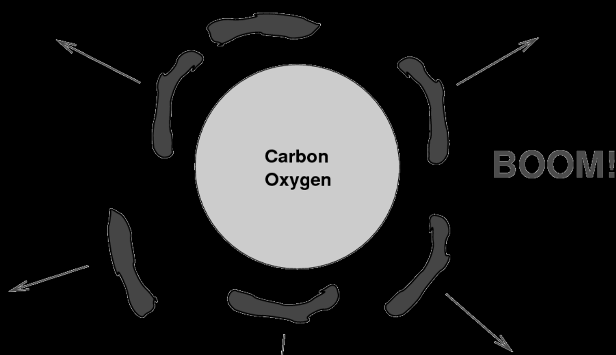
Classical Nova II



Michael Richmond
http://spiff.rit.edu/richmond/asras/sn_bh/sn_bh.html

Argelander Institut für Astronomie

Classical Nova III



Michael Richmond
http://spiff.rit.edu/richmond/asras/sn_bh/sn_bh.html

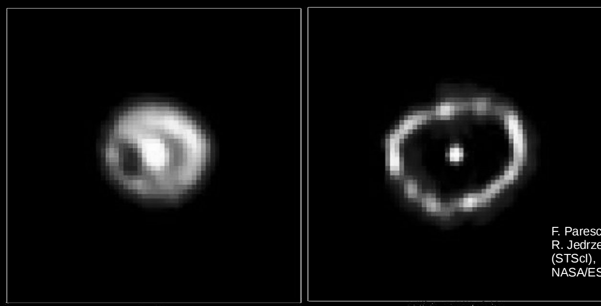
Argelander Institut für Astronomie

Thermonuclear Nova Properties

- Galactic rate $\sim 35 \pm 11\,\mathrm{yr}^{-1} (\sim 5 \text{ observed})$
- Mass return $\sim 4 \times 10^{-4}\,\mathrm{M}_\odot$ in $100 - 1000\,\mathrm{s}$
- Energy $E \sim 10^{45}\,\mathrm{erg}$
- Luminosity $L \sim 10^{4-5}\,\mathrm{L}_\odot$ (c.f. $10^{10}\,\mathrm{L}_\odot$ for SNe)
- Peak $T \sim 0.1 - 0.4\,\mathrm{GK}$
- Ejection velocity $\sim 10^3\,\mathrm{km\,s}^{-1}$ (c.f. $\sim 10^4$ for SNe)
- Binary progenitors $P \sim 1 - 12$ hours
  CVs!
- Periodic: typically $10^4 - 10^5$ years
- Rise time $\sim 1 - 2$ days

