Finish Evolution For $M \leq 6 M_\odot$ Stars

All of these objects burn Helium one way or the other (i.e. either via degen ignition < 2.2 or ND > 2.2). Helium white dwarfs have recently been turning up in binaries, where they presumably lost their H envelope during mass transfer.

What is special about $< 6 M_\odot$ stars is that they don't ignite C/O unless they exceed M_{ch}. and mass loss as far as we know always? intervenes?

$M \leq 2.2 M_\odot$
He Burning

2:8a

~~[illegible]~~

~~[illegible]~~ $L_\odot$

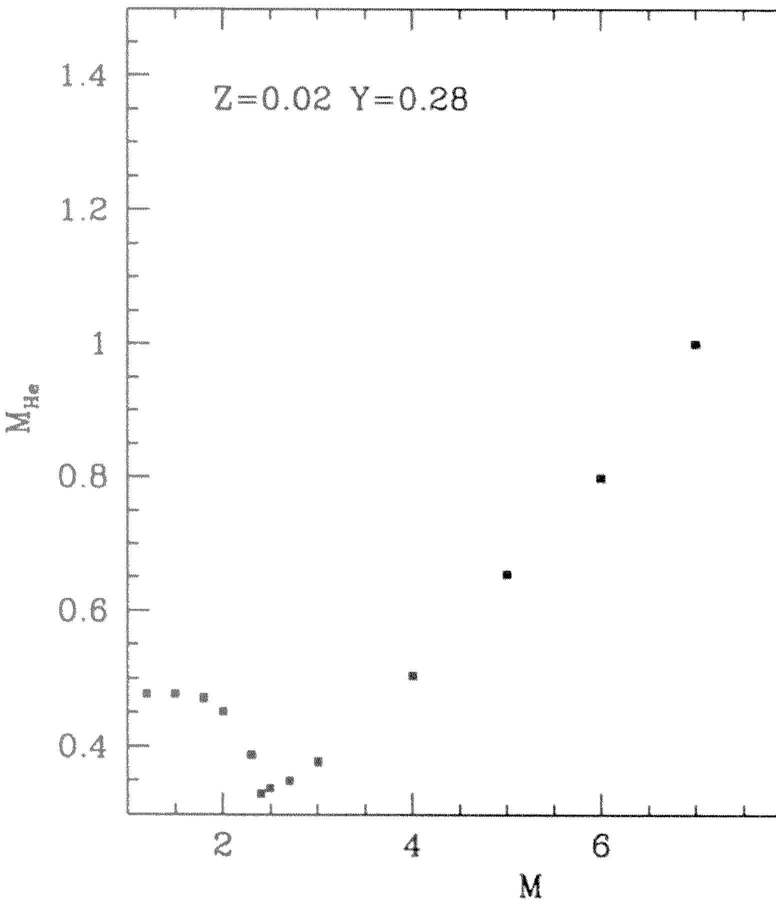
(1) For Stars less than $\simeq 2.2 M_\odot$

Go up the RGB burning H all the way & core is nearly isothermal at the H burning T. Eventually ignition is reached

$\Rightarrow$ $M \leq 2.2\, M_\odot$ undergo Helium core flash in order to lift degener.

$\Rightarrow$ Show core flash Results.

Low Mass Evolution



Dominguez et al. 1999

PROPERTIES OF THE MODELS WITH $Z = 2 \times 10^{-2}$, $Y = 0.28$

M ($M_\odot$) (1)	Δt_H (Myr) (2)	M_H^{cc} ($M_\odot$) (3)	He_{sur}^{1du} (4)	$\log L_{tip}^{RGB}$ (5)	M_{He}^1 ($M_\odot$) (6)	Δt_{He} (Myr) (7)	M_{He}^2 ($M_\odot$) (8)
1.2......	5121	0.056	0.300	3.440	0.477	110	0.525
1.5......	2233	0.141	0.294	3.445	0.477	111	0.536
1.8......	1307	0.242	0.290	3.413	0.471	119	0.540
2.0......	949	0.298	0.289	3.311	0.451	130	0.527
2.3......	636	0.388	0.291	2.856	0.388	192	0.501
2.4......	575	0.427	0.291	2.427	0.331	259	0.487
2.5......	505	0.448	0.292	2.490	0.339	234	0.495
2.7......	409	0.513	0.294	2.510	0.350	196	0.510
3.0......	307	0.608	0.296	2.560	0.378	141	0.545
4.0......	145	0.928	0.296	2.880	0.505	46.0	0.744
5.0......	84.5	1.275	0.296	3.187	0.655	20.8	1.024
6.0......	55.8	1.650	0.297	3.459	0.799	10.3	1.278
7.0......	39.9	2.048	0.297	3.685	1.001	7.3	1.591
8.0......	30.3	2.490	0.300	3.889	1.156	5.1	1.883
9.0......	24.2	2.869	0.301	4.052	1.415	4.0	2.223

[a] Off-center C burning.
[b] Central C burning.

In Tables 1, 2, 3, and 4 we have reported the fundamental properties of the evolutionary sequences: by column in each table, (1) the total mass, (2) the central H-burning lifetime (in Myr), (3) the maximum size (in solar mass units) of the convective core during central H burning, (4) the surface He mass fraction after the first dredge-up, (5) the tip luminosity of the first red giant branch (RGB), (6) the He core mass at the beginning of the He burning, (7) the central He-burning lifetime (in Myr), (8) the He core mass (in solar units) at the end of the He burning, (9) the surface He mass fraction after the second dredge-up, and (10) the He core mass (in solar units) at the beginning of the thermally pulsing asymptotic giant branch (TP-AGB) phase.

