Astrophysics I: Stars and Stellar Evolution

AST 4001

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Stars and Stellar Evolution, Fall 2008

Overview

1. Recap
   - Schönberg-Chandrasekhar Limit
   - Evolution Through Core Contraction
   - Evolution of a 8 $M_\odot$ Star
2. Intermediate-Mass Stars
   - Evolution of a 4 $M_\odot$ Star
   - Core Helium Burning
   - AGB Stars and Planetary Nebulae

Derivation of the Schönberg-Chandrasekhar Limit (IV)

- using the homolgy relation

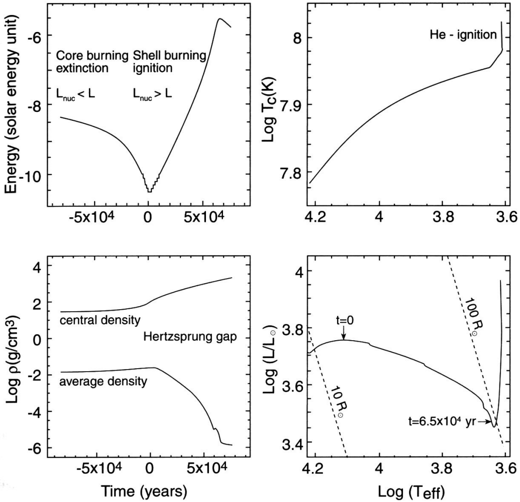
$$T_{\mathrm{c}} \propto \frac{\mu_{\mathrm{env}} G}{\mathcal{R}} \frac{M}{R}$$

  we can eliminate T_{c} and R and obtain

$$\frac{M_{\mathrm{c}}}{M} \lesssim C_2 \left(\frac{\mu_{\mathrm{env}}}{\mu_{\mathrm{c}}}\right)^2 , \quad C_2 \sim 0.37$$

- with $\mu_{\mathrm{env}} \approx 0.75$, $\mu_{\mathrm{c}} \approx 1.33$ one finds $M/M_{\mathrm{c}} \lesssim 0.12$.
  $\Rightarrow$ beyond that limit the core starts contacting.

Evolution Through Core Contraction



Note:

- Fast evolution too cool T_{eff}
- $\Rightarrow$ few stars are found in transition region
- $\Rightarrow$ "Hertzprung Gap" in HRD

Quiz - Radius in the HRD

Determine lines of constant radius in the HRD.

- Derive a Relation of the form

$$\log L(R) = A \log T_{\mathrm{eff}} + B \log R + C$$

- Determine the constants A, B, and C
- work in groups of 2-3 people, write down your solution and hand it in with names
- no grades

Solution - Radius in the HRD

Determine lines of constant radius in the HRD.

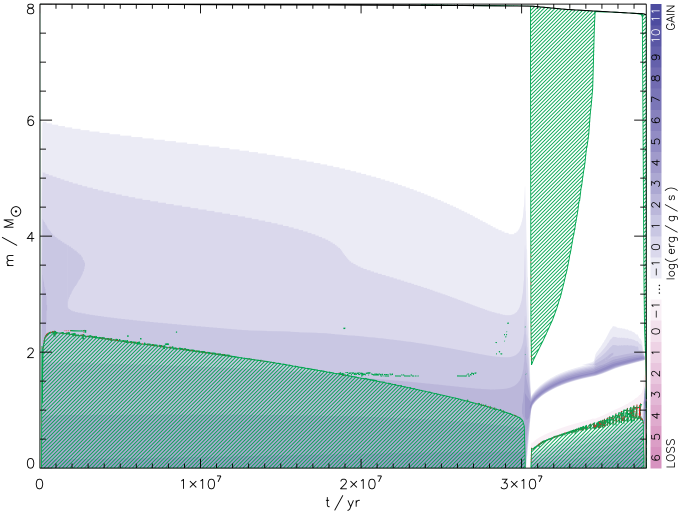
Derive a Relation of the form

$$\log L(R) = A \log T_{\mathrm{eff}} + B \log R + C$$

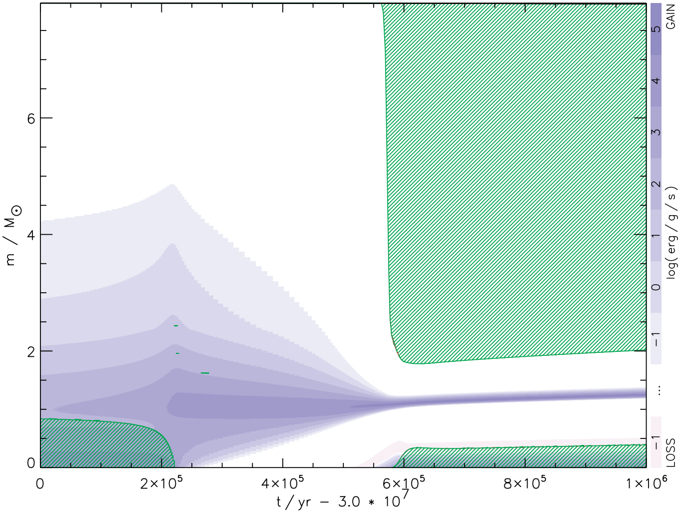
Solution

- $$L = 4\pi R^2 \sigma T_{\mathrm{eff}}^4$$
- $$\log L = 4 \log T_{\mathrm{eff}} + 2 \log R + \log(4\pi\sigma)$$
- $\Rightarrow A = 4,\ B = 2,\ C = \log(4\pi\sigma)$

Kippenhahn Diagram, 8 $M_\odot$ Star



Kippenhahn Diagram, 8 $M_\odot$ Star, He Ignition



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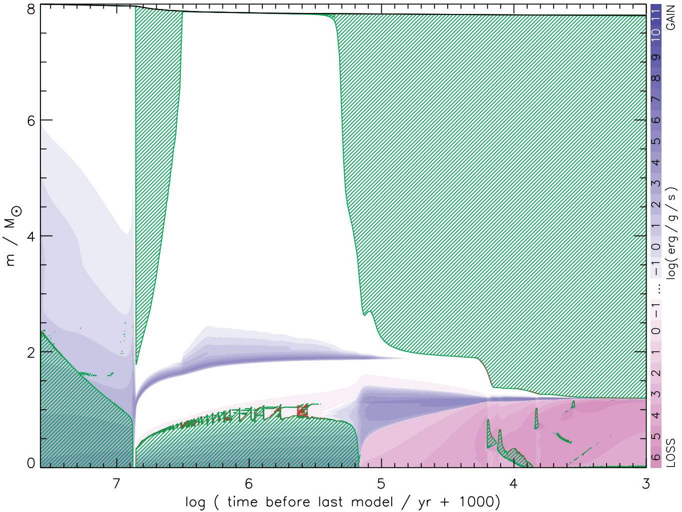
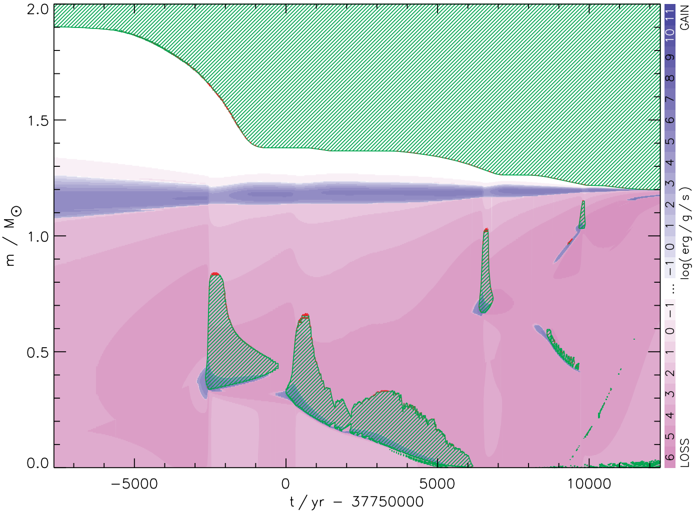