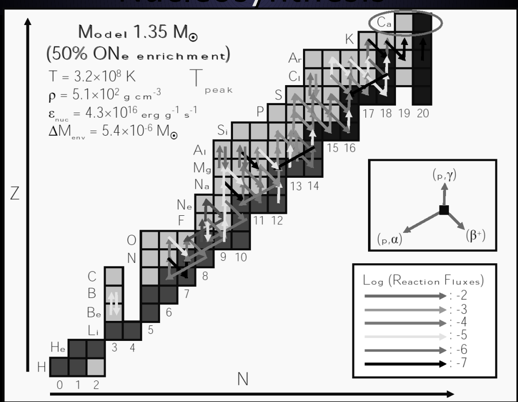
Nova Cygni 1992

Hubble Space Telescope
Faint Object Camera



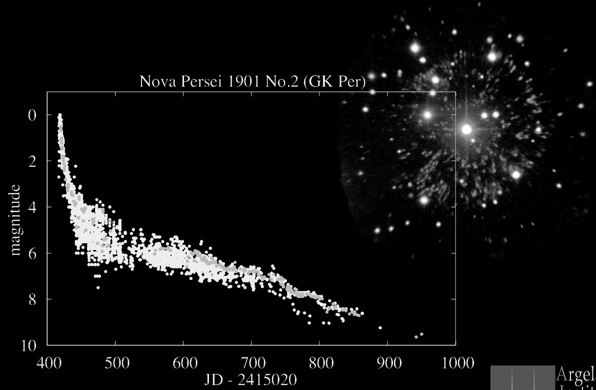
Note the "bar" in the orbital plane

Nucleosynthesis

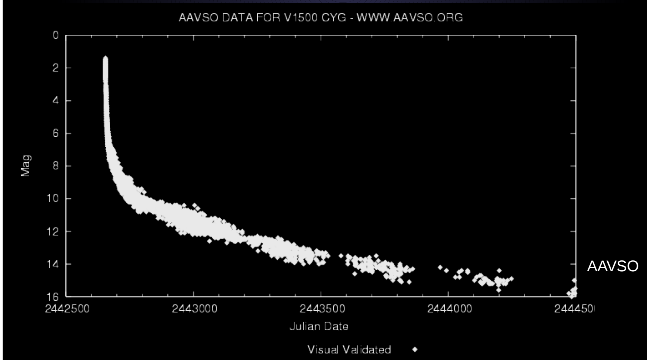


Stolen from Jordi Jose

GK Per

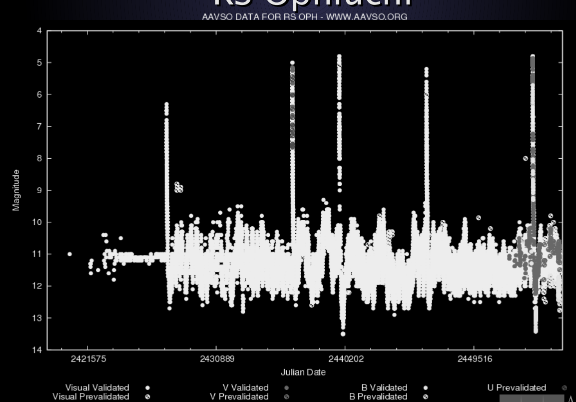


V1500 Cygni



AAVSO

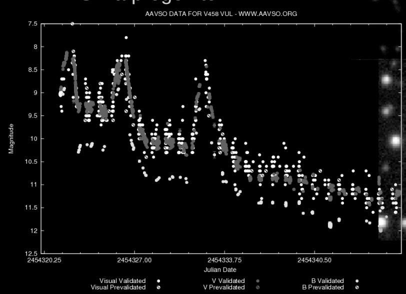
RS Ophiuchi



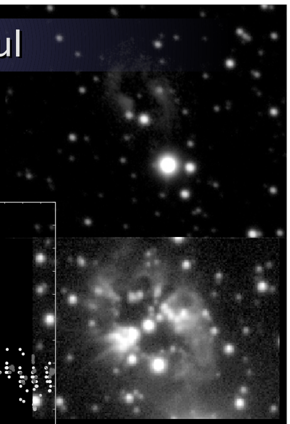
20 year period (1898, 1933, 1958, 1967, 1985, 2006)

V458 Vul

Nova inside a planetary nebula!
PN Estimated 14000 years old
Post common envelope
SNIa progenitor???



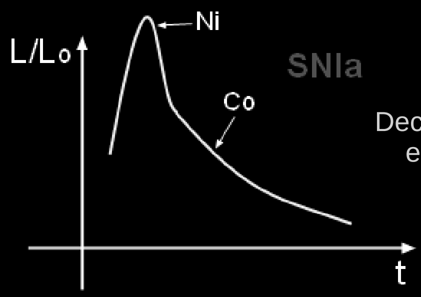
AAVSO



Wesson et al 2008

Argelander Institut für Astronomie

SNIa lightcurve

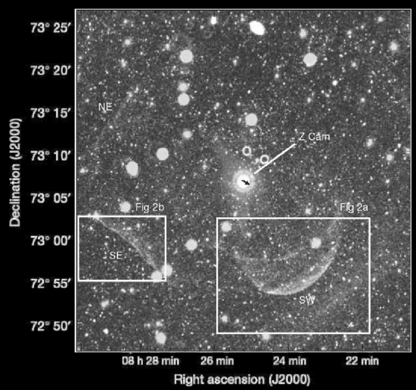


Decay of radioactive elements :
Nickel
Cobalt

Image from Wikipedia

Argelander Institut für Astronomie

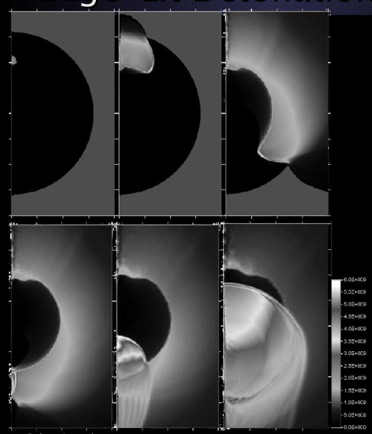
Classical - Dwarf Connection



Shara et al 2007
Nature 446,159

Argelander Institut für Astronomie

Edge-Lit Detonation (M<1.4)



colour=temperature

$\mathrm{white} = 6 \times 10^9 \mathrm{K}$
$M_{\mathrm{CO}} = 0.7\,\mathrm{M}_\odot$
$M_{\mathrm{He}} = 0.2\,\mathrm{M}_\odot$

