Introduction to Astronomy
Lecture 4:
The evolution of stars

Presented by
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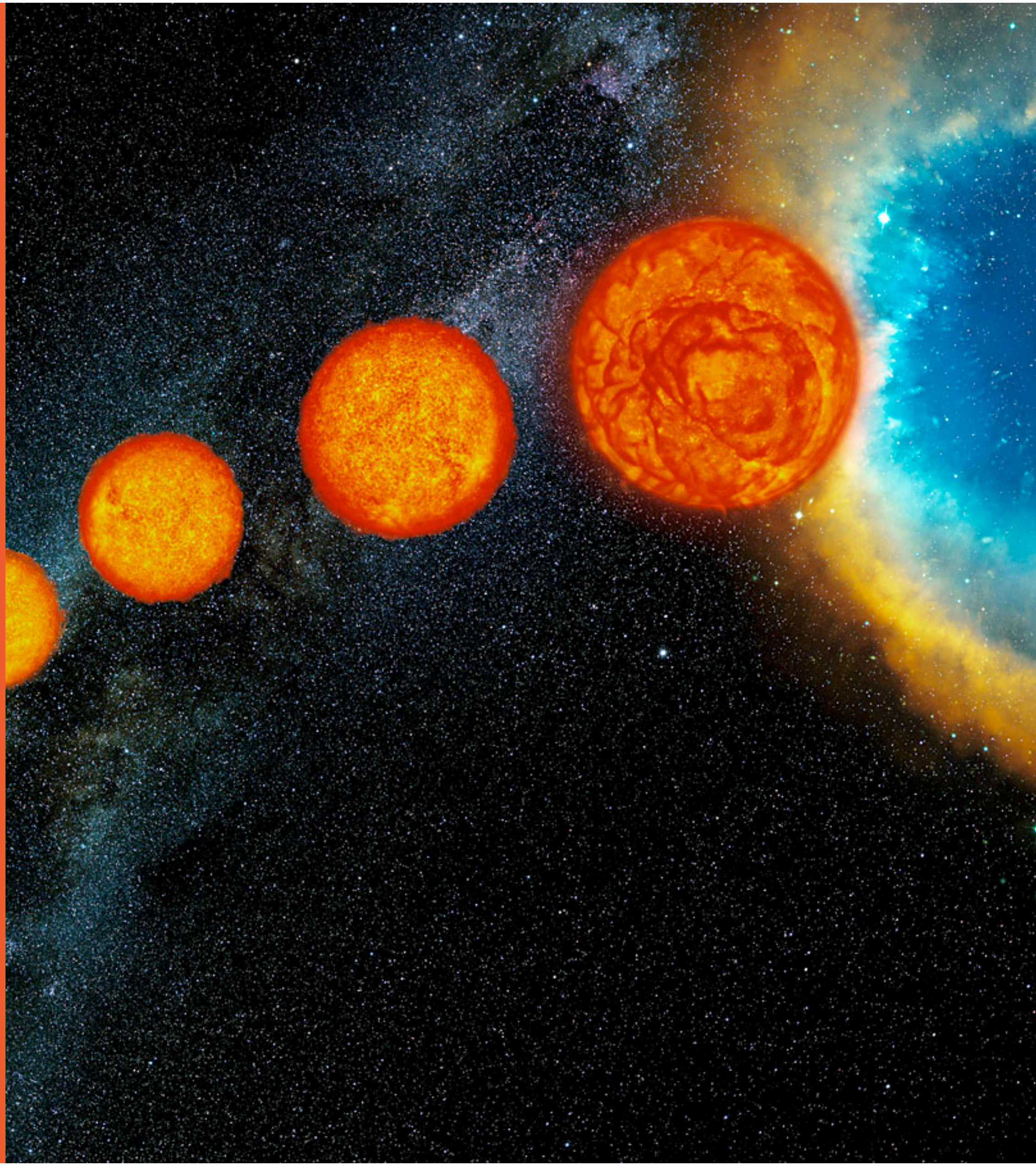
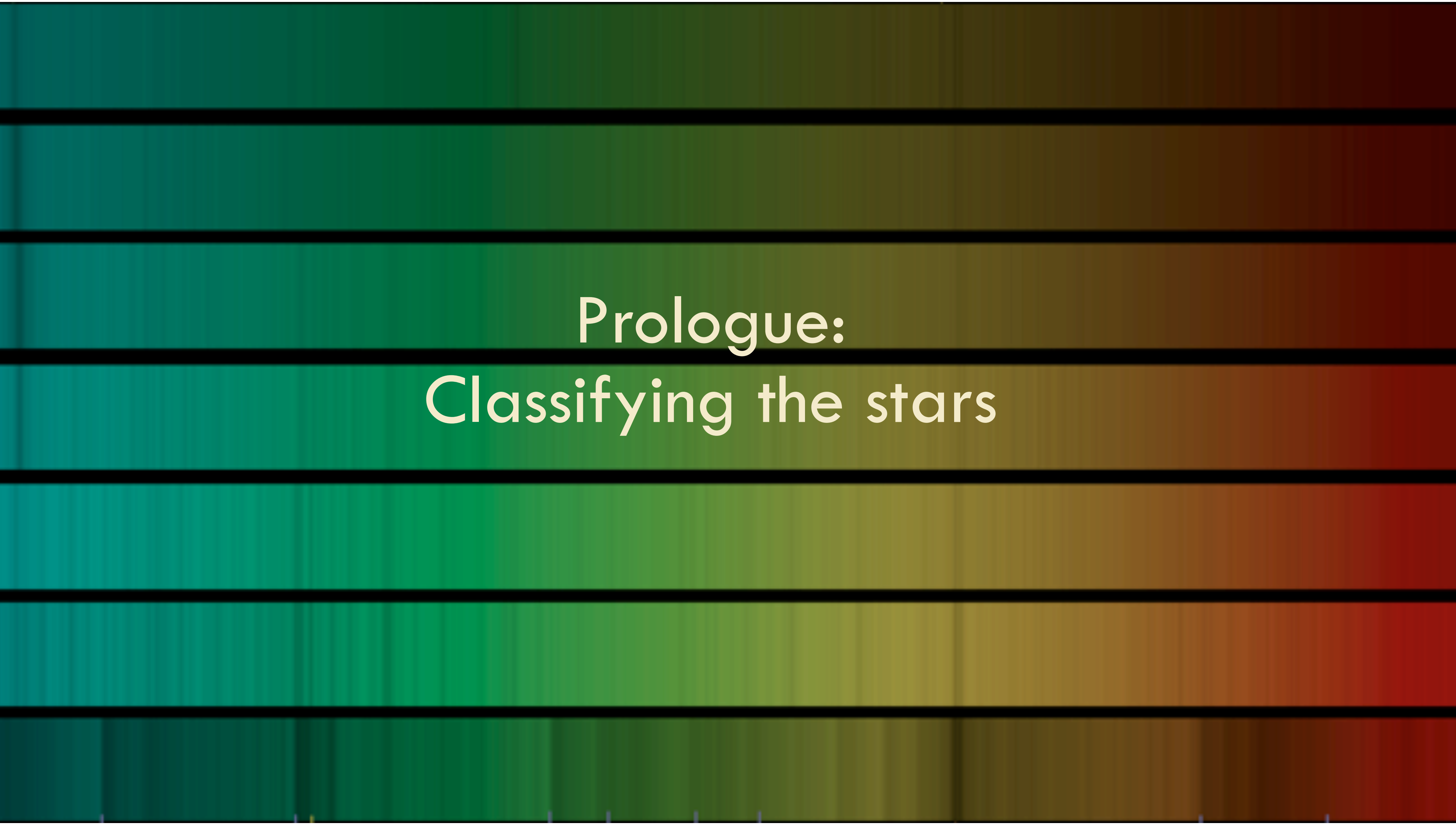
THE UNIVERSITY OF SYDNEY



In tonight's lecture

- Prologue: Classifying the stars
  - *set the scene of where we are*
- How stars work
  - *what keeps a star going*
- Stellar evolution
  - *how stars change with time*

Prologue: Classifying the stars



Classifying the stars

In the 1850s, Kirchoff and Bunsen discovered the science of spectroscopy. By the end of the century, the spectrum of many stars had been recorded with the newly-invented photographic techniques.

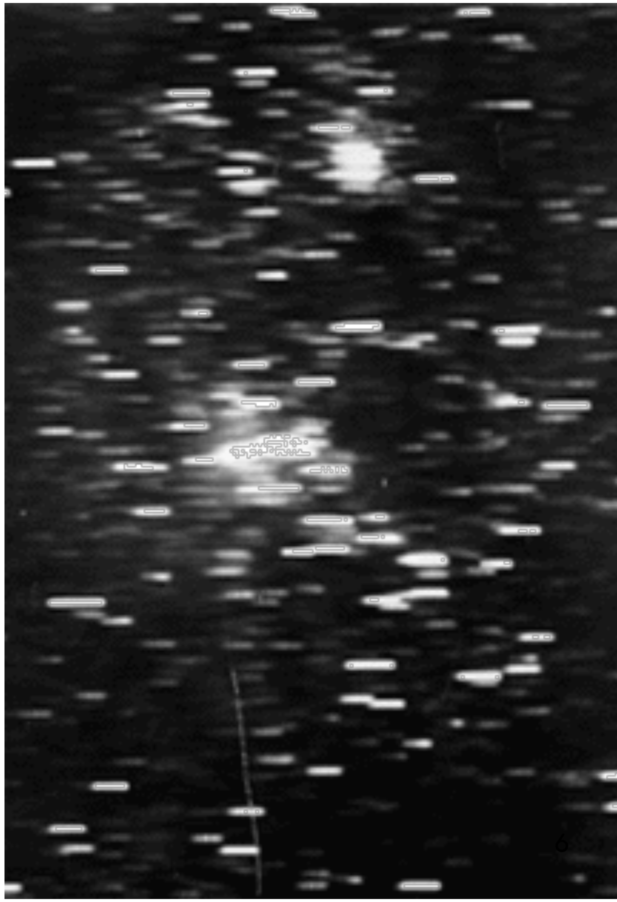
Many details were being learned about the colours and spectra of the stars. A classification scheme was needed.

The Harvard Women

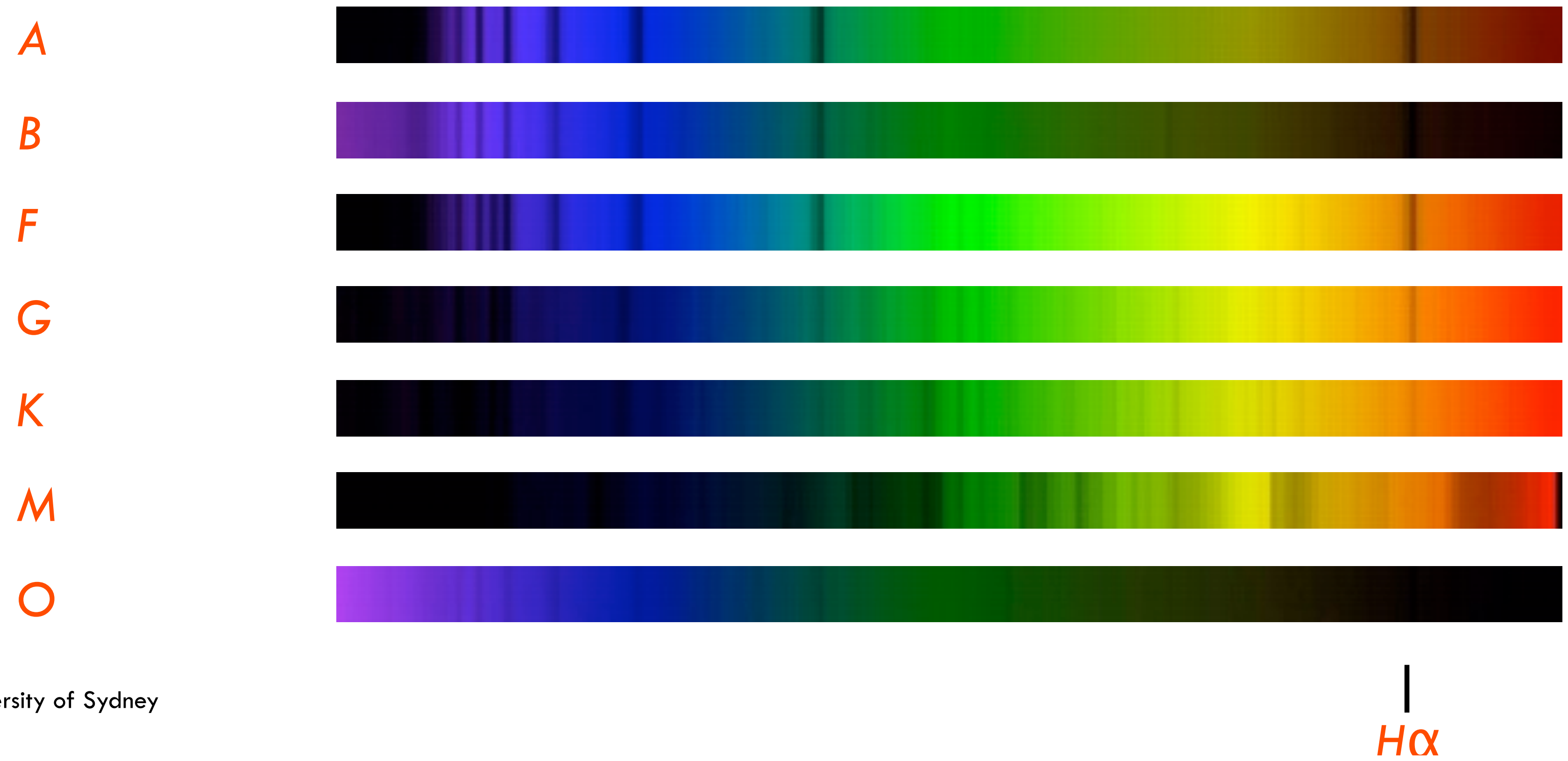
Harvard College Observatory was the site of many of the fundamental advances in stellar astronomy.

The director, Edward Pickering, hired large numbers of women as “computers” to do routine calculations.

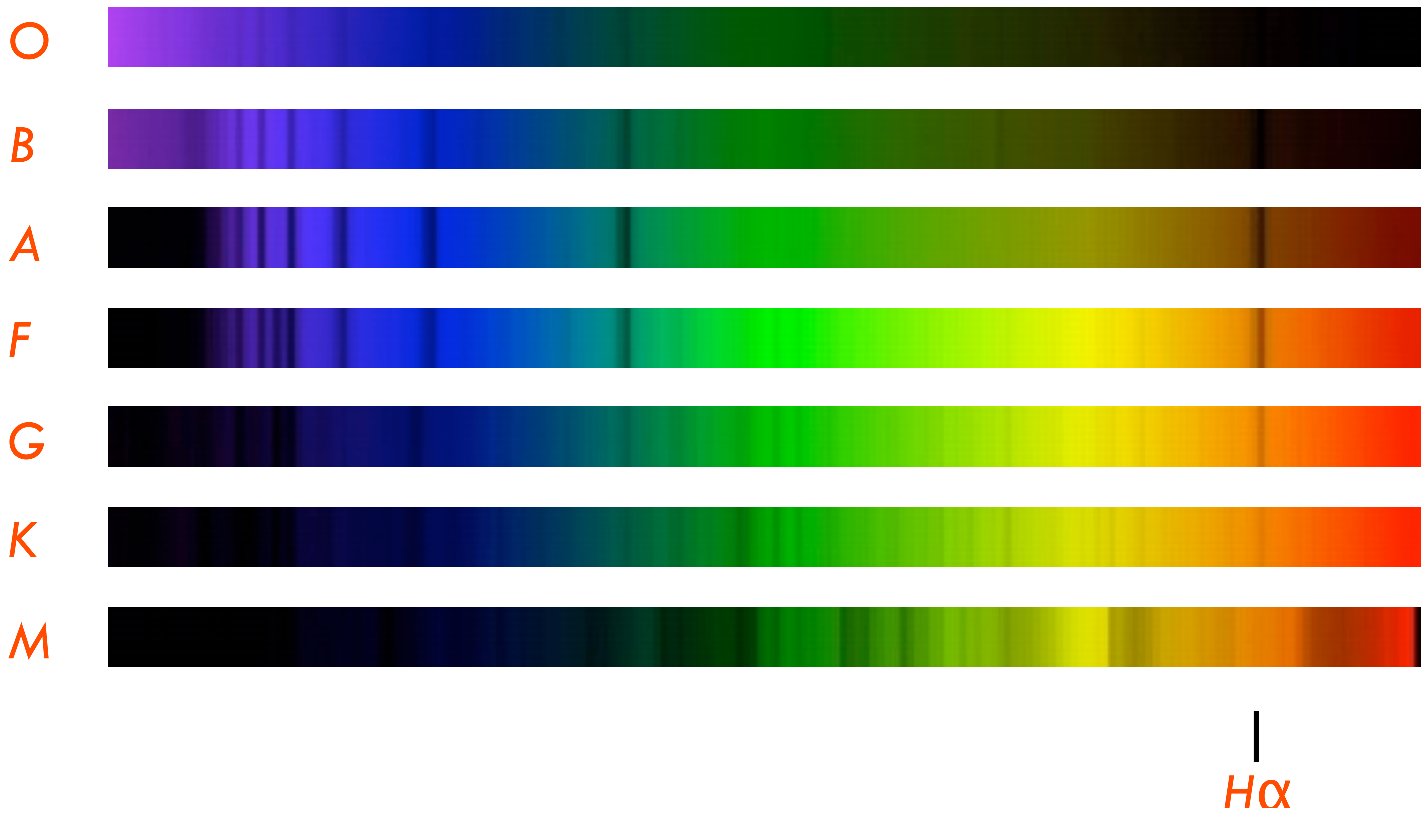
In 1886, Pickering began a giant project – the *Henry Draper Memorial* – to classify thousands of spectra of stars, with hundreds of spectra on each photographic plate. He wanted to develop a scheme that was easy to use, and free from theoretical bias.



Williamina Fleming classified 10,498 stars into an empirical system of 22 classes. She arranged them in order of decreasing strength of the Hα line. Stars with the strongest H-alpha were called A, then B, and so on down to Q.



Annie Jump Cannon rearranged them by order of temperature, and reduced the number of classes to seven.



Cannon *personally* classified over a quarter of a million stars, working from photographic plates with hundreds of spectra per plate.

Oh Be A Fine Girl, Kiss Me!

This is the final system Cannon came up with. Each class is subdivided into 10 sub-classes, like F0, F1,... F9, with F0 being hotter than F9. The spectra vary smoothly between the classes.