Kippenhahn Diagram, 8 $M_\odot$ Star, Off-Center C Ignition



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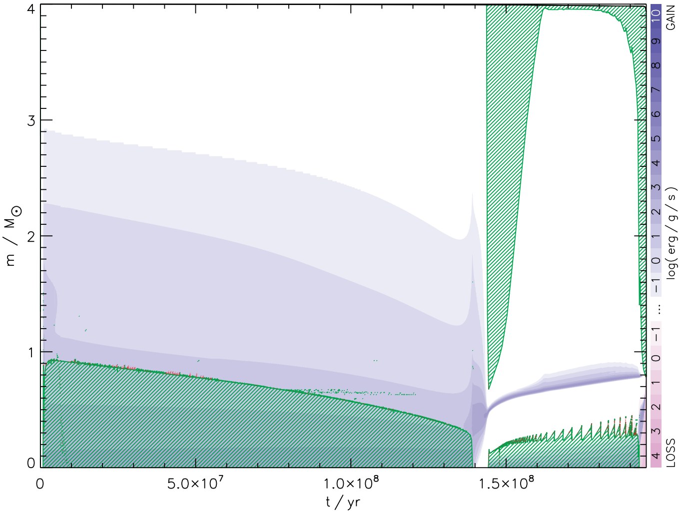
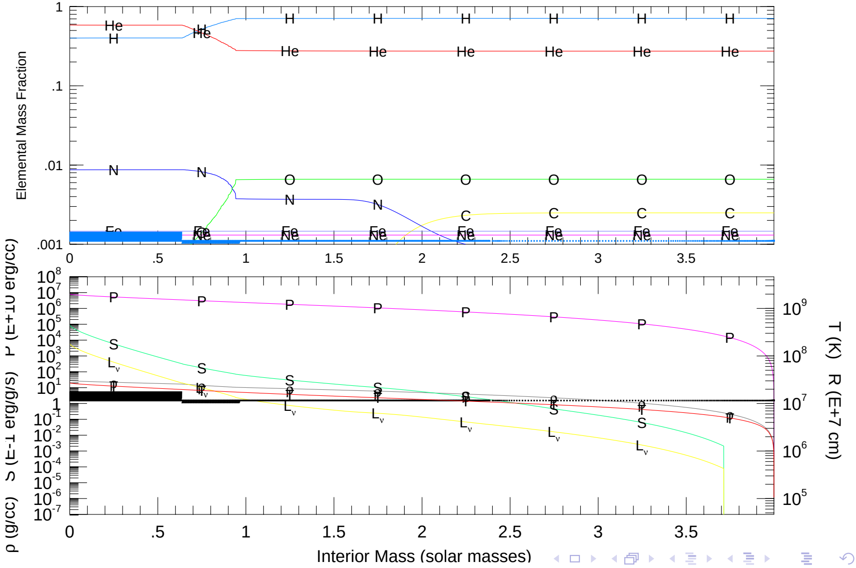
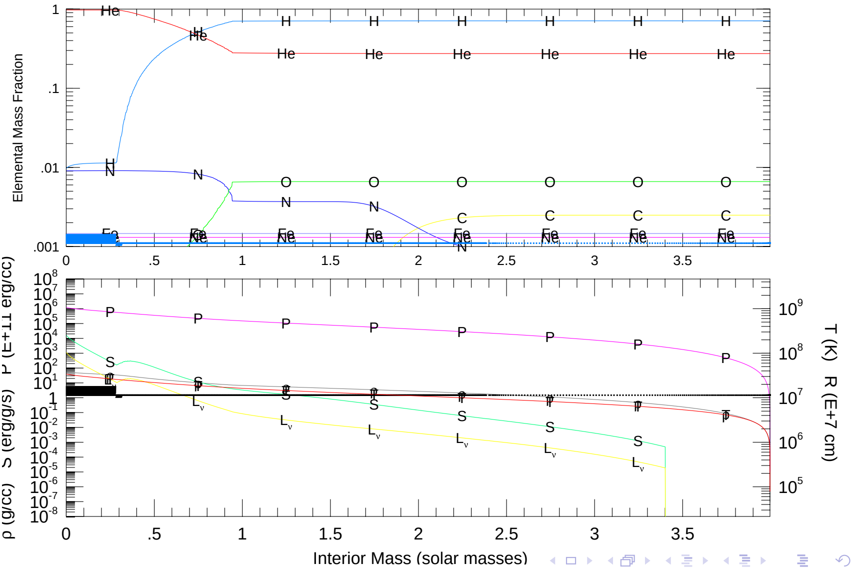


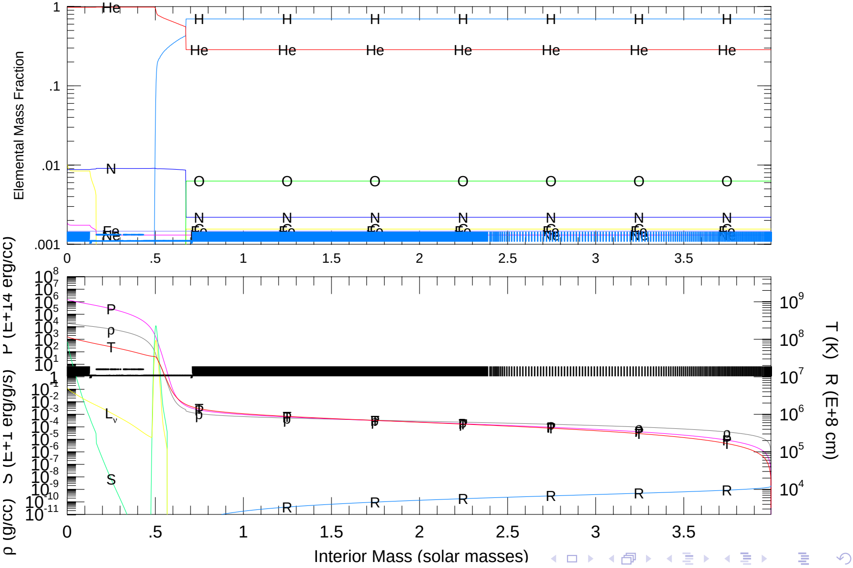
4 $M_\odot$ Star, Middle of Hydrogen Burning



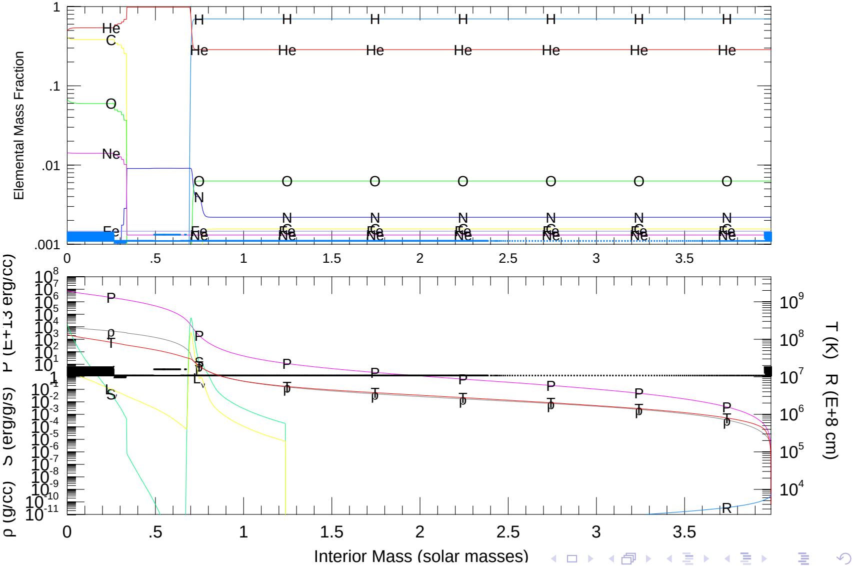
4 $M_\odot$ Star, End of Hydrogen Burning



