Miras, Mass-Loss, and the Ultimate Fate of the Earth

L. A. Willson & G. H. Bowen, Iowa State University

Fire and Ice:

Some say the world will end in fire,
Some say in ice.
From what I've tasted of desire
I hold with those who favor fire.
But if it had to perish twice,
I think I know enough of hate
To know that for destruction ice
Is also great
And would suffice

Robert Frost

Whether the Earth ends in fire or ice depends how, when, and how fast the Sun sheds mass.

Early or extended mass loss: Earth survives the red giant stages of the Sun and ends "in ice".

Late, abrupt mass loss: Earth is engulfed in the bloated Sun near the end of its red giant evolution.

1. Stages of Solar Evolution

10^{10} years (=10 Gyr) of
4H ← ← ← He in the core, then ← **Main Sequence**

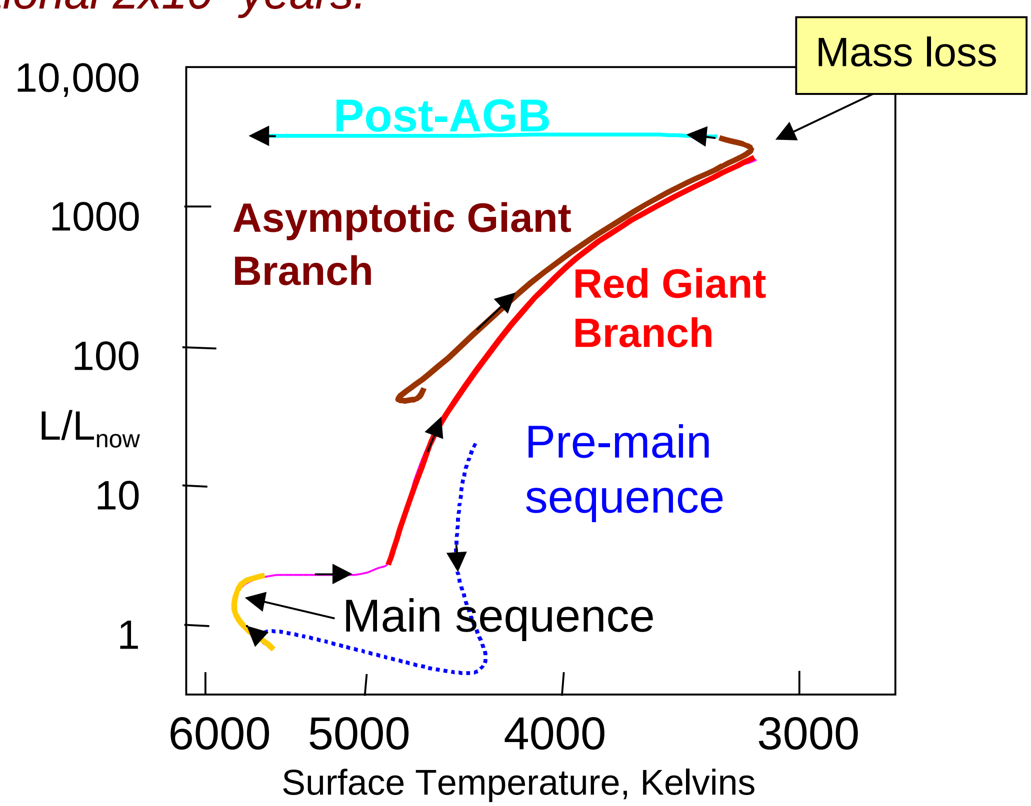
4H ← ← ← He around a core of He
to maximum $L \sim 2000 L_{now}$ ← **Red Giant Branch (RGB)**

abrupt start to **He to C and O** ← Helium Core Flash

core **He to C and O** at ~ $100 L_{nowV}$ ← **Horizontal Branch**

Alternating **H** and **He** "burning"
until the C+O core ~ 0.6 M_{Sun}, when
mass loss removes the rest. ← **Asymptotic Giant Branch (AGB)**

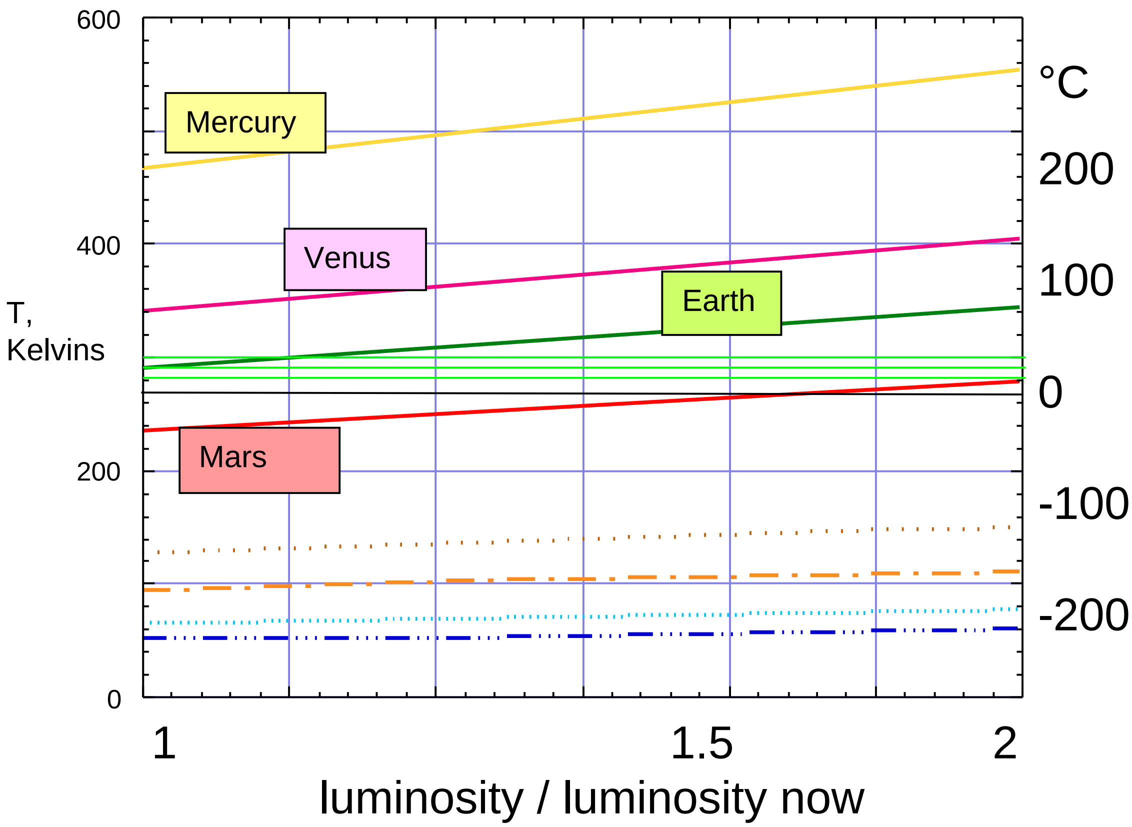
The post-main sequences stages leading up to "the end" take an additional $2x10^9$ years.