Type	Colour	Main characteristics
O	Blue	Ionised helium and metals; weak hydrogen
B	Blue	Neutral helium, ionised metals, stronger hydrogen
A	Blue	Hydrogen dominant,singly-ionised metals
F	Blue to white	Hydrogen weaker, neutral and singly-ionised metals
G	White to yellow	Singly-ionised calcium, hydrogen weaker, neutral metals
K	Orange to red	Neutral metals, molecular lines begin to appear
M	Red	Titanium oxide molecular lines dominate, neutral metals

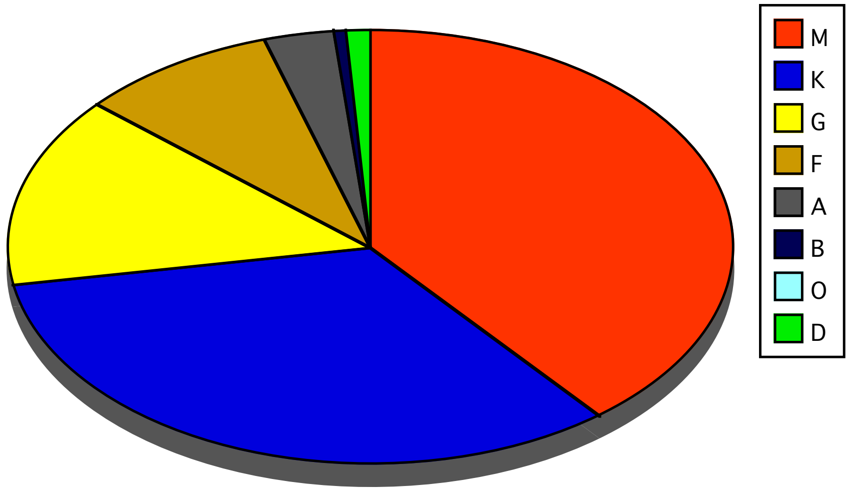
These spectral types (with a few minor extensions) describe the spectrum of *every* star.

Here's that list of the nearest stars again, this time including their spectral types:

star	apparent mag	stellar type	distance (pc)
Proxima Centauri	11.5	M5 V	1.3
Alpha Centauri	0.1	G2 V	1.3
Barnard's Star	9.5	M5 V	1.8
Wolf 359	13.5	M6e	2.3
Lalande 21185	7.5	M2 V	2.5
Sirius	–1.5	A1 V	2.6
Luyten 726–8	12.5	M6e V	2.7
Ross 154	10.6	M5e V	2.9
Ross 248	12.2	M6e V	3.2
Epsilon Eridani	3.7	K2 V	3.3

Note how nearly all of them are *red* stars.

How many of each type of star are there near the Sun? Here are all stars within 20 parsecs.



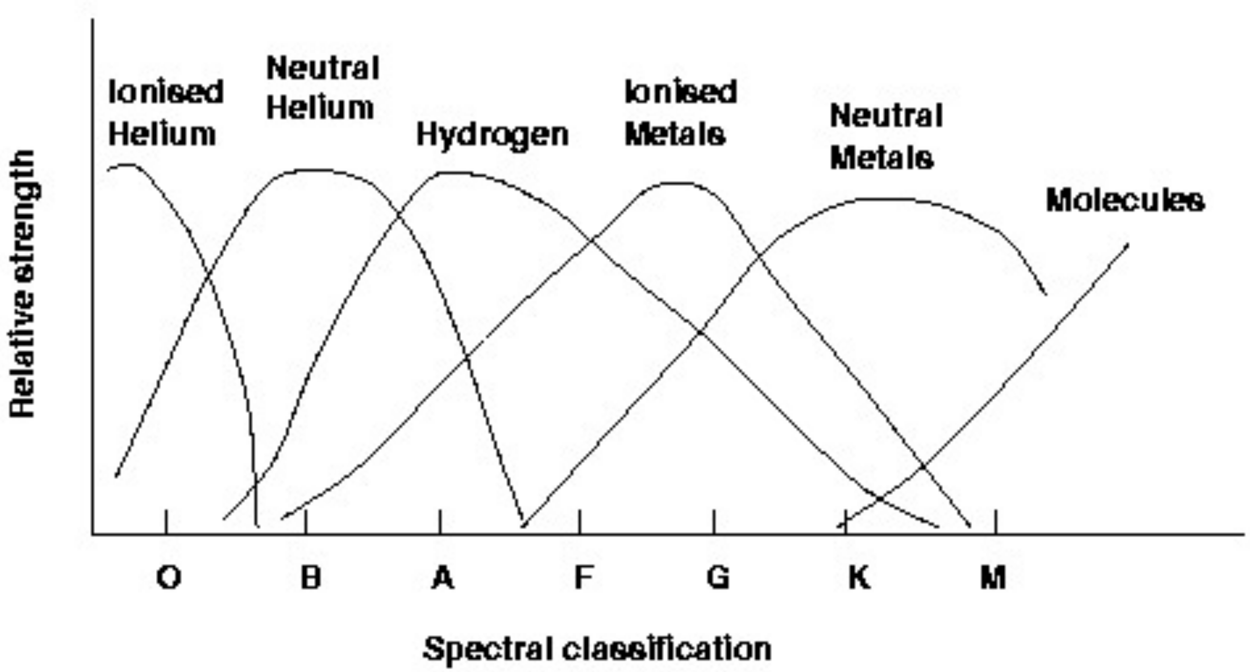
More than 70% are of types K and M.

Initially, it was thought that the differences between the spectral types reflected wildly varying chemical composition.

However, in the 1920s Cecilia Payne demonstrated* that the differences are almost entirely due to different temperatures in the stars.

**in her PhD thesis, described by Otto Struve as ``undoubtedly the most brilliant PhD thesis ever written in astronomy"*

As the temperature in the star increases, the electrons in the atoms get ionised. Once they are removed, they can no longer produce spectral lines. Some atoms hold on to their electrons more tightly than others, so different lines appear and disappear as the temperature increases.



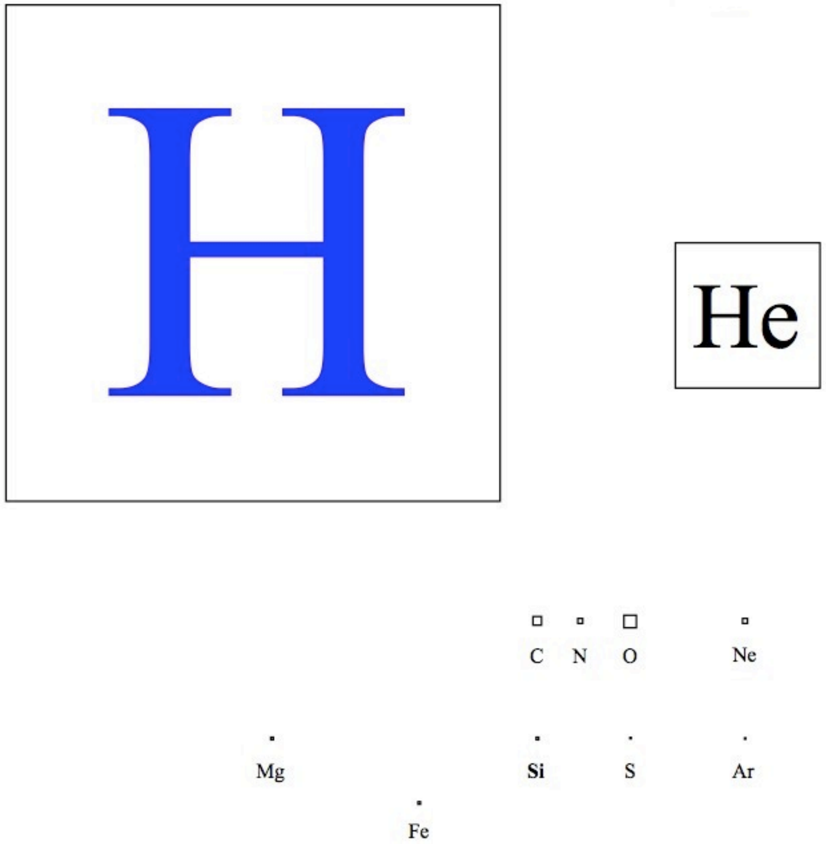
Thus we can measure the *temperatures* of the stars, just by looking at their spectra.

We can then determine the underlying composition of the star as well. Most stars have very similar compositions.

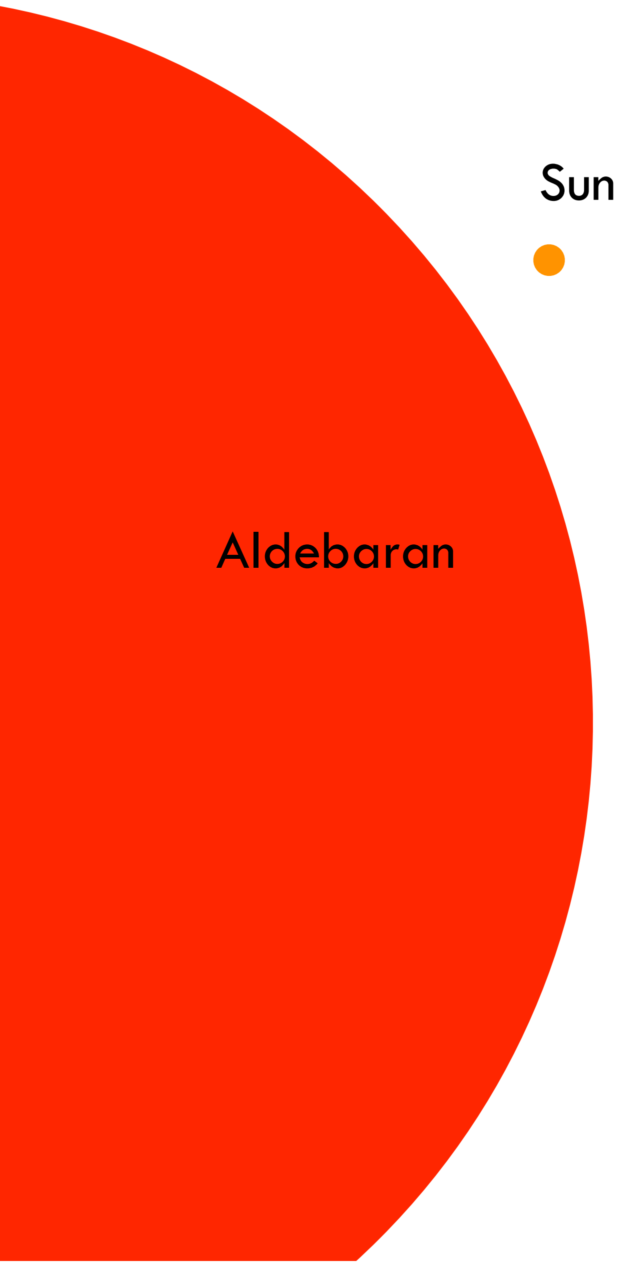
Stars are made up of 90% hydrogen, 10% helium, and tiny traces of heavy elements (everything else).

Element	Abundance (% number of atoms)	Abundance (% total mass)
Hydrogen	91.2	71
Helium	8.7	27.1
Oxygen	0.078	0.97
Carbon	0.043	0.4
Nitrogen	0.0088	0.096
Silicon	0.0045	0.099
Magnesium	0.0038	0.076
Neon	0.0035	0.058
Iron	0.03	0.014
Sulfur	0.015	0.04

Recall that the interstellar material from which the solar system formed consists mostly of hydrogen and helium, with other elements less than one-thousandth as abundant as hydrogen.

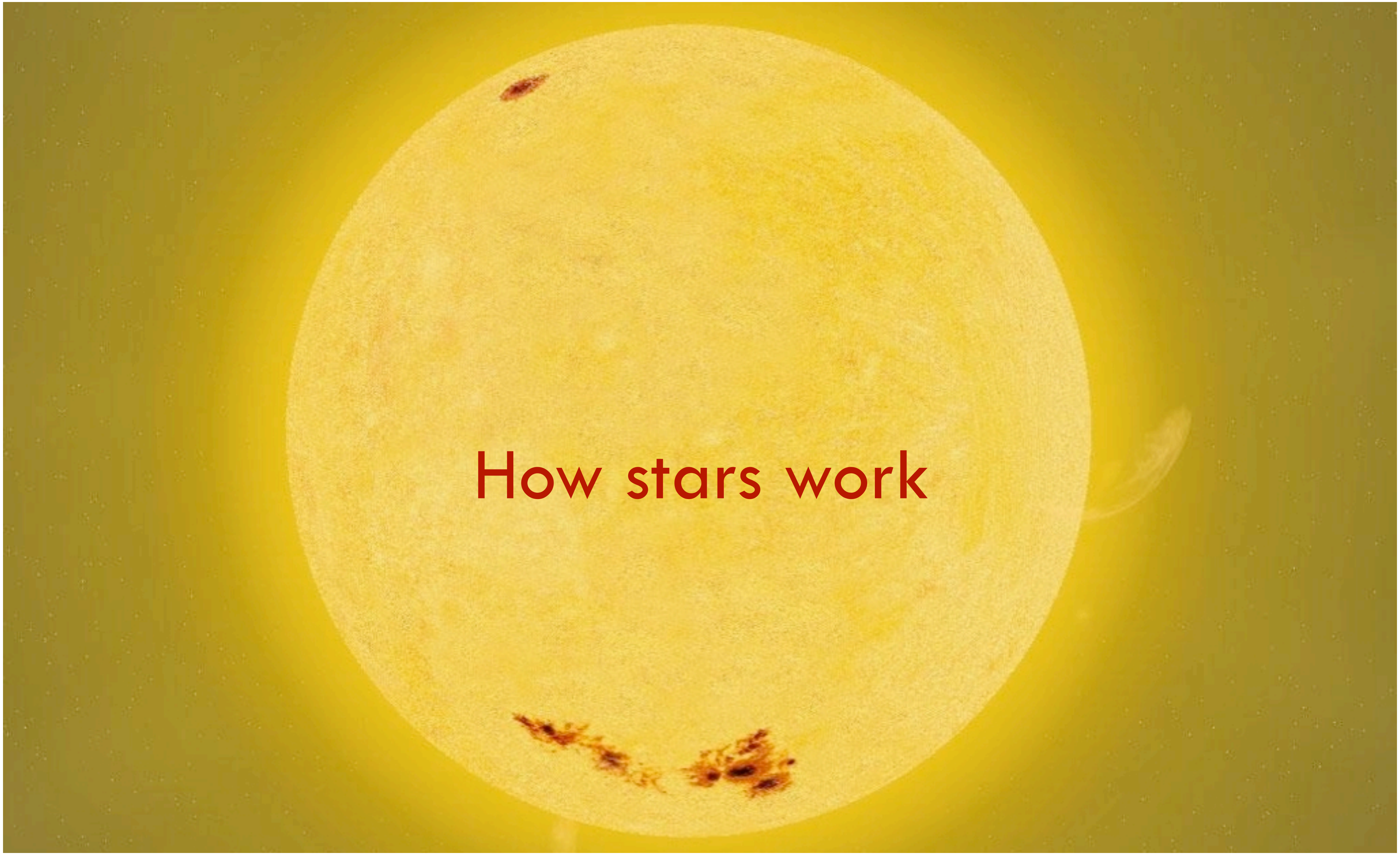


The "Astronomer's Periodic table", with the size of the element indicating its abundance by weight. (Figure by Ben McCall)



Knowing the temperature and brightness of the star, we can determine one more important quantity: the star's *size*. It turned out that some stars are much larger than stars like the Sun: these are now called *giant* and *supergiant* stars.

Here is an artist's impression of what it would be like on a world circling a red supergiant: the star Antares at about the distance that Saturn is from our Sun.

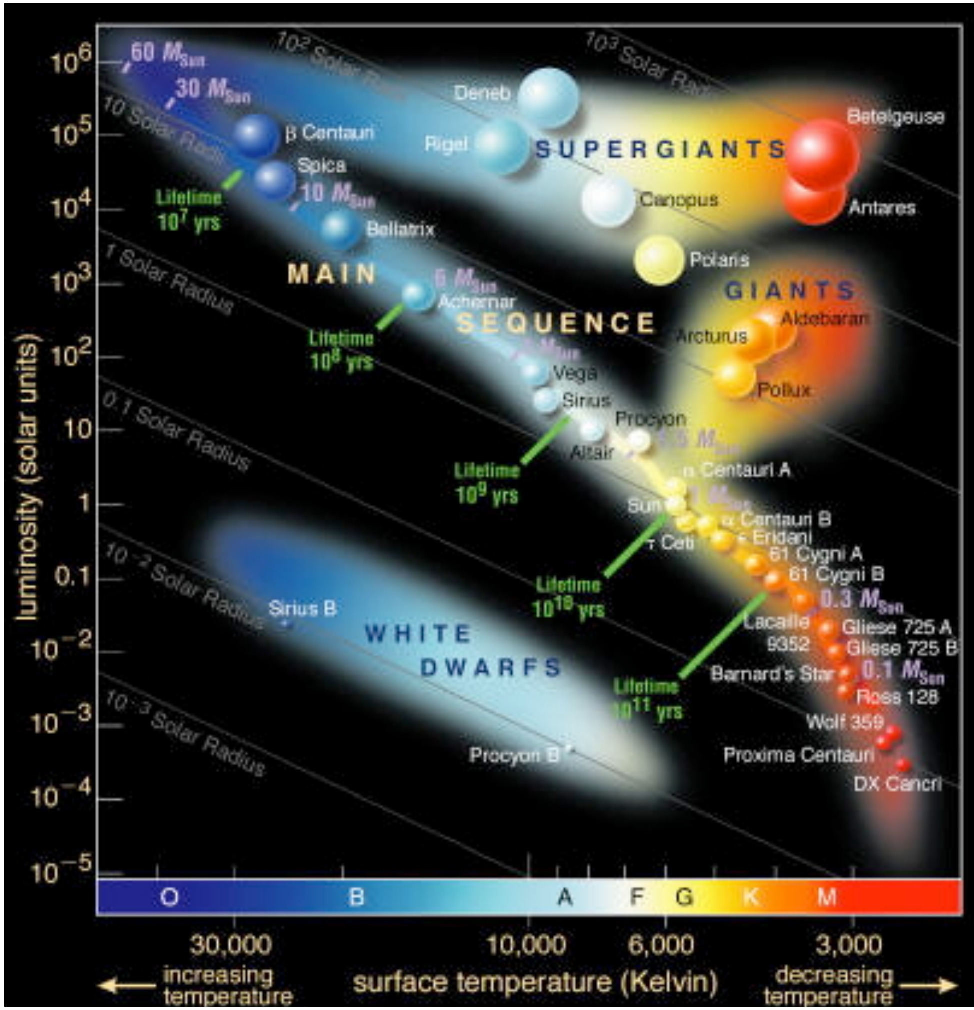

How stars work

Once stellar temperatures could be determined, and true brightnesses worked out, patterns started to be noticed.

Henry Norris Russell noticed that stars do not have random values of absolute magnitudes or colours, but fall in localised bands.

He published a diagram which had actually been discovered nearly ten years earlier by the Danish astronomer (then only an amateur) Ejnar Hertzsprung.