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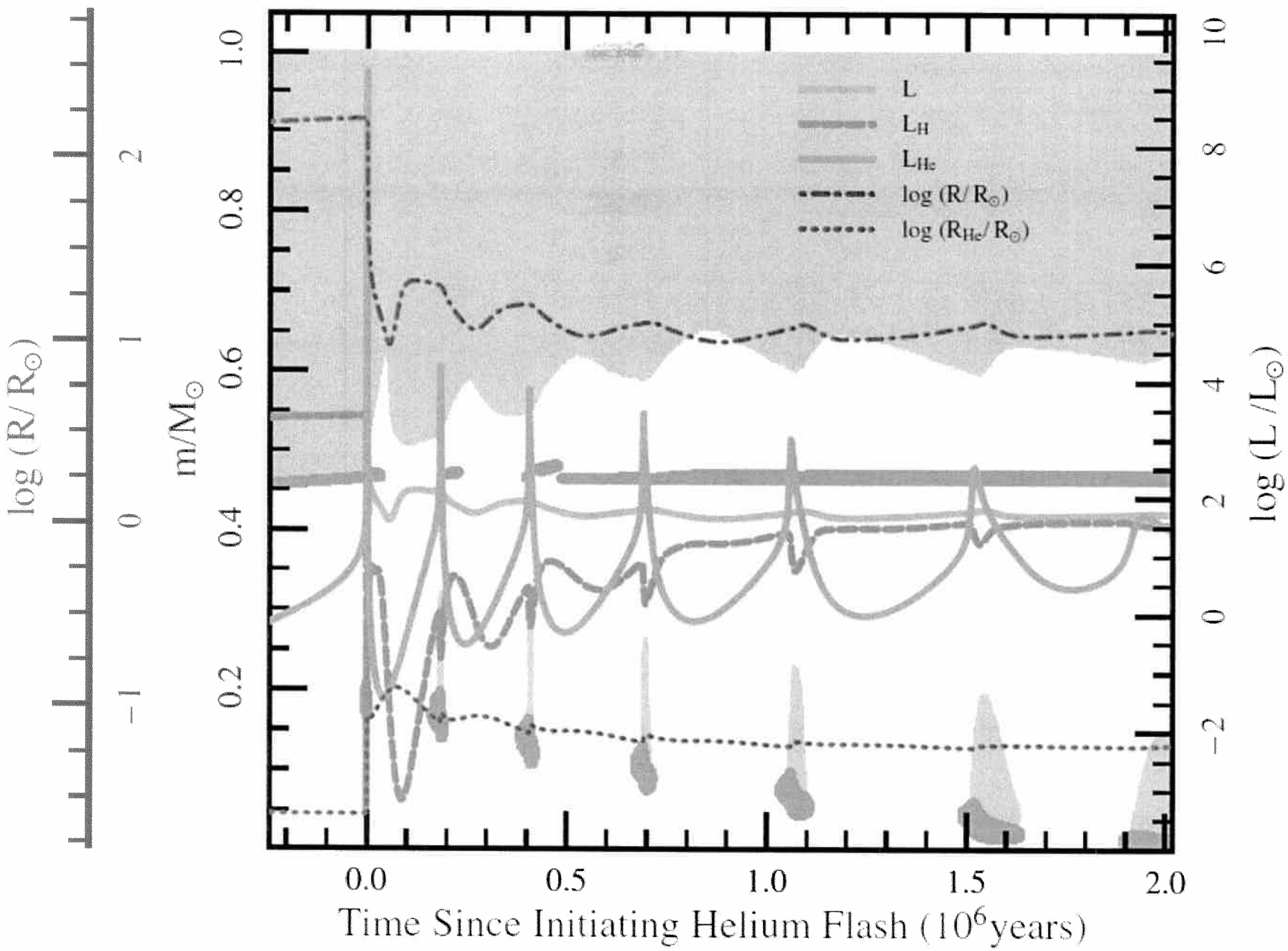

L
L_H
L_{He}
$\log (R/R_\odot)$
$\log (R_{He}/R_\odot)$
$\log (R/R_\odot)$
-1
0
1
2
$m/M_\odot$
0.2
0.4
0.6
0.8
1.0
$\log (L/L_\odot)$
-2
0
2
4
6
8
10
0.0
0.5
1.0
1.5
2.0
Time Since Initiating Helium Flash (10^6years)

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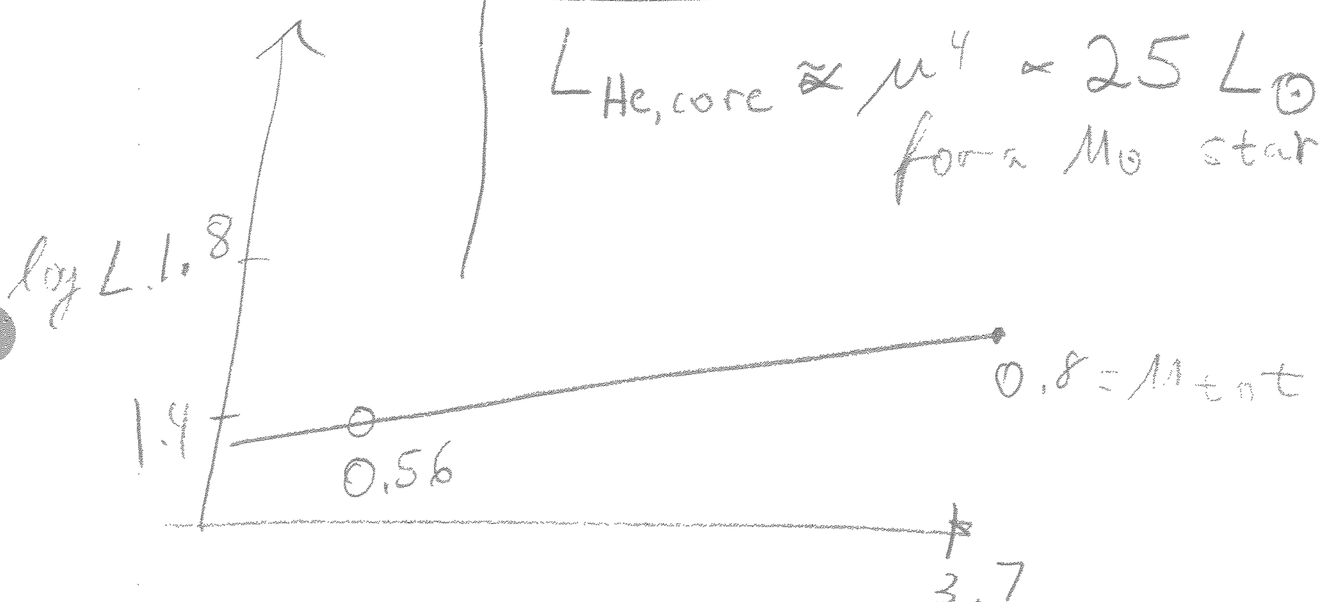
Horizontal Branch

The core flash lifts the degeneracy in the core and the star ends up burning the He in a nondegen core, while at the same time undergoing H shell burning.