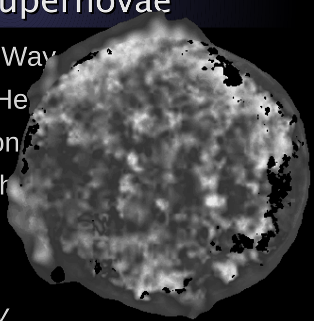
Total time < 2 seconds!

Forcada, Garcia-Senz, Jose 2007

Argelander Institut für Astronomie

Type Ia supernovae

- 1/250 years in Milky Way
- Spectrum: Si; No H,He
- White dwarf explosion
- Sub-MCh/MCh/>MCh
- Mag Mv=-19
- "Standard Candles"
- Useful for *cosmology*
- Iron-peak nucleosynthesis
  Fe, Ni, Co, Ti …



Tycho's SN remnant
NASA/MPIA/Calar Alto Observatory,
Oliver Krause et al.

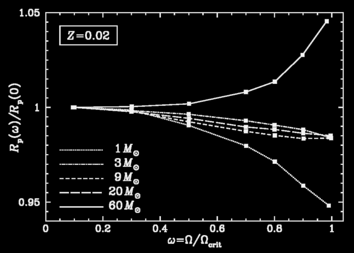
Argelander Institut für Astronomie

Pause for coffee

Argelander Institut für Astronomie

An aside: dimensions of rotating stars

- Can we treat stars as essentially *single stars*?
- Polar radius is approx const.



Variations in the polar radius as a function of the ratio $\omega = \Omega/\Omega_{crit}$, normalized to the non-rotating value, for various masses at standard metallicity.

Ekstrom et al 2008 A&A 478, 467

Fitting Formulae

- Time evolution function of $\tau = t/t_{MS}$

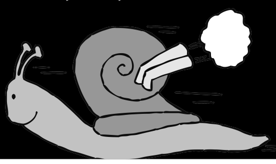
$$t_{MS} = \frac{2550 + 669M^{2.5} + M^{4.5}}{0.0327M^{1.5} + 0.346M^{4.5}}.$$

- Then

$$\log_{10} L = \log_{10} L_0 + \alpha\tau_{MS} + \beta\tau_{MS}^2$$
$$\log_{10} R = \log_{10} R_0 + \alpha'\tau_{MS} + \beta'\tau_{MS} + \gamma'\tau_{MS}^3$$

Rapid Stellar Models

- Creating *detailed* stellar models is slow and difficult
- Rapid or synthetic stellar models are faster
- Replace details solver with pre-solved model set:
  - Fitting formulae
  - Or lookup tables
- Sacrifice (usually unwanted) details for speed: up to 10,000,000 times faster.



Fitting formulae

$$\alpha = \begin{cases} 0.2594 + 0.1348\log_{10} M & M \le 1.334 \\ 0.09209 + 0.05934\log_{10} M & M > 1.334 \end{cases}$$
$$\beta = \begin{cases} 0.144 - 0.833\log_{10} M & M \le 1.334 \\ 0.3756\log_{10} M - 0.1744\,(\log_{10} M)^2 & M > 1.334 \end{cases}$$

$$\alpha' = \begin{cases} 0 & M \le 1.334 \\ 0.1509 + 0.1709\log_{10} M & M > 1.334 \end{cases}$$
$$\beta' = \begin{cases} 0.2226\log_{10} M & M \le 1.334 \\ -0.4805\log_{10} M & M > 1.334 \end{cases}$$
$$\gamma' = \begin{cases} 0.1151 & M \le 1.334 \\ 0.5083\log_{10} M & M > 1.334 \end{cases}.$$

Even more complicated formulae apply for later phases of evolution!
But computers *do not care* ...

