Hertzsprung-Russell Diagram, the Death of Stars, and The Elements of the Solar System

Physics 090

2020-04-27

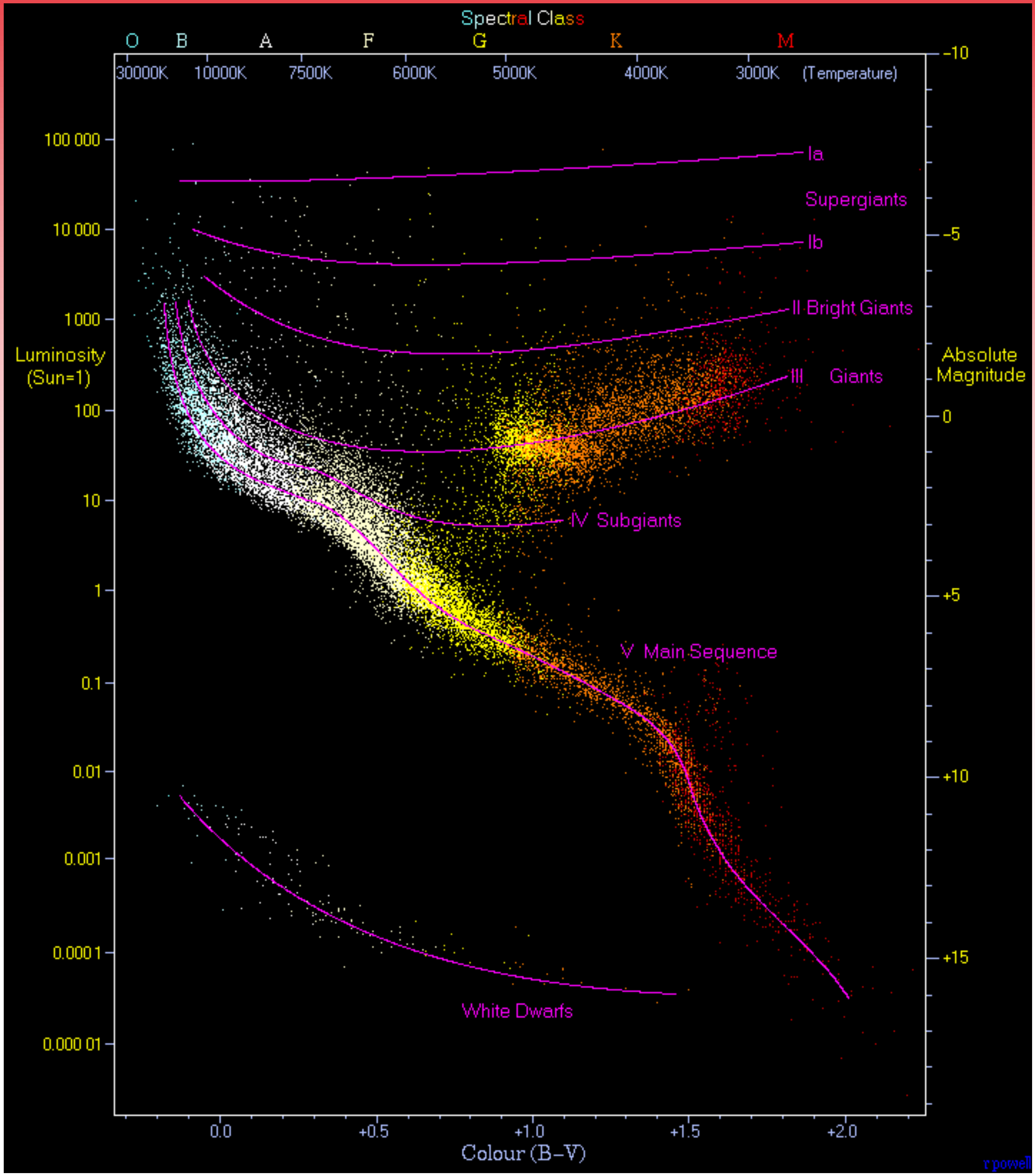
SAINT MARY'S COLLEGE of CALIFORNIA

The entire last week of lectures was on classifying stars with the help of the Hertzsprung-Russell diagram. Prof. Aaron Lee explained:

- Star Formation and the Main Sequence

We still have to explain the other two groupings!