These stars end up on the horizontal branch where the ZAHB looks like.

$$L_{He,core} \approx \mu^4 \sim 25 L_\odot$$
for a $M_\odot$ star



$M_c = 0.45 M_\odot$, $M_H = M - M_c$.

For Globular clusters, all stars which are presently evolving off the Main sequence eventually populate the HB. Possible explanations of the full range of locations include:

1. Mass Loss either before or after He core flash
2. Varying Metallicities.

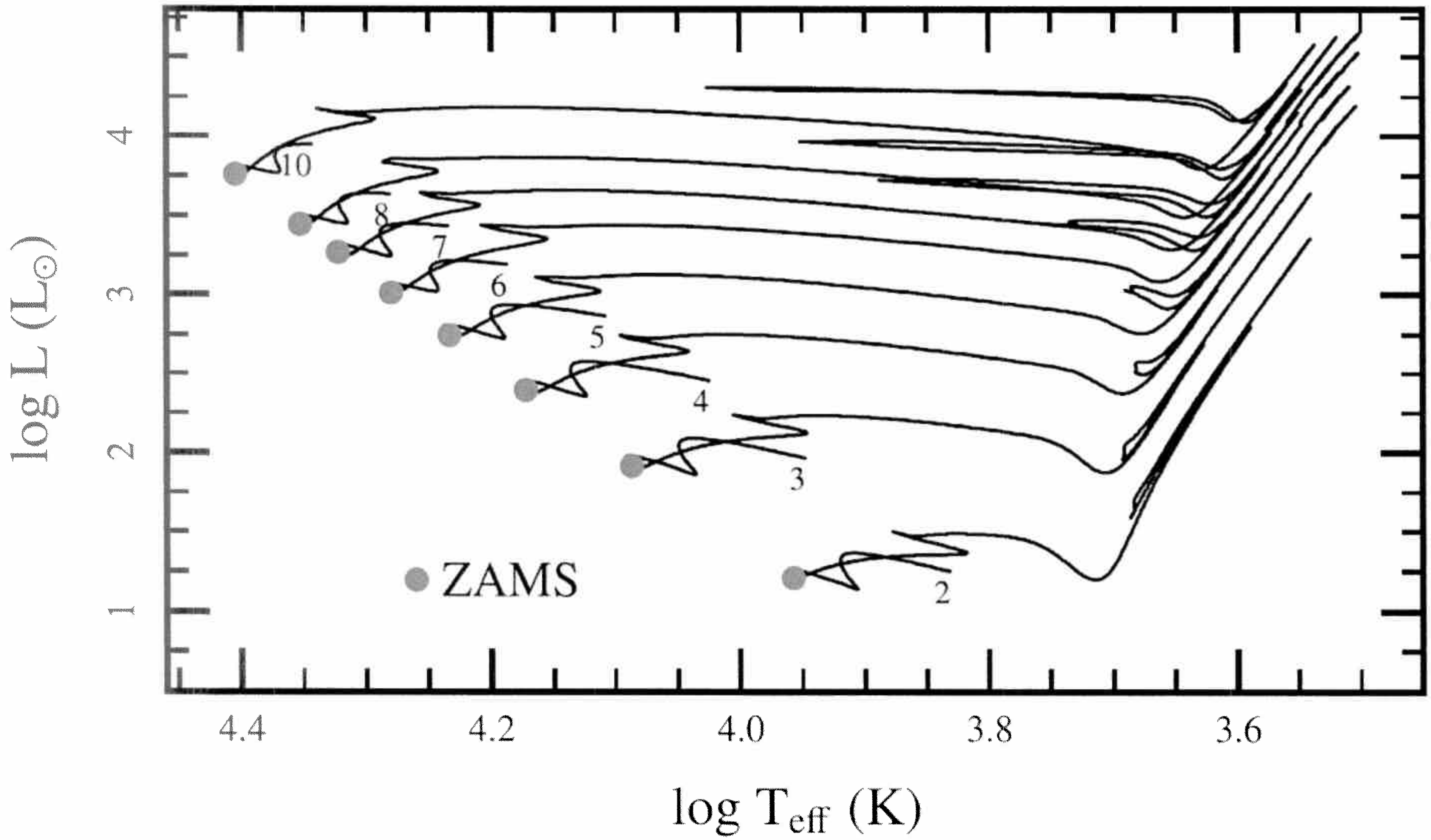
This is still an active field of research as new disc. of different morphologies of HB's cont. give us new information.

There is both He core burning + H shell burning at this time.

Eventually the He in the core is <u>depleted</u> and we have only C/O. The C/O core then is forming a W.D.