Increasing Solar Power => increasing T for the planets

Radiative equilibrium temperatures for the planets are approximately given by

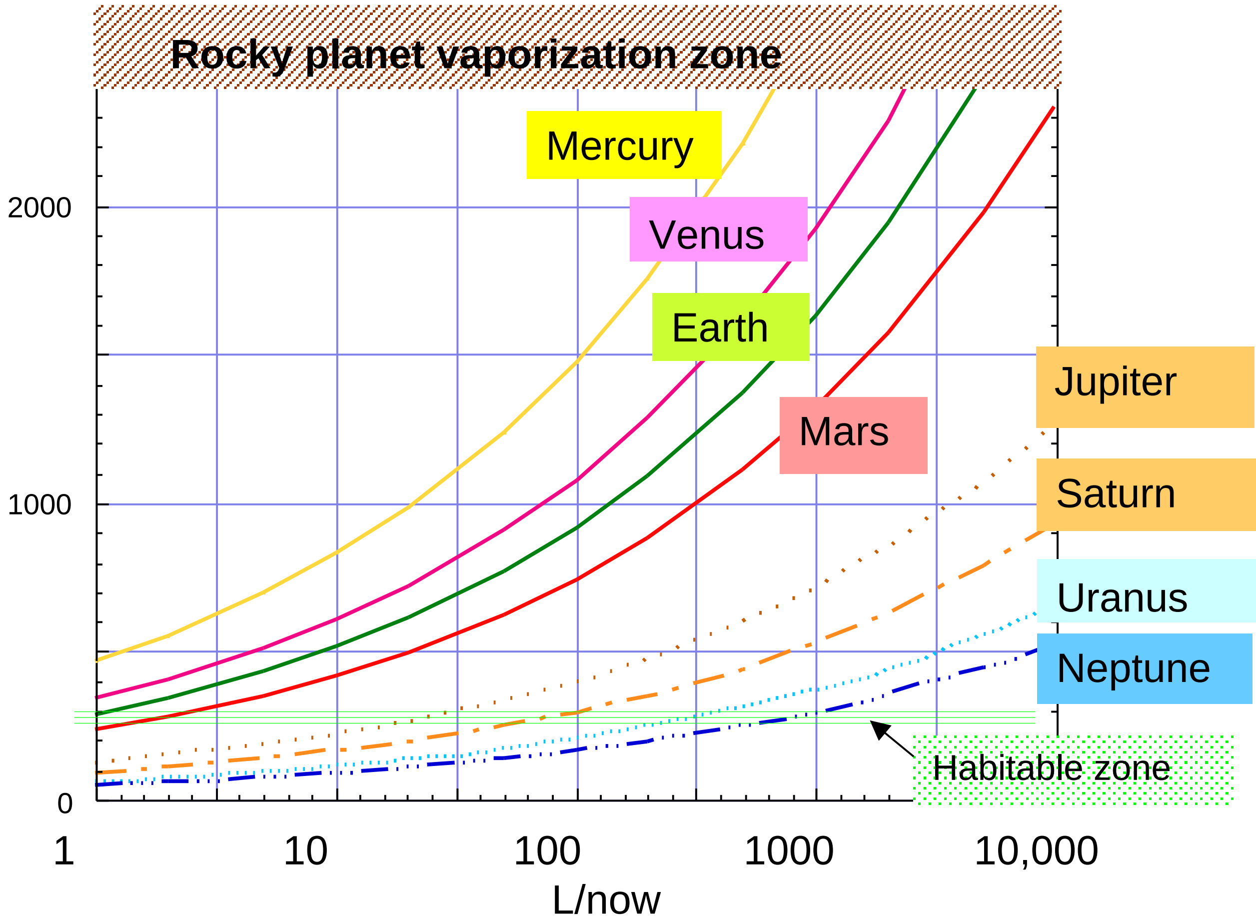
$$T_{RE} = 290K\ (L/now)^{1/4}\ /\ (\text{distance in AU})^{1/2}$$



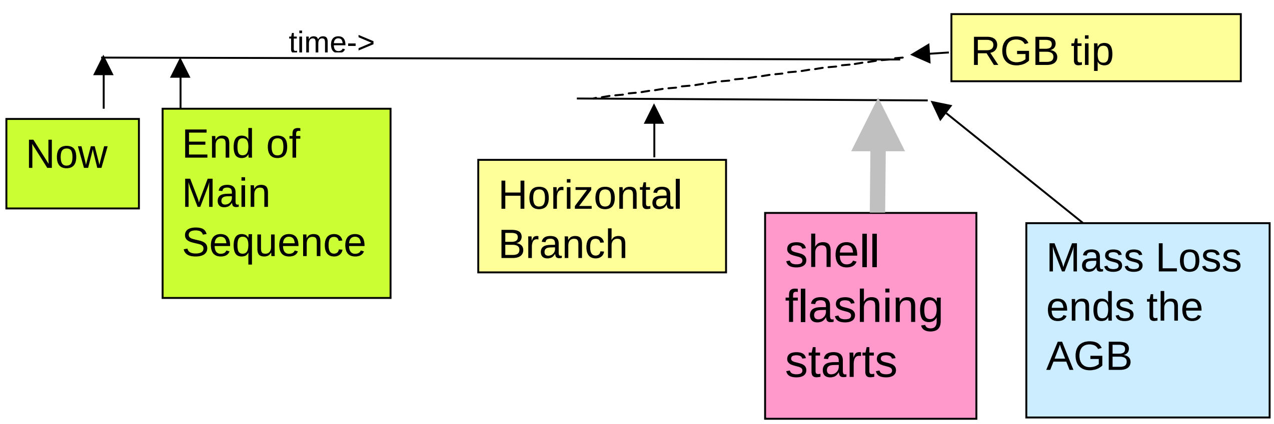
The evolution of planetary temperatures during the main sequence (now to about 5×10^9 years ahead)

Habitable zone (approximate):

Extending this to the end of the AGB:



Mercury



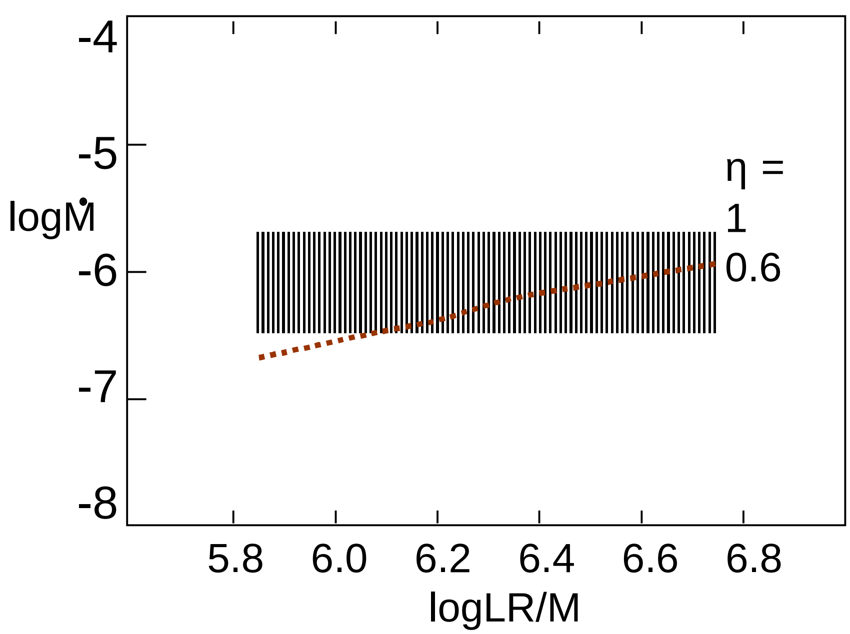
The maximum temperature a planet achieves depends on its distance from the Sun and the maximum luminosity of the Sun - both of these, in turn, depend on the mass loss that ends the AGB.

Most astronomers have been using Reimers' Relation as a recipe for mass loss

$\dot{M}$ = -dM/dt = η $4x10^{-13}$ (L/L_{Sun}) $(R/R_{Sun})/(M/M_{Sun})$ M_{Sun}/year

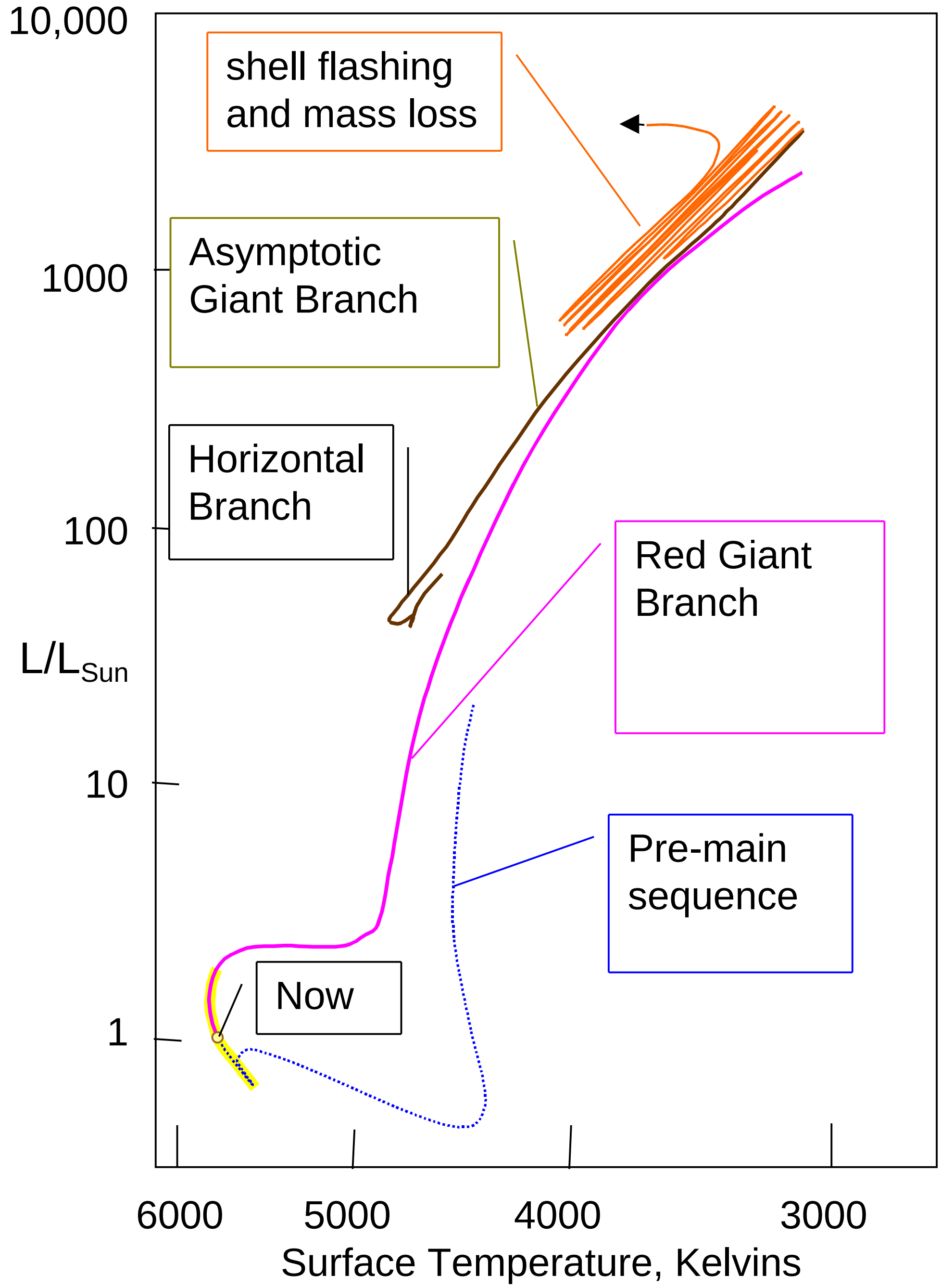
where L_{Sun}, R_{Sun}, and M_{Sun} refer to our present-day Sun.

This relation was derived from a fit to observations of mass loss from red giants, with the adjustable parameter η added later when it was found that the original relation killed stars too soon.