- Red Giants
- White Dwarfs



Using Newton's Laws applied to binary stars, we learn their masses.

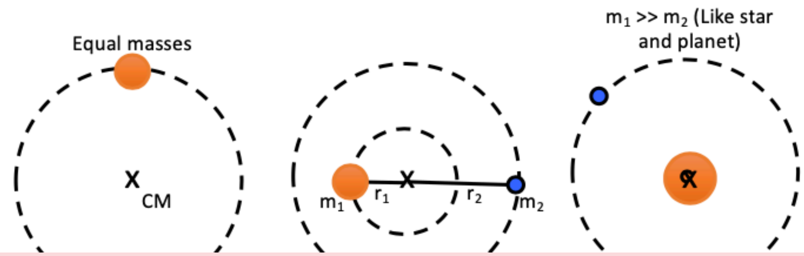
Using the Stefan-Boltzmann Formula, we learn their radii.

So for each star added to the catalog we now have:

- Mass, M
- Luminosity, L
- Radius, R
- Temperature, T

Binary Stars gives Mass

- Over 50% of the "stars" you see are actually multiple systems bound by gravity. Most are double. Many triple and higher.
- Yet another application of Kepler's and Newton's laws.



Sizes of stars

- **Stefan-Boltzmann Law:** Derived in upper-level thermodynamics.

$$L = 4\pi R^2 \sigma T^4$$