⇓

$\boxed{AGB}$



240a

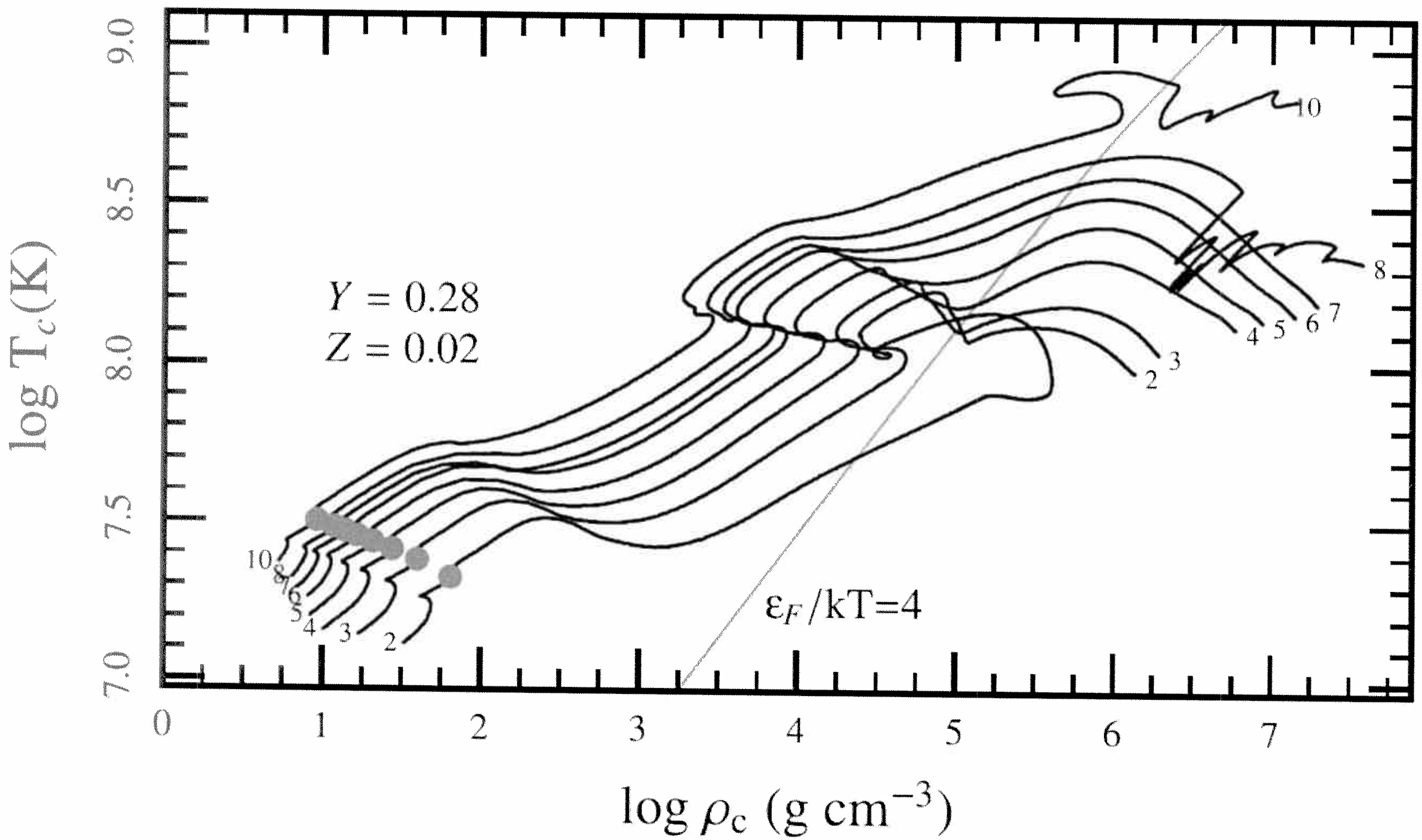


Figure 22. Top: `MESA star` H-R diagram for 2–10 $M_\odot$ models from the PMS to the end of the first thermal pulse (2–7 $M_\odot$) or into C-burning (8 and 10 $M_\odot$).

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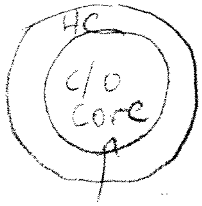
Thin Shell Burning

Schwarzschild + Harm (1965) discovered a rather remarkable phenomenon in the late evolution of stars, which is a thermal instability when nuclear burning occurs in a thin shell ($\Delta r << R$). They discovered it in the case of ^4He burning on the C/O core during the AGB.

H-Burning Active



$\approx 0.6 M_\odot$

Lets go back, as always, to the entropy equation, where we write:

$$T \frac{ds}{dt} = \varepsilon_{3\alpha} - \frac{1}{\rho}(\nabla \cdot F)$$

Now, in a very thin shell ($H<<R$), we have one crucial difference, which is that the pressure is constant during any perturbation in the thermal conditions. Why is this?

$$\Rightarrow \quad \frac{dP}{dr} = -\frac{G\,m(r)}{r^2}\rho(r)$$

Integrate:

$$\int_{P_{sh}}^{0} dP = \int_{R_{sh}}^{\infty} -\frac{G m(r)}{r^2}\rho(r)\,dr$$

$$\Rightarrow 0 - P_s = -\int^{M} \frac{G m(r)}{4\pi r^4}\,dm$$

$$\Rightarrow \quad P_S = \int_m^M \frac{G}{4\pi r^4} m' dm'$$

imagine that $r(m) = R$, then

$$P_S = \frac{G}{4\pi R^4} \frac{1}{2} \left(M^2 - m^2\right)$$

$$= \left(\frac{GM}{R^2}\right) \frac{M}{8\pi R^2} \left[1 - \left(\frac{m}{M}\right)^2\right]$$

imagine that $M - m = \Delta m \ll M$. $m = M - \Delta m$

$$1 - \left(\frac{M - \Delta m}{M}\right)^2 = 1 - \left(1 - \frac{2\Delta m}{M}\right) = 2\frac{\Delta m}{M}.$$

so

$$P_S = \underbrace{\frac{GM}{R^2}}_{g} \underbrace{\frac{\Delta m}{4\pi R^2}}_{y} \quad \text{just as we expect.}$$

Now, if $r(m)$ does not change, then the pressure in the shell has very little change. $\Rightarrow$ Want a thin region.