4 $M_\odot$ Star, Beginning of Helium Burning



4 M$_\odot$ Star, Middle of Helium Burning



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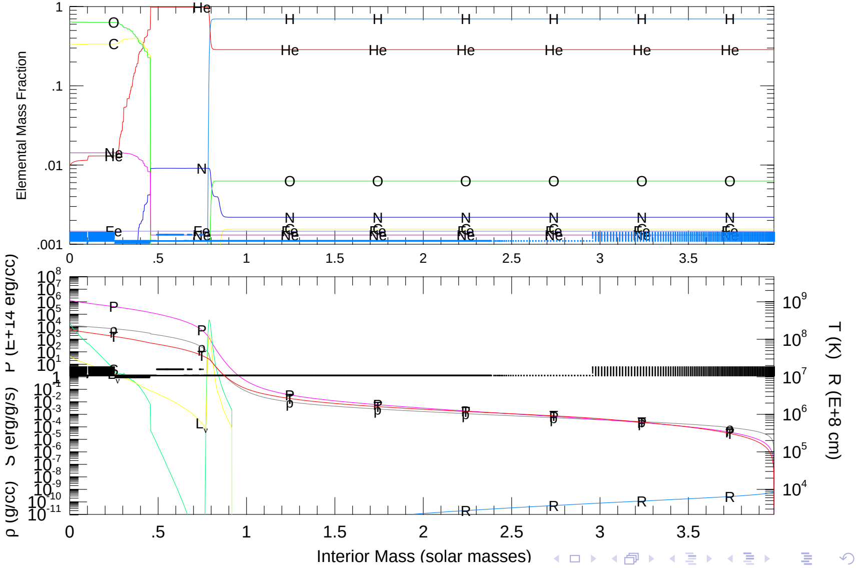
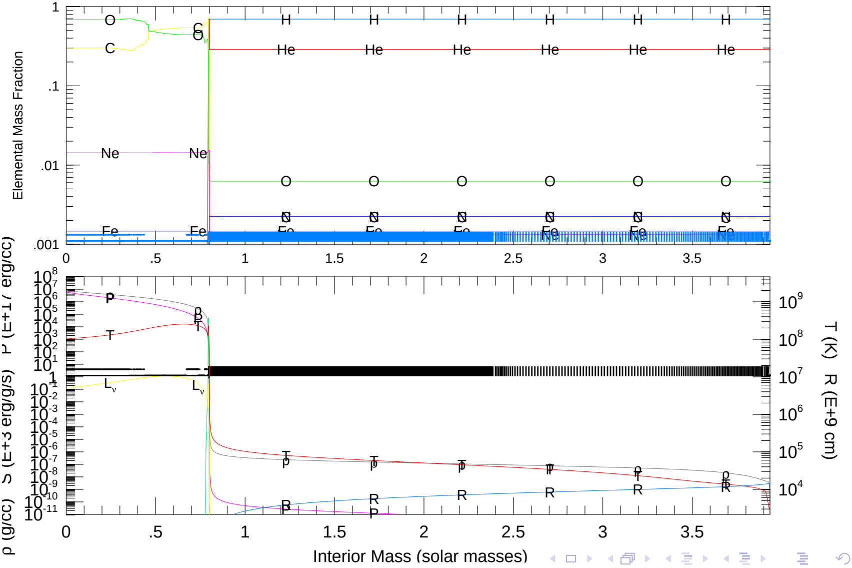
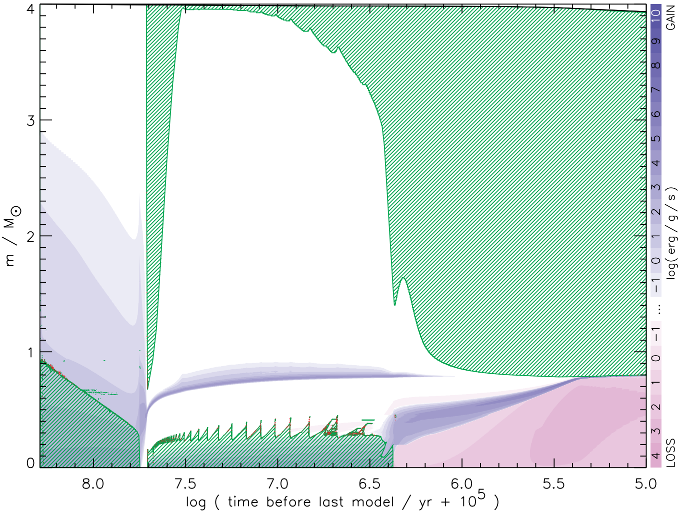


4 $M_\odot$ Star, Last Model Computed



Kippenhahn Diagram, 4 $M_\odot$ Star



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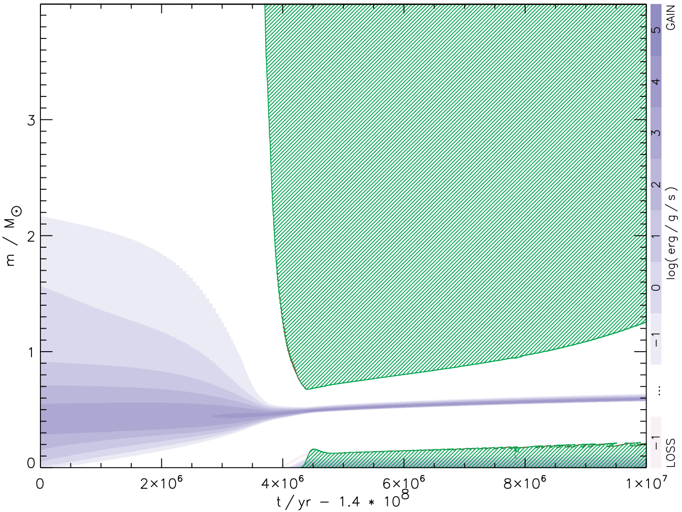
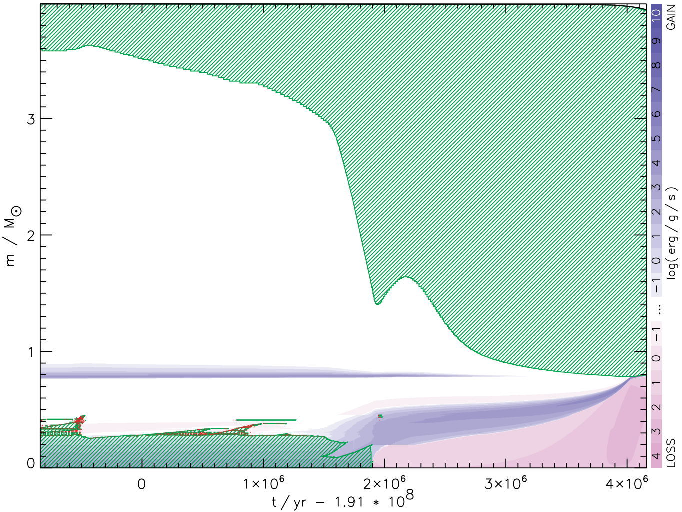


Kippenhahn Diagram, 4 $M_\odot$ Star, He Depletion



Core Helium Burning

- shorter life time due to
  - less energy yield per unit mass burnt (by about a factor 10)
  - higher luminosity (by about a factor 10)
  - less mass involved (core smaller than inter star)
- but additional contribution to luminosity from hydrogen shell burning
- red giant close to Hayashi line in HRD

Intermediate Mass Stars

- stellar masses $2 - 10\,M_\odot$
- "quiet" ignition of core helium burning
- two sources of energy generation:
  - core helium burning
  - hydrogen shell burning
- both yield about comparable contribution to total luminosity
- when energy contribution from helium burning gets big enough, the envelope contracts the star moves back to higher surface temperature
- but remain close to red giant branch
- "loop" more extended for more massive stars