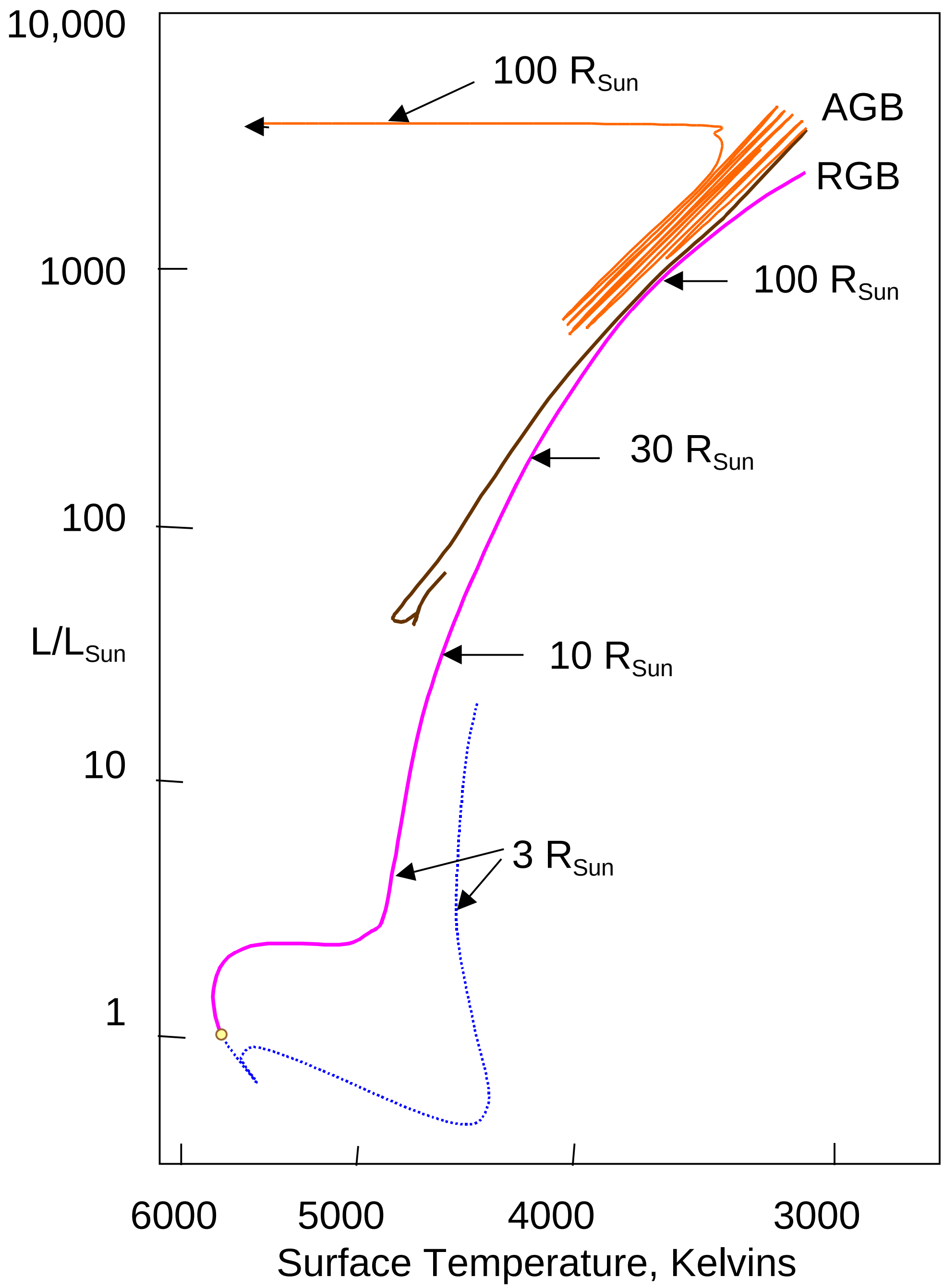


Sackmann, Boothroyd and Kraemer (1993, Ap. J. 418, 457) modeled future solar evolution using Reimers' Relation with η=0.6.

Evolutionary stages in the Sackmann, Boothroyd and Kraemer models:



Compared with the radius of Earth's orbit, the Sun is small until it reaches nearly the tip of the red giant or asymptotic giant branch:



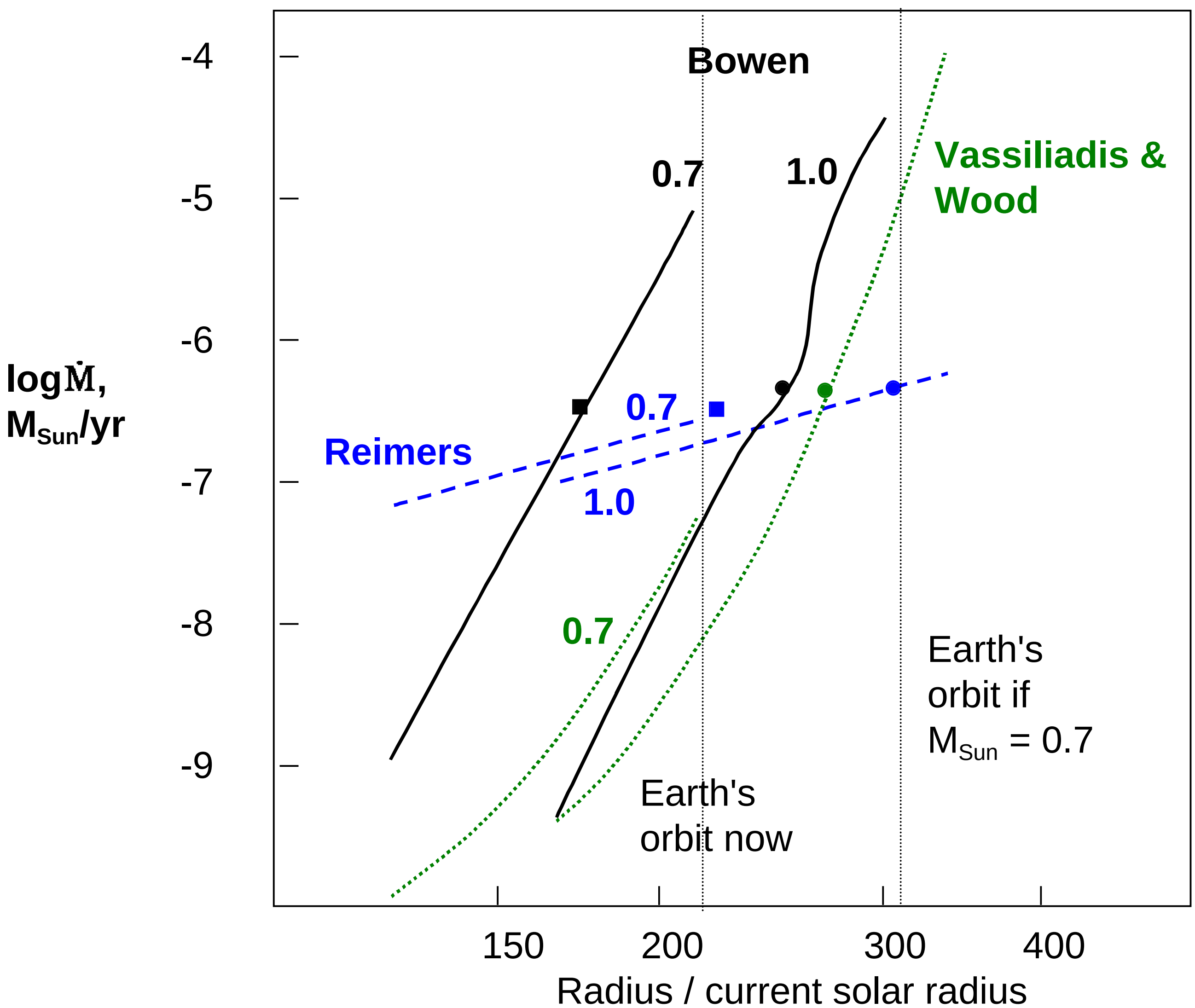
In their models Earth escapes its fiery fate mainly because 0.275 solar masses are removed on the first ascent of the red giant branch.