Sidebar

Conv. Env.

$$\frac{d\ln T}{d\ln P} = \frac{2}{5} \Rightarrow T \propto P^{2/5}$$

but $P \propto \rho T$ $\quad T \propto P/\rho \quad \frac{P}{\rho} \propto P^{2/5}$

$\rho \propto P^{3/5} \quad P \propto \rho^{5/3}$

$$\frac{dP}{dr} = -\rho \frac{Gm(r)}{r^2} \qquad \frac{dm(r)}{dr} = 4\pi r^2 \rho$$

Lets imagine that the envelope has $\Delta m \ll M$, so $\frac{dP}{dr} = -\rho \frac{GM}{r^2}$ / $\frac{dm(r)}{dr} = 4\pi r^2 \rho$

So, if the pressure is constant, then we can write:

$$C_p \frac{dT}{dt} = \epsilon - \frac{1}{\rho} \nabla \cdot F$$

But the latter term is roughly

$$F = \frac{1}{3} c \frac{1}{\kappa \rho} \frac{d}{dr} a T^4 = \frac{c}{3} \frac{1}{\kappa y} a T^4$$

so

$$\frac{1}{\rho} \nabla \cdot F \propto \frac{c}{3\kappa} \frac{1}{y^2} a T^4$$

where $y = \int \rho \, dz$ in the shell, so the latter term is $\propto T^4$. Now imagine we have ^4He burning where

$$\epsilon \propto \rho^2 T^{\nu} \qquad \nu = \frac{44}{T_8}$$

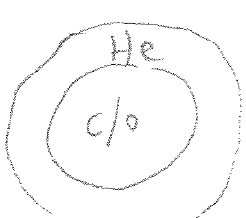
then any slight perturbation will lead to a thermal runaway when

$$\epsilon \simeq \frac{1}{\rho} \nabla \cdot F$$

beforehand. This leads to "Helium" shell pulses about every 10^4–10^5 yrs.

$\Rightarrow$ H-burning

H burning piles ^4He onto the core. Eventually ^4He ignites



Now, the Helium shell burns up all the accreted ^4He in a short time. There is an intriguing play off, as the H burning gives

$$L = 6 \times 10^4 L_\odot (M_c - 0.5 M_\odot) \quad = 2.4 \times 10^{38} \times$$

which leads to buildup of ^4He, which flashes to C/O. Now the timescale is

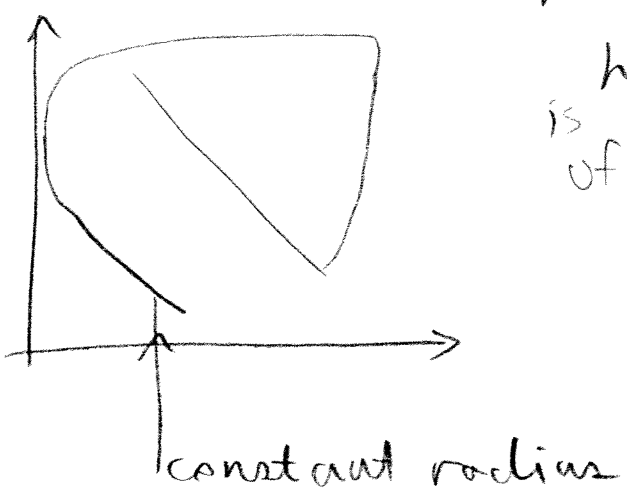
$$\tau = 3.6 \times 10^6 \text{ yrs}$$

and so things should grow in this time. There is, however, one other thing that happens, which is copious mass loss. It ends up that the mass loss wins out, in which case the envelope gets sent away

There are AGB stars which have lots of dust formation; opacity $\dot{M}$ is huge!

$\Rightarrow$ All $M \leq 2.3 M_\odot$ stars seem to produce $0.6 M_\odot$ WD's.

The resulting W.D. is born hot & then marches over ~~towards~~ the blue as the envelope collapses.



Once the WD has contracted, and is a copious source of UV photons, which act to light up the surrounding matter that were ejected in the wind.

This gives what is ~~ca~~ referred to as a Planetary Nebulae. ~~So~~ ⇒ Picture.

~~You are working on the WD cooling problem for the HW, so I will not go into it in more detail here.~~

Stars with $2 < M < 6$: These basically have a similar evolution, but do not undergo core convergence, as they ignite ^4He before becoming degenerate. This leads, on average to smaller ^4He cores and typically smaller C/O cores (in fraction) than others. End state is the same, which is $\leq 1.4 M_\odot$ C/O W.D.'s with the rest of the stuff sent back out.