$$(\sigma = constant)$$

- Takeaway: relates L and T to R!

Trends for Main-Sequence Stars

- Once all stellar properties were measured, trends emerged. Eventually derived.
- All stellar properties can be scaled to mass ("scaling relations")
- These relations are true only for main-sequence stars (nuclear physics built into these expressions)

$$L \propto M^4$$
$$R \propto M$$
$$T \propto M^{1/2}$$

- The mass-luminosity relation implies that massive stars live short lives. They have more fuel, but burn through it faster!

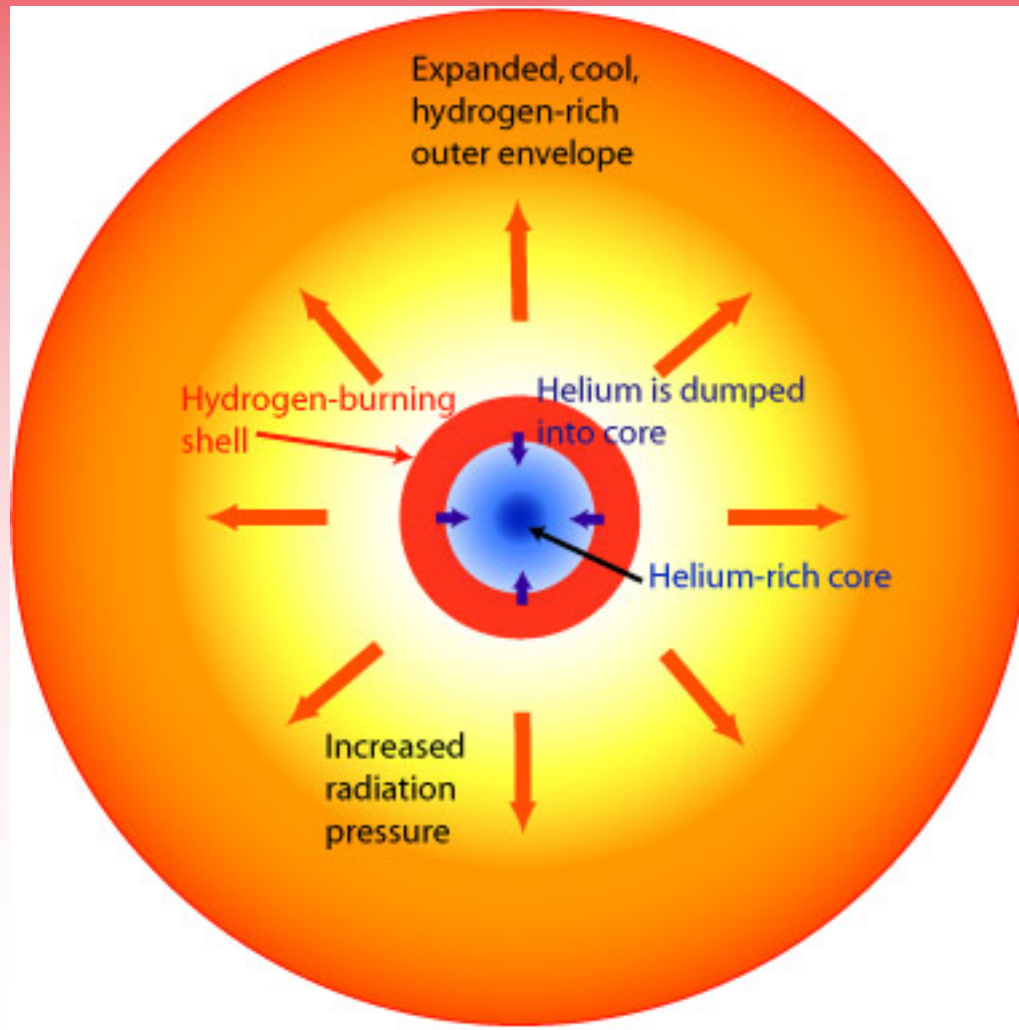
Main Sequence Mass and Lifetime Examples

