The Universe in my pocket

TUIMP No. 29

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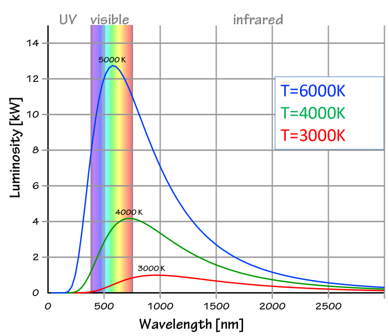


This diagram shows the luminosity of a body as a function of wavelength. The colder the body, the more the luminosity peak moves towards longer wavelengths.

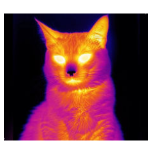


Photo of a cat taken with a thermal camera, sensitive in the infrared. As the nose is colder, it appears less luminous.

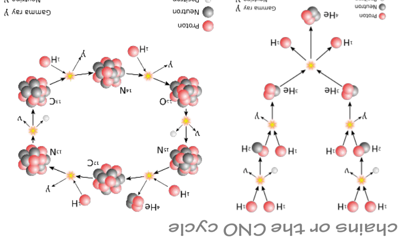
Why the stars shine

We've long wondered what makes the Sun shine. Does it burn coal? Does it undergo chemical reactions? We finally realised that the Sun shines simply because it is made of very hot gas, which is luminous in visible light.

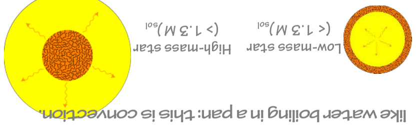
Depending on their temperature, bodies peak in luminosity at different wavelengths. The diagram opposite shows luminosity as a function of wavelength. Stars shine brightest in visible light.

Living beings are also luminous, but in the infrared. If we compare the energy that a cat emits per unit mass, it is 5,000 times larger than that emitted by the Sun per unit mass, because chemical reactions (our metabolism) are more efficient in producing heat.

Formation of helium by proton-proton chains or the CNO cycle



When radiation is no longer an efficient means to transport energy, matter starts to move, like water boiling in a pan: this is convection.



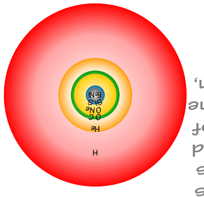
Because the intensities of their nuclear reactions are very different, low-mass stars do not have the same structure as high-mass stars: radiative core and convective envelope for the former, convective core and radiative envelope for the latter.

It all happens in the core

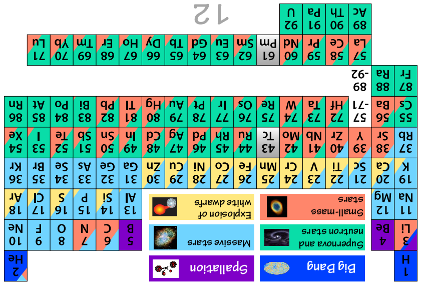
We observe the surface of stars, but everything that determines their evolution takes place in their core. This is heated to several million degrees by gravitational contraction, which is hot enough to trigger nuclear reactions.

These reactions sustain the star because the energy they generate produces a pressure that counteracts gravity. The nuclear reactions that transform hydrogen into helium (see TUIMP 14) sustain the star for 90% of its life. Smaller mass stars fuse protons together to form helium (proton-proton chains). Stars of larger mass use the nuclei of carbon, nitrogen and oxygen as catalysts (CNO cycle), which enables them to generate much more energy, but with a much shorter lifetime.

The nuclear reactions of successive phases take place deeper and deeper in the cores of massive stars. At the end of their evolution, stars have an onion-like structure of multiple layers.



All the heavy elements are produced in stars. This table shows in which type of star (after C. Kobayashi 2020)

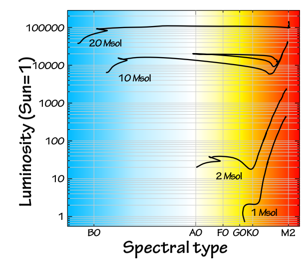


The stars: element factories

After burning hydrogen and then helium in their cores, the most massive stars successively use carbon, neon, oxygen and silicon as fuel, forming heavier and heavier elements deeper and deeper in their cores. Evolution accelerates as the star produces more and more neutrinos, which carry away the energy generated in the core without heating the star. Carbon burns out in a few thousand years, while silicon can support the star for only a few days!

Some of the elements produced in the stellar cores are ejected into the interstellar medium by planetary nebulae or supernovae. Others remain forever imprisoned in white dwarfs, neutron stars or black holes and do not participate in the chemical evolution of the Universe.

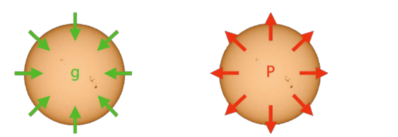
Quiz



This diagram shows the evolution of stars of 1, 2, 10 and 20 solar masses. Place the following stars on it:

	Luminosity	Spectral type
Sun	1	G2
Sirius A	25	A1
Canopus	13600	F0
Betelgeuse	105000	M2

1) Which is the coldest of these stars? The hottest?
2) What are the masses of these stars?
3) Which ones have not finished burning all the hydrogen in their core?
4) Which stars will go supernova?
5) Which star will live the longest?



