The Sun, among many stars

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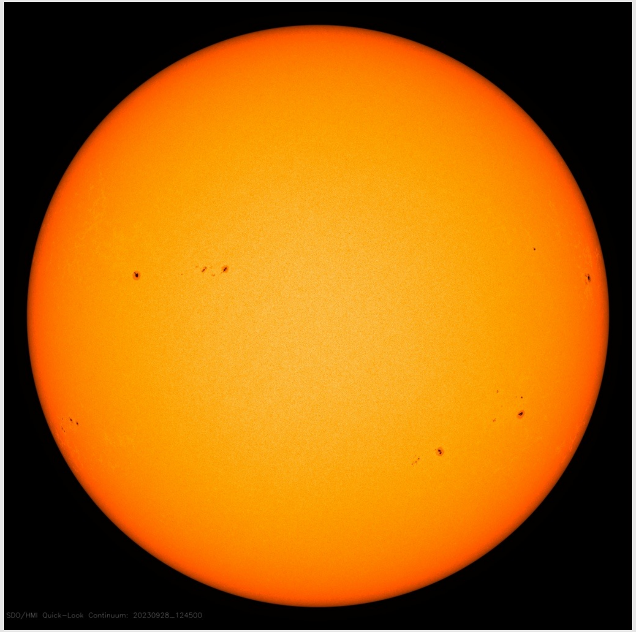
The Sun

The Sun today



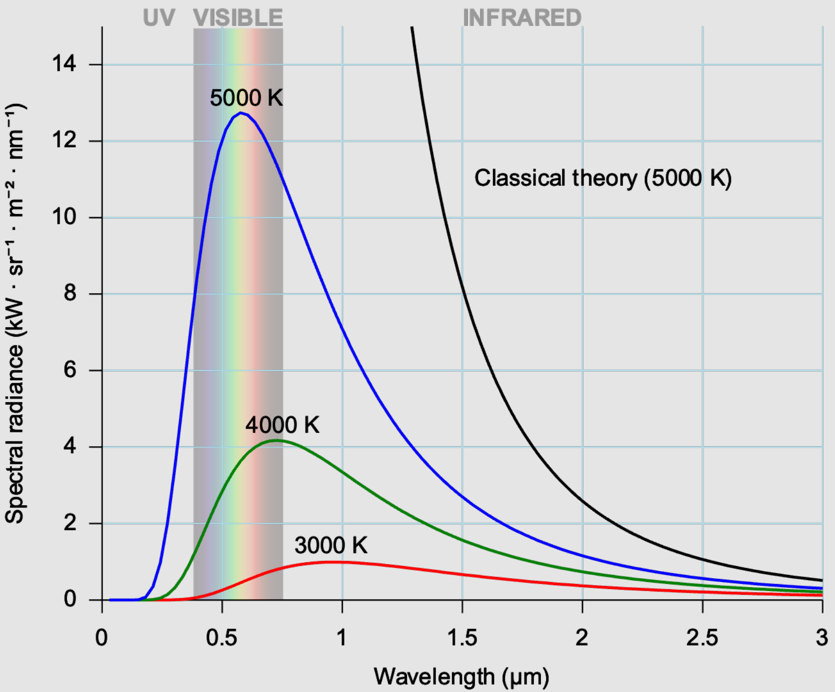
Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams

Radius: $R_\odot = 7 \cdot 10^8\ m$

Mass: $M_\odot = 2 \cdot 10^{30}\ kg$

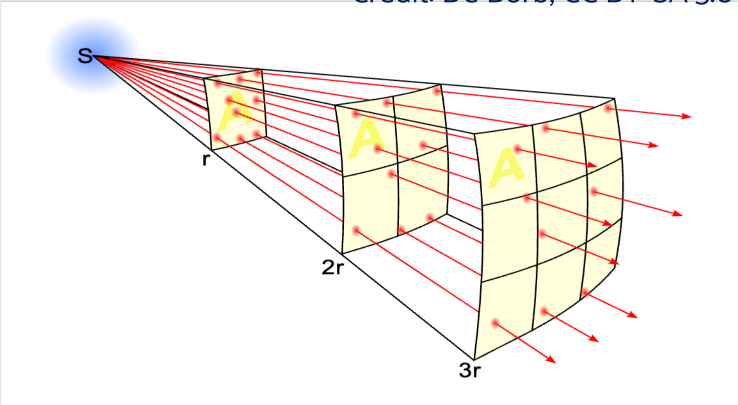
Luminosity: $L_\odot = 4 \cdot 10^{26}\ W$

Black-body emission (Planck's law)

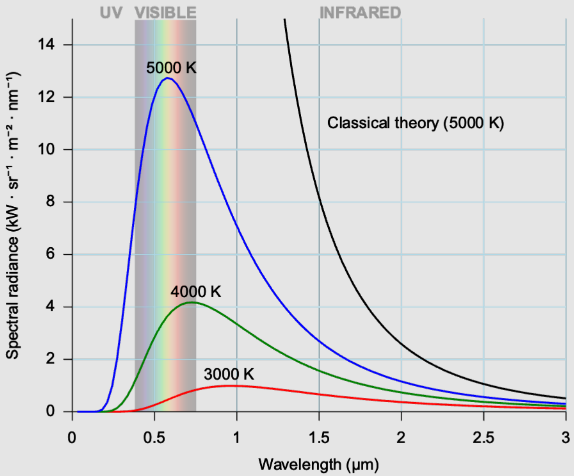


The Sun

Credit: De Borb, CC BY-SA 3.0



Black-body emission (Planck's law)



Flux arriving on Earth:

$$F_T = \frac{L_\odot}{4\pi d_{T-S}^2} = 1360\ W/m^2$$

Stefan-Boltzmann's Law: $F = \sigma T_{eff}^4$

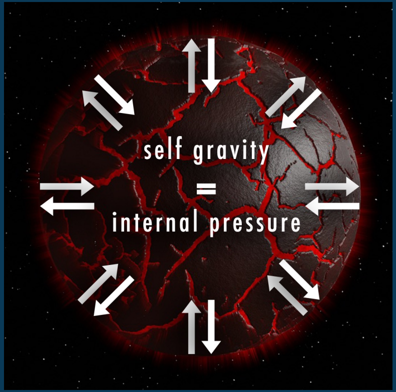
$$T_{eff} = 5780\ K$$

Wien's law: $\lambda_{max} \cdot T = 0.0029\ K \cdot m$

$$\Longrightarrow \lambda_{max} = 5 \cdot 10^{-7} m = 500\ nm$$

(green)

Hydrostatic equilibrium



The Sun is a **stable structure**. The forces acting upon every element must be in **equilibrium** ➡️ There is a balance between:

- Force due to pressure from material above the element

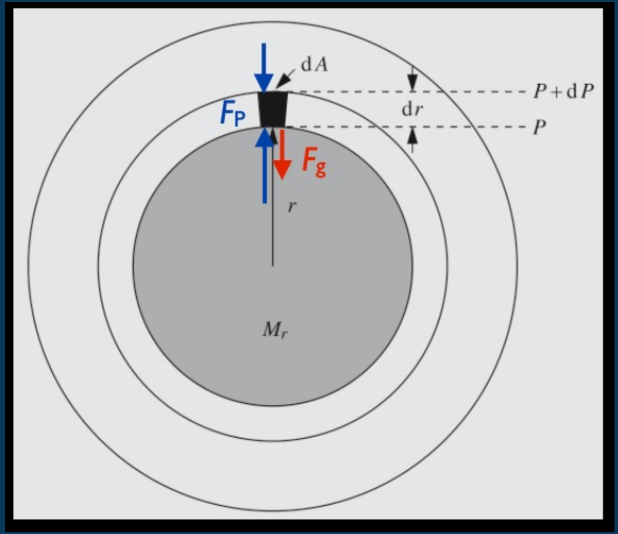
- Force due to pressure from material below the element

- The weight of the element itself

$$dF_g = -G\frac{M(r)dm}{r^2} = -G\frac{M(r)\rho}{r^2}dA\,dr$$

$$dF_P = P\,dA - (P + dP)\,dA = -dP\,dA$$

$$dF_g + dF_P = 0 \quad \Rightarrow \quad \frac{dP}{dr} = -G\frac{M(r)\rho}{r^2}$$

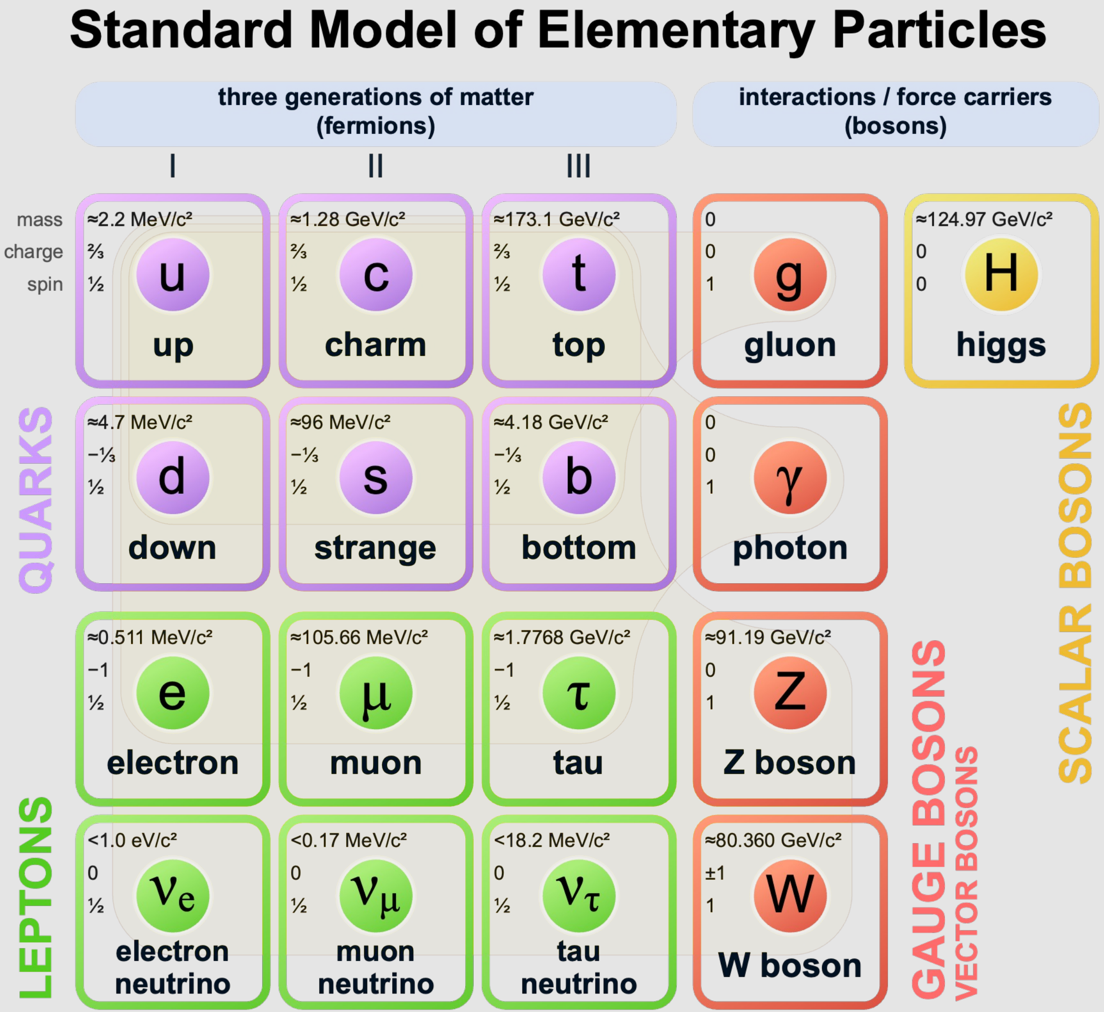


Particle zoo

Elementary particle:
subatomic particle that is not composed of other particles

The Standard Model has 17 distinct particle (12 fermions, 5 bosons)