Surface Temperature (K)	Mass (Mass of Sun = 1)	Lifetime on Main Sequence (years)
9600	3.3	500 million
7350	1.7	2.7 billion
6050	1.1	9 billion
5240	0.8	14 billion
3750	0.4	200 billion

From OpenStax Astronomy, Table 22.1

As our Sun nears the end of its 9,000,000,000 years on the main sequence, what is next?

The core is exhausted of Hydrogen. A shell around the core continues to burn Hydrogen into Helium. The Helium goes to the core.



Hydrogen Shell Burning on the Red Giant Branch

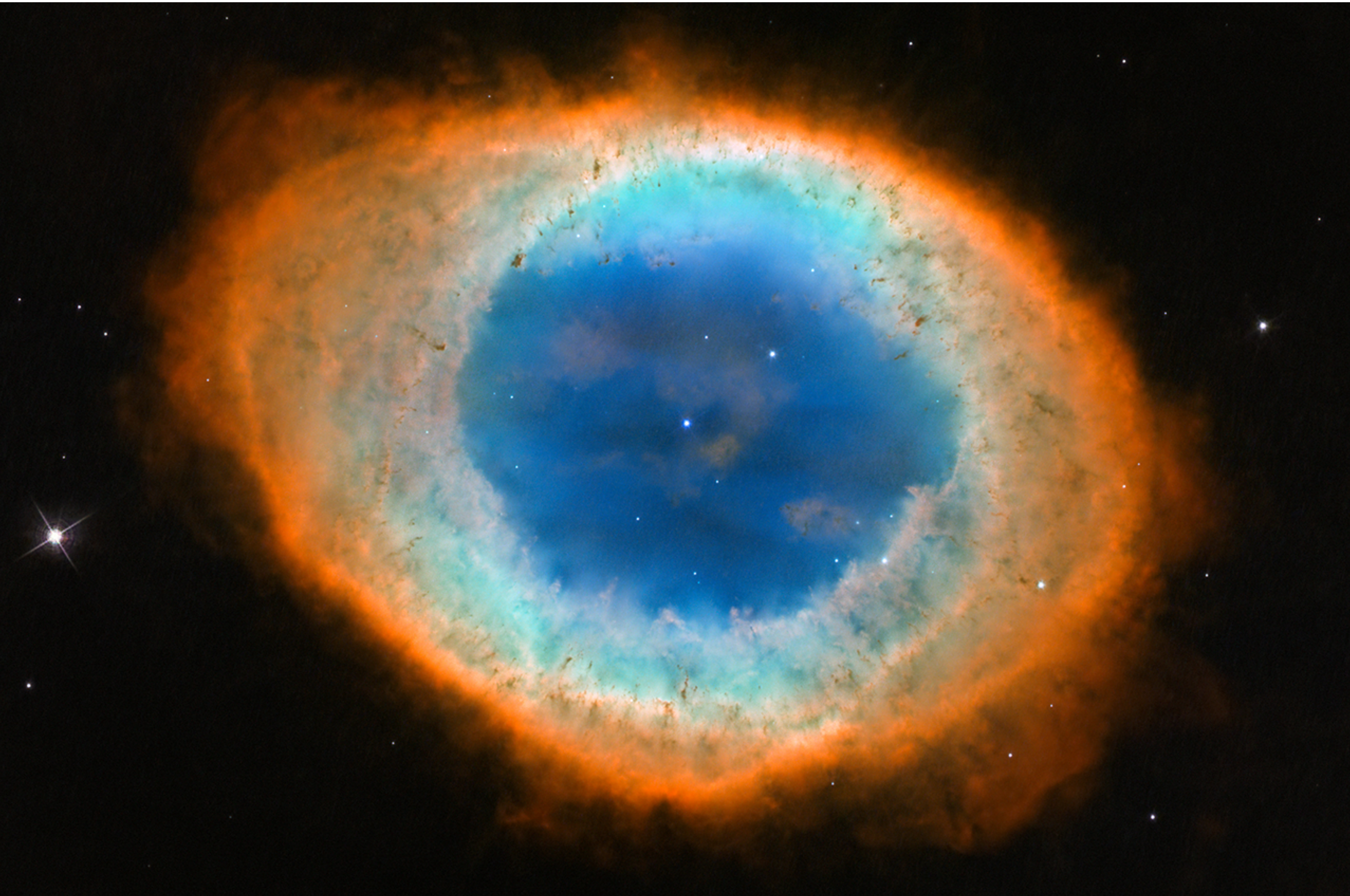
Reference and image credit, Australia National Telescope Facility:
https://www.atnf.csiro.au/outreach/education/senior/astrophysics/stellarevolution_postmain.html

The Lifecycle of our Sun

- Most of life at a fixed place on the main sequence (another 5 billion years for our Sun)
- Balloon up to 100x its current size and cool off as a Red Giant (as the Hydrogen in the core runs out), engulfing Mercury and Venus
- Explodes as a nova (leaving a nebula and a white dwarf)!
- Because nobody had a clue what these nebula were when they were first observed, they have and have kept their very wrong name: planetary nebula.