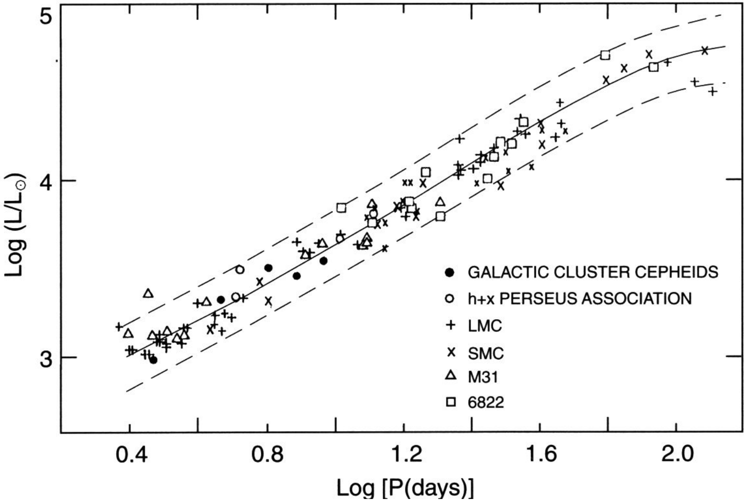
Cepheids

- intermediate mass stars also pass through an instability strip
- they become pulsationally unstable Cepheid variables
- A clear relation between intrinsic luminosity of the Cepheids and the pulsational period exists
- this relation can be used to determine the distance of the star based on the observed intensity I_{obs}

$$d = \left[\frac{L_{\mathrm{Cepheid}}(P_{\mathrm{obs}})}{4\pi I_{\mathrm{obs}}} \right]^{1/2}$$

- They were used as cosmological standard candels and were used to first establish the cosmological distance scale

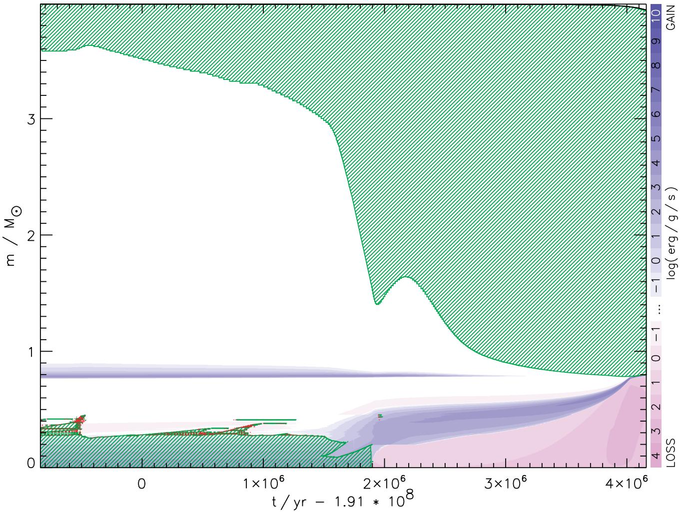
Period-Luminosity Relation for Cepheids



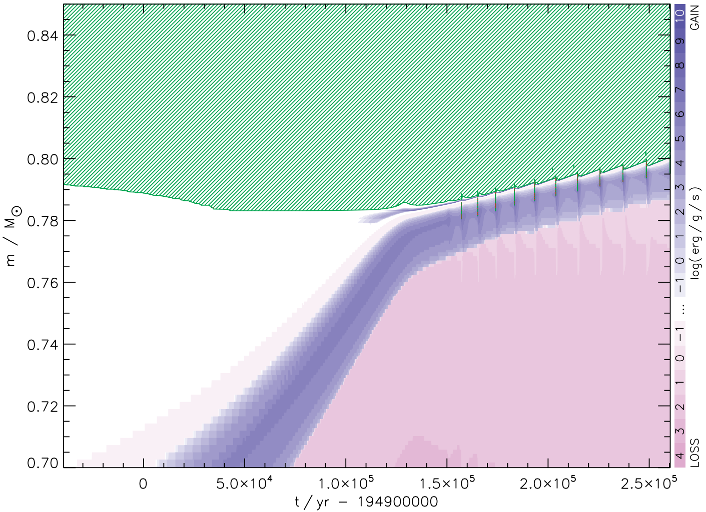
Intermediate Mass Star - Late Evolution

- after core helium burning, helium burning continues in a shell on top of the CO core / He core boundary
- a significant dredge-up reduces the mass of the helium core above that interface and brings nitrogen and helium to the surface of the star
- the envelope is enriched
- the star becomes redder and climbs up the red giant branch one more time; it reaches the asymptotic giant branch (AGB)
- the stars aver very close to the Hayashi line, bigger and redder then before
- they have become red super giants (RSG)
- they have a degenerate, isothermal core, similar to a white dwarf star

Kippenhahn Diagram, 4 $M_\odot$ Star, He Depletion



Kippenhahn Diagram, 4 $M_\odot$ Star, Post-Core He burning



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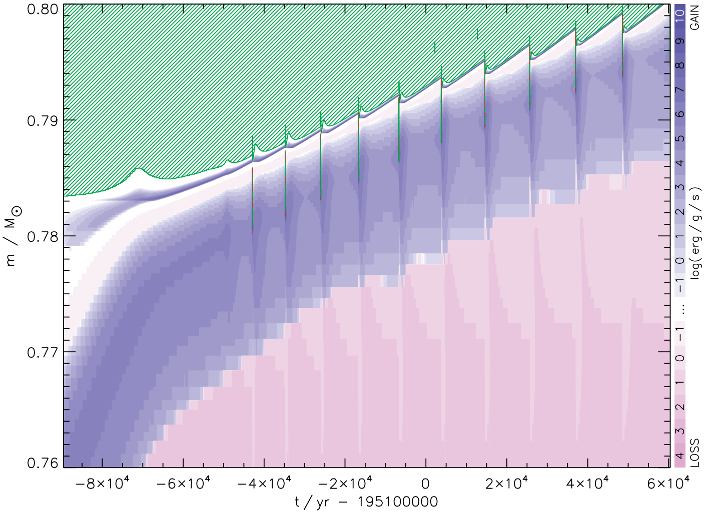

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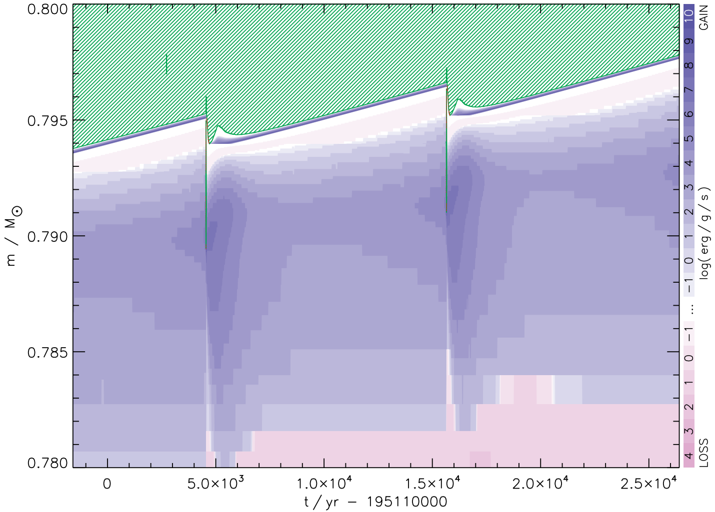

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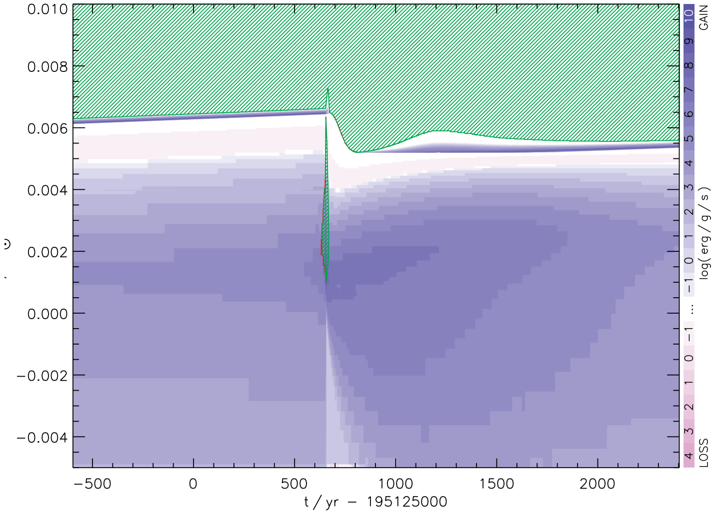