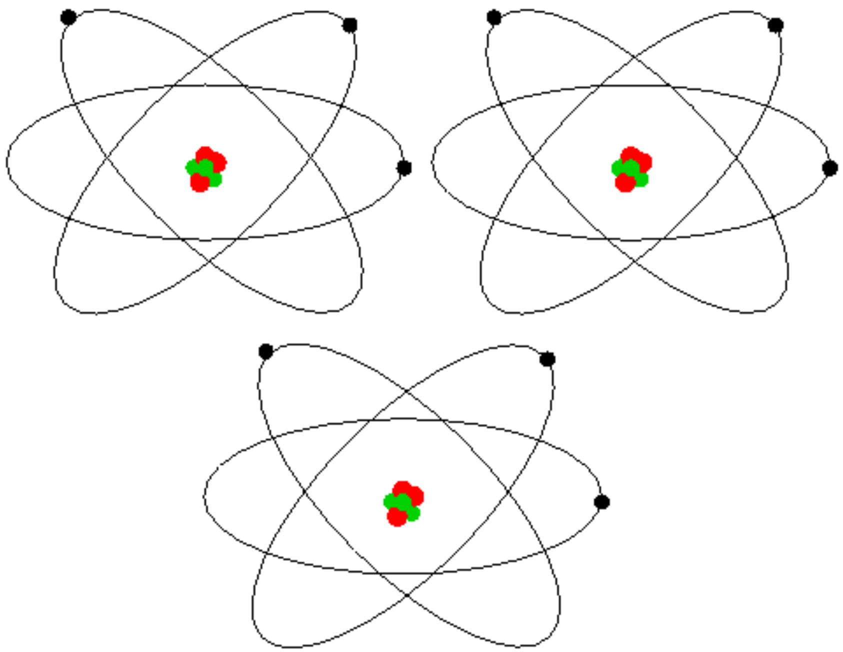
Hertzsprung and Russell plotted the magnitude of stars against their colours, and produced a decided pattern: the *Hertzsprung–Russell diagram*, also called a colour–magnitude diagram.

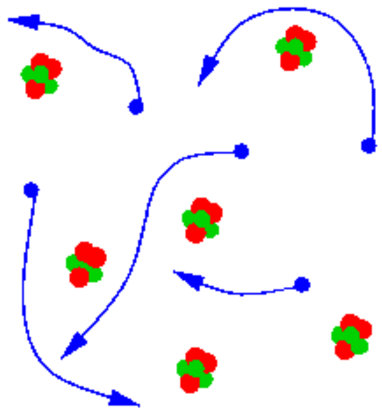


90% of stars fall on a narrow diagonal band from the red M dwarfs to the blue-white O stars.

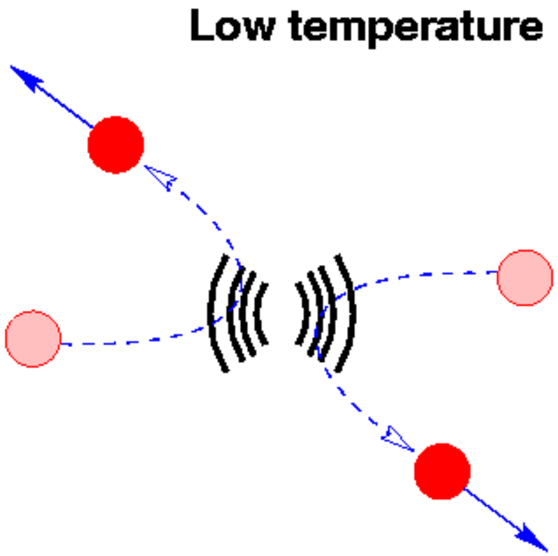
Last week, we had just shown how a star was formed from the collapse of a cloud of interstellar gas. The cloud collapses from the inside out, with the central regions getting hotter and denser as they are squeezed by the pressure of the infalling material.

As the temperature increases, the electrons are ripped from the atoms, and the bare nuclei can move freely through a sea of electrons.

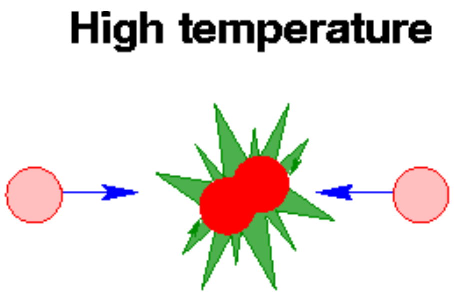




No longer protected by their electron shells, the nuclei can now approach much closer to each other, smash into each other, and fuse to form helium.

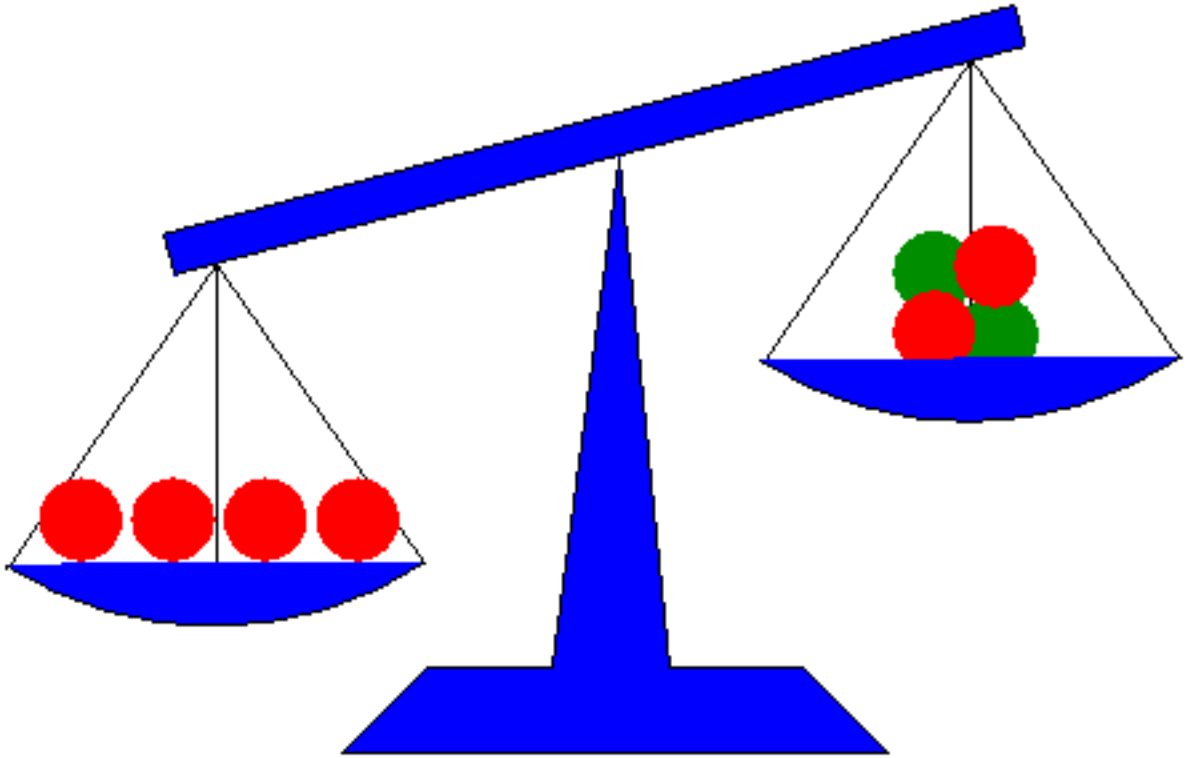


At *low temperatures*, hydrogen nuclei (protons) are prevented from colliding by the electromagnetic force, which repels the protons

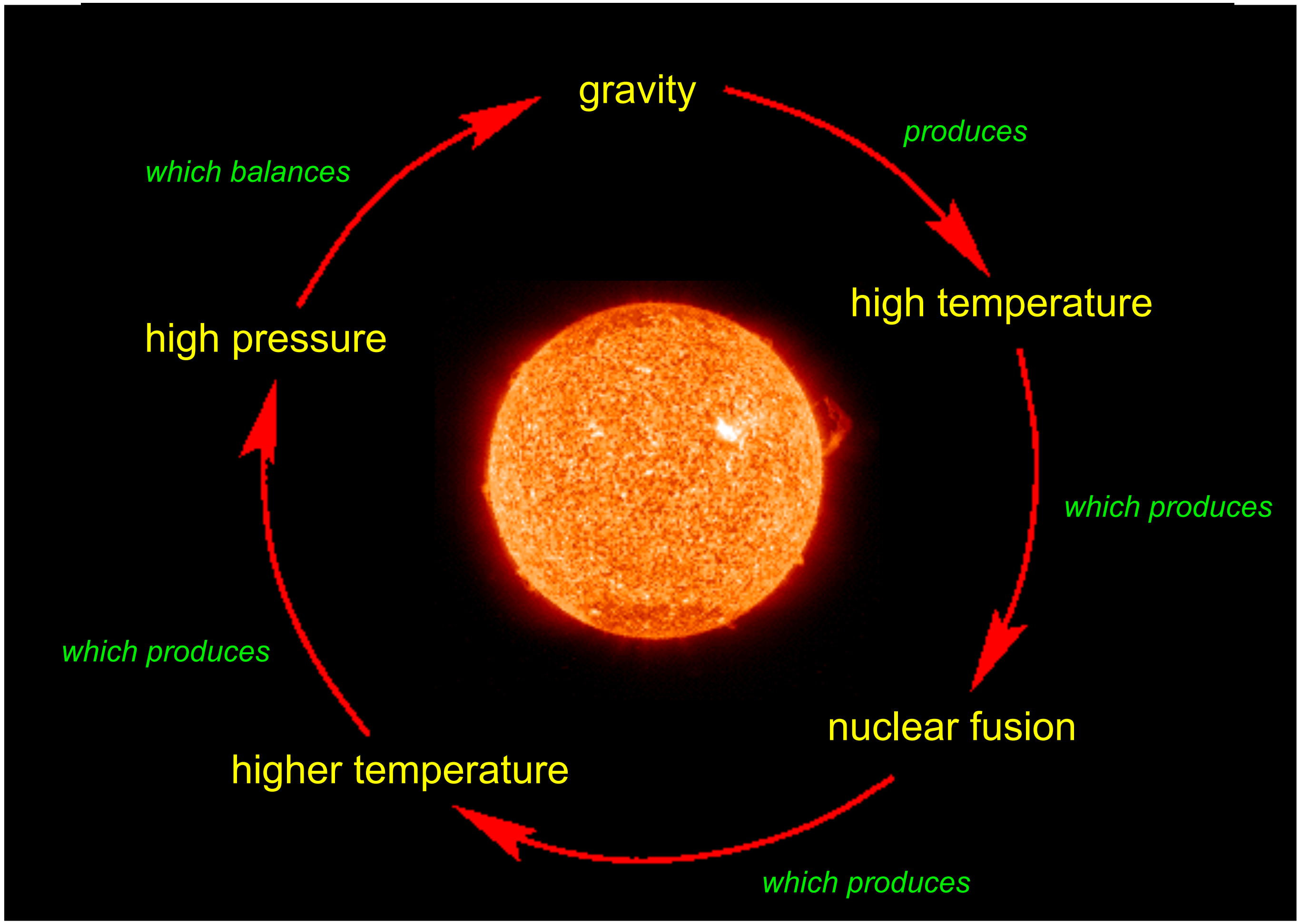


At *high temperatures* the nuclei can approach close enough that the strong nuclear force can bind them together: fusion.

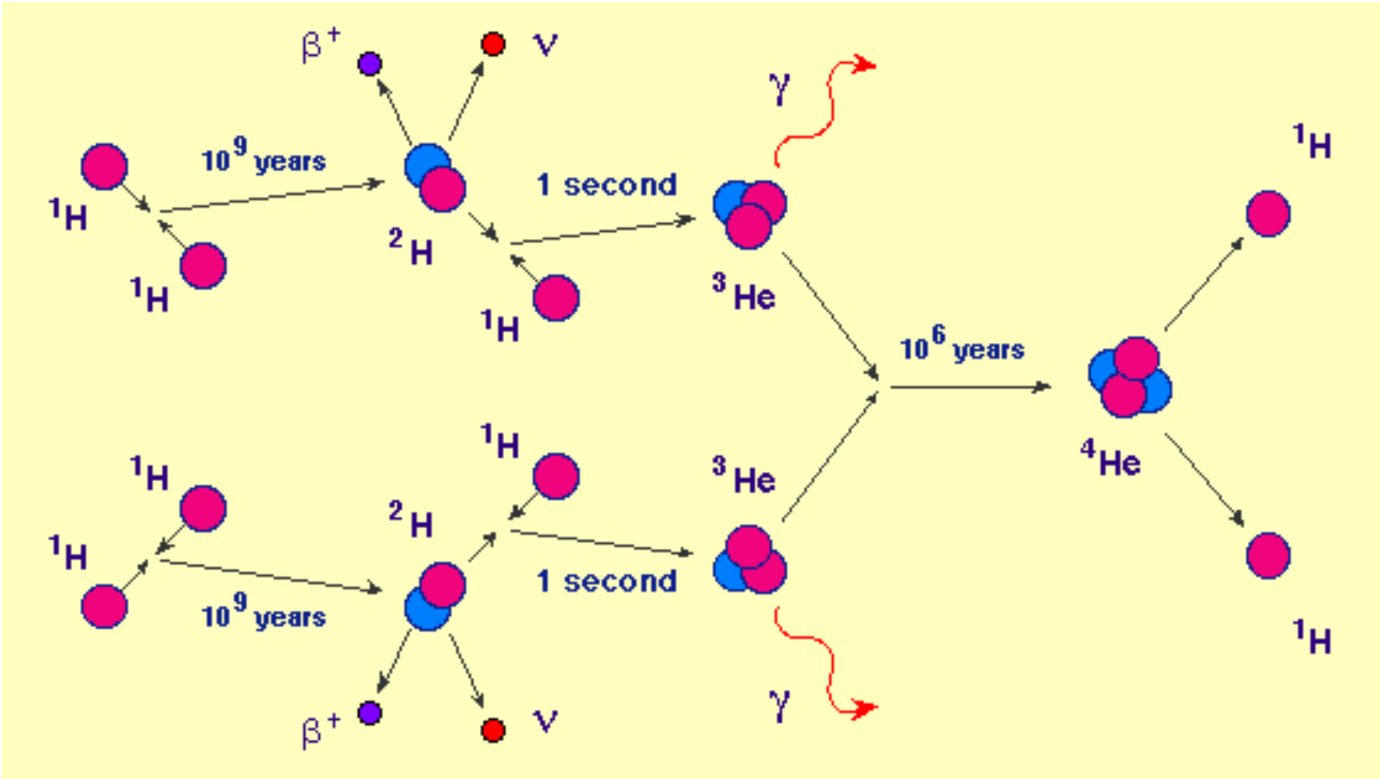
One helium atom weighs slightly less than four hydrogen atoms: about 0.7% less. This missing mass is converted into energy, and is what powers the star.



The structure of a star results from a series of finely balanced processes.

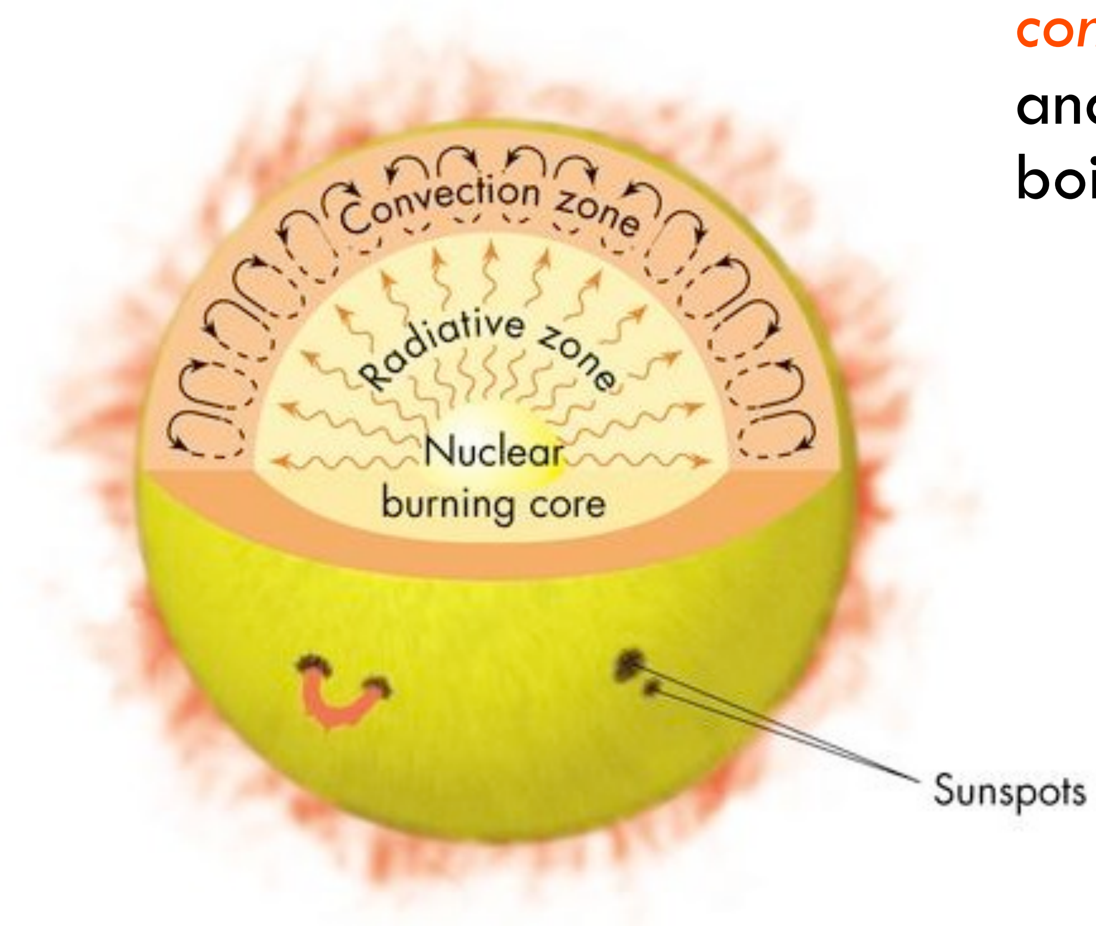


The reaction forming helium from hydrogen actually takes four hydrogen atoms, and takes place in several steps.



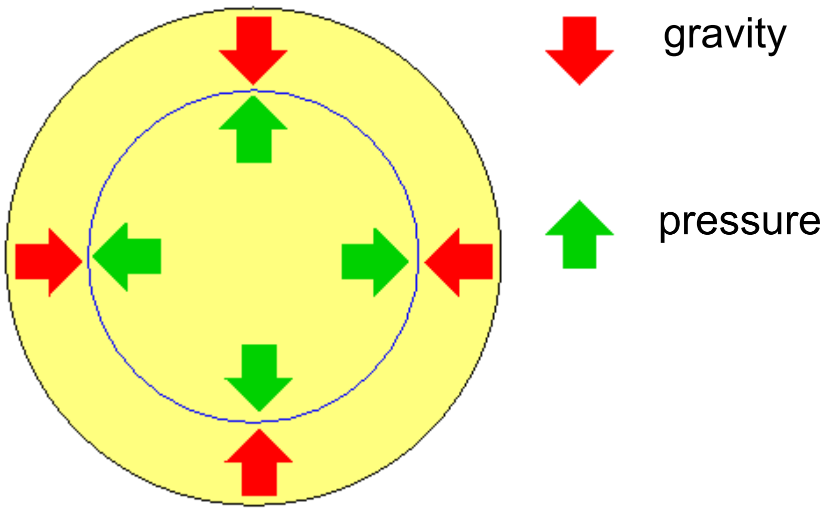
Fusion only happens at temperatures above about 3 million degrees, and increases rapidly with temperature.