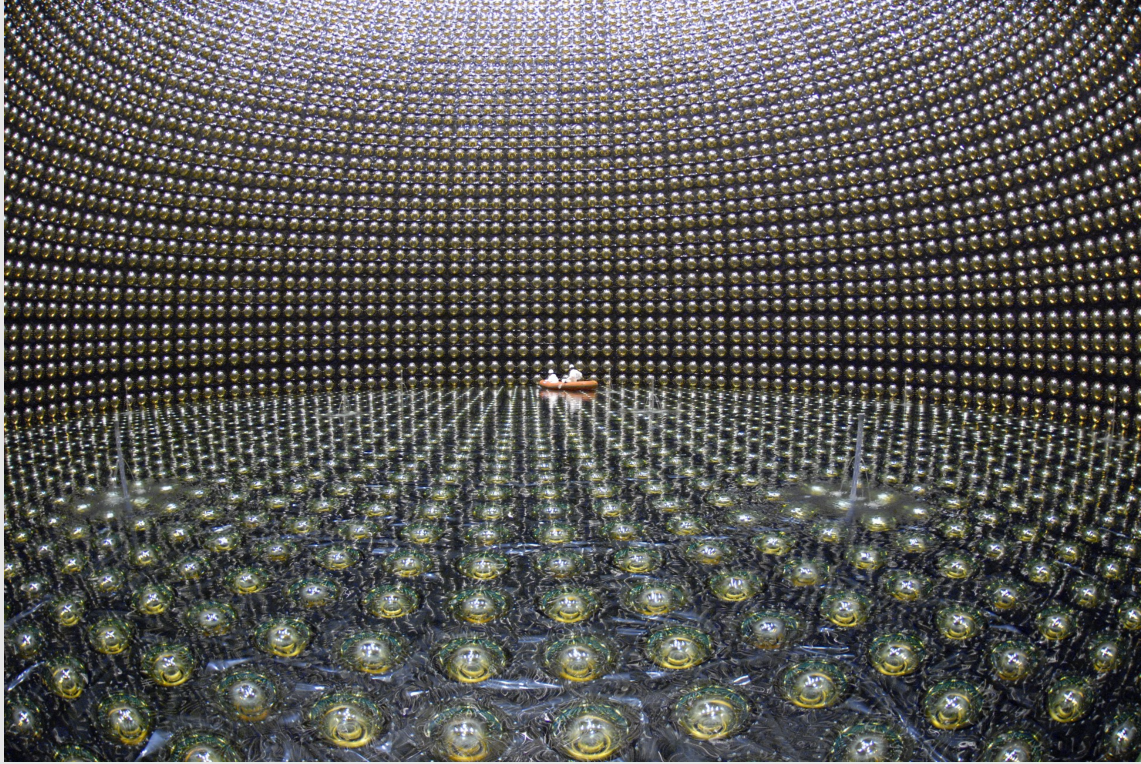
Flavour, colour and antimatter produce 48 and 13 variations of fermions and bosons, respectively



Solar neutrinos

Neutrinos are neutral particles (zero charge) proposed by Wolfgang Pauli in 1930 to explain conservation of energy and momentum in beta decay reactions

$$p^+ \rightarrow n^0 + e^+ + \nu_e \ (\beta^+)$$
$$n^0 \rightarrow p^+ + e^- + \overline{\nu}_e \ (\beta^-)$$



Credit: Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), U. Tokyo

Experiments around the 60s-90s were detecting only 1/3 of solar neutrinos predicted by theory (solar neutrino problem). Was theory wrong?

Solar neutrinos

- The Sun produces all **3 types of neutrinos**
- On their way to Earth, they spontaneously transform to other types (**neutrino oscillations**)
- In 1998, experiments finally detected all 3 types of neutrinos – no missing neutrino problem

Torn between identities – tau-, electron- or muon-neutrino?

Credit: Johan Jarnestad/The Royal Swedish Academy of Sciences

The Nobel Prize in Physics 2015

© Nobel Media AB. Photo: A. Mahmoud

Takaaki Kajita

Prize share: 1/2

© Nobel Media AB. Photo: A. Mahmoud

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

To cite this section
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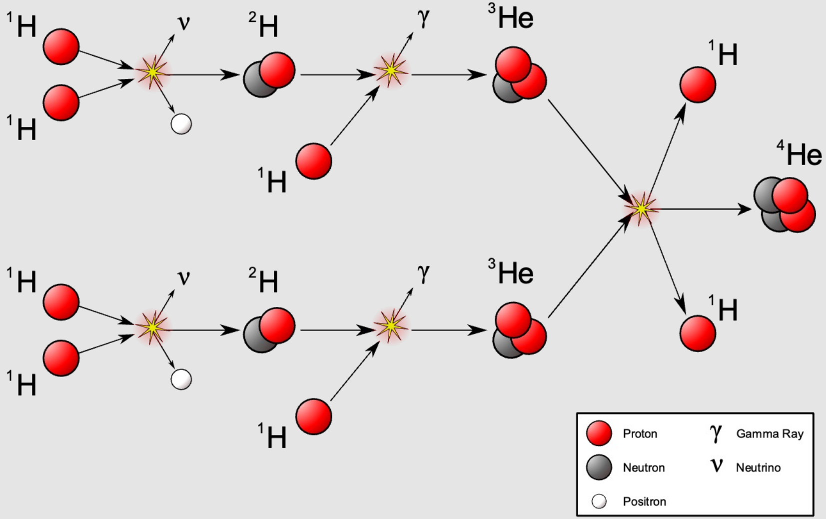
Exercise 1. Source of energy in the Sun

The Sun is stable: it must generate energy at the same rate it emits energy.

A) Chemical energy

B) Energy liberated in gravitational contraction

C) Nuclear energy



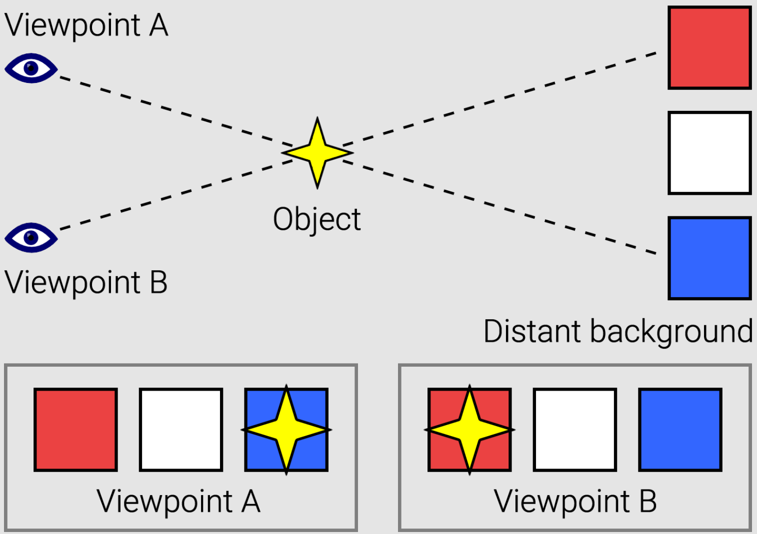
Parallax and distance measurements

We use the **change in the apparent position** of a star with respect to the background when it is observed from 2 points along the Earth's orbit around the Sun