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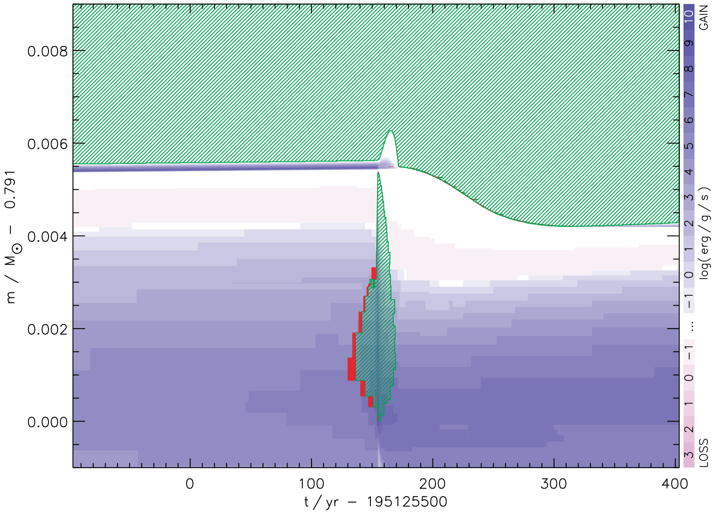

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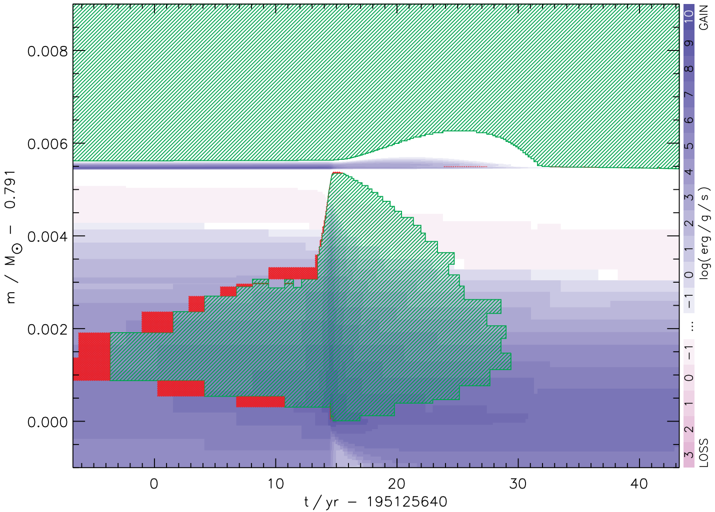


The Asymptotic Giant Branch (I)

asymptotic giant branch stars are characterized by

- two burning shells, hydrogen burning and helium burning, in an unstable configuration, leading to thermal pulses
- luminosity uniquely determined by core mass, not total mass
- strong stellar winds from the surface, driven by pulsations and radiation pressure on dust forming in the outer layers

The Asymptotic Giant Branch (II)

Eventually the entire envelope is blown away leaving behind a white dwarf star. Typical wind mass loss rates are of the order of $10^{-6}\,\mathrm{M}_\odot/\mathrm{yr}$

$$\dot{M} \sim 10^{-13}\mathrm{M}_\odot/\mathrm{yr}\,\frac{L}{\mathrm{L}_\odot}\frac{R}{\mathrm{R}_\odot}\frac{\mathrm{M}_\odot}{M}$$

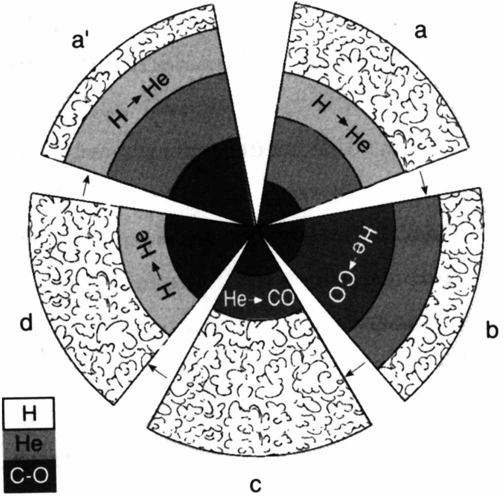
for $M > 0.5\mathrm{M}_\odot$ luminosity is given by

$$\frac{L}{\mathrm{L}_\odot} = 6\times10^4\left(\frac{M}{\mathrm{M}_\odot} - 0.5\right)$$

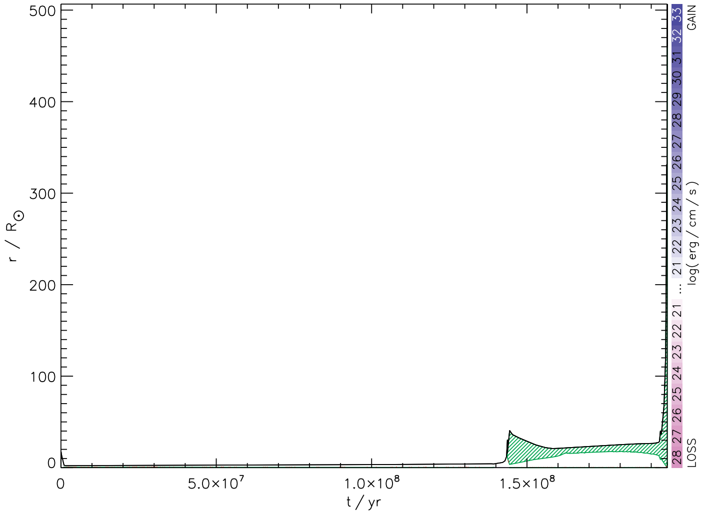
The Asymptotic Giant Branch (III)

- an extended phase of steady hydrogen shell burning builds up an increasingly thicker degenerate helium layer for some hundred years
- thermonuclear runaway in helium shell, $L \sim 10^8\,\mathrm{L}_\odot$
- "third" dredge-up after after helium shell flash
- nucleosynthesis of the strong component of the *s*-process in the helium shell making heavy elements up to lead starting from iron
- dredge-up brings freshly synthesized material into the envelope where winds blow it away.
- growth of the core is due to competition ("race") of dredge-up after helium shell flash and mass loss