The energy in the core leaks out to produce the radiation we see. It cannot reach the surface directly: instead it is transported by *radiation*, where atoms absorb and then re-emit photons; or by *convection*, where hot material rises and colder material sinks, just like a boiling pot.



The outward pressure of the hot gas exactly balances the inward force due to gravity.

This acts as a thermostat which keeps the star in equilibrium. If the temperature in the core is too high, the rate of fusion would increase faster than energy could escape, so the core would expand a bit, which in turn makes the temperature drop a bit, which reduces the rate of fusion back to the equilibrium rate



A star is in *dynamic equilibrium*: it can survive only so long as it can produce energy in its core.

A star is not a truly stable object.

What's more, how bright a star is depends on its mass.

More mass $\Rightarrow$ more compression

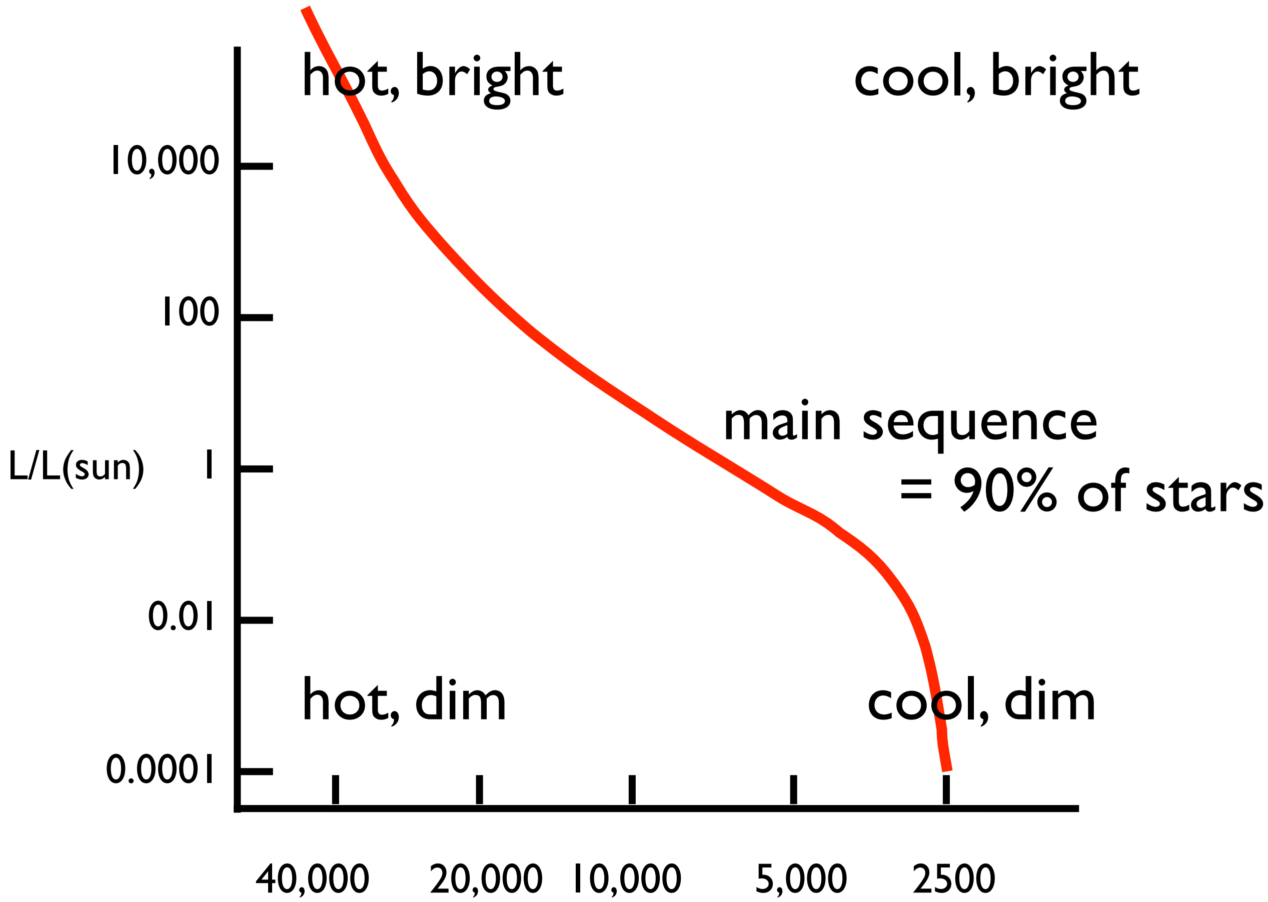
$\Rightarrow$ higher temperature

$\Rightarrow$ much higher rate of fusion

$\Rightarrow$ much higher luminosity

A *small* increase in mass leads to a *large* change in luminosity.

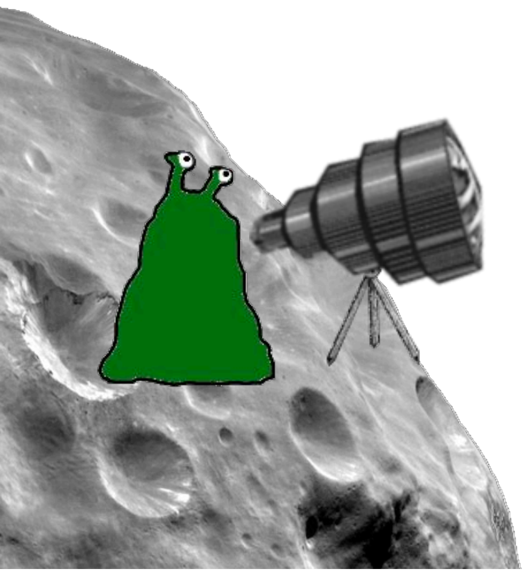
Let’s go back to the Hertzsprung-Russell diagram for a minute. You recall that most stars fall in a narrow band, running from cool and dim to hot and bright.



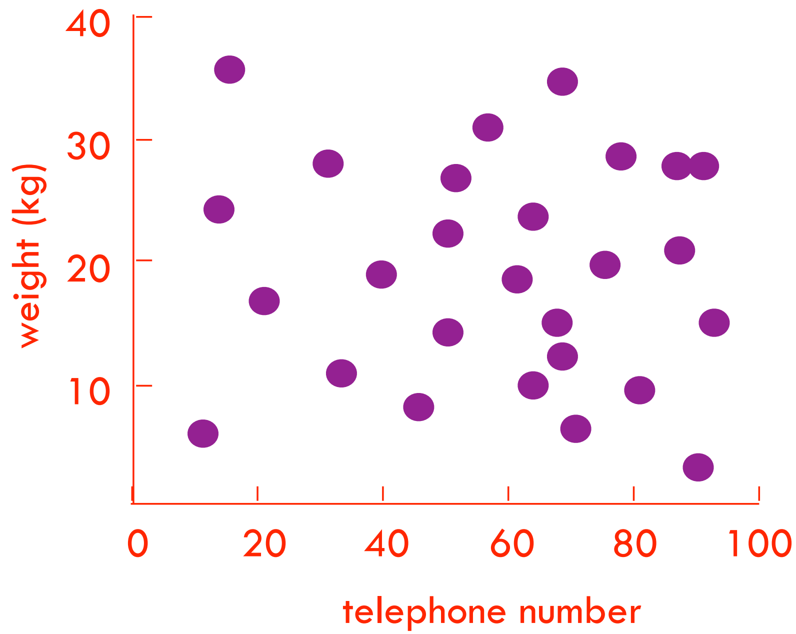
The relation between luminosity and temperature tells us there is an underlying physical link between these properties.

What is this link?

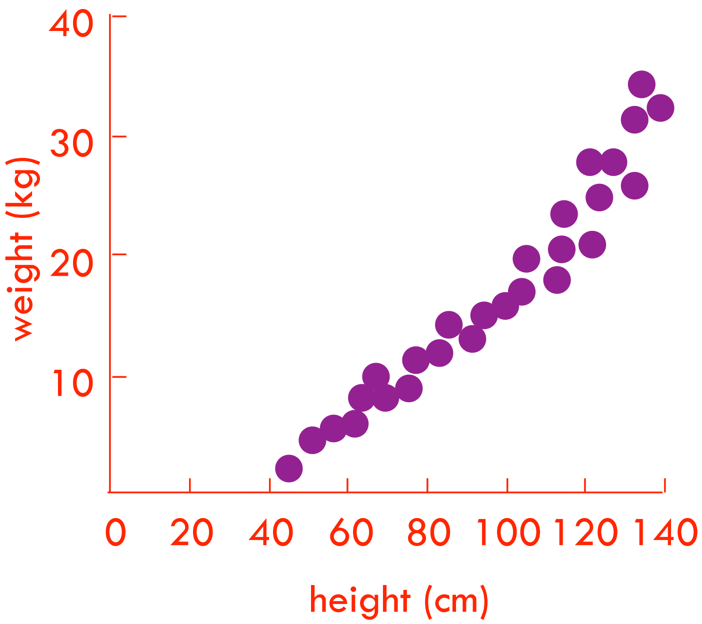
For example, consider an alien scientist constructing a similar diagram for school children.



Our intrepid scientist measures as many numerical quantities as zyx can. Plotting the children's weight against the last two digits of their telephone number shows no pattern.



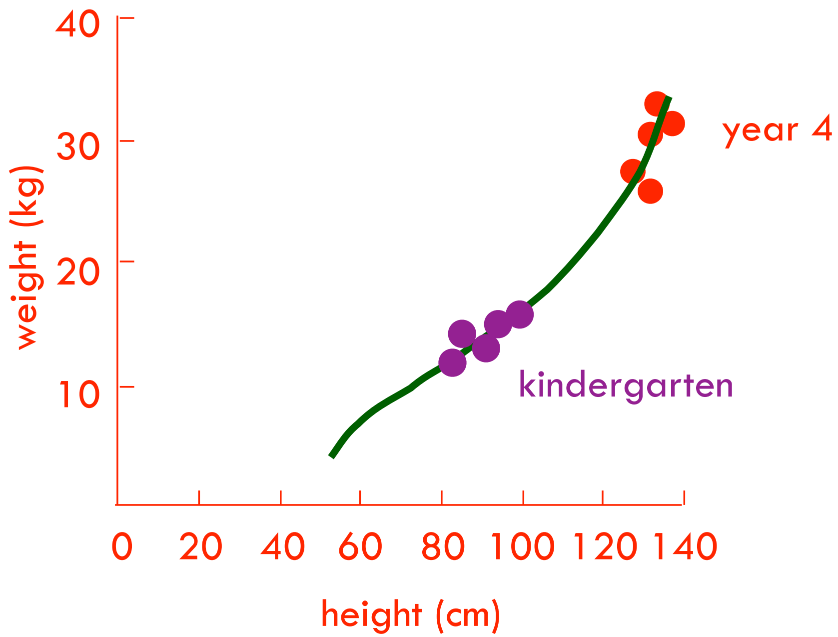
But plotting weight against height shows a decided pattern: indicating there is an *underlying factor*.



This factor is, of course, age.

Picking children of the same age finds this pattern.

And a single child would trace out the curve as he or she grew.

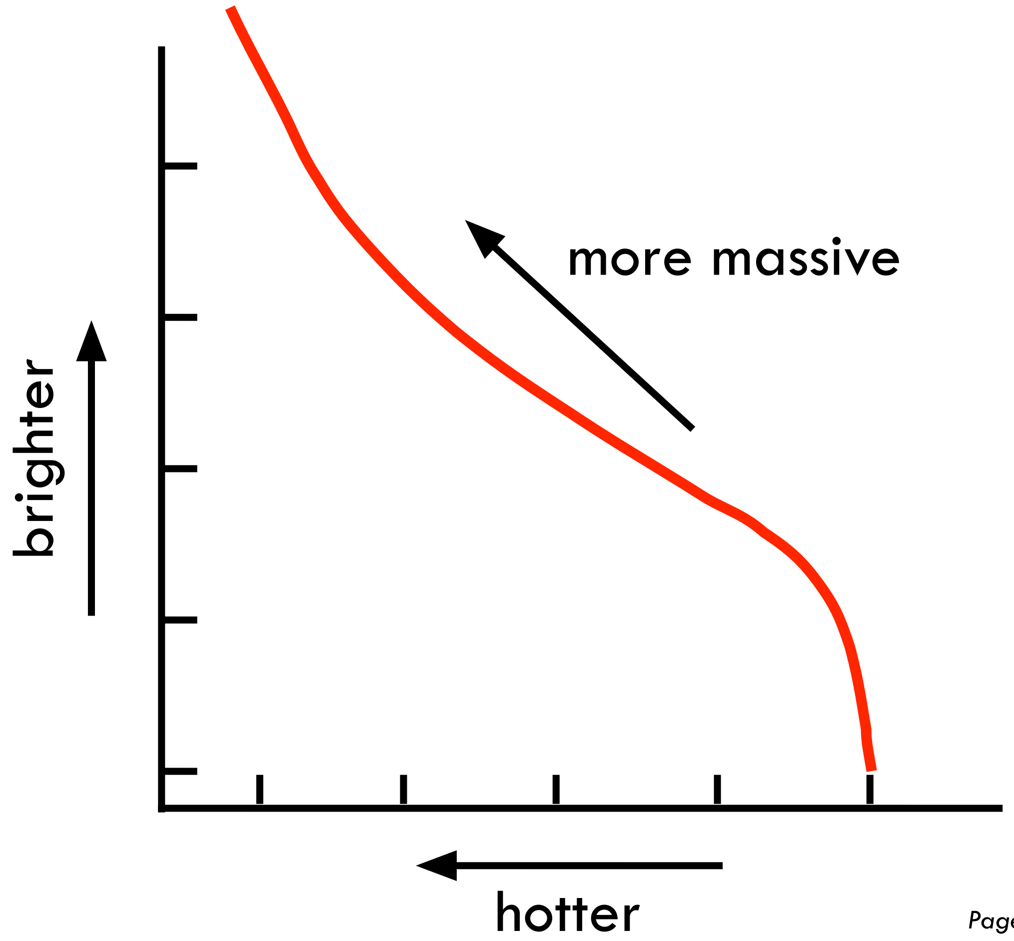


So is this the explanation for the main sequence – an age sequence?

No. Measurement of the masses of stars led to the answer: the further up the main sequence you go, the more massive the stars are.

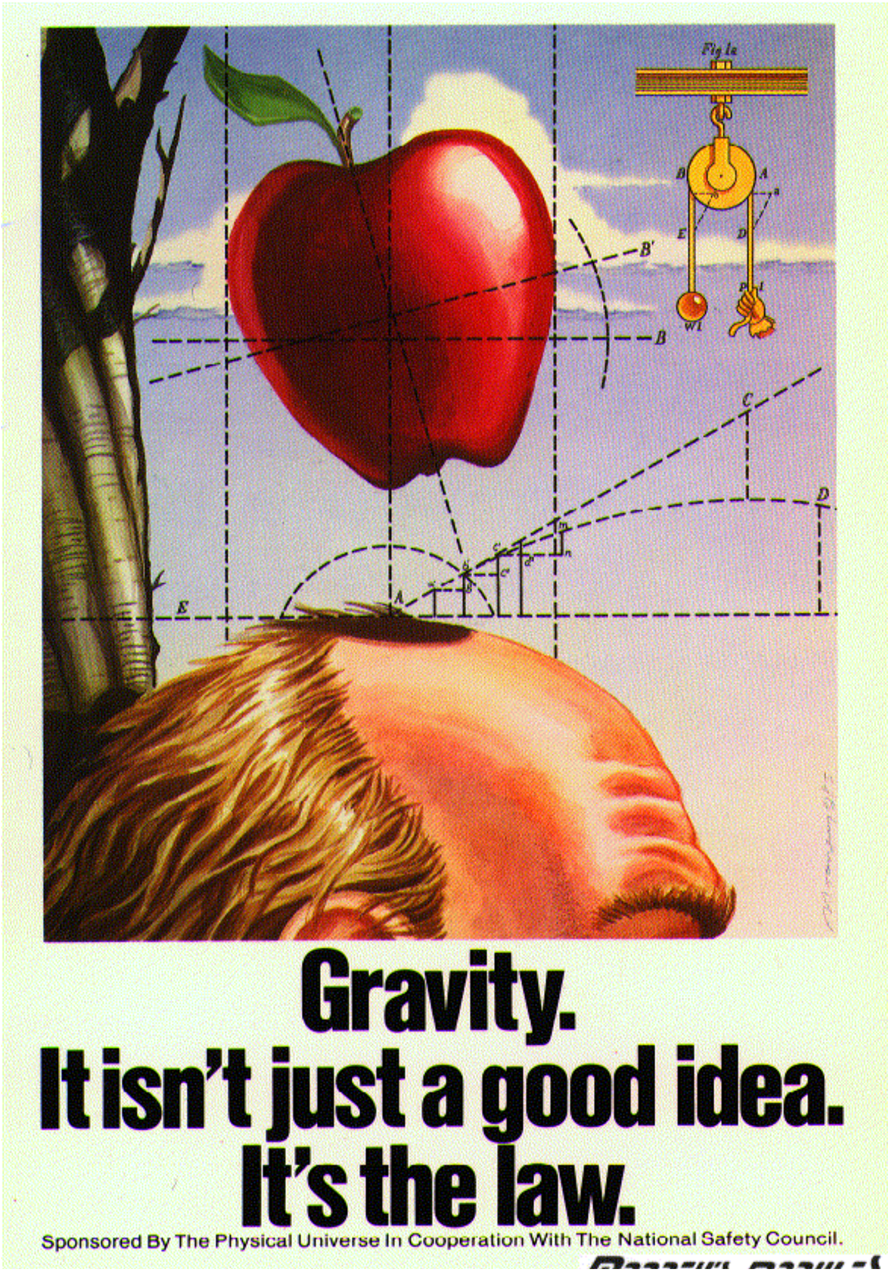
The main sequence is a *mass* sequence.

All the properties of a star are dictated by its *mass*.



Why is mass the important factor for stars?

Because the whole of a star's life is a sequence of attempts to hold off *gravity*.


Gravity.
It isn't just a good idea.
It's the law.
Sponsored By The Physical Universe In Cooperation With The National Safety Council.