parsec (pc): distance at which $1AU$ subtends an angle of $1''$

$$1pc = 2.063 \cdot 10^5 AU = 3.09 \cdot 10^{13} km = 3.62\ ly$$

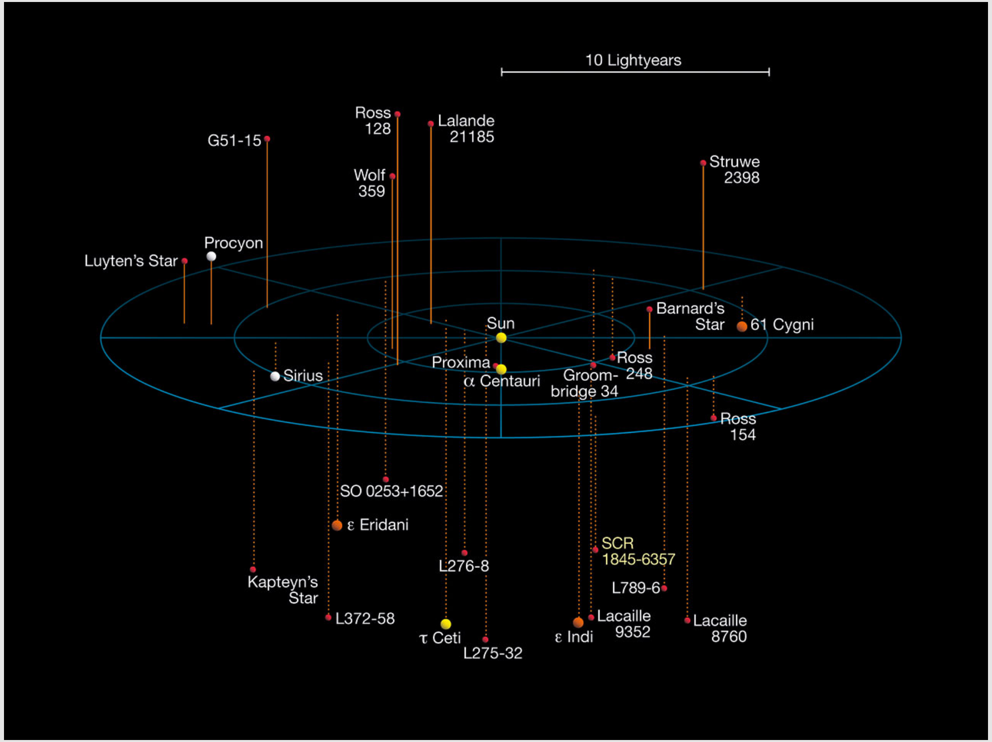
Credit: Justin Wick CC BY-SA 3.0



$$d = \frac{1\ AU}{\tan p} \simeq \frac{1}{p[rad]} AU = \frac{2.063 \cdot 10^5}{p['']} AU \Longrightarrow d = \frac{1}{p['']} pc$$

Parallax and distance measurements

Credit: ESO, Richard Powell



All stars have parallaxes less than 1″. The first one was measured in 1838 by Bessel