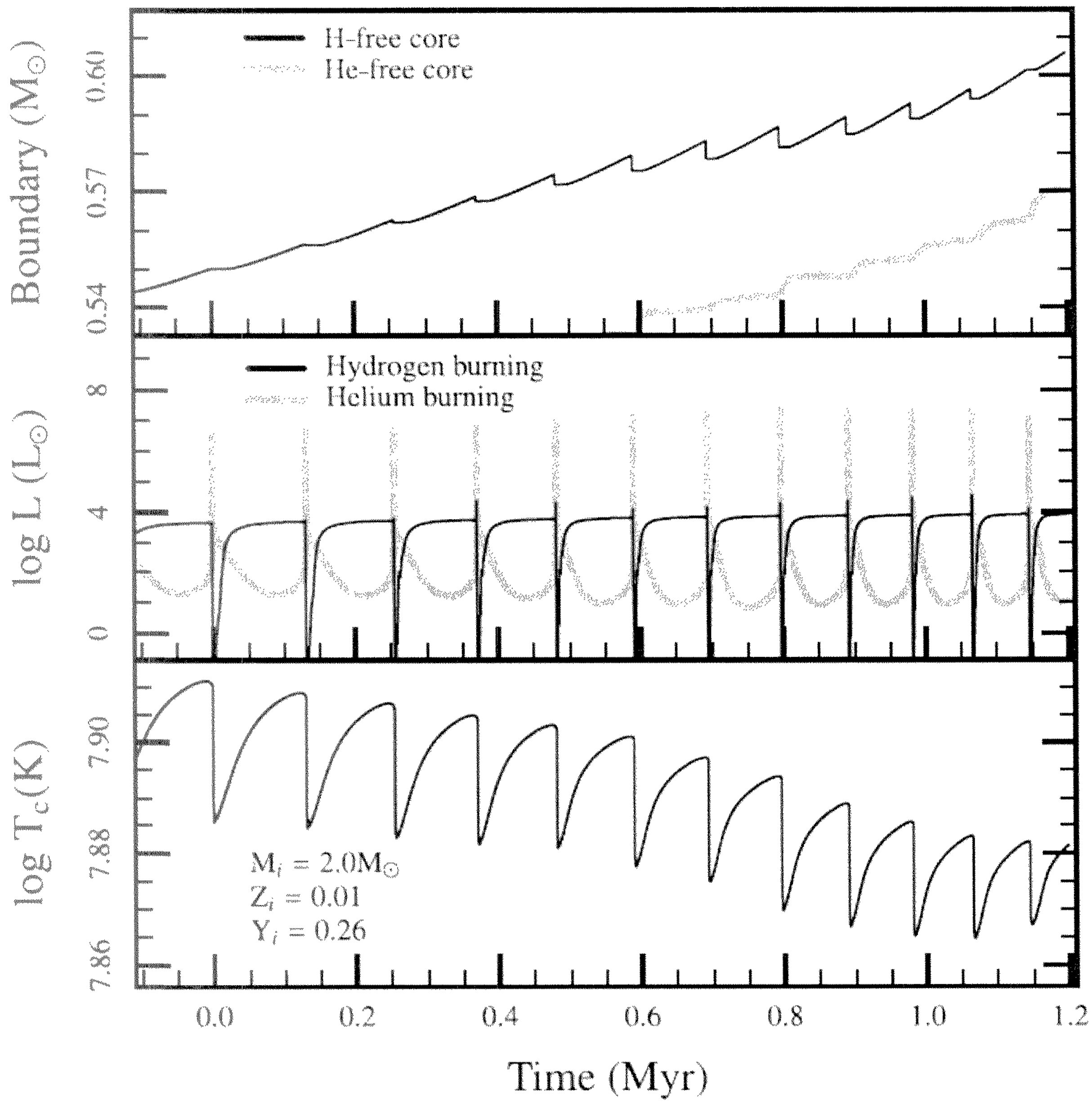


Figure 24. Properties of an $M_i = 2\,M_\odot$ star from `MESA star` as it approaches the end of the AGB. Top: the boundaries of the C/O core and the He layer.