Stellar evolution
– how stars change with time

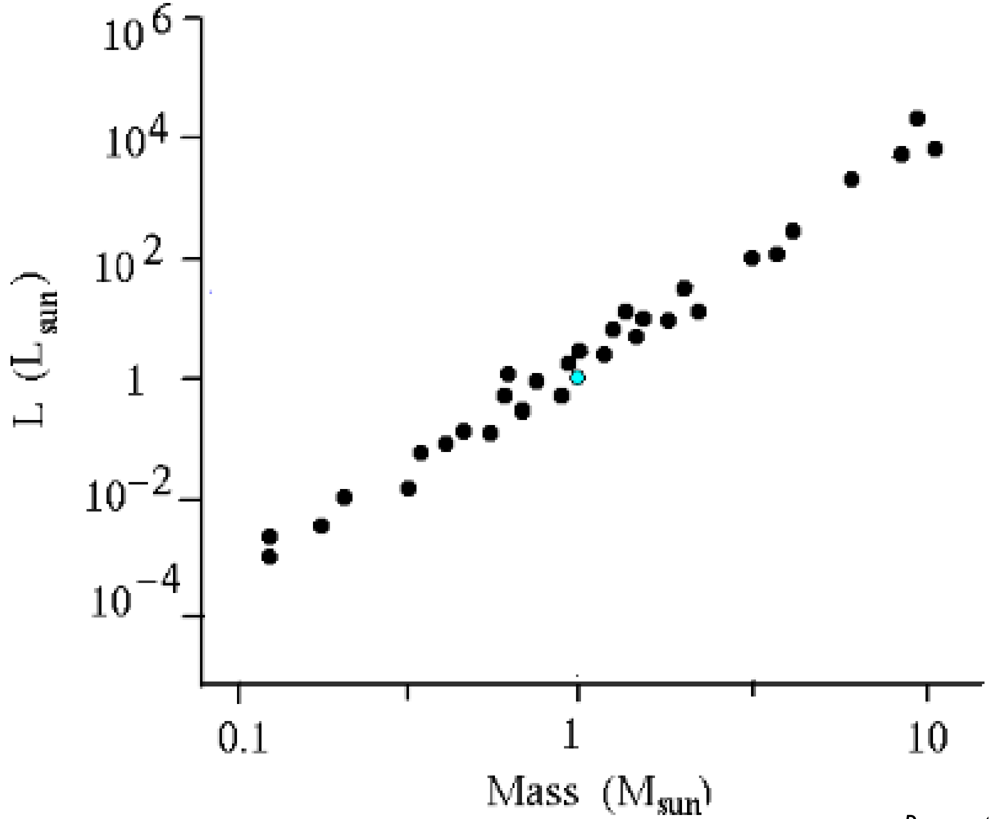
Stars are not stable because they have to consume fuel – hydrogen – in order to sustain the pressure which stops them collapsing.

But since this fuel doesn't last forever, this means stars change with time: they *evolve*.

Let's look at the different stages a star goes through as it evolves, starting with how long it takes.

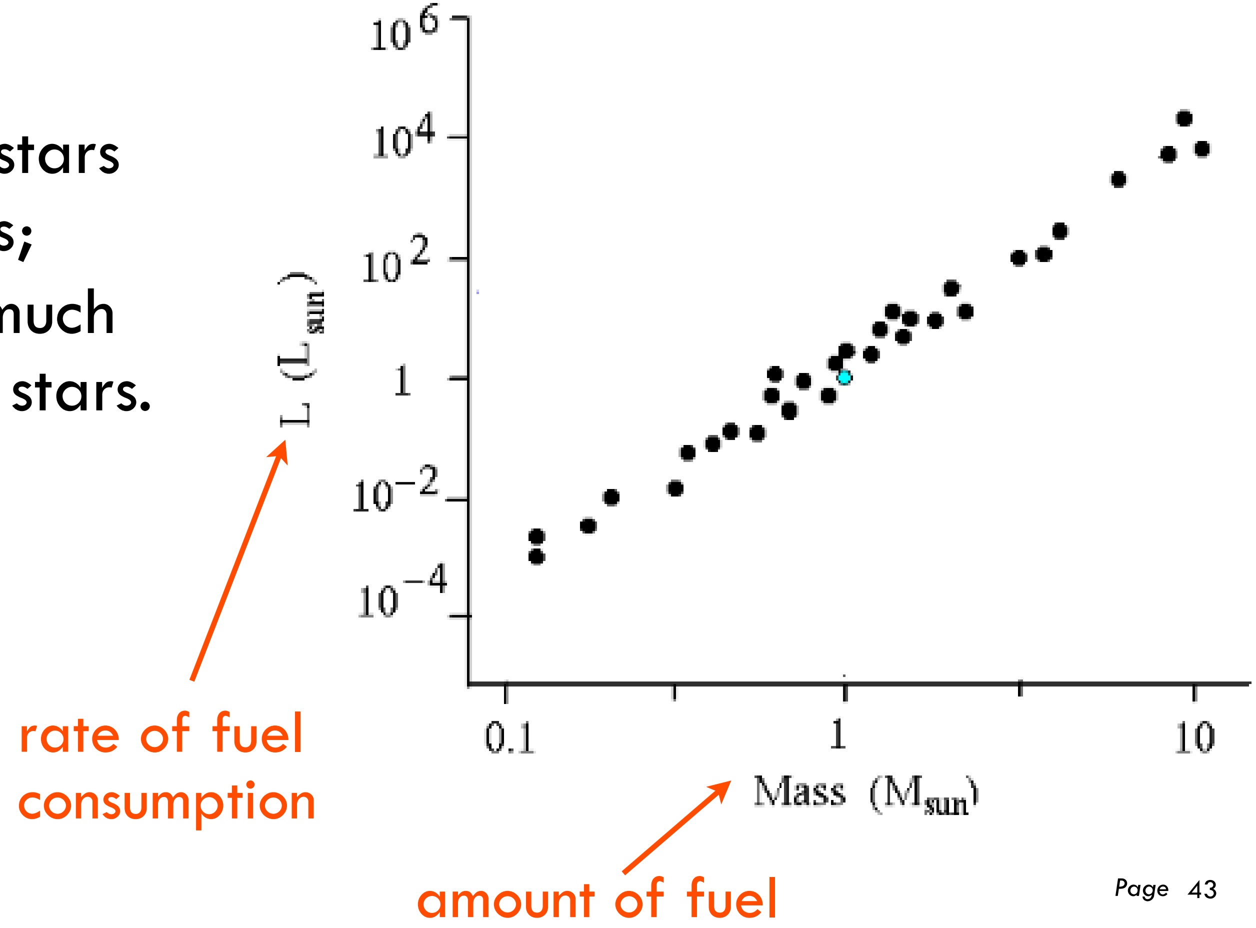
If we plot a star’s mass against its luminosity, we find a factor of 10 increase in mass corresponds to a factor of 3000 increase in luminosity.

So massive stars are *much* brighter.



How long a star lives depends on both how much nuclear fuel it has, and how fast it burns it. Like calculating how long a tank of petrol is going to last, you need to know both how much fuel you have, and how fast you consume it.

We saw how the luminosity of stars goes up very rapidly with mass; this means massive stars have much shorter lifetimes than low-mass stars.

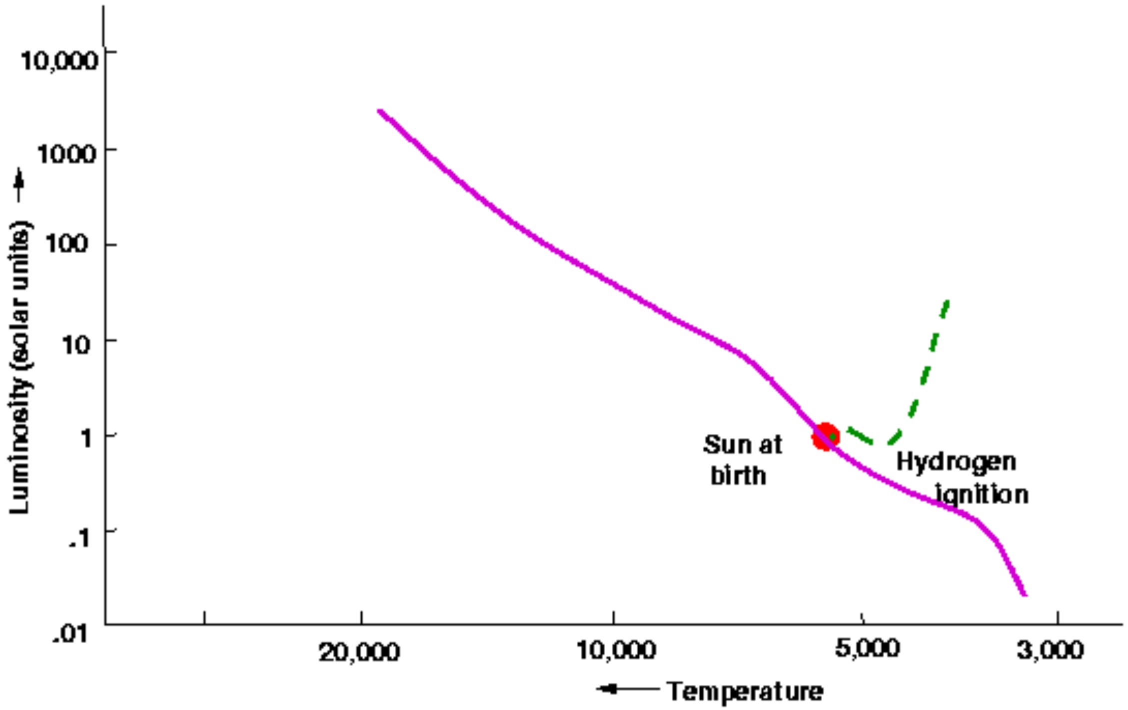


Changes on the main sequence

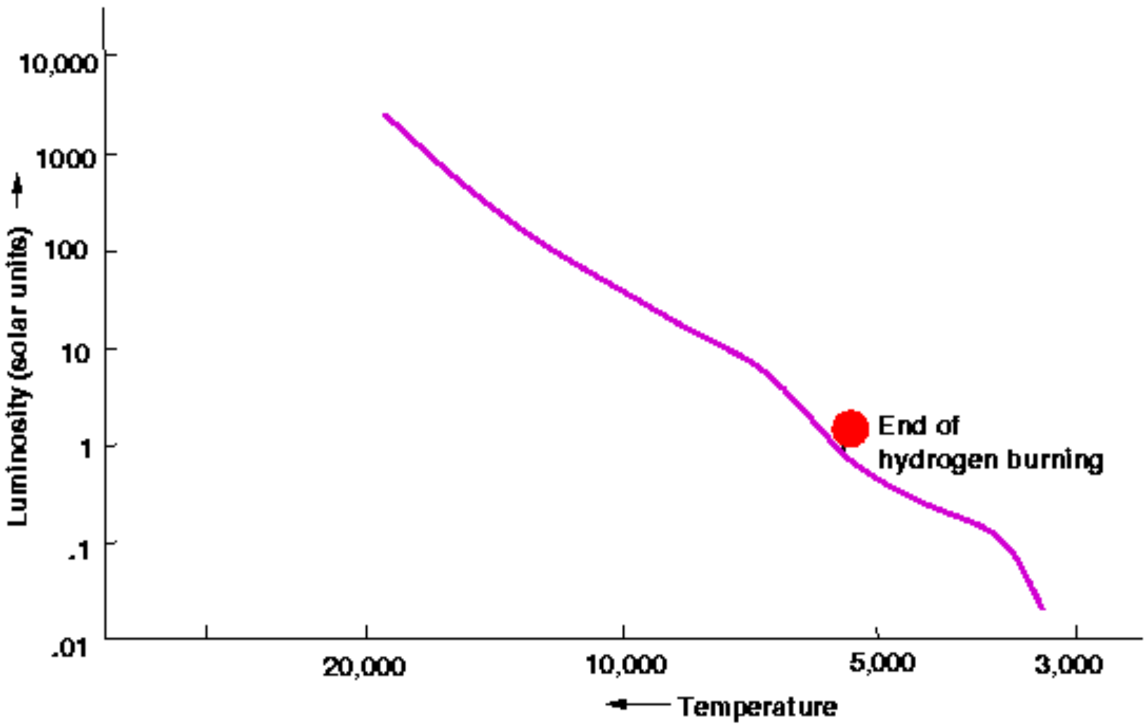
A star remains at a given spectral type during the entire main sequence stage – the main sequence is not an evolutionary sequence. However, while on the main sequence, stars do change very slowly. As the hydrogen is used up, the core is gradually converted to helium. The outside of the star becomes a bit brighter and a bit cooler.

We can show what happens to the colour and brightness of a star as it evolves, by showing how the star moves through the H-R diagram.

As a protostar collapses to become a star, it gets fainter (because it is getting smaller); then when hydrogen ignites it gets hotter and brighter, until it reaches equilibrium on the main sequence. On the Hertzsprung-Russell diagram, it follows a track like this:

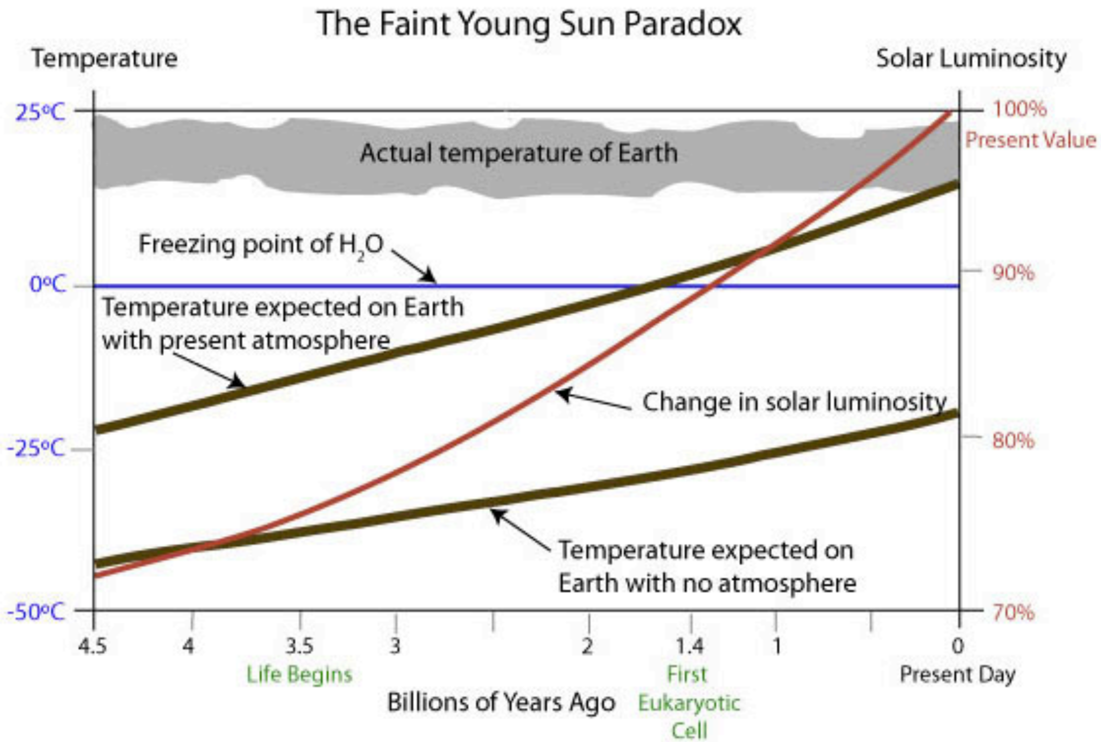


Once on the main sequence, the star remains in roughly the same place, becoming slightly brighter and cooler. Thus the main sequence is not a perfectly sharp line, but a narrow band.



This means the Sun's brightness has changed significantly over geological time. When the Sun began its main sequence life about 5 billion years ago, it was only 70% as bright as it is now. In another 5 billion years, it will be roughly twice as bright, which will raise the average temperature of the Earth at least 19° C.

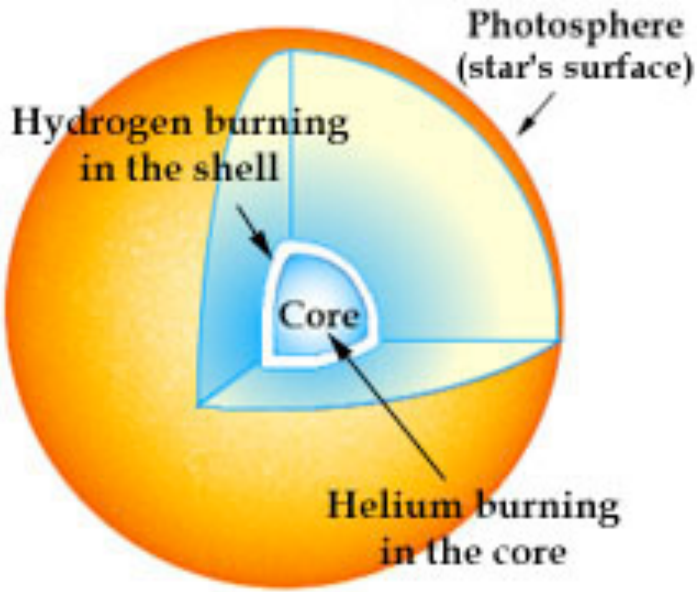
In fact, we have a hard time reconciling these temperatures with the geological record (the "faint young sun paradox").



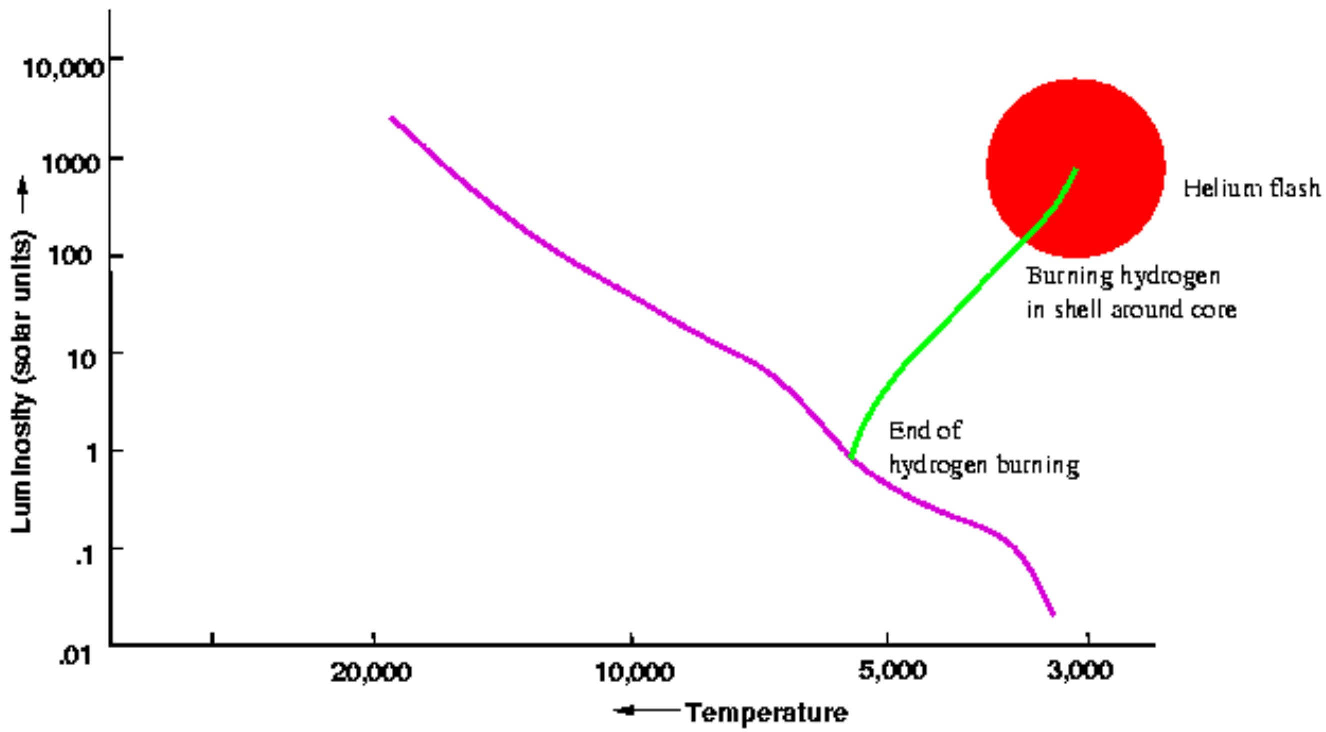
Even though the Sun was about 30% dimmer than it is now, the temperature on Earth has been more or less stable.