The closest star to the Sun (Proxima Centauri) has $p = 0.77''(d = 4.2ly)$

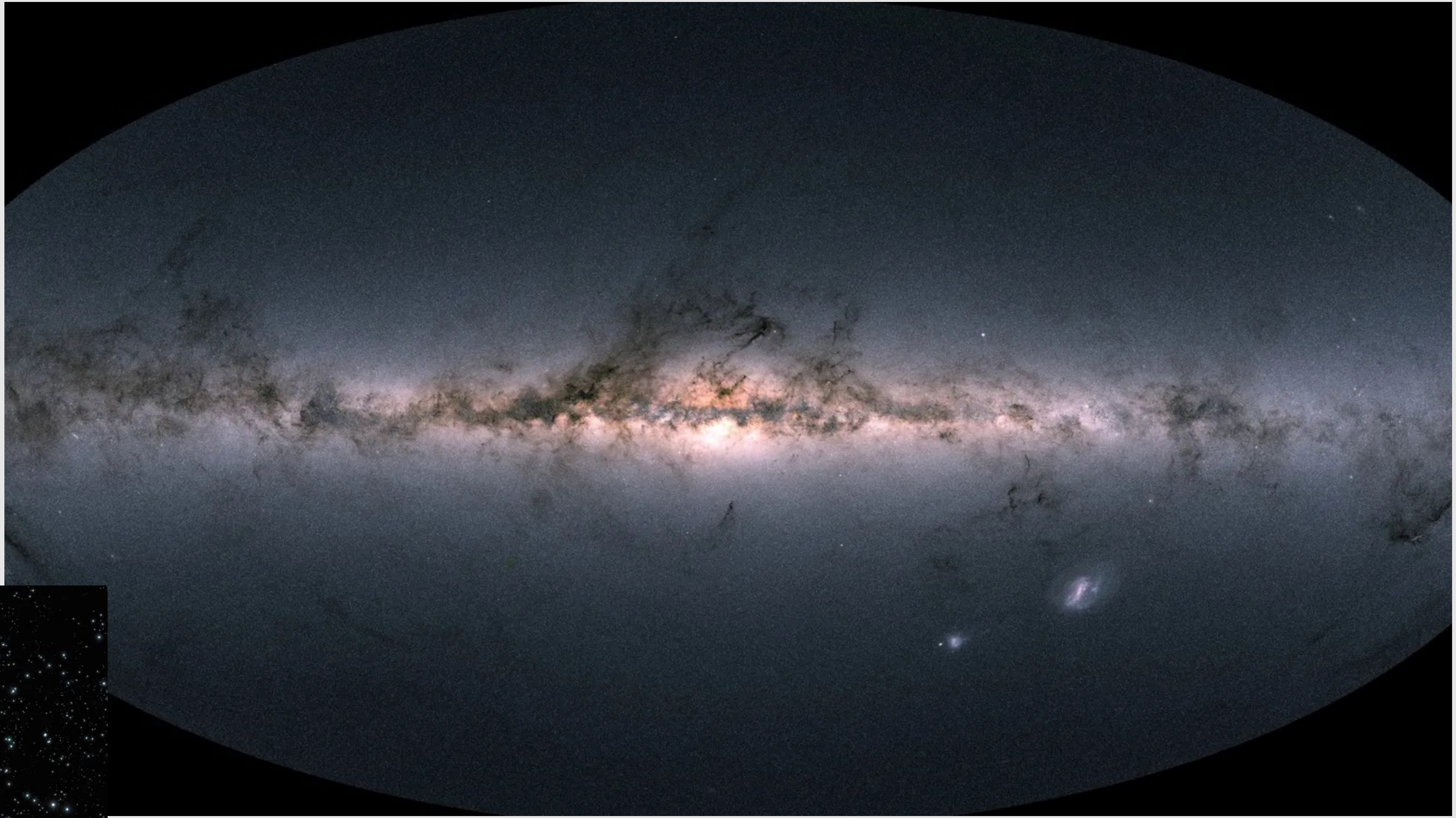
$$1'' = \frac{1}{3600} deg$$

A human hair held ten metres away would cover one arcsecond of sky

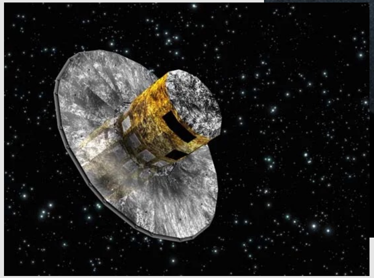
Gaia Satellite

Measuring parallaxes of 10^9 stars in our Galaxy

Credit: ESA

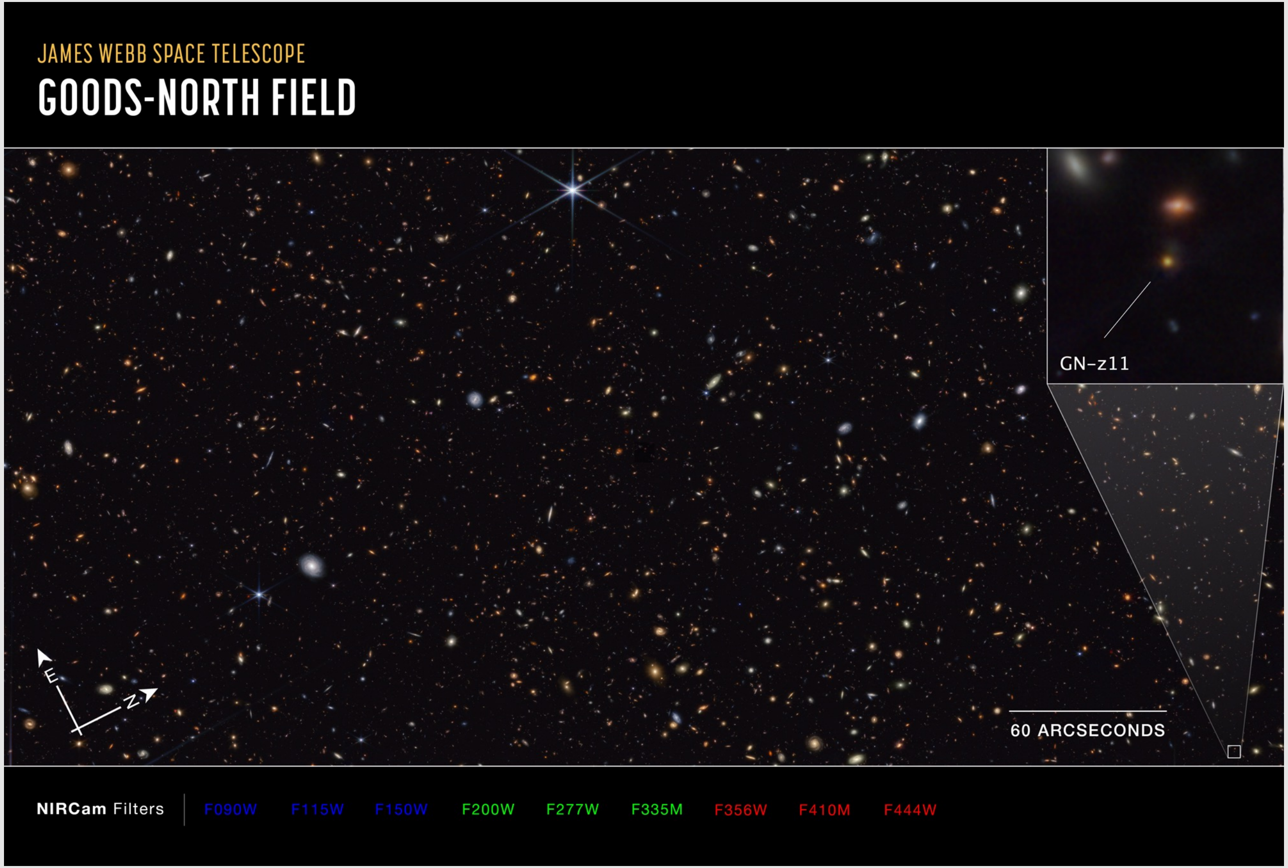


Credit: ESA



James Webb Telescope

Credit: NASA, ESA, CSA, STScI, Brant Robertson (UC Santa Cruz), Ben Johnson (CfA), Sandro Tacchella (Cambridge), Marcia Rieke (University of Arizona), Daniel Eisenstein (CfA)



Credit: NASA GSFC/CIL/Adriana Manrique Gutierrez

Luminosity, distance, apparent magnitudes

Luminosity L: energy star emits per second

Apparent brightness b: energy received per second per unit area

$$b = \frac{L}{4\pi d^2}$$

$$\frac{L}{L_\odot} = \left(\frac{d}{d_\odot}\right)^2 \frac{b}{b_\odot}$$

Star luminosities vary between 10^{-4} and 10^{6} solar luminosities

Magnitude Scale

Hipparco (II A.C.) designed a system for the apparent magnitudes:

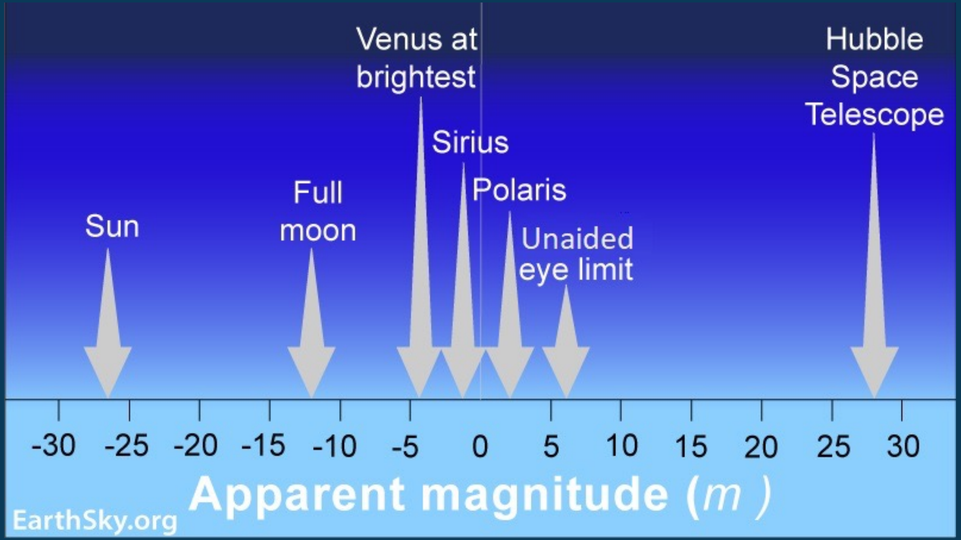
$m = 1$: brightest stars; $m = 6$: dimmest stars