Their RGB mass loss is entirely due to the Reimers' relation - there is no mass loss "event" associated with the helium core flash.

Given an evolutionary track of the form

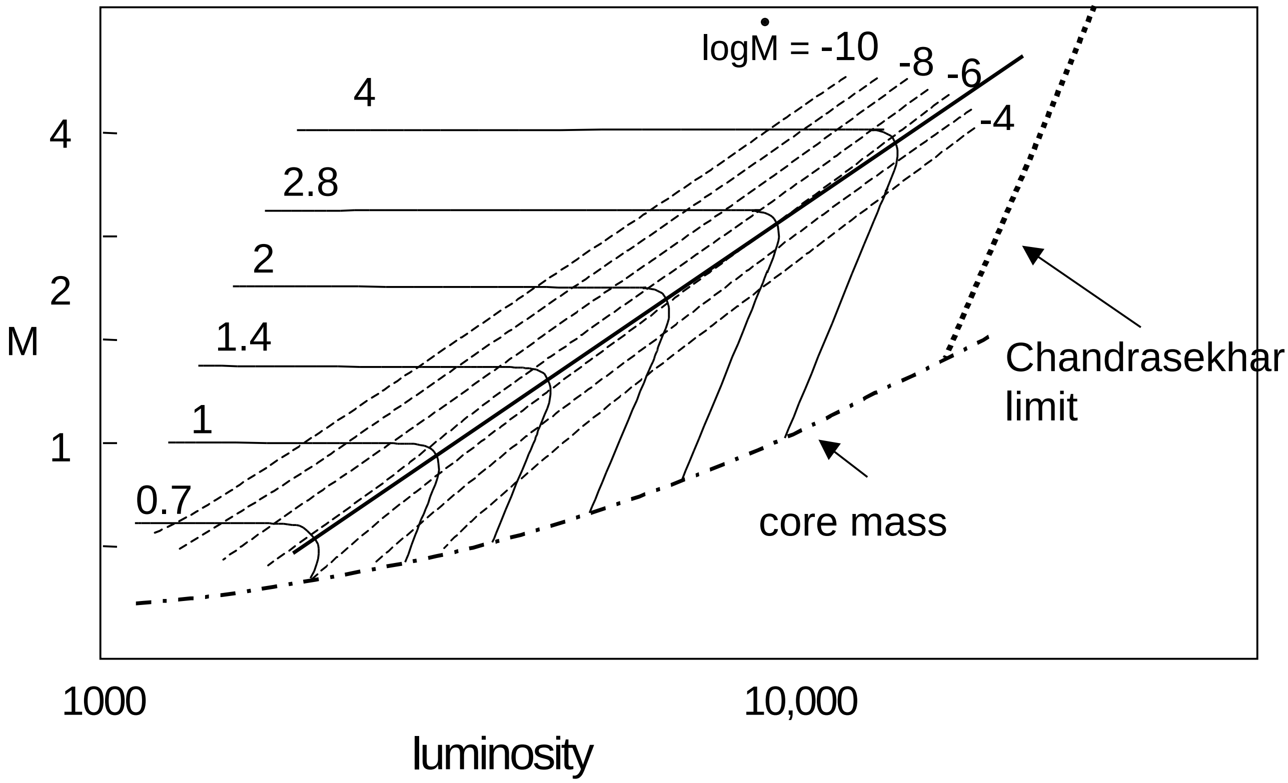
R = function (M, L, Z),

any mass loss law $\dot{M}(L, R, M, Z)$ may be expressed as $\dot{M}(R, M, Z)$.

