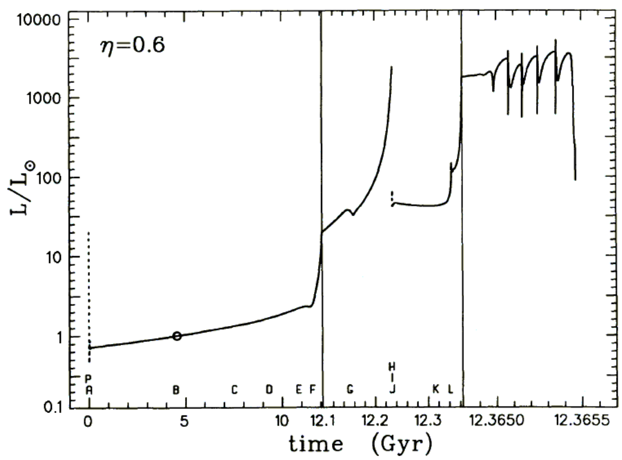
Solar Evolution and The Ultimate Destruction of Life on Earth

The following data are taken from a 1992 article in the *Astrophysical Journal*, in which the authors performed detailed computer models of the history and future evolution of our Sun.

Label	Time	Mass	Luminosity	Temp.	Radius
P	0 Gyr	1 M_{sun}	19.95 L_{sun}	4400 K	7.71 R_{sun}
A	0.048	1	0.7015	5586	0.897
B (now)	4.55	1	1	5779	1
C	7.56	1	1.33	5843	1.13
D	9.37	1	1.67	5819	1.275
E	10.91	1	2.21	6517	1.575
F	11.64	0.9998	2.73	4902	2.3
G	12.15	0.9935	34	4540	6.38
H	12.233	0.7249	2349	3107	165.8
I	12.233	0.7249	57.7	4595	12.0
J	12.234	0.7241	41.0	4724	9.5
K	12.316	0.7133	42.4	4819	9.4
L	12.345	0.708	130	4375	20
M	12.365	0.538	2999	3160	180.3
N	12.365	0.541	5190	3660	177.0
O	12.365	0.541	90	74080	0.058



(Note: Gyr = 1 billion years)

Historical evolution of the Sun

1. Compared to now, was the Sun fainter or brighter at the moment fusion began (point "P")?

The Sun is now fainter (luminosity of 1.0 L_{Sun}) than it was at ignition (~20 L_{Sun}).

2. Had you been on Earth around the time of its formation (a few tens of millions of years after the Sun's), would the Sun then look brighter or fainter than it does today?

The Sun would have looked fainter – immediately after ignition, the Sun became much less luminous and around the time of Earth's formation (point A) had a luminosity of about 0.7 L_{Sun}.

The Sun on the Main Sequence

3. Is the Sun currently getting brighter, or fainter?

The Sun is currently getting brighter, as can be seen from the rising slope in the left part of the diagram. (Note that main-sequence stars do change slightly in their luminosity over time.)

4. Once temperatures at Earth's surface reach the boiling point (or perhaps somewhat earlier), it is believed that a runaway greenhouse effect will occur, vaporizing the oceans and turning Earth into a sweltering inferno (like Venus). Approximately a 50-100% increase in Solar luminosity should be sufficient for this to happen. How long do we have until life on Earth is destroyed?

The Sun's luminosity will have doubled approximately halfway between points D and E – 10 billion years after formation, or 5.5 billion years from today. (However, the rising luminosity of the main-sequence Sun is going to present some very serious challenges for life on Earth well before this point.)

The Sun off the Main Sequence

5. About how long from now does the Sun leave the main sequence to turn into a red giant?

The Sun's luminosity starts to rise dramatically around point F, 12 billion years after formation (or 7.5 billion years from now.) The changes in luminosity before this point due to evolution on the main sequence will seem trivial compared to the Sun's behavior from this point on as it really begins to move on the H-R diagram.

Original worksheet by D. Perley

6. Earth orbits the Sun at a distance of about 215 R_{sun}. Will our (long-dead) planet be safe, or will it be enveloped by the Sun at some point? What about Mercury (80 R_{sun}) and Venus (155 R_{sun})?

According to this model, Earth is safe, as the Sun maxes out at a radius of approximately 180 times its current radius. Mercury is fried – although, interestingly, Venus barely escapes because the Sun's mass loss causes its gravity to weaken, and Venus migrates outward in its orbit.

7. Earth's surface temperature is proportional to $L_{Sun}^{1/4}$. Assuming Earth survives, how hot will the surface temperatures get at the time of the Sun's peak luminosity? Earth's current temperature is about 300 K. Compare your answer to the melting point of typical rocks (1000-2000 K).

The Sun's peak luminosity is about 5200 times its current luminosity (point 2) – at this point it is fusing helium in the core as well as hydrogen in a surrounding shell in furious, unstable cycles that cause its luminosity to undergo a series of violent pulses. If we neglect Earth's migration away from the Sun, this means that the temperature on Earth will increase by a factor of about $(5200)^{1/4} = 8.5$, and so Earth's surface temperature rises to about 2500 K. This will liquefy the surface and turn the planet in to a global magma ocean.

8. How long does the red-giant phase last? Compare this to the Sun's main-sequence lifetime.

The red giant phase is short-lived (note the uneven distribution of the x-axis). The red giant phase begins at about 12 billion years after formation and lasts until 12.365 billion years – a total duration of only 365 million years, compared to the approximately 12 billion years on the main sequence.

9. How stable (in terms of luminosity, radius, etc.) is the Sun during its red giant phase compared to its main sequence phase?

The red giant Sun is extremely unstable – in its first phase (points F through H, hydrogen shell fusion) it brightens from about 3 to 2000 solar luminosities, then suddenly plummets to about 40 when it first begins helium fusion. Its luminosity then increases catastrophically a second time and undergoes a violent series of pulses, each of which ejects a great deal of mass, until it finally ejects its envelope completely after point N.

10. What kind of star is the Sun when it reaches state "O" on the table?

The Sun's temperature at this point is now 75,000 Kelvin, and it has lost about half its mass, but its radius is only 5% of the current Sun's. This extremely dense and hot object is an early white dwarf. Its luminosity is still quite high for a white dwarf, but with fusion reactions stopped it will quickly cool with time and become much fainter.

11. The table indicates that the Sun's mass at this final point has been reduced to almost half its initial value. Where did the rest go?

The mass was ejected during the pulsations at the end of its life to form a planetary nebula.