In the XIX century, we measured that $m = 1$ stars were approximately 100 times brighter than $m = 6$ stars. The human eye follows a logarithmic scale. The magnitude system was redefined so that

$$\Delta m = 5\, mag \leftrightarrow \times 100 \text{ brightness}$$

$$\frac{b_2}{b_1} = 100^{\frac{m_1 - m_2}{5}}$$

$$m_1 - m_2 = -2.5 \log_{10}\left(\frac{b_1}{b_2}\right)$$



Credit: Chelynne Campion/EarthSky

Absolute magnitudes and distance modulus

The absolute magnitude M of an object is defined as the apparent magnitude it would have if it was situated at a distance of $10pc$

$$b = \frac{L}{4\pi d^2} \rightarrow \frac{b(10\text{ pc})}{b} = \left(\frac{d}{10}\right)^2$$

$$m_1 - m_2 = 2.5\log\frac{b_2}{b_1}$$

$$\rightarrow m - M = 2.5\log\frac{b(10\text{ pc})}{b} = 2.5\log\left(\frac{d}{10}\right)^2 = 5\log\frac{d}{10}$$

$$m - M = 5\log d[pc] - 5$$

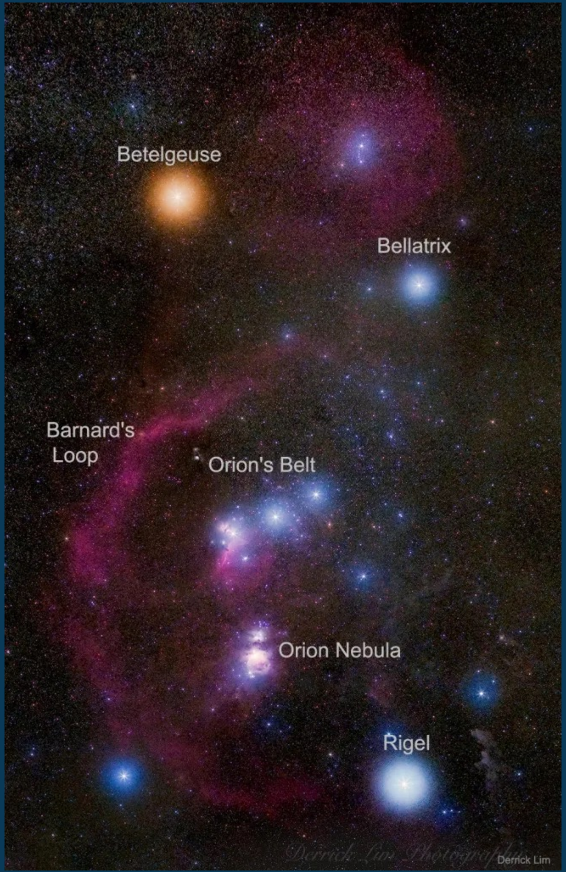
$$M = m - 5\log d + 5$$
$$M = m + 5\log p('') + 5$$

The difference between apparent and absolute magnitudes is directly related to distance

$$M_1 - M_2 = -2.5\log\frac{L_1}{L_2}$$

$$\left.\begin{aligned} m_\odot &= -26.81 \\ d &= 1\text{ UA} = 4.85\times10^{-6}\text{ pc} \end{aligned}\right\} \Rightarrow M_\odot = 4.75 \rightarrow M = 4.75 - 2.5\log\frac{L}{L_\odot}$$