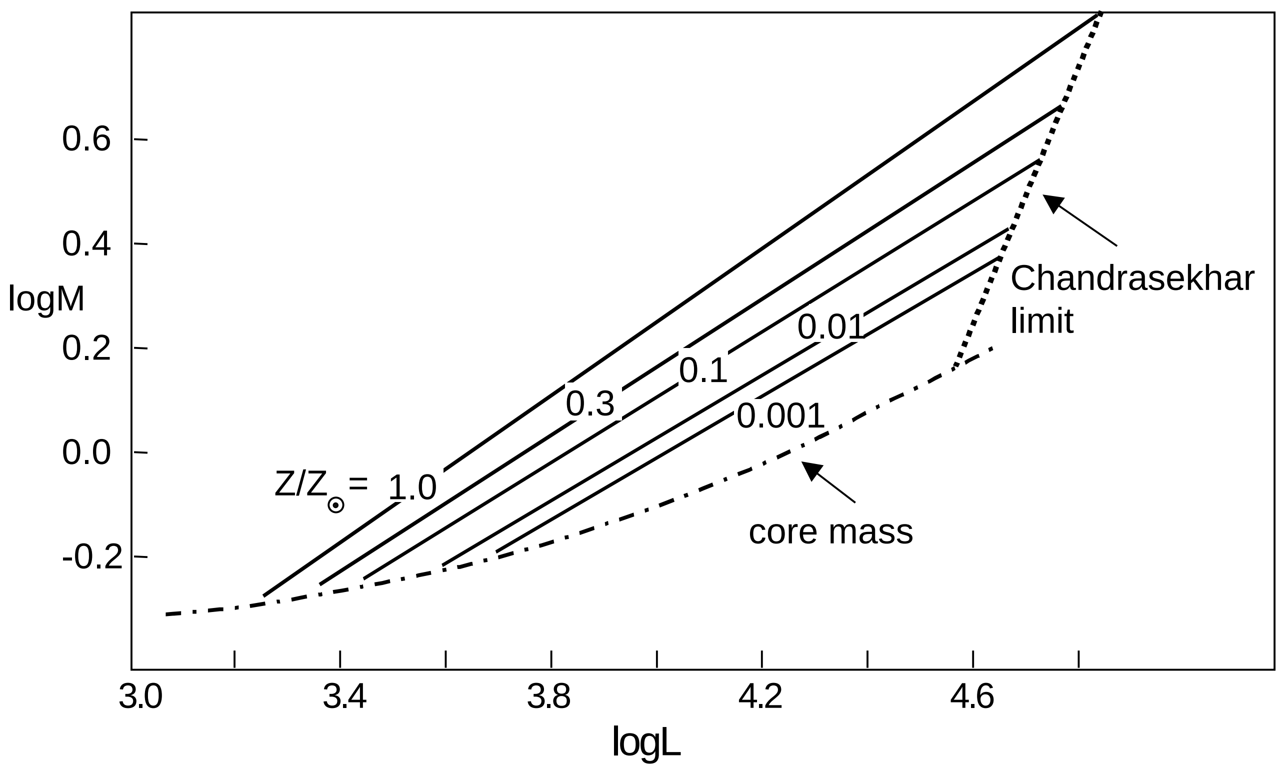


Evolution ends near dlogL/dt = **-**dlogM/dt - closer to this for steeper mass loss laws, but always close. This is indicated by the squares ($0.7M_{Sun}$) and dots ($1M_{Sun}$).

Using the Bowen model results, one finds that AGB evolution ends with a "cliff"

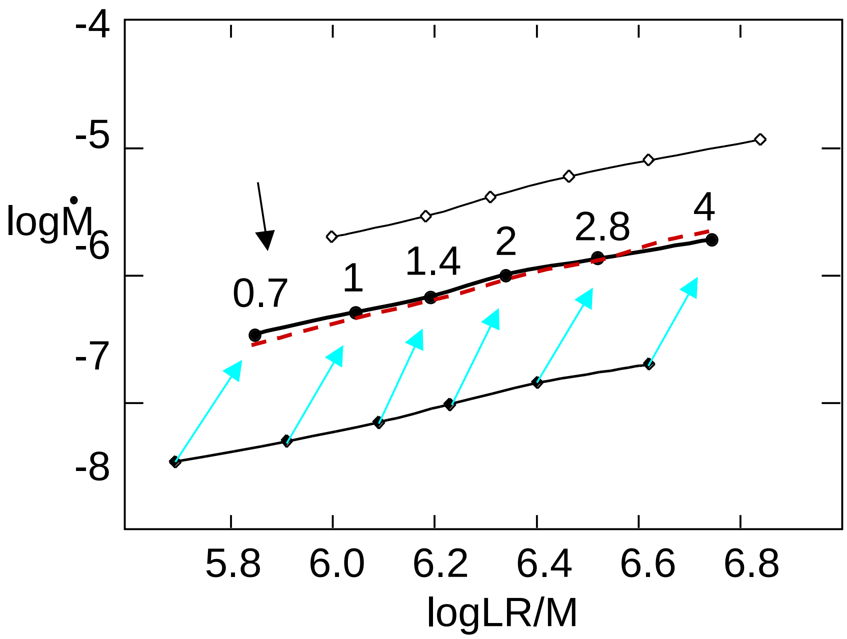


whose position depends on mass and metallicity.



How can the empirical relation (Reimers' relation) and the theoretical mass loss law (Bowen's results) be so very different? Is one of these wrong?

A steep mass loss law => severe selection effects:



Reimers' Reln. for η=1 is shown as a dashed red line

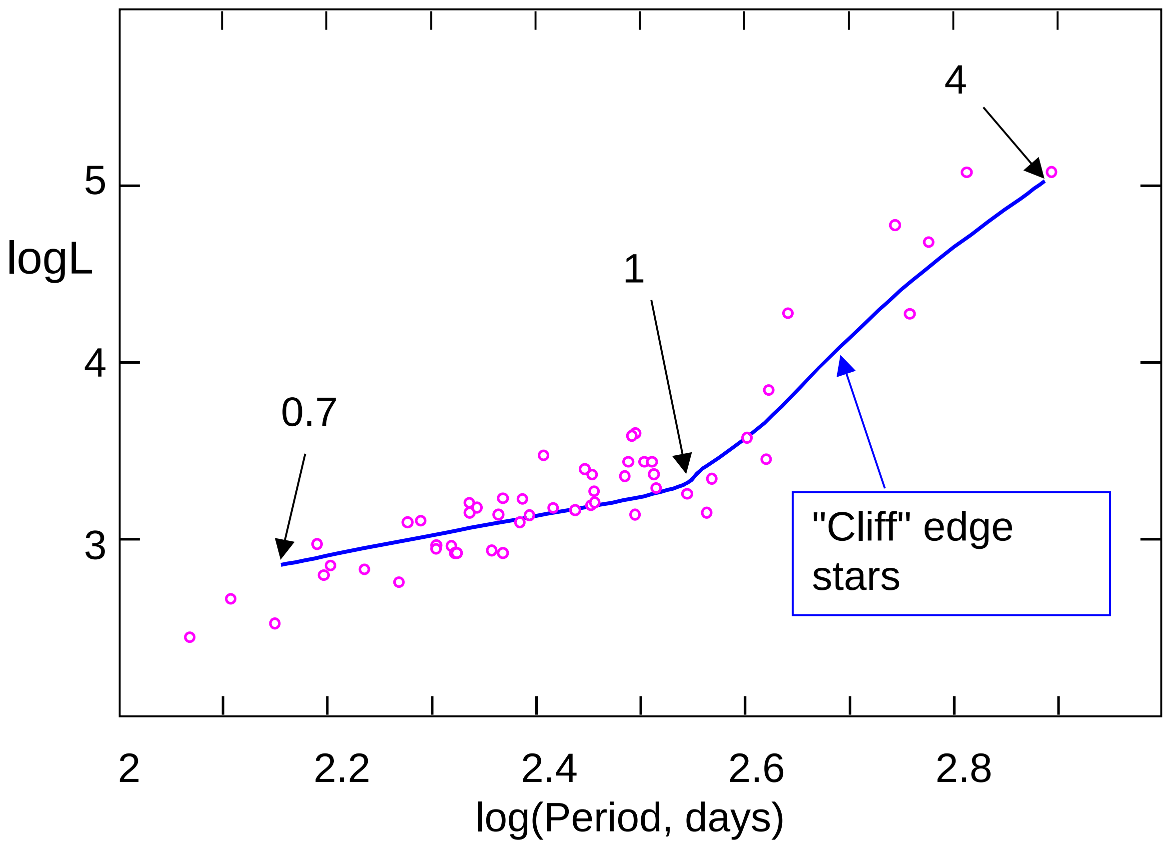
The cliff is the bold black line, with mass labels

Evolution follows the blue arrows

Reimers' relation reinterpreted: **It tells us which stars are losing mass, not how a star loses mass.**

(Analogous to: The main sequence is not an evolutionary track but the location of stars "burning" hydrogen in their cores.)