Change of Structure During AGB Cycle



Kippenhahn-Radius Diagram, 4 $M_\odot$ Star



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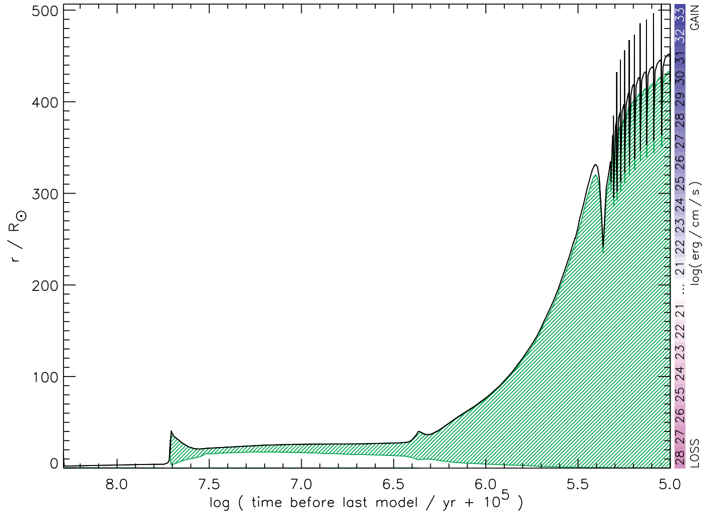
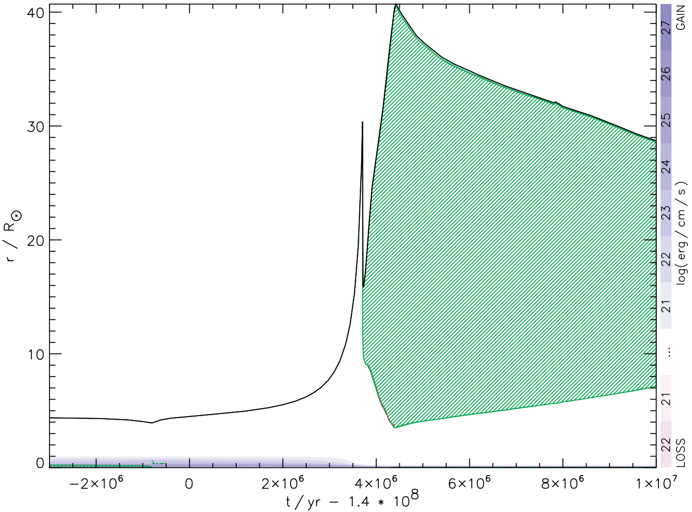
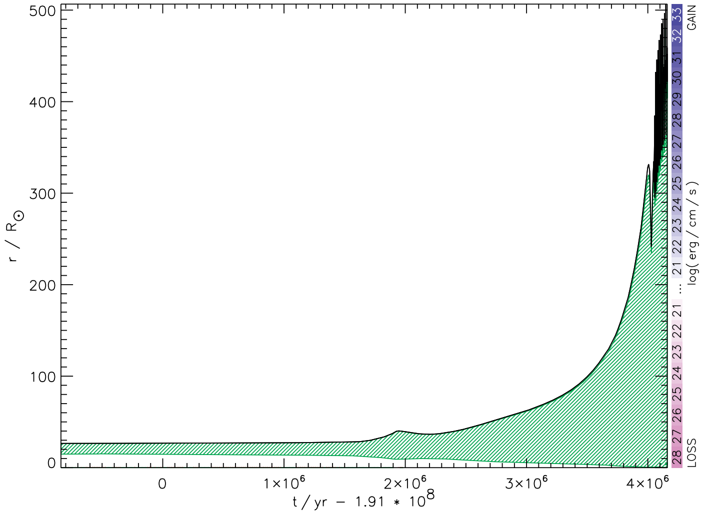


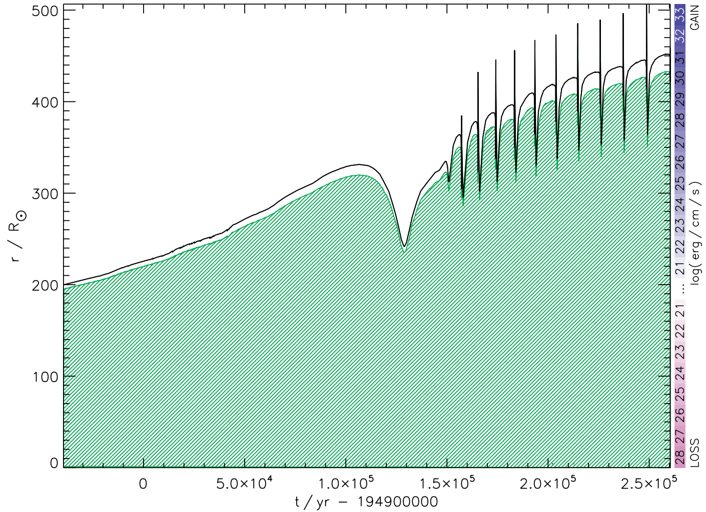
Kippenhahn-Radius Diagram, 4 $M_\odot$ Star, Helium Ignition



Kippenhahn-Radius Diagram, 4 $M_\odot$ Star, He Depletion



Kippenhahn-Radius Diagram, 4 $M_\odot$ Star, Start of AGB



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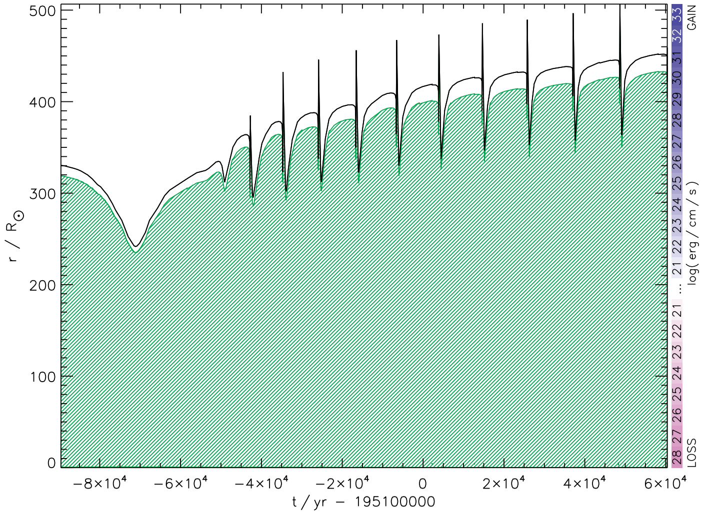

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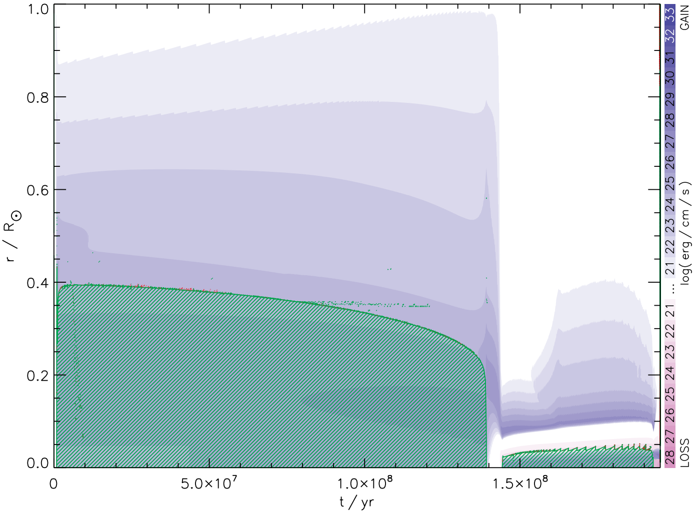

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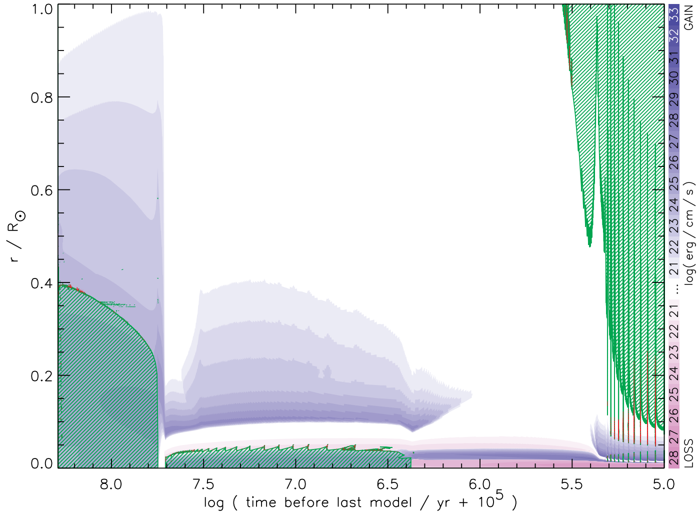

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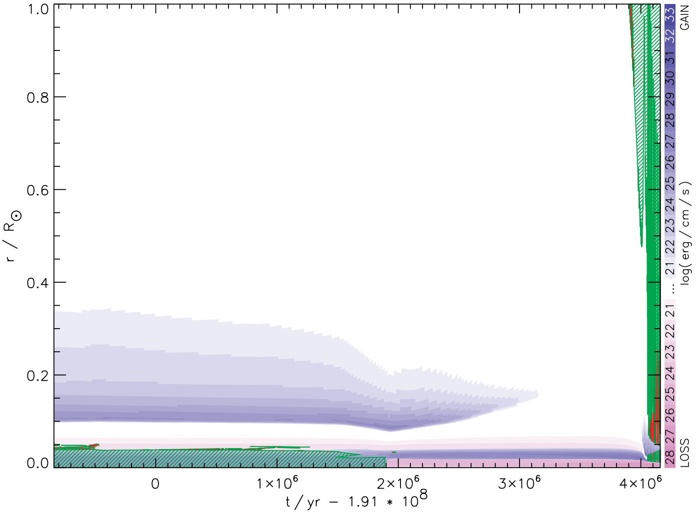