Colour and temperature



Credit: Derrick Lim /nasa.gov

Stars have different colours

Credit: ESA/Hubble & NASA

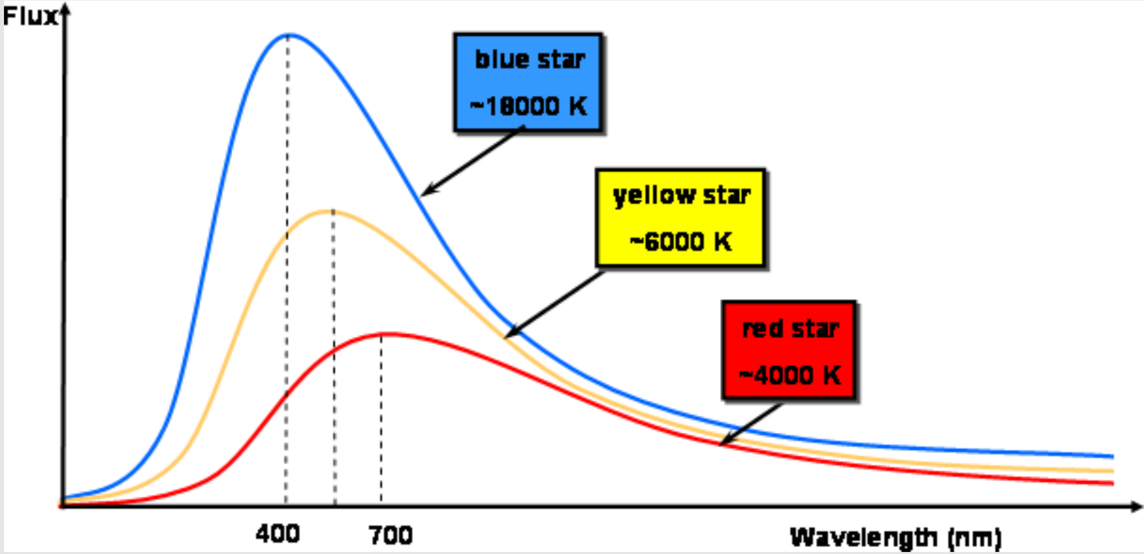
Colour and temperature

Wien's law: $\lambda_{max} \cdot T = 0.0029\ K \cdot m$

As the star's temperature increases, it emits more light at shorter wavelengths

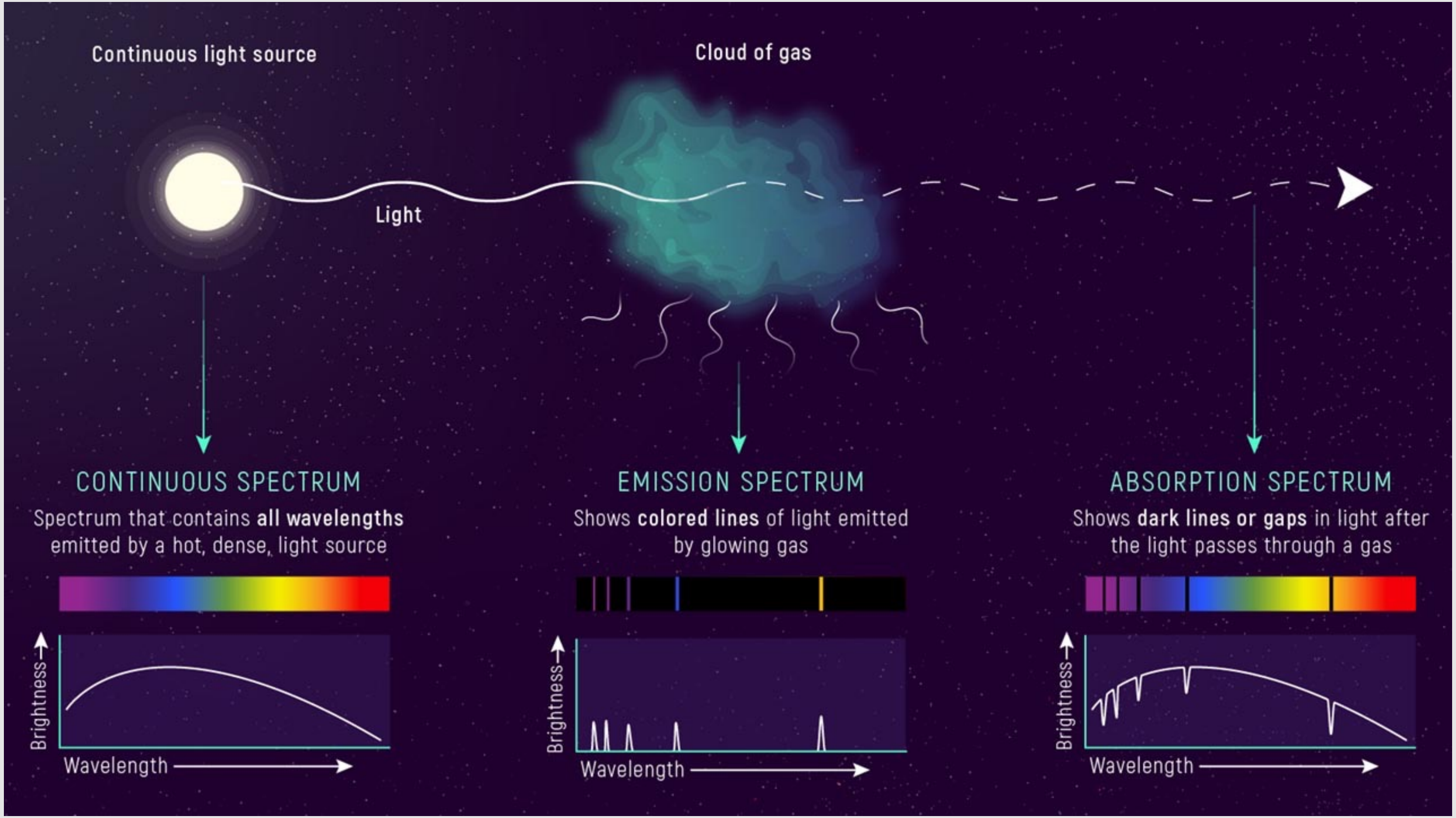
Red stars have relatively low surface temperatures

Blue stars have relatively high surface temperatures



Credit: Swinburne

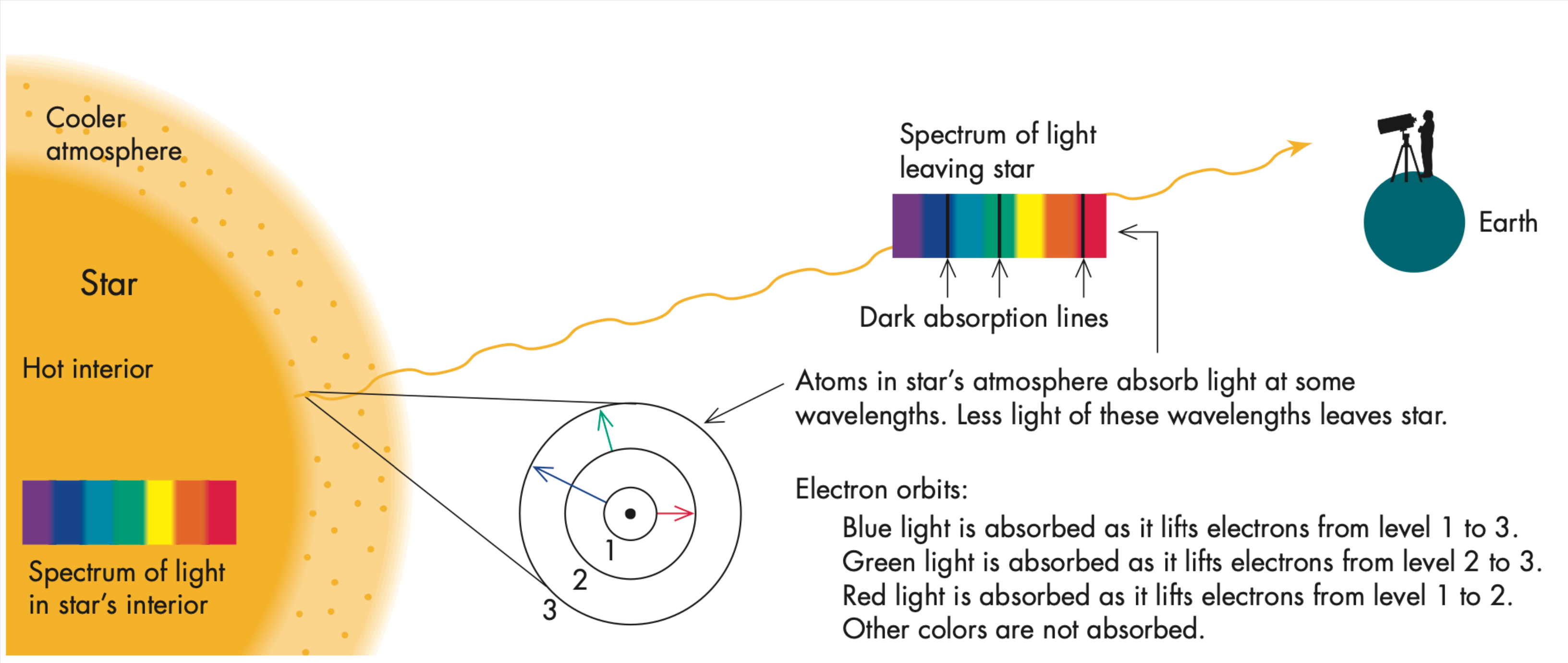
Types of Spectra



Credit: NASA, ESA, Leah Hustak (STScI)