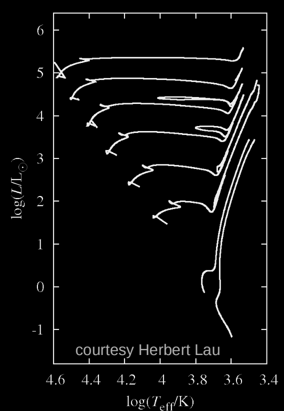
Fitting Formulae

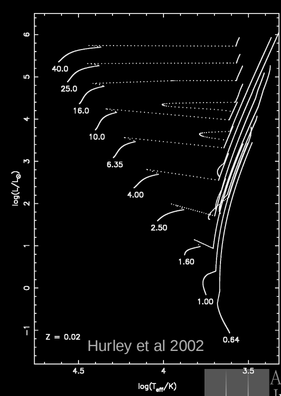
- Eggleton, Fitchett, Tout 1989, Hurley et al 2000,2002
- Zero-age main sequence:

$$L_0 = \begin{cases} \frac{1.107M^3+240.7M^9}{1+281.9M^4} & M \le 1.093 \\ \frac{13990M^5}{M^4+2151M^2+3908M+9536} & M \ge 1.093 \end{cases}$$

$$R_0 = \begin{cases} \frac{0.1148M^{1.25}+0.8604M^{3.25}}{0.04651+M^2} & M \le 1.334 \\ \frac{1.968M^{2.887}-0.7388M^{1.679}}{1.821M^{2.337}-1} & M \ge 1.334 \end{cases}$$

Real vs Synthetic HRD



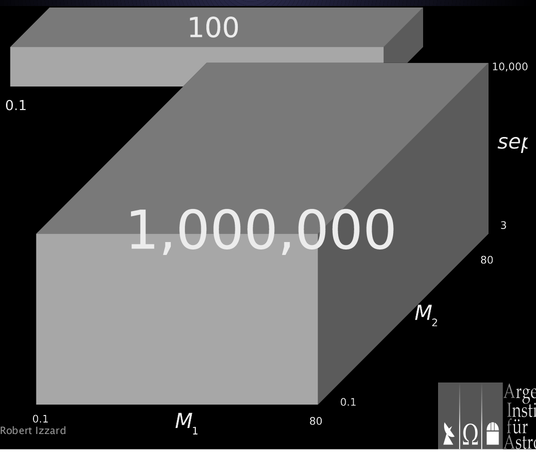


Pros and Cons

- Pros
  - Faster to compute
  - Stable
- Cons
  - Fixed input physics (but could use tables!)
  - Discard of potentially useful information
  - Off-grid treatment
  - Fitting errors (<5%)

$$\begin{aligned}\log_{10} L &= \log_{10} L_0 + \alpha\tau_{\mathrm{MS}} + \beta\tau_{\mathrm{MS}}^2 \\ \log_{10} R &= \log_{10} R_0 + \alpha'\tau_{\mathrm{MS}} + \beta'\tau_{\mathrm{MS}} + \gamma'\tau_{\mathrm{MS}}^3\end{aligned}$$

Parameter Spaces



Population Synthesis

The process of combining stellar models into a stellar population upon which meaningful statistical analysis can be performed and compared to observations to better constrain the underlying physics.

1. Make your stellar models
2. Weight these according to mass, separation, time etc.
3. Extract simulated value(s)-compare
4. Determine the "real-life" distribution from obs.
5. Compare the two, see what's wrong
6. Refine your stellar models
7. Return to step 1 until you are happy

(or funding runs out)

Popsyn + rapid code

The Parameter Space Problem

- To make a single star population, one parameter only: Mass M_1
- Runtime is $\sim N \times \Delta t$
- Binaries many parameters :
  - Primary mass M_1
  - Secondary mass M_2
  - Sep/Period a or P
  - Maybe more e.g. e
- Runtime $\sim N^3 \times \Delta t$