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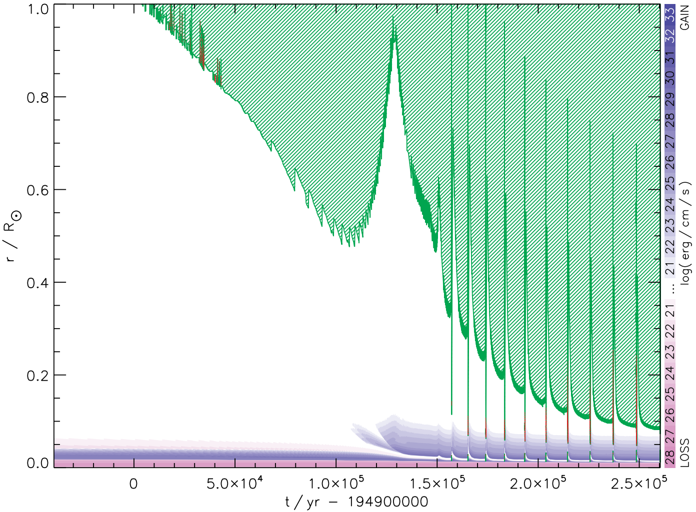

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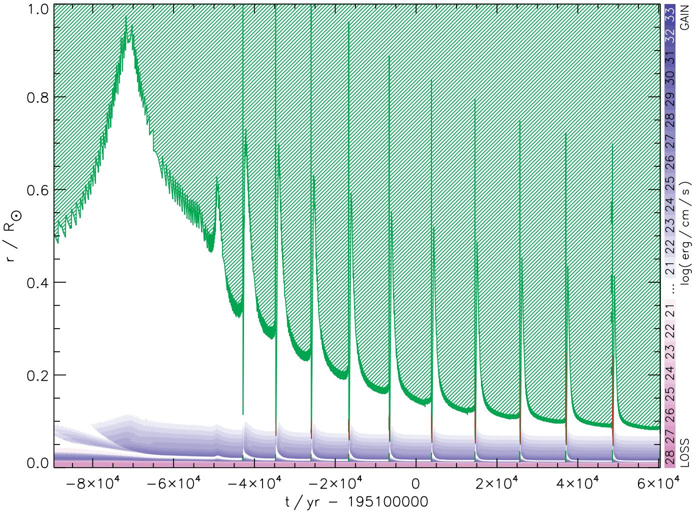

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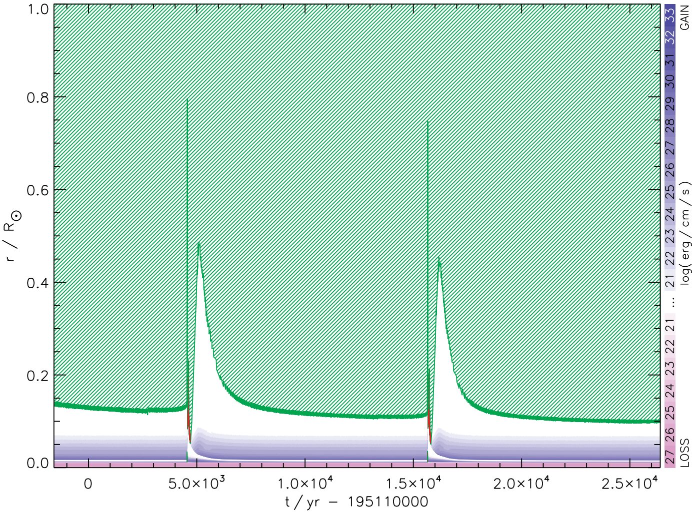

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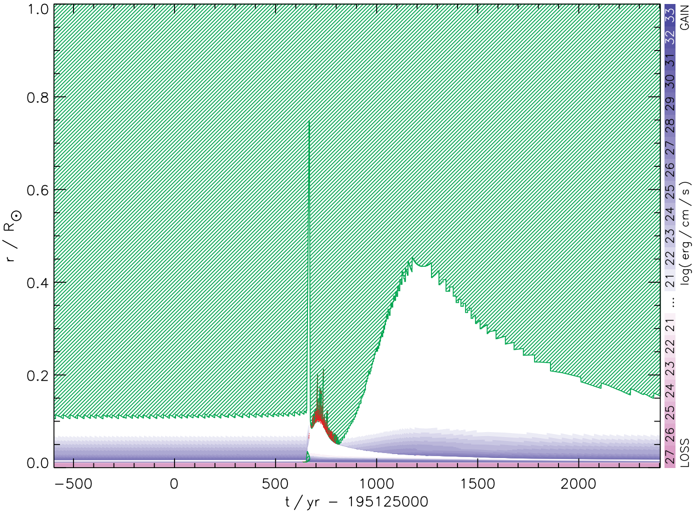

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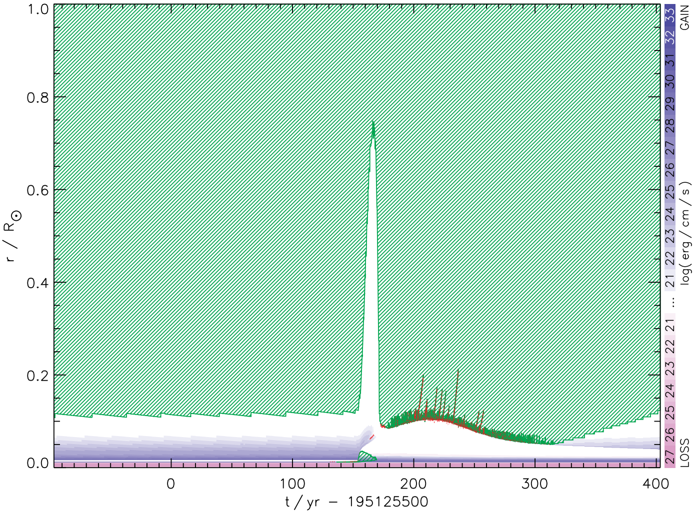

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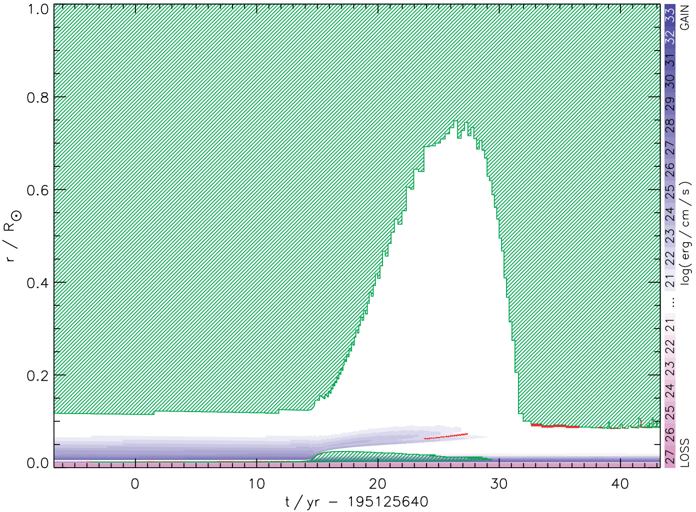

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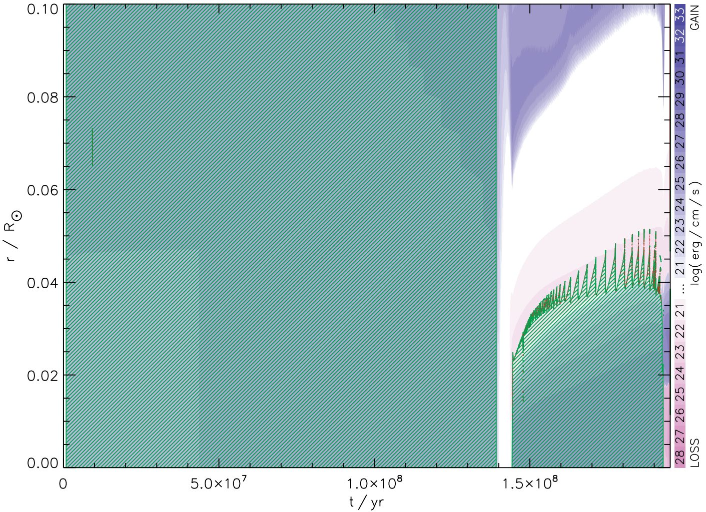