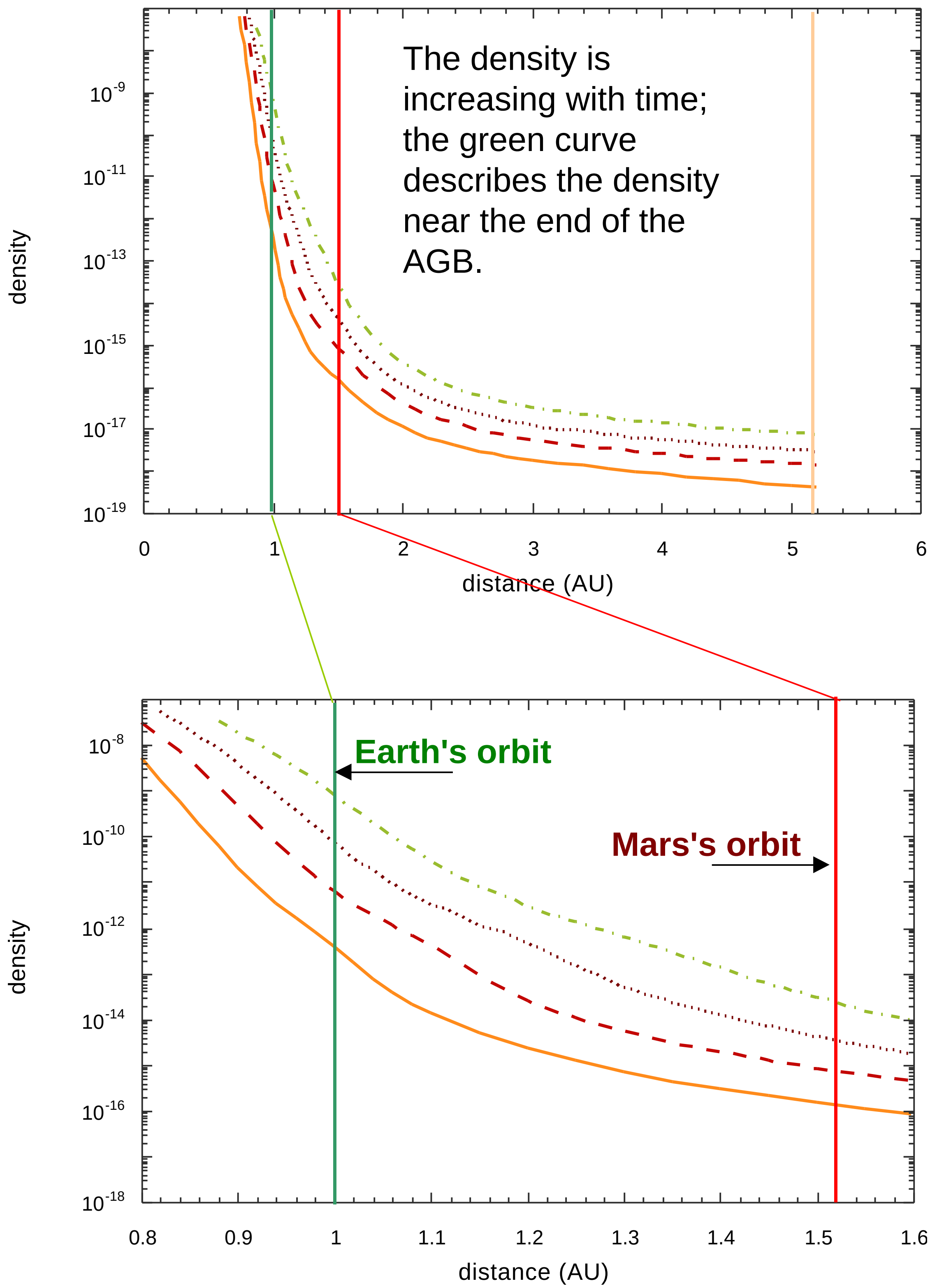
The "cliff" edge stars are the Miras:



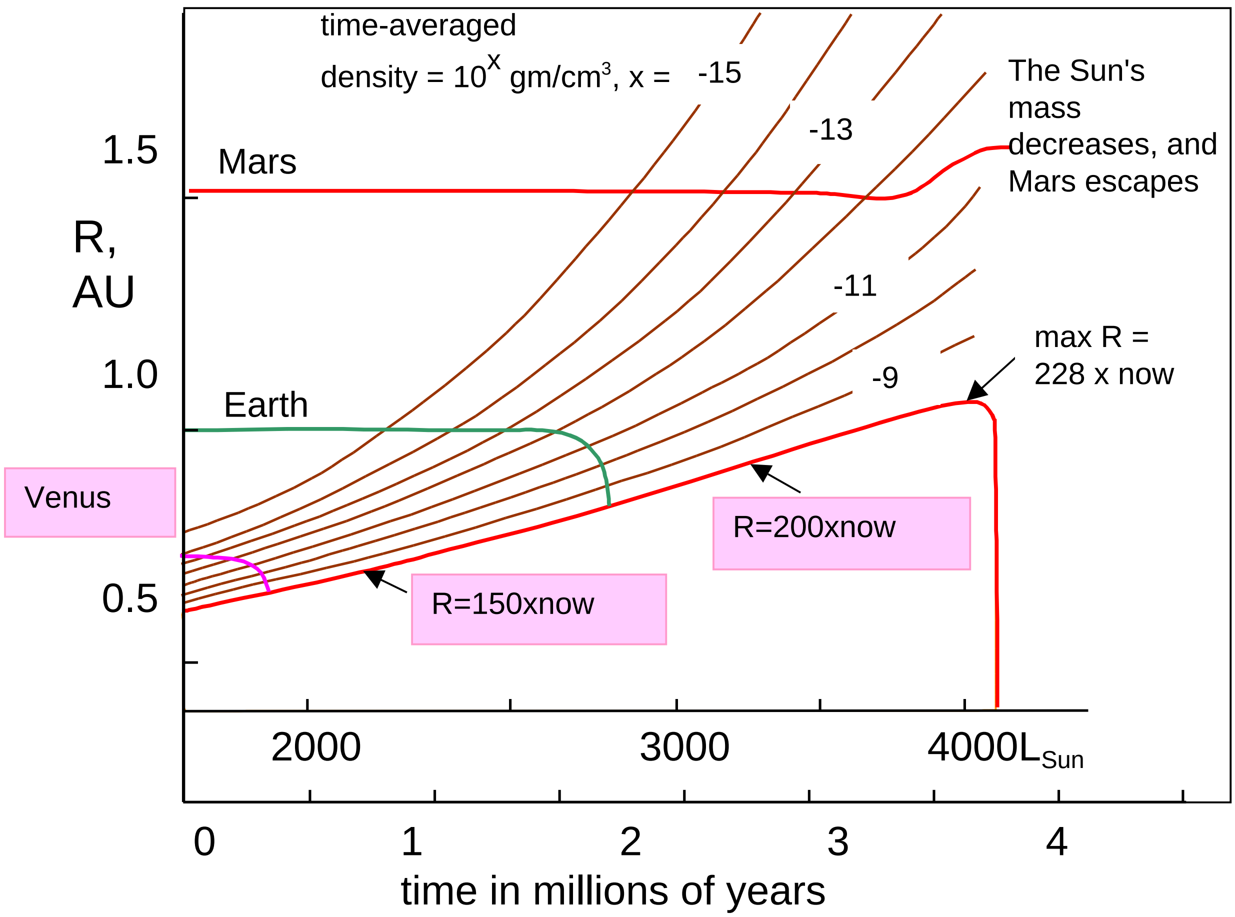
The Sun will end up between the 0.7 and the 1 solar mass points in this plot, depending on how much mass it loses at the helium core flash.