Discretising Parameter Space

- Single Stars

$$\delta \ln M = \frac{\ln M_{\max} - \ln M_{\min}}{n}$$

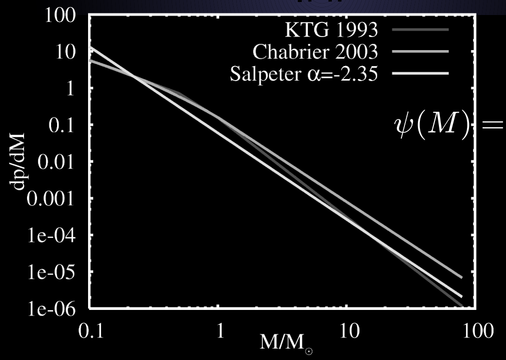
- Each star has a probability of existence

$$\delta p_i = \psi(M_i)\, \delta \ln M$$

- Where ψ is the *initial mass function*

$$\Sigma_i \delta p_i = 1$$

IMF



$$\psi(M) = \frac{dN_{stars}}{dM}$$

Salpeter IMF $\psi \propto M^{-2.35}$

Stellar accounts

- Define

$$\delta(\text{phase}) \; = 1 \quad \text{during the phase,}$$
$$= 0 \quad \text{otherwise.}$$

- Time a star spends in a phase of interest

$$\Delta t_i = \sum_{t=t_{\min}}^{t_{\max}} \delta(\text{phase at } t)_i \, \delta t$$

Discretising Parameter Space

- Binary Stars

$$\delta \ln x \quad = \quad \frac{\ln x_{\max} - \ln x_{\min}}{n_x}$$

where x is M_1, M_2, a(, P,e...)

- Each star has a probability of existence

$$\delta p_i \quad = \quad \Psi_i(M_1,\, M_2,\, a)\, \delta V$$

- Where Ψ is the *initial distribution function*

Stellar accounts

- The number of stars in the phase is

$$\text{count} \quad = \quad \sum_i S \delta p_i \Delta t_i$$
$$= \quad \sum_i S \delta p_i \sum_{t_{\min}}^{t_{\max}} \delta(\text{phase})_i \, \delta t$$

where S is the star formation rate

- In general we have to convolve a birth function with a star formation rate function
-

Initial Distribution Function

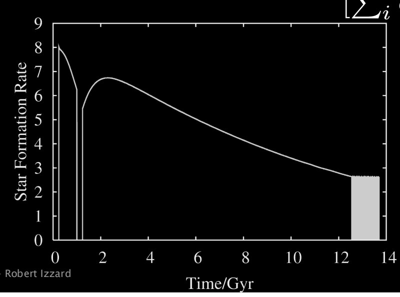
$$\Psi_i \quad = \quad \psi\left(M_{1i}\right) \phi\left(M_{2i}/M_{1i}\right) \chi\left(a_i\right)$$

$$\psi(M_1) \quad = \quad \psi(M)$$
$$\phi\left(q = \frac{M_1}{M_2}\right) \quad = \quad \text{constant}$$
$$\chi(a) \quad \propto \quad a^{-1}$$
$$\chi(\ln a) \quad = \quad \text{constant}.$$
$$\delta p_i \quad = \quad \Psi_i \delta V_i$$
$$\delta V \quad = \quad \delta \ln M_1 \delta \ln M_2 \delta \ln a$$
$$\Sigma_i \delta p_i = 1$$

Stellar accounts

- Simple case : S = constant
- Divide counts to get ratios : S drops out

$$\text{ratio} \quad = \quad \frac{\left[\sum_i \delta p_i \Delta t_i\right]_1}{\left[\sum_i \delta p_i \Delta t_i\right]_2}.$$



Galactic SFR
Chiappini et al 1997

Stellar accounts

- The number of stars in the phase is

$$\Sigma_i S \delta p_i \Delta t_i$$

where *S* is the star formation rate

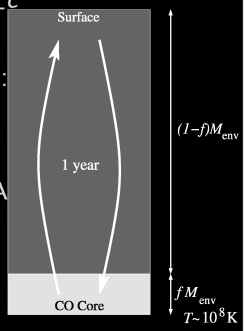
- In general we have to convolve a birth function with a star formation rate function

$$\sum_{t'_{\min}}^{t'_{\max}} \sum_i S(t) \delta p_i \delta(\text{phase at } t')_i \, \delta t'$$

Argelander Institut für Astronomie

binary_c/nucsyn

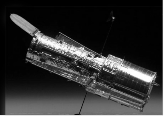
- Added *nucleosynthesis* to *binary_c*
- First and second dredge up
- TPAGB based on Karakas' models:
  - Third dredge up
  - Hot-bottom burning
    - (CNO, NeNa, MgA
  - S-process (Torino group)
- SN II/Ibc yields, novae
- Thermohaline mixing
- Physics updates over last few years