Gravity (g) causes the star to contract. The gas heats up and generates a pressure (P) that counteracts the gravitational force: this is the `hydrostatic equilibrium' phase.

The colour of stars indicates their surface temperature. The hottest stars are blue, the coolest are red.

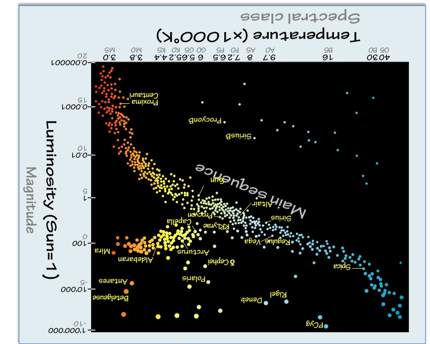
What is a star?

It's a big ball of hot gas.

Because it is so massive, gravity causes it to contract in on itself, and this compression of the gas heats it up: the gas reacts by shaking the atoms of the star, producing a pressure that counteracts the gravitation. The more massive the star, the stronger the gravity, and the hotter and brighter the star.

Visually, a hotter star is bluish, like the star Rigel in the constellation Orion, while a cooler star is reddish, like Betelgeuse, also in Orion. Our star, the Sun, at almost 6000°K, is yellow.

Luminosity versus temperature diagram of stars in the Sun's neighbourhood.



During their lifetime, stars move around in this diagram. The main sequence is where they stay for the longest time.

Spectral type	Temperature(°K)	% of stars
O	>30000	0.05
B	9700-30000	0.13
A	7200-9700	0.6
F	6000-7200	3
G	5200-6000	7.6
K	3800-5200	12.1
M	2500-3800	76.5

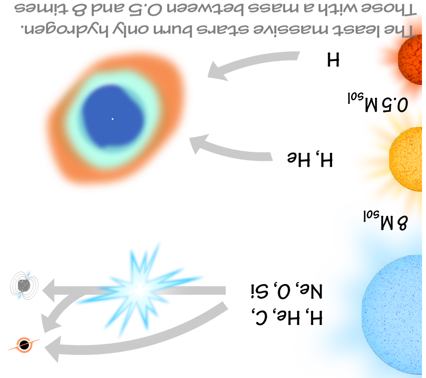
The main sequence

When we plot the stars in a diagram of luminosity versus temperature, we see that 90% of them lie on a large diagonal line called the Main Sequence. This shows that for most stars, there is a link between luminosity and temperature: the most luminous stars are also the hottest.

Stars are classified according to their spectral type, defined by the presence and intensity of their spectral lines (see TUIMP 30), which are a function of their surface temperature (and therefore their colour): O, B, A, F, G, K, M, from hottest to coolest. Each class goes from 0 to 9. O and B stars are the rarest. In fact, these stars of more than 8 solar masses represent only 0.18% of all the stars.

The Sun is class G2.

Chart of the evolution of stars according to their initial mass



The least massive stars burn only hydrogen. Those with a mass between 0.5 and 8 times the mass of the Sun also burn helium, then end their lives as white dwarfs surrounded by a planetary nebula.

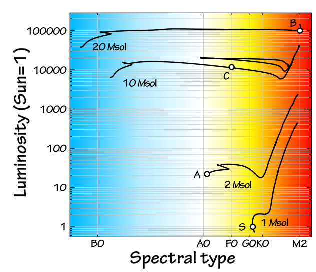
Stars of more than 8 solar masses fuse even larger atoms, such as C, Ne, O and Si. They eventually explode as a supernova or collapse into a black hole.

How stars evolve

When the hydrogen in the core is depleted, the core contracts, increasing its temperature until it reaches the fusion temperature of helium. This contraction releases gravitational energy, causing the envelope to swell and the star to become a red giant. When the helium runs out, the core contracts again.

For stars of less than 8 solar masses, this is the end of evolution. Their core becomes a white dwarf and no longer evolves. It cools slowly, while the atmosphere becomes a planetary nebula (see TUIMP 36).

Massive stars, on the other hand, reach very high temperatures in their cores and go through a series of fusion phases, interspersed with contraction phases. The evolution of massive stars ends with a supernova explosion or direct collapse into a black hole.



Answers

On the diagram, the positions of the Sun, Sirius A, Betelgeuse and Canopus are represented by the letters S, A, B and C.

Answers to questions:

1) Betelgeuse. Sirius A.
2) 1, 2, 10, 20 solar masses.
3) The Sun and Sirius A.
4) Betelgeuse and Canopus.
5) The Sun.

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Sylvia Ekström, from Geneva Observatory, is the author of this booklet, written in 2025. The booklet was revised by Grażyna Stasińska from Paris Observatory and Stan Kurtz from IRyA (Morelia, Mexico).

Cover image: A glimpse inside the Sun. The superheated core generates energy through nuclear reactions. The envelope is stirred by convection like water in a saucepan. All the images in this booklet are by Sylvia Ekström, except for the reaction chains on page 8 (Wikimedia Commons) and the photo of the cat (https://www.facebook.com/FLIR/posts/happy-internationalcatday/2476717149041777/).

To find out more about this series and the subjects covered in this booklet visit http://www.tuimp.org.

Translation: Stan Kurtz