With a very steep mass loss relation, it is less likely than for the "Reimers' mass loss formula" case that the Sun will lose much mass on the first ascent of the red giant branch. The most likely cases are "all" or "nothing" with the possible exception of a finite ΔM ejected at the core flash.

Averaged over the pulsation cycle,



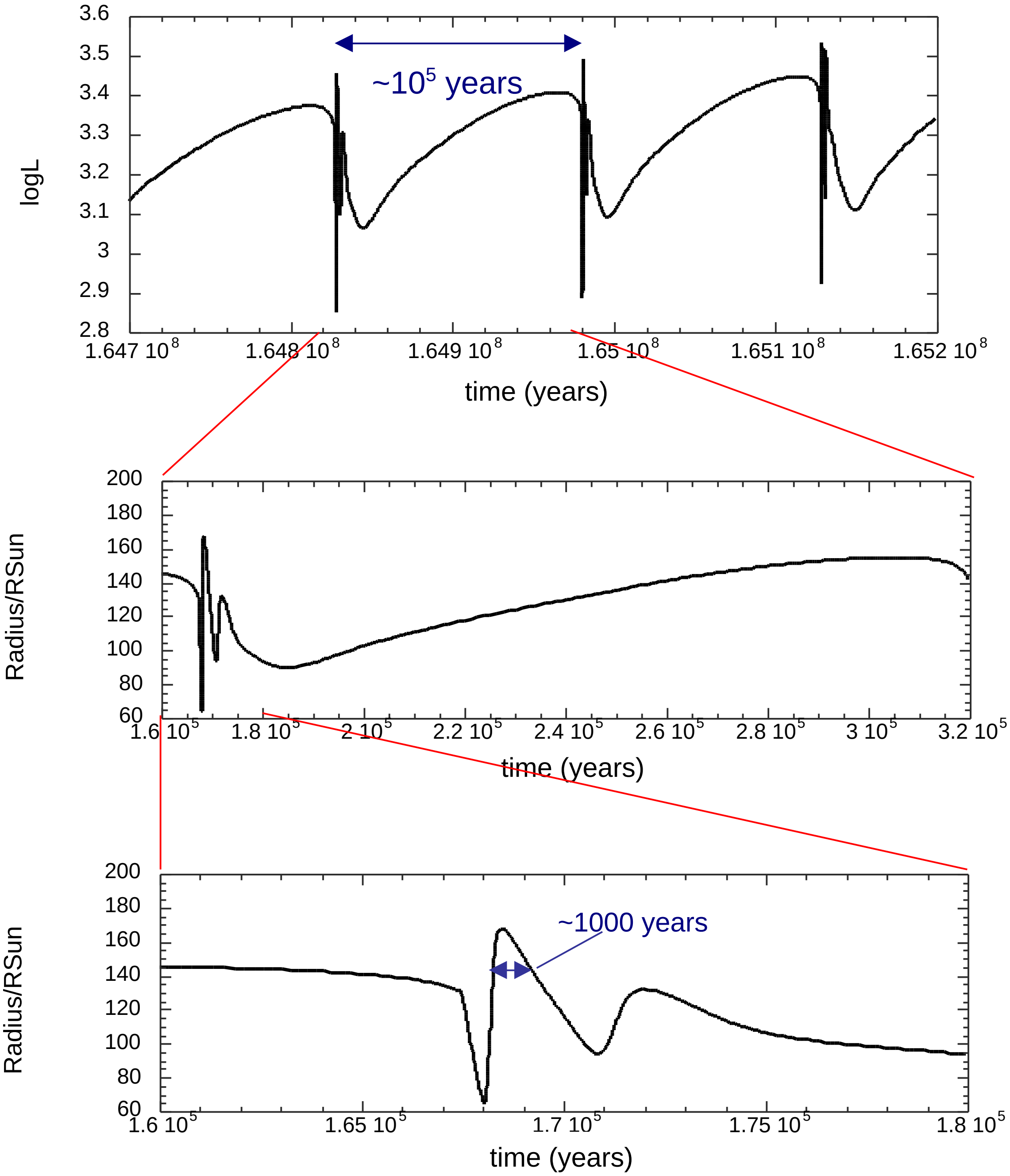
Assuming the Sun starts the AGB with a mass about the same as it is today, we find:



At the crash:
R_{Sun} = 180 R_{now} (varying from 173 to 188 with P = 313 days)
L_{Sun} = 2790 L_{now}

At the end:
L_{Sun} = 3950 is the maximum achieved.

Shell flashes modify L and R on a scale of 1000-10^5 years*:



This will need to be included in future mass-loss calculations.

---

* Models by S. Kawaler using ISUEVO, February 2000

The final fates of the planets, their moons, and the asteroids:

Object	distance from Sun (now)	peak T reached (L≤4000K)	Final fate
Mercury	0.387	***	Into the Sun, RGB
Venus	0.723	***	Into the Sun, early AGB
Earth	1.000	<2306>	Into the Sun, late AGB, unless $\Delta M_{RGB} \geq 0.2\ M_{Sun}$
and its Moon			Crashes into Earth before Earth dies.
Mars	1.524	1868	Escapes unless $\Delta M_{RGB} \approx 0$
asteroids			Small ones (<<100km) spiral in to Sun after Earth dies.
Jupiter	5.203	1011	Baked but not destroyed
Saturn, Uranus, and Neptune			Also baked but not destroyed