Argelander Institut für Astronomie

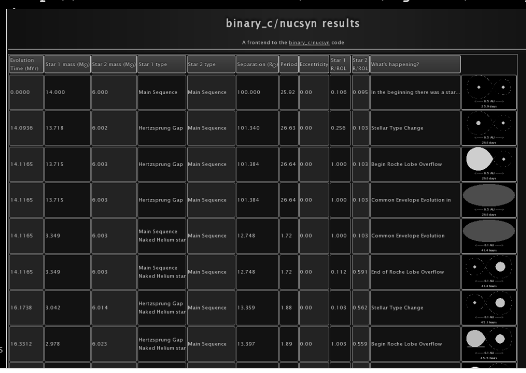
Compare to Observations

- Statistics!
  - Boring (but not for everyone!)
  - Necessary e.g χ^2 ,KS test
  - Key to good science
- Beware observational selection effects
  - Often very hard to model
  - Data combined from multiple surveys might be impossible to model!
  - Sometimes whole papers are wrong because they neglect this! (not deliberately)



Some examples of binary_c

- Remember to try it yourself!
- `http://www.astro.uni-bonn.de/~izzard/cgi-bin/binary3.cg`



binary_c/nucsyn results

A frontend to the binary_c/nucsyn code

Evolution Time (MYr)	Star 1 mass ($M_\odot$)	Star 2 mass ($M_\odot$)	Star 1 type	Star 2 type	Separation ($R_\odot$)	Period	Eccentricity	Star 1 R/ROL	Star 2 R/ROL	What's happening?
0.0000	14.000	6.000	Main Sequence	Main Sequence	100.000	25.92	0.00	0.106	0.095	In the beginning there was a star...
14.0936	13.718	6.002	Hertzsprung Gap	Main Sequence	101.340	26.63	0.00	0.256	0.103	Stellar Type Change
14.1165	13.715	6.003	Hertzsprung Gap	Main Sequence	101.384	26.64	0.00	1.000	0.103	Begin Roche Lobe Overflow
14.1165	13.715	6.003	Hertzsprung Gap	Main Sequence	101.384	26.64	0.00	1.000	0.103	Common Envelope Evolution in
14.1165	3.349	6.003	Main Sequence Naked Helium star	Main Sequence	12.748	1.72	0.00	1.000	0.103	Common Envelope Evolution
14.1165	3.349	6.003	Main Sequence Naked Helium star	Main Sequence	12.748	1.72	0.00	0.112	0.591	End of Roche Lobe Overflow
16.1738	3.042	6.014	Hertzsprung Gap Naked Helium star	Main Sequence	13.359	1.88	0.00	0.103	0.562	Stellar Type Change
16.3312	2.978	6.023	Hertzsprung Gap Naked Helium star	Main Sequence	13.397	1.89	0.00	1.003	0.559	Begin Roche Lobe Overflow

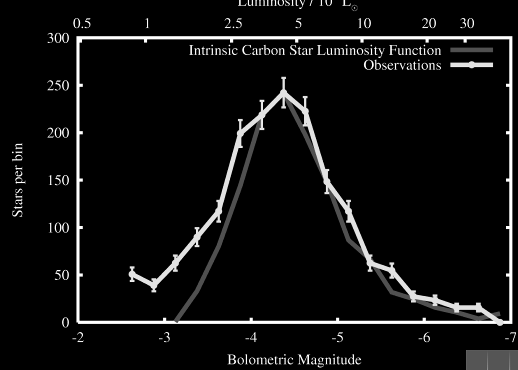
Argelander Institut für Astronomie

A rapid code: *binary_c*

- My code, my lectures, so …
- Based on *SSE/BSE* of EFT89, Hurley et al 2000, 2002 (e.g. see prev. eqs)
- Has fitting functions for stellar evolution
- +orbital algorithm: RLOF, Wind, Tides
- Common env., Novae, SNe Ia, Mergers etc.
- Online
- **http://www.astro.uni-bonn.de/~izzard/cgi-bin/binary3.cgi**