The death of stars

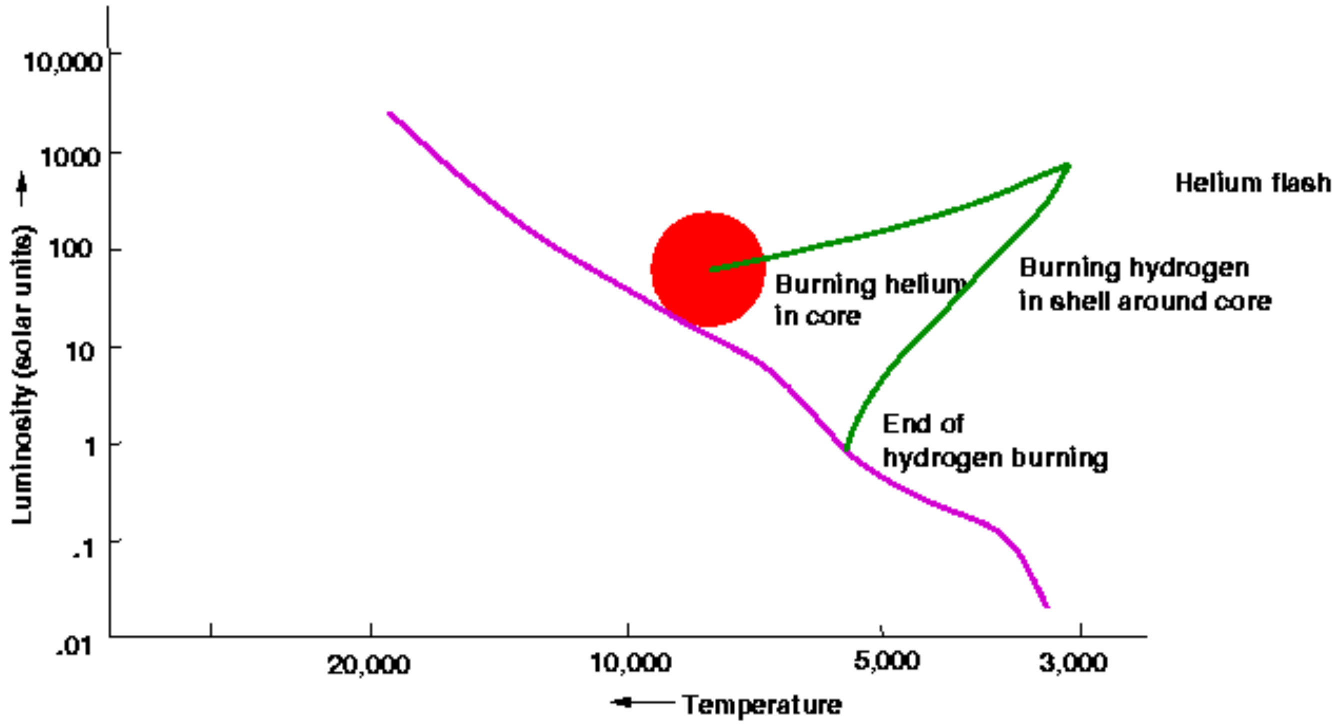
When the core runs out of hydrogen to burn, the core contracts and heats up. This forces the outer envelope of the star to expand dramatically: it becomes a *red giant*. Unburnt hydrogen in a shell around the core starts to burn.



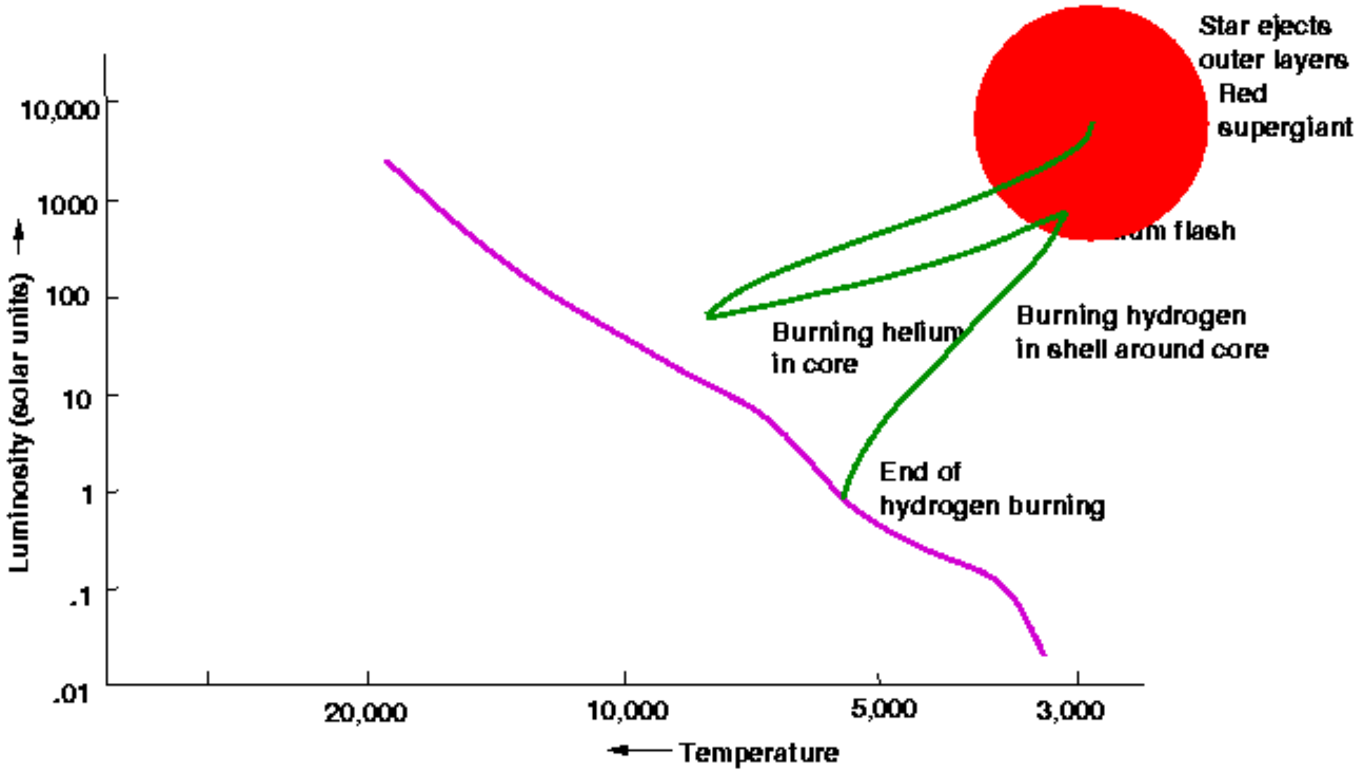
As the inert helium core continues to contract, the temperature continues to rise, until the helium ignites...



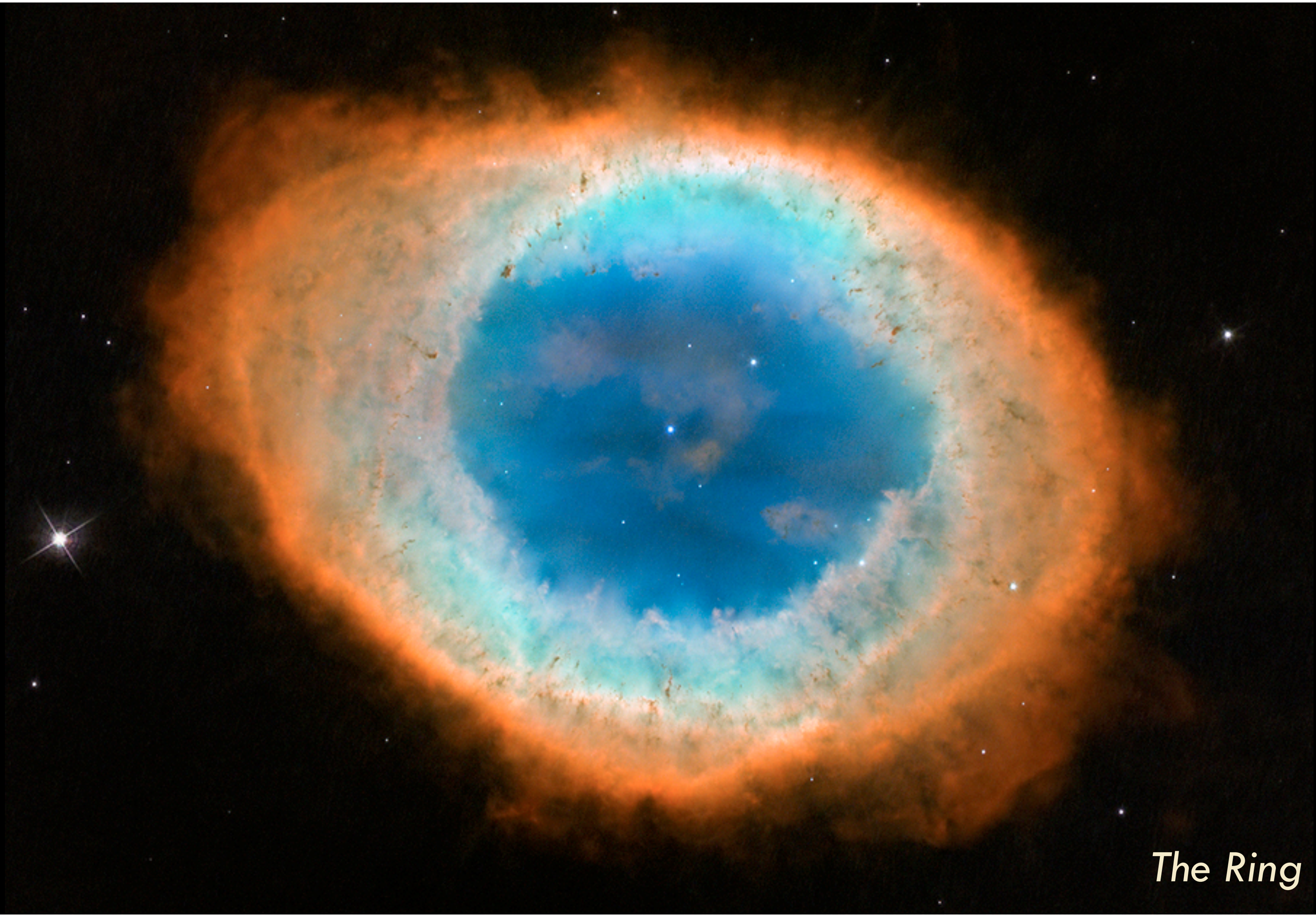
and the star begins burning helium steadily in its core, as well as burning hydrogen in a shell.



Burning both hydrogen and helium, the star expands once more.



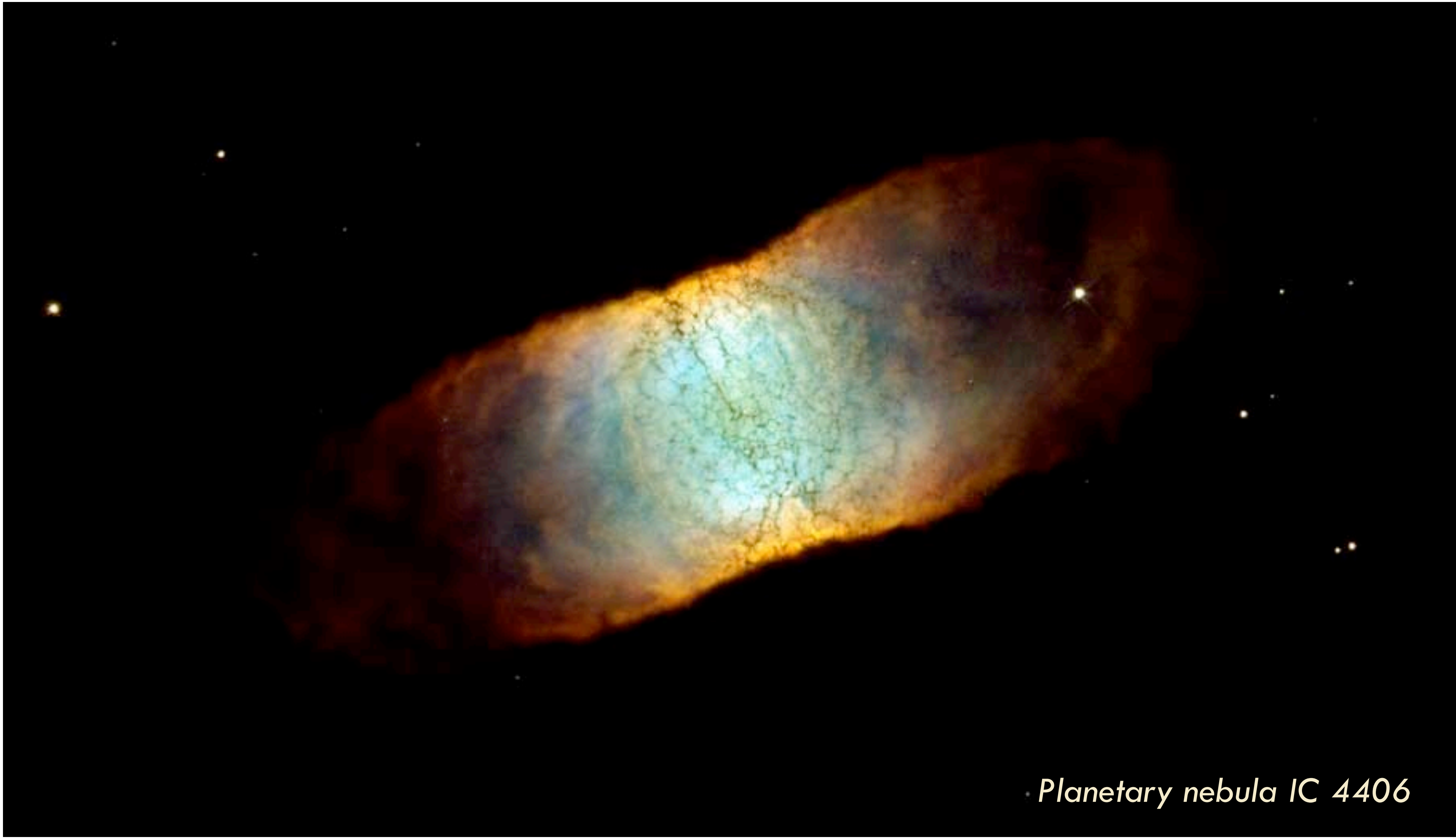
With low and medium mass stars, the outer layers are ejected in the supergiant phase to form a *planetary nebula*.



The Ring Nebula, M57

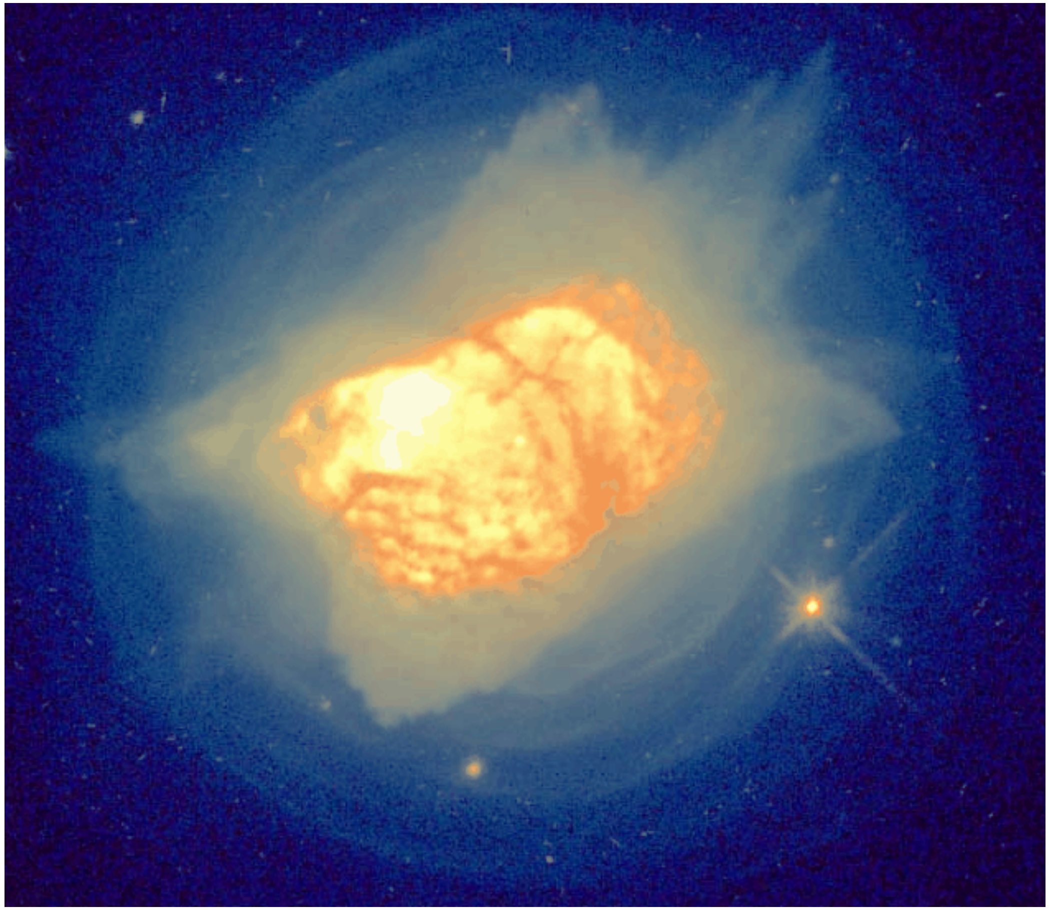
Many planetary nebulae are spherical, but there are some spectacularly beautiful examples of other shapes