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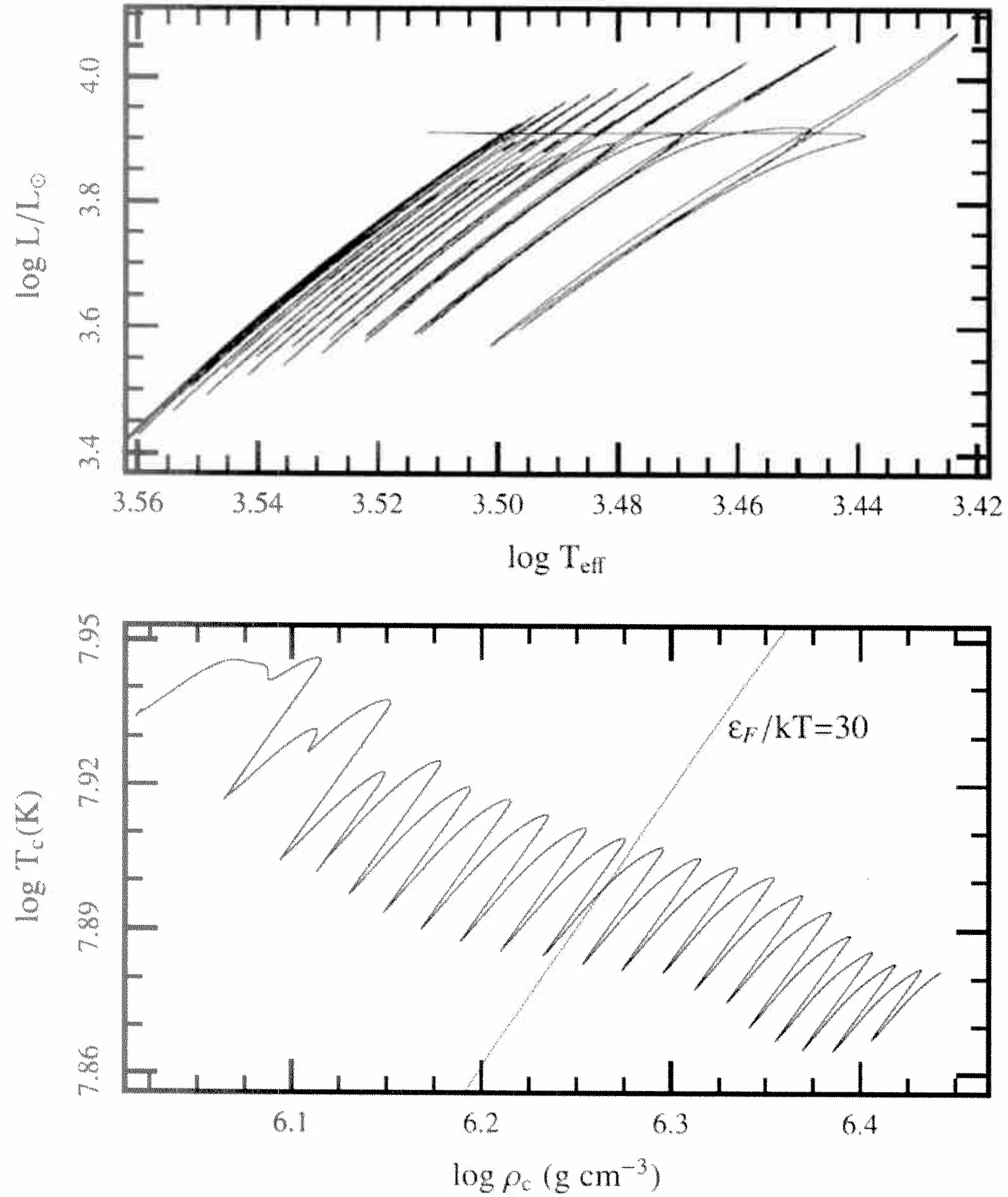
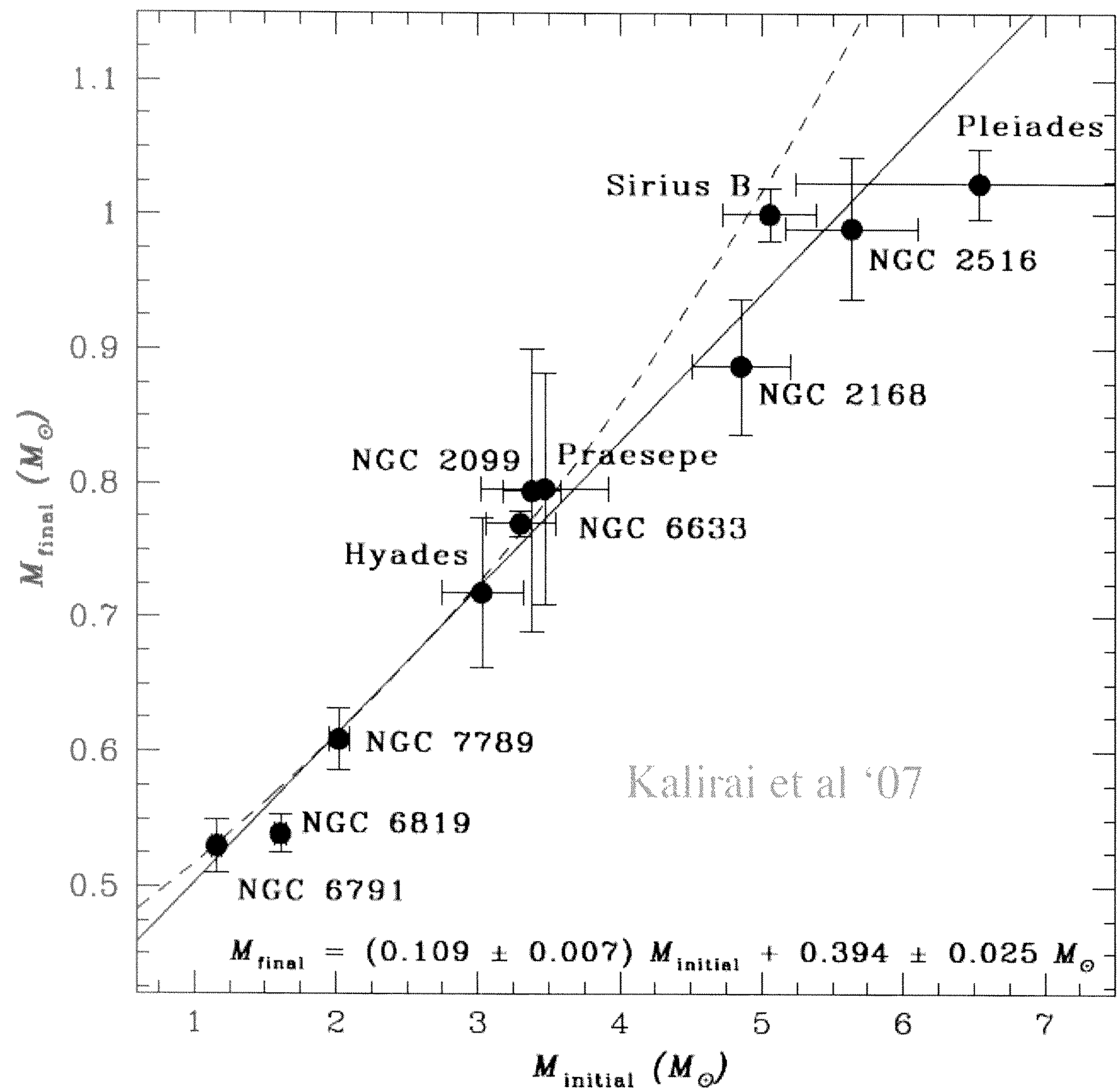


Figure 25. Top: H-R diagram for the 2 $M_\odot$ `MESA star` model from Figures 23 and 24 during the AGB thermal pulses. Bottom: trajectories of the same model's

Table 11
Comparison of `MESA star` and EVOL Models with $M_i = 2\,M_\odot$, $Z = 0.01$

Quantity	`MESA star`	EVOL
Main-sequence lifetime (Gyr)	0.939	0.962
Deepest penetration of first dredge-up ($M_\odot$)	0.328	0.327
H-free core mass at the end of He-core burning ($M_\odot$)	0.466	0.454
Core mass at first thermal pulse ($M_\odot$)	0.504	0.481
Age at first thermal pulse (Gyr)	1.269	1.328
Core mass at second thermal pulse with DUP ($M_\odot$)	0.563	0.563
Following interpulse time (1000 yr)	116	106
Following pulse-to-pulse core growth ($10^{-3}\,M_\odot$)	6.4	6.9
Dredge-up mass at following pulse ($10^{-3}\,M_\odot$)	1.1	1.3

245b



Pleiades
Sirius B
NGC 2516
NGC 2168
NGC 2099
Praesepe
NGC 6633
Hyades
NGC 7789
NGC 6819
NGC 6791
Kalirai et al '07
$M_{final} = (0.109 \pm 0.007)\ M_{initial} + 0.394 \pm 0.025\ M_\odot$
$M_{final}\ (M_\odot)$
$M_{initial}\ (M_\odot)$