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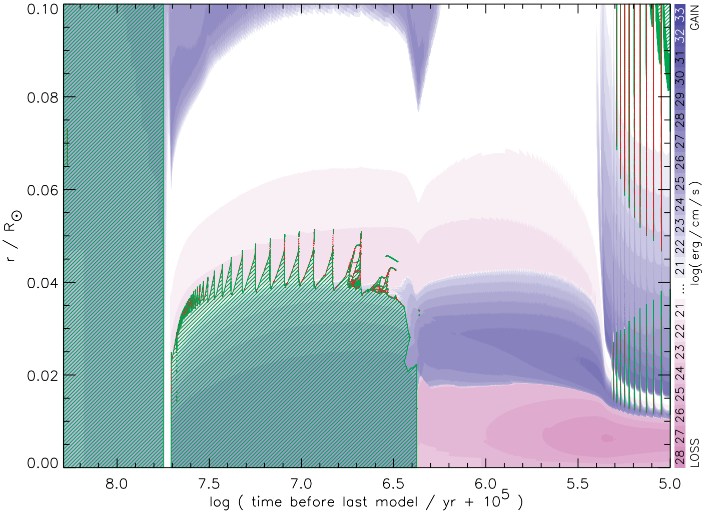

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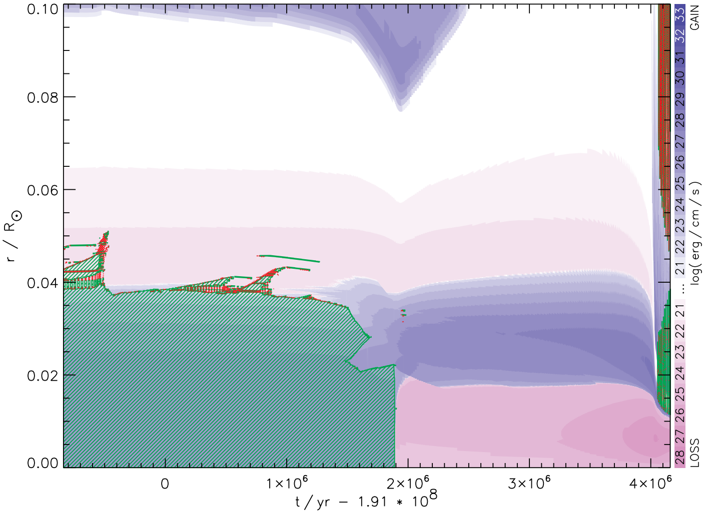

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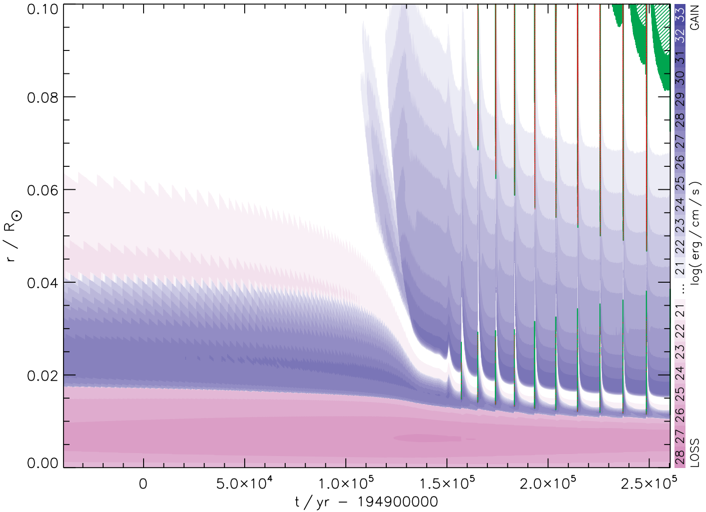

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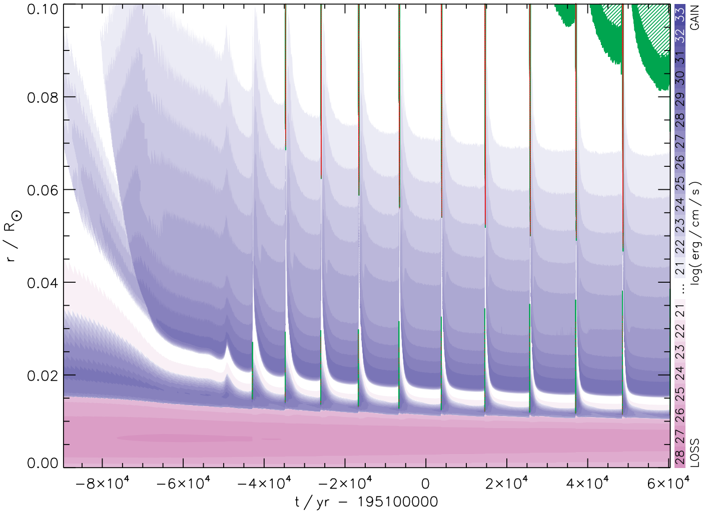
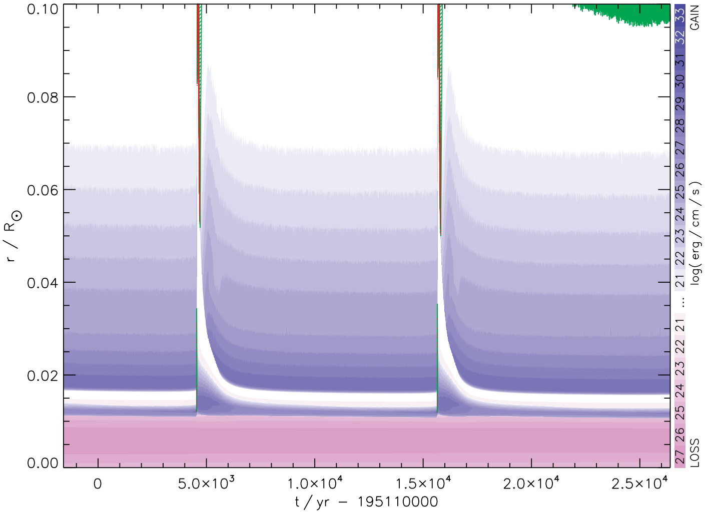


Kippenhahn-Radius Diagram, 4 $M_\odot$ Star, AGB Phase



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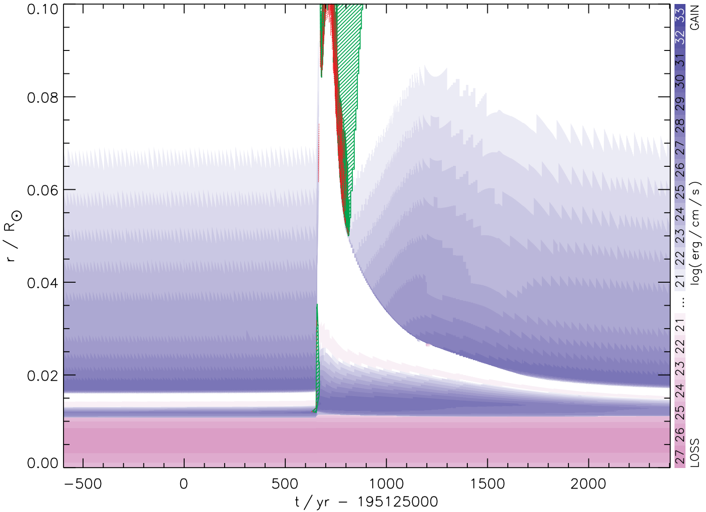

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