The Spirograph Nebula, IC 418


Planetary nebula IC 4406

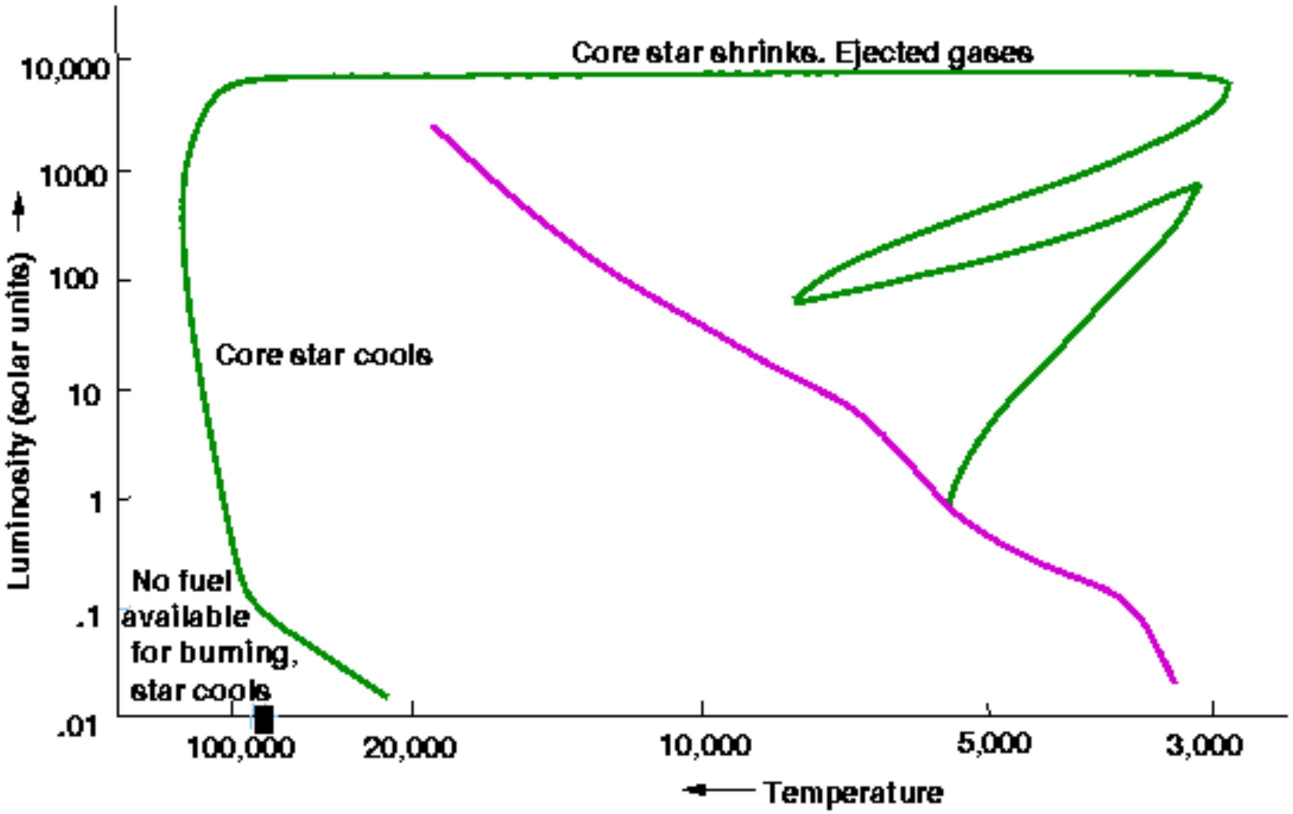
The Cat's Eye nebula, NGC 6543

Here, Hubble catches a star near the end of its lifetime, just after ejecting its outer layers in several stages.



Composite optical/IR image of NGC 7027

As the outer layers of the star are removed to expose the hot core, the star becomes much bluer. Once the core, now a *white dwarf*, has shrunk to its final size, it just cools down.



This is the final fate of our Sun. As it ages, it will expand and become a red giant: will the Earth survive?

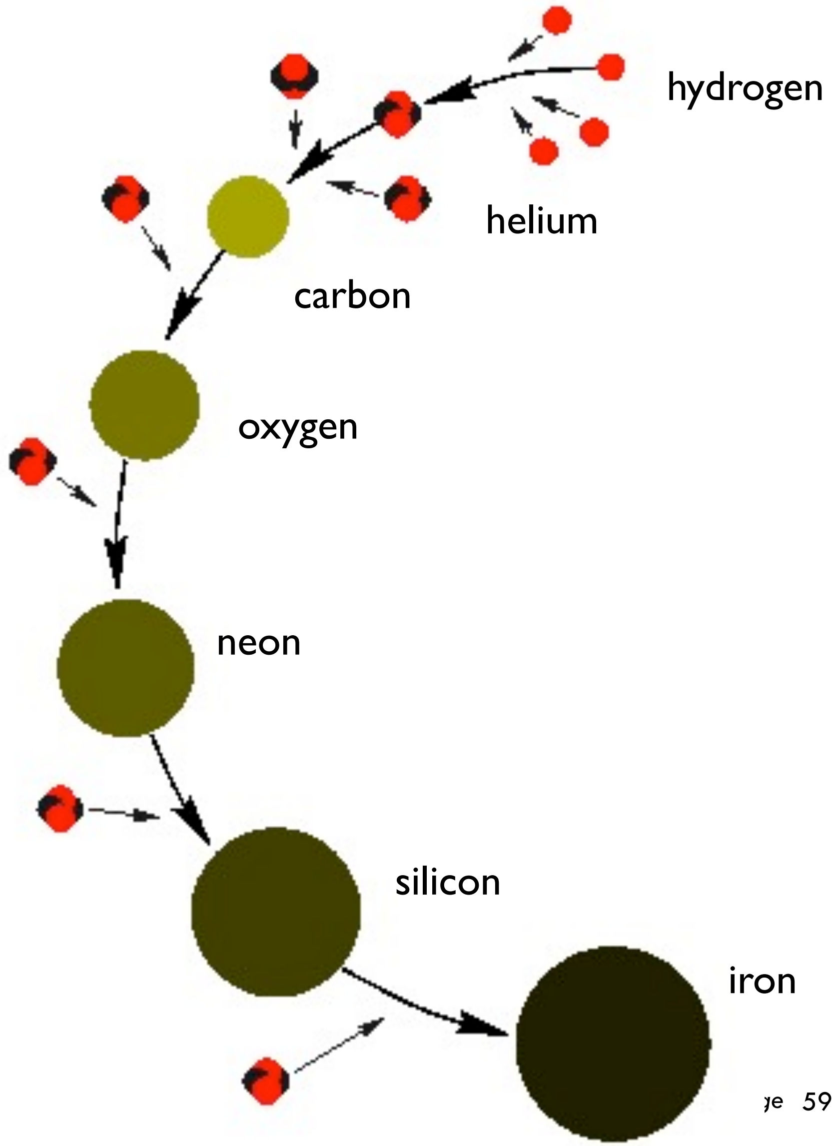
Recent calculations* suggest that although the Sun's outer surface may not quite reach Earth, tidal interaction between the Earth and the giant Sun will drag the Earth inwards, to be engulfed by the Sun.

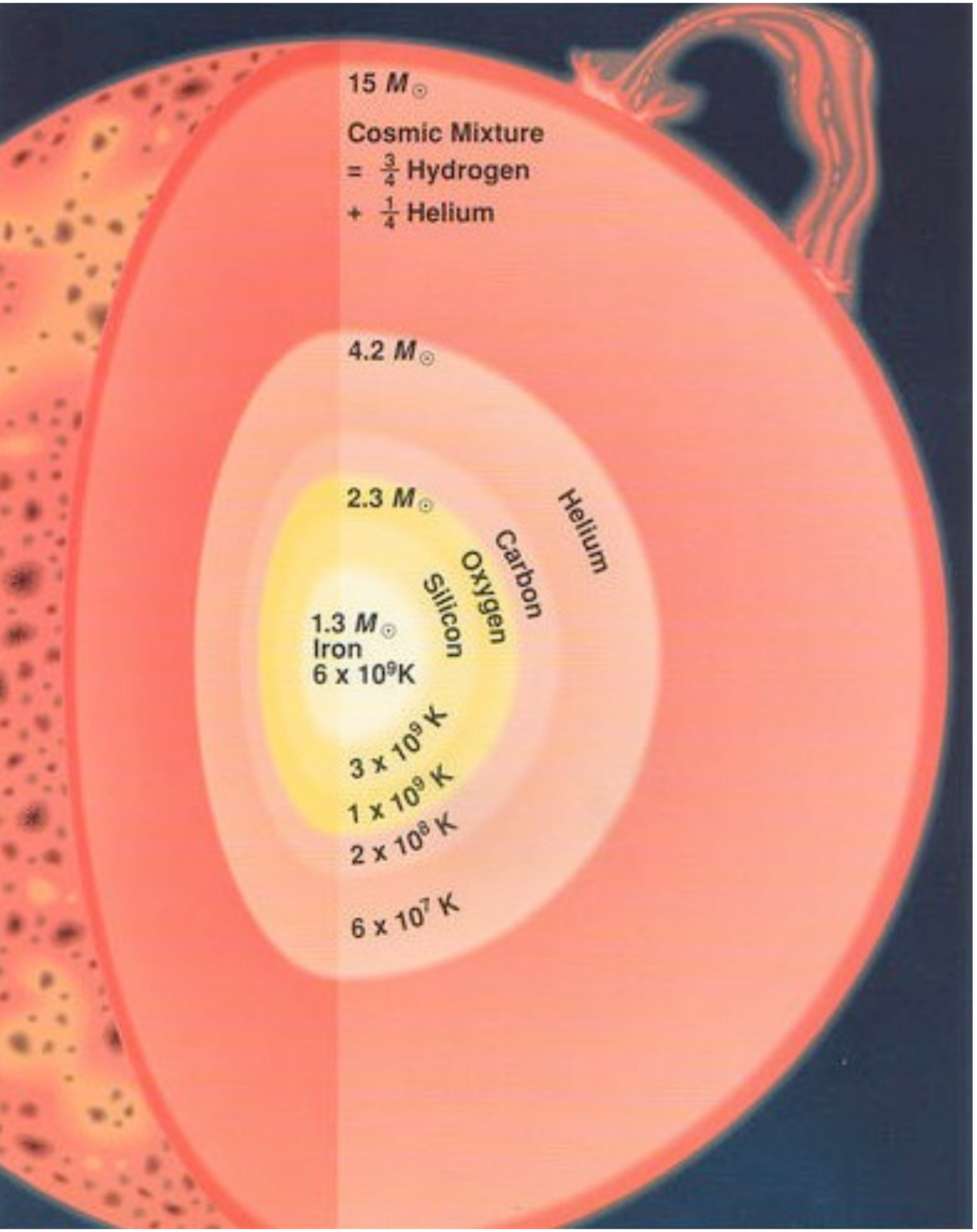
This will take place just before the Sun reaches the tip of the RGB, around 7.59 $\pm$ 0.05 Gyr from now.

In any case, the Earth is likely to become uninhabitable long before that point is reached.

** "Distant future of the Sun and Earth revisited" by K-P Schroder & R C. Smith (2008)*

Massive stars, on the other hand, continue to burn all elements up to iron.

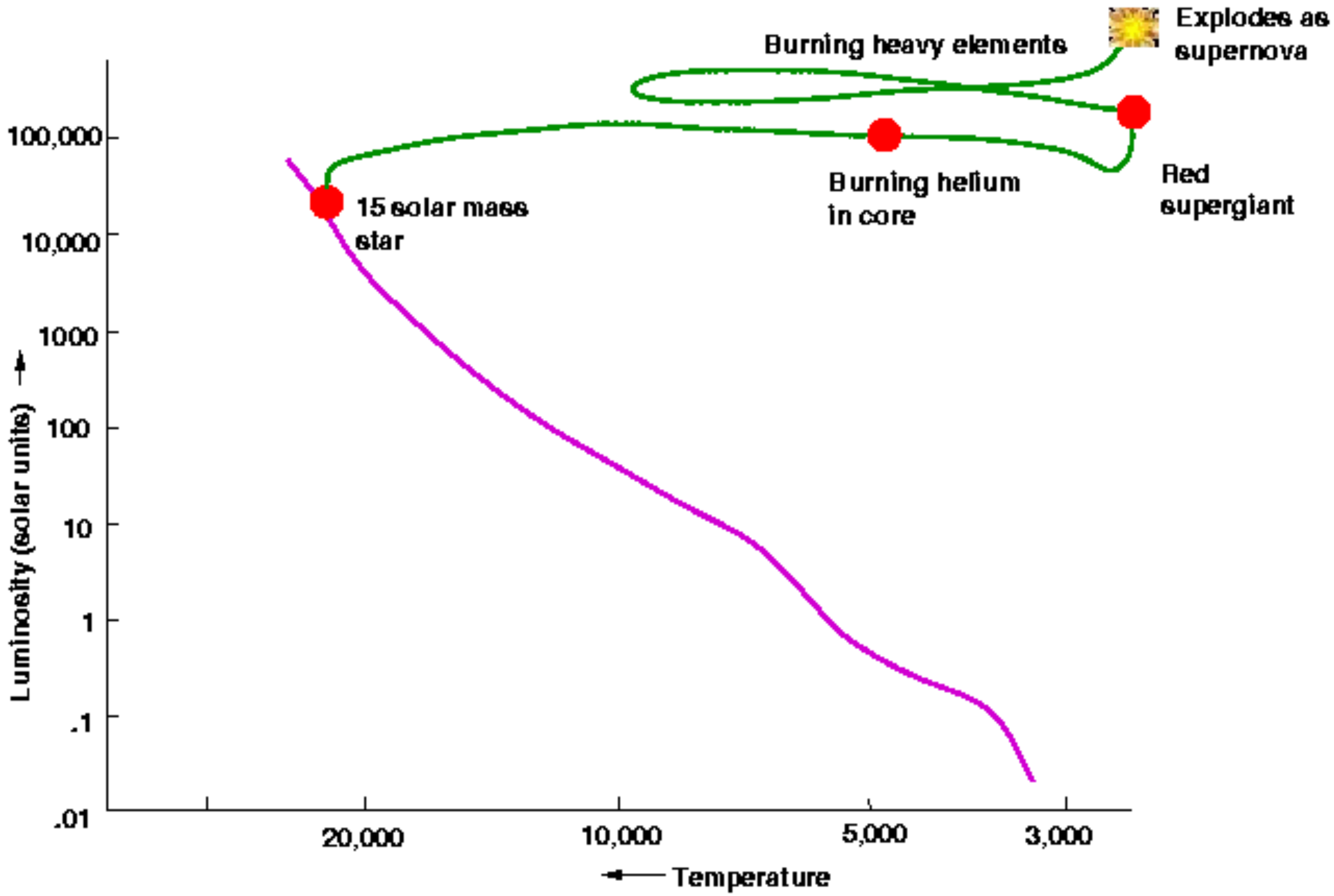




These elements collect and burn in concentric shells, like an onion.

Once the silicon in the core has fused to make iron, the star can no longer support itself against collapse.

The evolution of a massive star



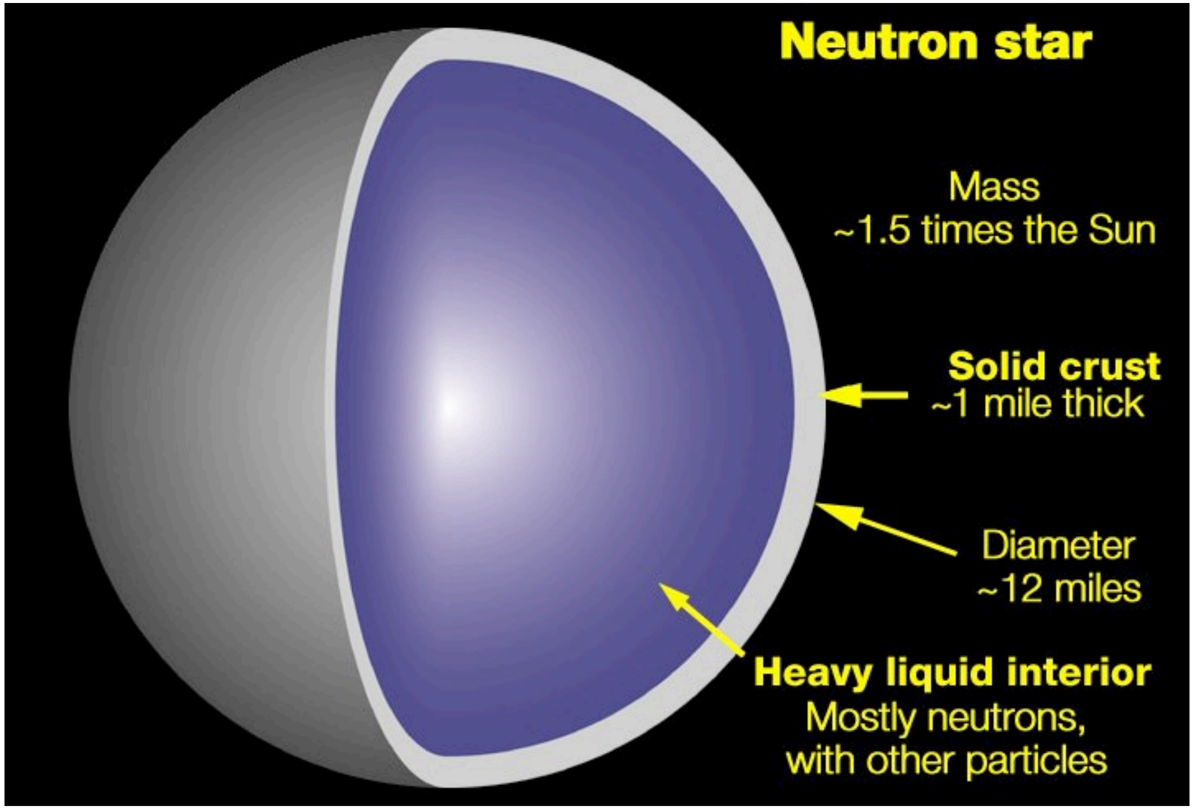
When the star explodes, the resulting *supernova* can outshine a whole galaxy.