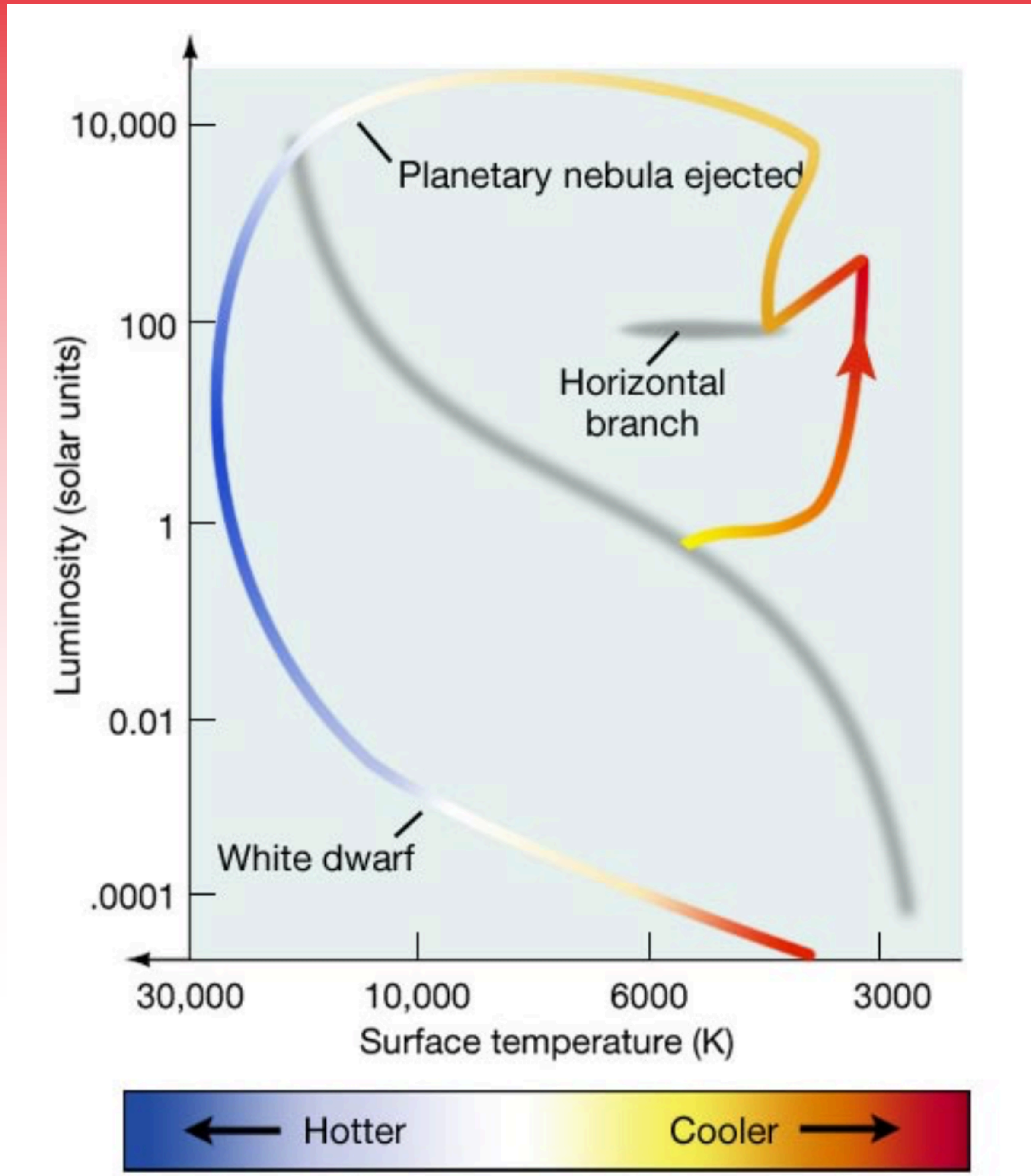
So your understanding of the Hertzsprung-Russell diagram (why there is a main sequence, a group of red giants, and a group of white dwarfs) is explained! A star like our Sun goes through all those phases!

This is typical of stars of our Sun's size. Coming shortly: what about larger stars? It turns out stars with mass greater than 8x our Sun's mass have a very different endgame!



The Ring Nebula. A star that has exploded creating a nebula and leaving a white dwarf (visible in center)
Image Credit: NASA, ESA, and the Hubble Heritage (STScI / AURA)- ESA / Hubble Collaboration