Argelander Institut für Astronomie

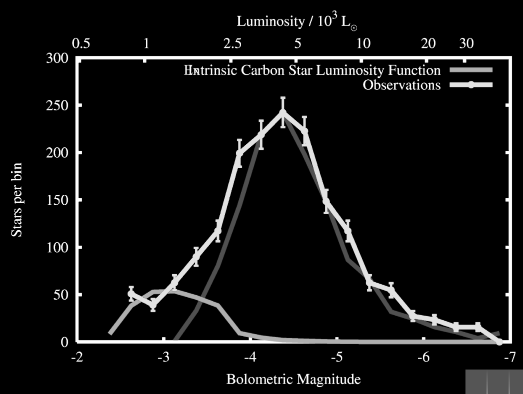
Low-L Carbon Stars



Izzard and Tout 2004

Argelander Institut für Astronomie

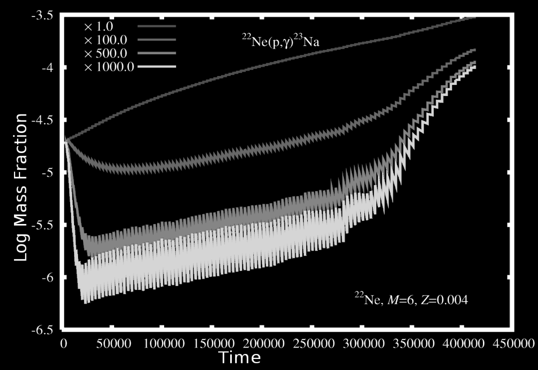
Low-L Carbon Stars



Izzard and Tout 2004

Argelander Institut für Astronomie

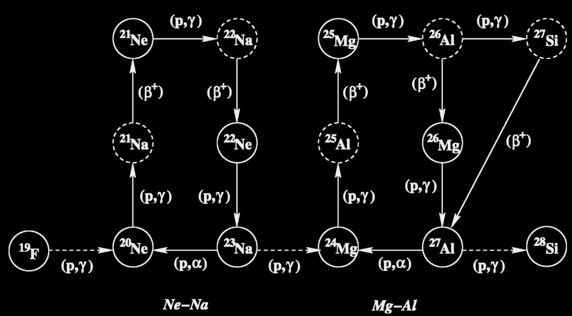
Nuclear Burning Rates



Izzard et al. 2007

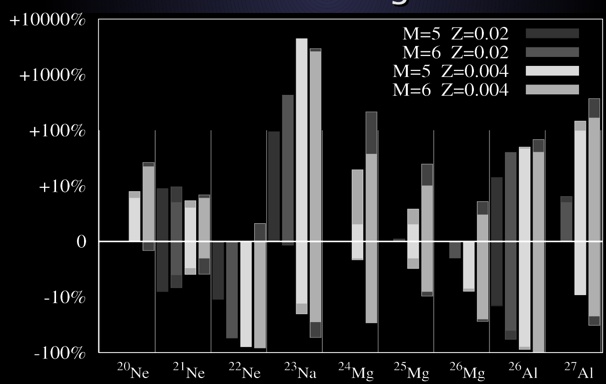
Argelander Institut für Astronomie

Nuclear Burning Rates



Argelander Institut für Astronomie

Nuclear Burning Rates



Izzard et al. 2007

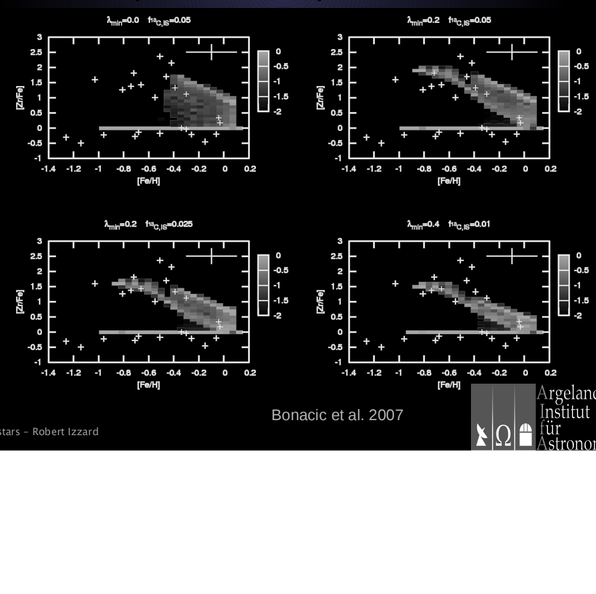
Argelander Institut für Astronomie

Nuclear Burning Rates

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

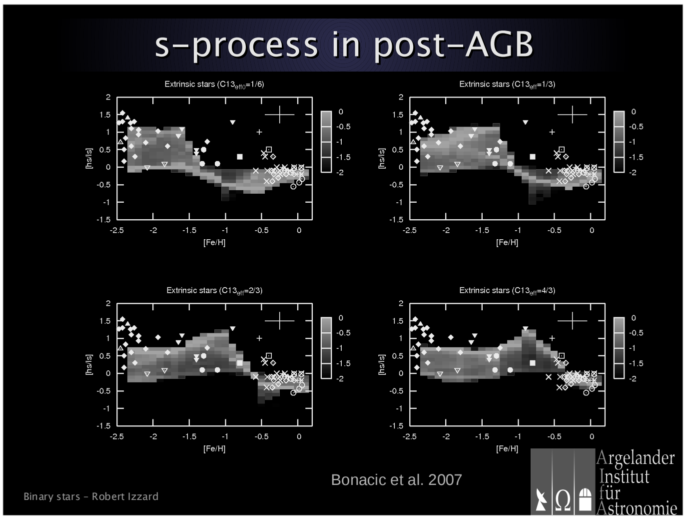
Argelander Institut für Astronomie