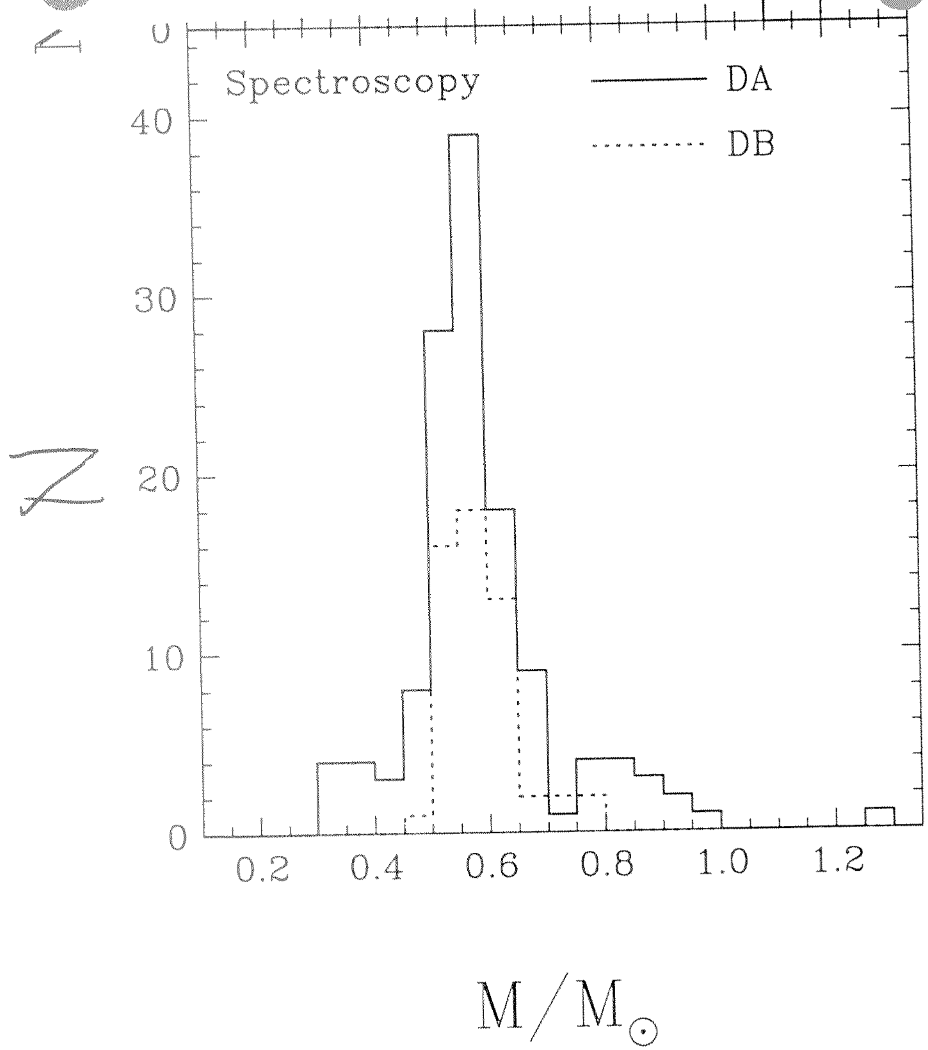
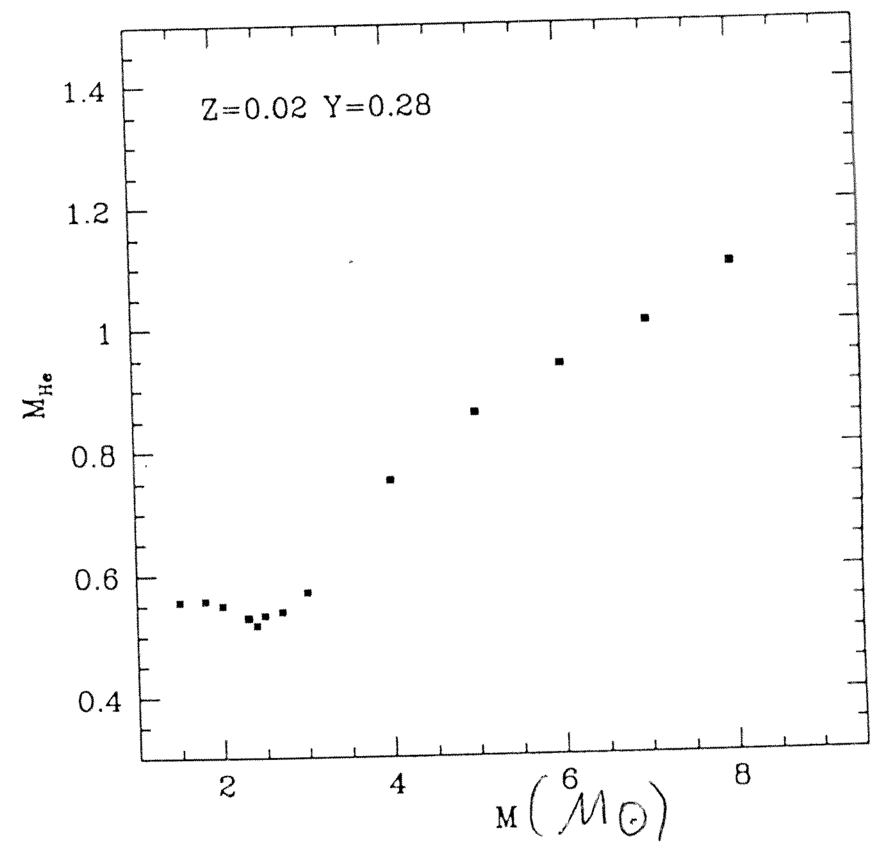


FIG. 22.—*Top panel*: Mass distributions for the hydrogen- and helium-rich atmosphere white dwarfs in our parallax sample. The mean mass of the hydrogen-rich subsample is $\langle M \rangle = 0.61\ M_\odot$ with a dispersion of $\sigma(M) = 0.20\ M_\odot$, and the corresponding values for the helium-rich subsample are $\langle M \rangle = 0.72\ M_\odot$ and $\sigma(M) = 0.17\ M_\odot$. *Bottom panel*: Mass distributions for hotter DA and DB stars determined from spectroscopic analyses. The mean mass and dispersion for the DA stars are $\langle M \rangle = 0.59\ M_\odot$, $\sigma = 0.13\ M_\odot$, and for the DB stars $\langle M \rangle = 0.59\ M_\odot$, $\sigma = 0.06\ M_\odot$.



Core mass at beginning of AGB.

245a