Our Sun's future Path through the Hertzsprung-Russell Diagram

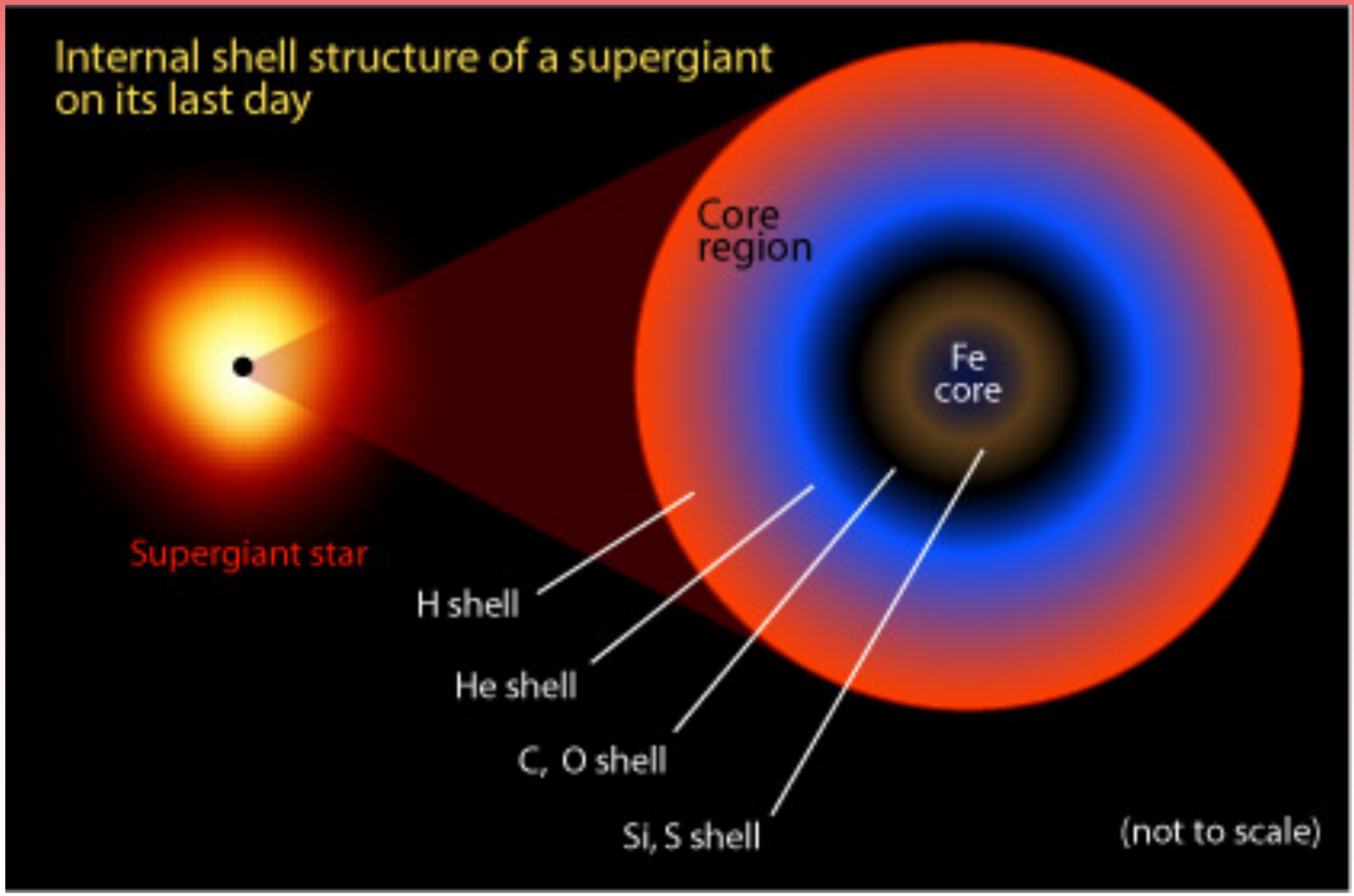


Two Final Stages
(depending on the star's mass)

Sun-like Stars, end in nova, producing a nebula and a white dwarf.

Stars >8 times the mass of our Sun, end in a supernova, producing a nebula and a neutron star or a black hole. The explosion is much more violent and is due to a kind of fusion that can only occur under the most extreme pressure. We haven't discussed this type of fusion. Suffice it to say that protons and electrons fuse to form neutrons.

Core of a Supergiant



Fusion in layers of all elements up to Iron

Reference and image credit, Australia National Telescope Facility:

https://www.atnf.csiro.au/outreach/education/senior/astrophysics/stellarevolution_postmain.html

A supergiant star after it has exploded into a supernova.
Image Credit: FORS Team, 8.2-meter VLT, ESO

The Elements in our Solar System

The Milky Way is 13.5 billion years old. Our Sun is only 4.5 billion years old. Stars that were in our part of the Milky Way Galaxy before our Sun was here, formed, burned their fuel, and exploded.

The novas can produce all the elements up to and including Iron. The supernovas can produce heavier elements (Gold, Platinum, Uranium).

In other words, the only reason our solar system has elements other than Hydrogen and Helium is the remnants of prior stars which have come and gone.