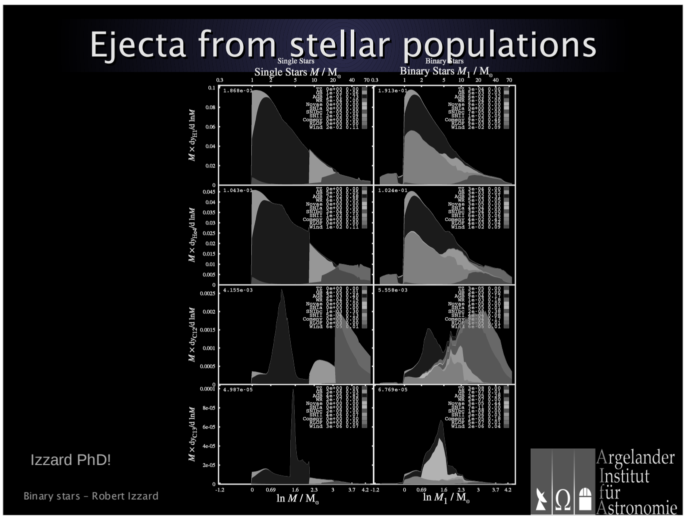
s-process in post-AGB

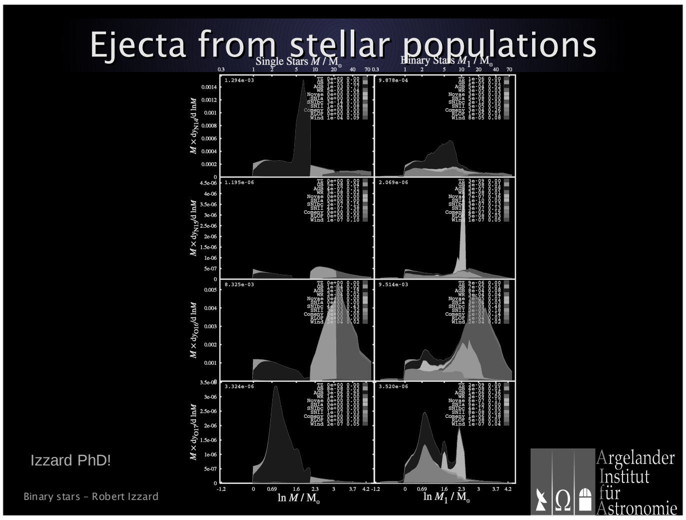


Bonacic et al. 2007

Argelander Institut für Astronomie


s-process in post-AGB
Extrinsic stars (C13eff=1/6)
Extrinsic stars (C13eff=1/3)
Extrinsic stars (C13eff=2/3)
Extrinsic stars (C13eff=4/3)
[hs/ls]
[Fe/H]
Bonacic et al. 2007
Binary stars - Robert Izzard
Argelander Institut für Astronomie


Ejecta from stellar populations
Single Stars M / M⊙
Binary Stars M1 / M⊙
ln M / M⊙
ln M1 / M⊙
Izzard PhD!
Binary stars - Robert Izzard
Argelander Institut für Astronomie


Ejecta from stellar populations
Single Stars M / M⊙
Binary Stars M1 / M⊙
ln M / M⊙
ln M1 / M⊙
Izzard PhD!
Binary stars - Robert Izzard
Argelander Institut für Astronomie