Hubble image of supernova 1994D in galaxy NGC 4526

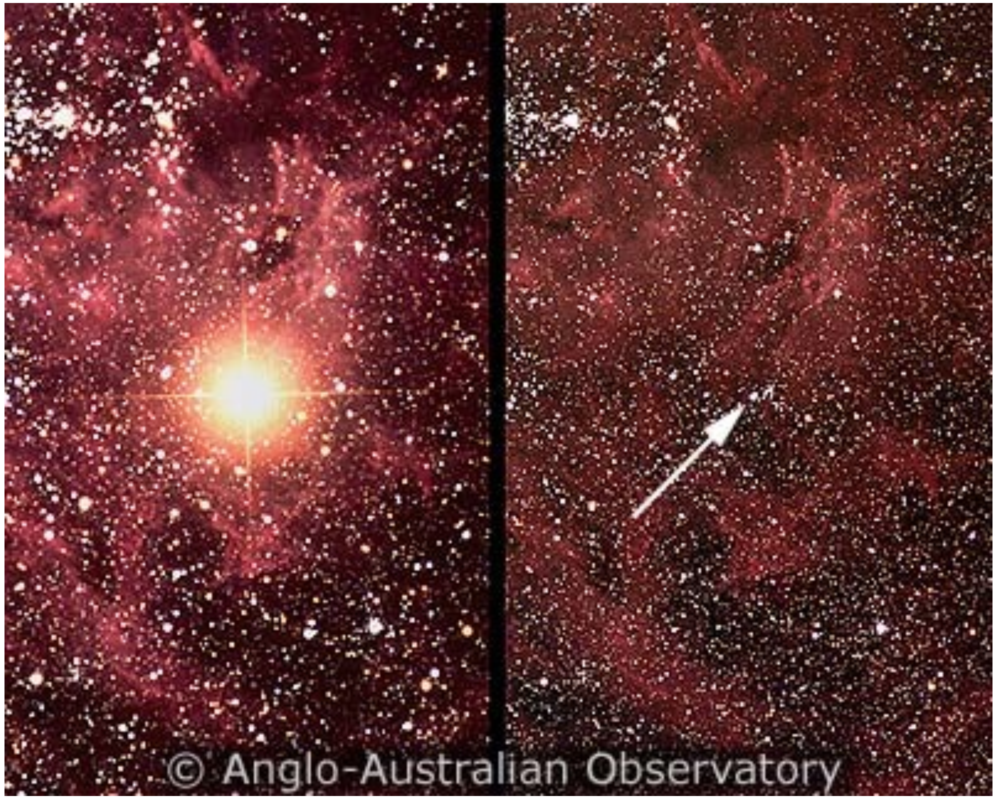
The explosion ejects material into interstellar space, including not only stellar material, but also elements formed during the explosion. This material expands for thousands of years as a *supernova remnant*.

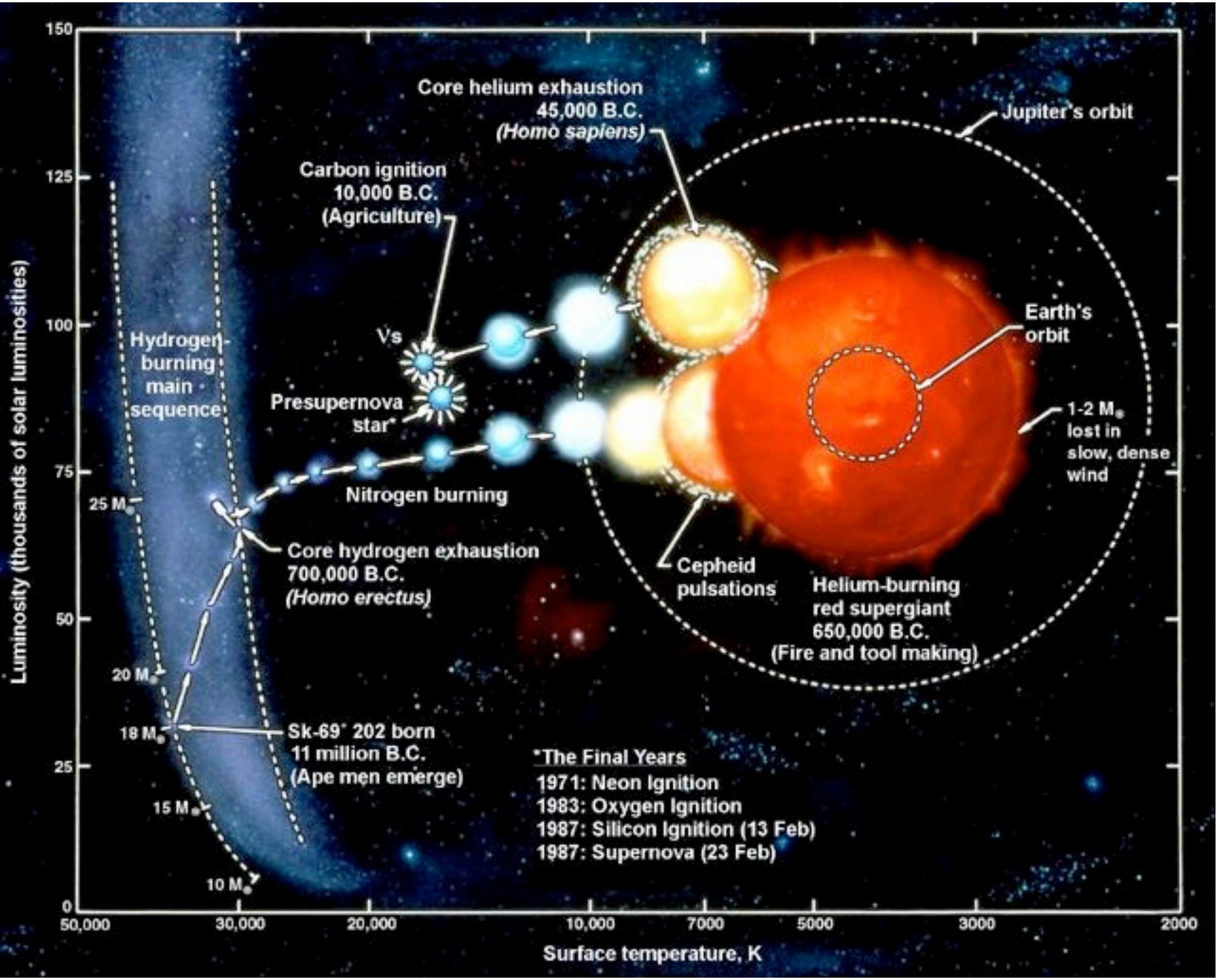
The Crab Nebula

The iron core collapses with such force that the electrons are forced to combine with protons to form neutrons: a *neutron star* is born.



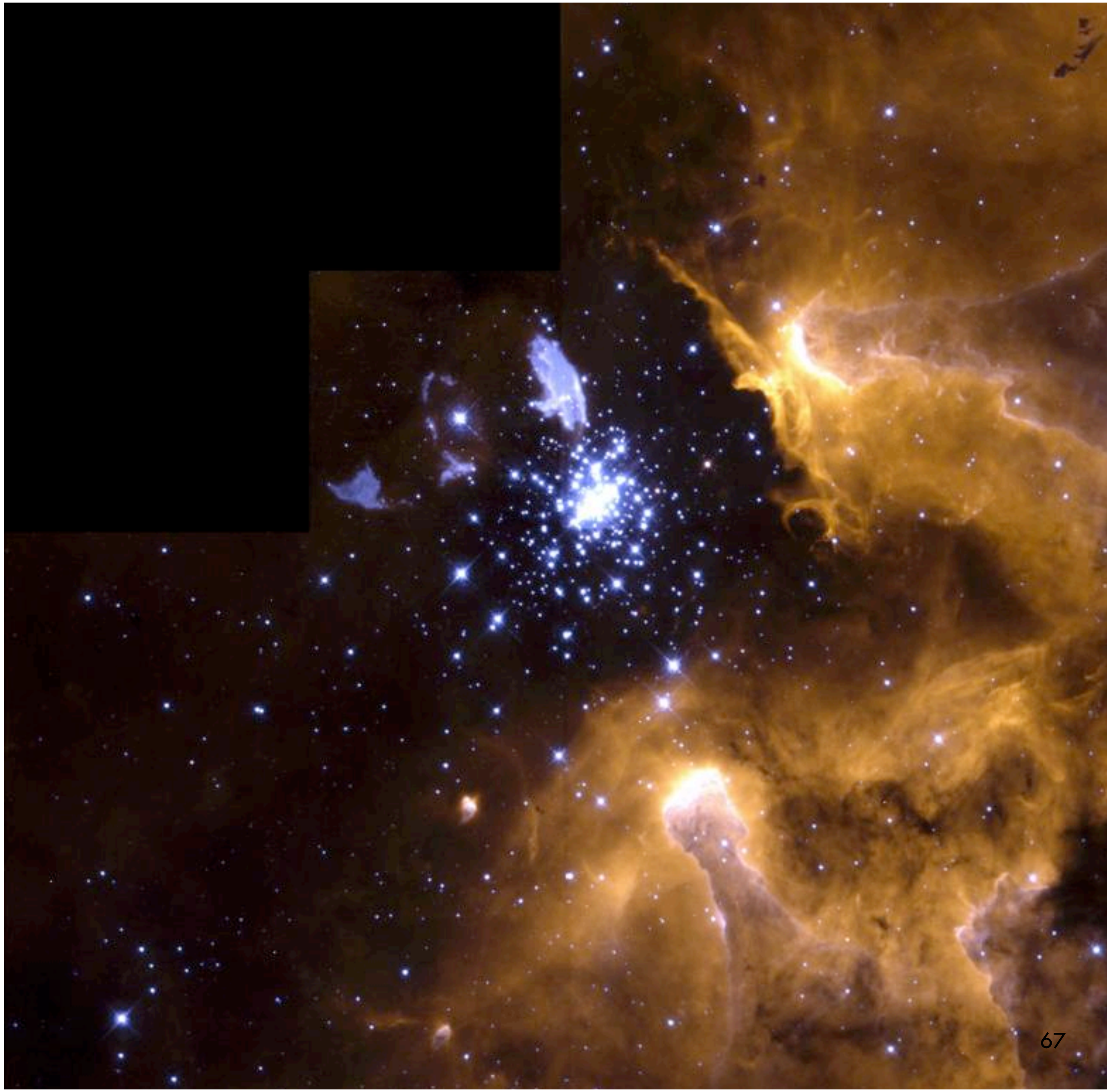
Supernova 1987A in the Large Magellanic Cloud was the closest supernova to the Earth in over 400 years.

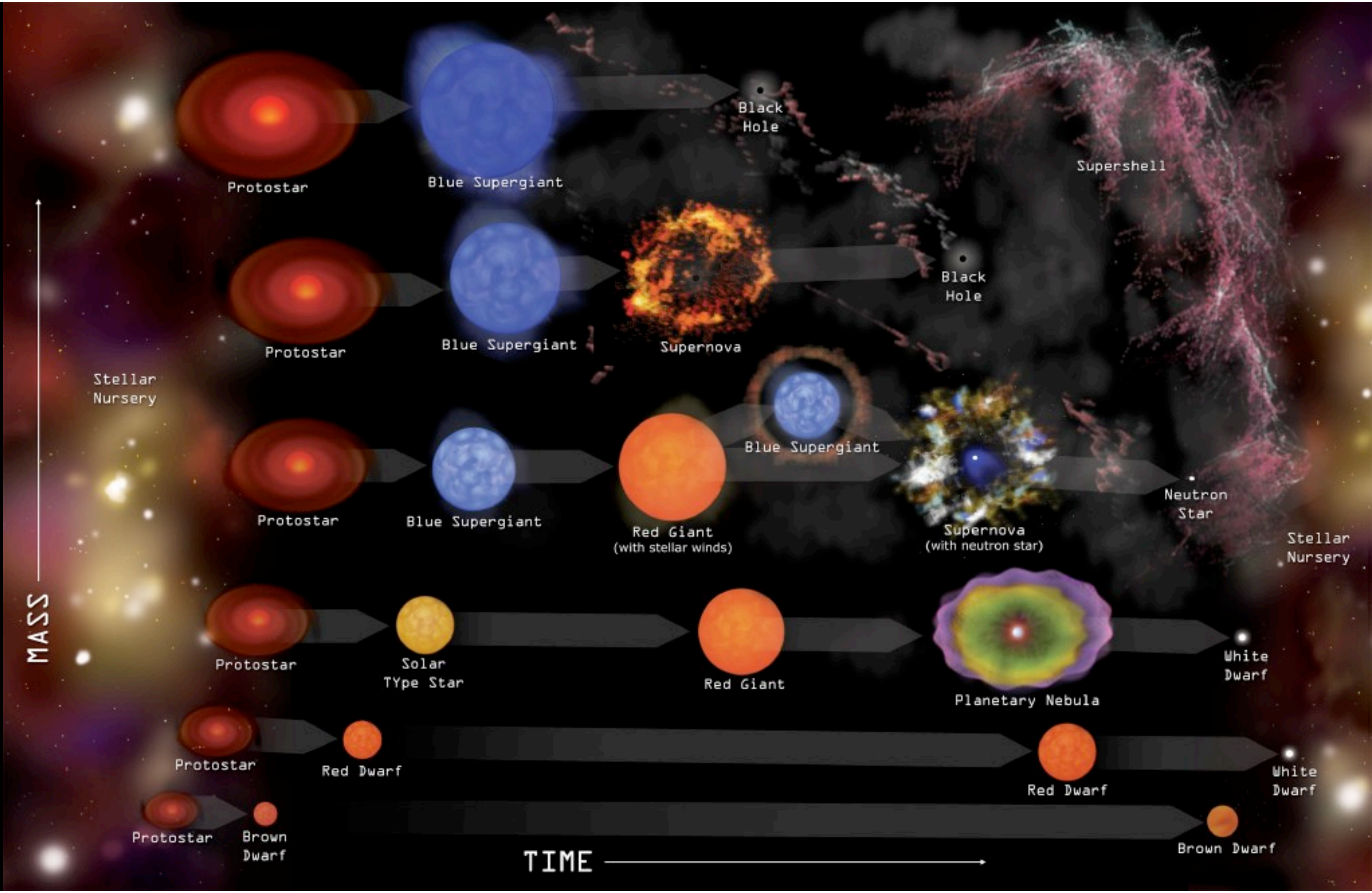




The life of the star that exploded in SN1987A

In this picture of the galactic nebula NGC 3603, HST captures various stages of the life cycle of stars in one single view.





Protostar
Blue Supergiant
Black Hole
Supershell
Protostar
Blue Supergiant
Supernova
Black Hole
Stellar Nursery
Protostar
Blue Supergiant
Red Giant (with stellar winds)
Blue Supergiant
Supernova (with neutron star)
Neutron Star
Stellar Nursery
MASS
Protostar
Solar TYpe Star
Red Giant
Planetary Nebula
White Dwarf
Protostar
Red Dwarf
Red Dwarf
White Dwarf
Protostar
Brown Dwarf
Brown Dwarf
TIME

Next week

… we'll look in more detail at the "stellar graveyard": the remnants that stars leave behind – white dwarfs, neutron stars and black holes.

Further reading

- Some of the work Annie Jump Cannon did is touched on in a recent biography of Henrietta Leavitt, the discoverer of the Cepheid period-luminosity relation: "**Miss Leavitt's Stars**: The untold story of the woman who discovered how to measured the universe" by George Johnson (Atlas Books, 2005).
- Dava Sobel (who wrote "Longitude") has written a book about the ladies of the Harvard Observatory, called "**The Glass Universe**" (Viking, 2016). An interesting read, though it's sometimes hard to keep track of all the people who keep coming in and out of the story.
- Sky and Telescope has a nice article called "**The Spectral Types of Stars**": http://skyandtelescope.com/howto/basics/article_560_1.asp
- James Kaler has several books about stars and stellar spectra. "**Stars and their Spectra**: An introduction to the Spectral Sequence" (Cambridge UP, 1989) is a detailed look at the spectral classification of stars, possibly a bit more technical than most people would like. "**Extreme Stars: At the Edge of Creation**" is a more popular level book, which starts out with a brief overview of stars and stellar evolution, then looks in more detail at the largest, the smallest, the hottest, the youngest, and so on. "**The Cambridge Encyclopedia of Stars**" (Cambridge UP, 2006) is an excellent in-depth look at much of what we're going to be talking about. He also has a web-site "**Portraits of Stars and their Constellations**: Dedicated to showing that all stars are not the same" at http://www.astro.uiuc.edu/~kaler/sow/sow.html

Sources for images used:

- Stellar spectra image: from http://www.museumofflight.org/iya-anniejumpcannon
- Harvard College Observatory women: from Geoffrey Marcy, "The History of Women in Astronomy" http://astron.berkeley.edu/~gmarcy/women/history.html
- Spectral classes: adapted from "Spectral Classes" by Michael Lemke and C. S. Jefferey http://www.sternwarte.uni-erlangen.de/www/tot/spek/SPEK_E.HTML
- Annie Jump Cannon: from Women in Astronomy http://astro.wsu.edu/worthey/astro/html/lec-women.html
- Spectral types near the Sun: data from the Hipparcos catalogue http://astro.estec.esa.nl/SA-general/Projects/Hipparcos/
- Comparison of Aldebaran with the Sun: from Astronomy 122: Birth and Death of Stars by Jim Schombert http://zebu.oregon.edu/~js/ast122/lectures/lec06.html
- Antares from a planet: painting by Bill Hartmann http://www.psi.edu/hartmann/
- Hertzsprung-Russell diagram: from Universe Today http://www.universetoday.com/39974/hertzsprung-russell-diagram/
- Proton-proton chain: from Astronomy 162: Stars, Galaxies and Cosmology: The Proton-Proton Chain http://csep10.phys.utk.edu/astr162/lect/energy/ppchain.html
- Planetary nebula images: from Hubble Heritage, http://heritage.stsci.edu/gallery/gallery.html
- NGC 7027: composite of HST optical and infrared images; Astronomy Picture of the Day 1996 January 17 http://antwrp.gsfc.nasa.gov/apod/ap960117.html
- Artist's impression of planet around a red giant: image by Dirk Terrell http://www.boulder.swri.edu/~terrell/dtart_old.htm
- Calculations of the fate of the Earth: "Distant future of the Sun and Earth revisited" by K.-P. Schroder & R. Connon Smith, MNRAS 386 155 http://adsabs.harvard.edu/abs/2008MNRAS.386..155S
- Structure of a massive star: from Astronomy 1301-02 by Tony Hall: Deaths of Massive Stars http://lepus.physics.uair.edu/~tahall/EXAM3/Week3.htm
- Supernova 1994D in galaxy NGC 4526; from Hubble press release STScI-1999-19, "Hubble Completes Eight-Year Effort to Measure Expanding Universe", http://hubblesite.org/newscenter/archive/releases/1999/19/
- Crab nebula: VLT image, from Astronomy Picture of the Day 2002 July 14 http://antwrp.gsfc.nasa.gov/apod/ap020714.html
- Interior of a neutron star: from Science @NASA: Crusty star makes its presence felt http://science.nasa.gov/newhome/headlines/ast29sep98_1.htm
- SN 1987A before and after: images by David Malin, http://www.aao.gov.au/images/captions/aat050.html
- The life cycle of SN 1987A: from http://jupiter.as.arizona.edu/~burrows/papers/rob/Stellar_Evolution.jpg
- NGC 3603: from Hubble News Center, http://hubblesite.org/newscenter/newsdesk/archive/releases/1999/20/
- Stellar fates: from Chandra Resources: Stellar evolution http://chandra.harvard.edu/resources/illustrations/stellar_evolution.html