Stellar Spectra

They provide information on the physical properties of the star's atmosphere

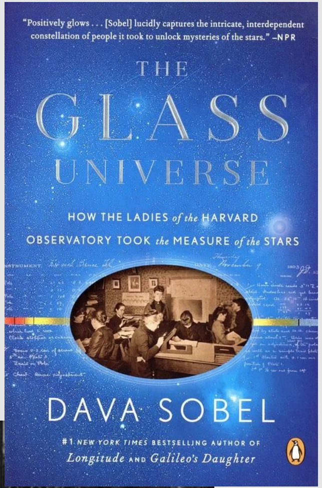


http://www.mhhe.com/arny

Harvard computers

At the end of the 19th century, there was a massive effort conducted in the Harvard Observatory to spectrally classify 225,300 stars

Spectral types: O B A F G K M (Oh Be A Fine Girl, Kiss Me)



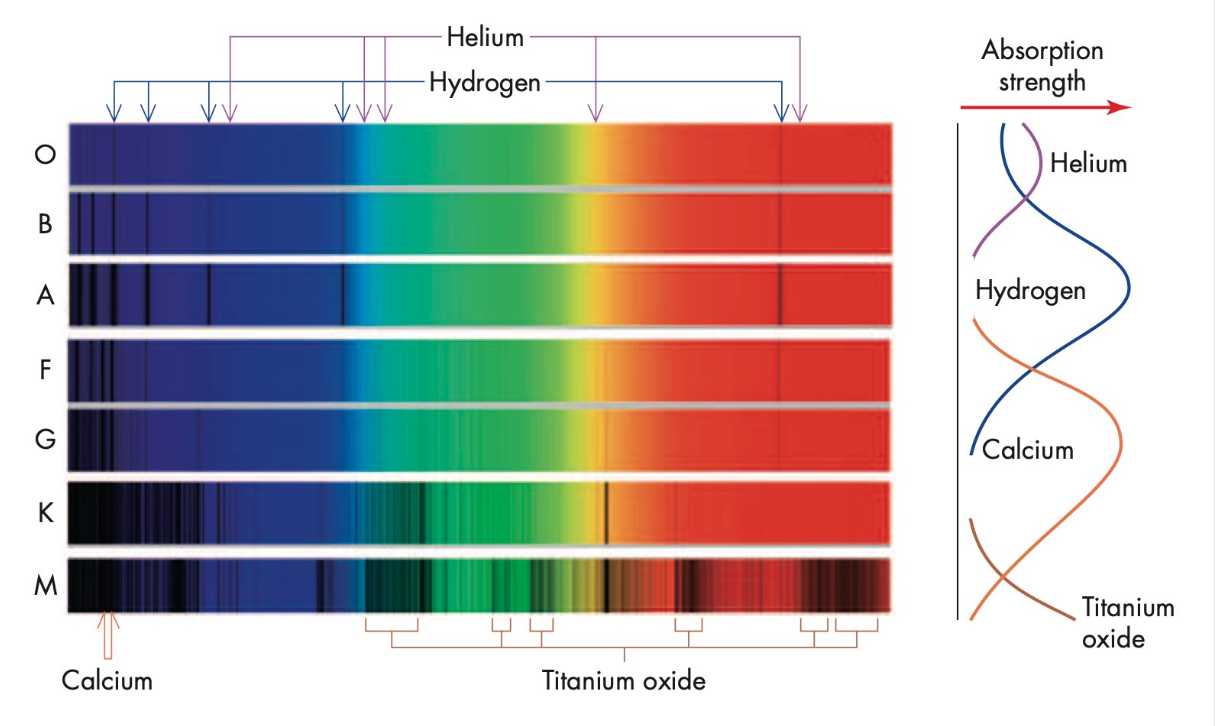
Credits: Harvard College Observatory/Wikimedia Commons

Types of stars

Spectral classification such that all lines change continuously.

Spectral types follow a sequence in temperature. The effective temperature is the main parameter determining the presence and intensity of the different lines.

Element abundance has a smaller effect.



http://www.mhhe.com/arny

Hydrogen: If $T \gg 10000K$, all atoms are ionized

If $T \ll 10000K$, all electrons are in the fundamental level

At $T{\sim}10000K$, sweet spot for electrons to make transitions

Size of stars

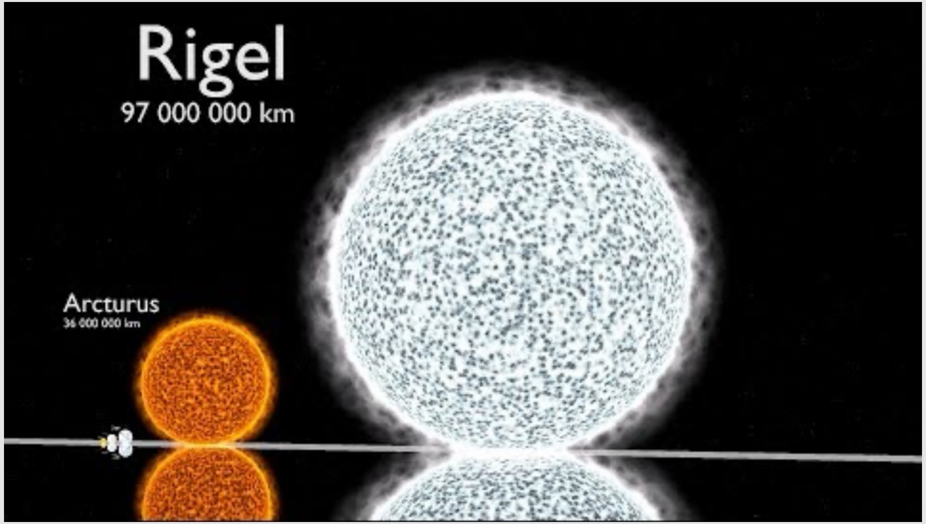
Flux: $F = \frac{L}{4\pi d^2}$

Stefan-Boltzmann's Law: $F = \sigma T_{eff}^4$

$$L = 4\pi R^2 \sigma T_{\text{ef}}^4$$

$$R = \frac{\sqrt{L/4\pi\sigma}}{T_{\text{ef}}^2}$$

$$\frac{L}{L_\odot} = \left(\frac{R}{R_\odot}\right)^2 \left(\frac{T_{\text{ef}}}{T_{\text{ef}\,\odot}}\right)^4$$



https://www.youtube.com/watch?v=i93Z7zljQ7I

Exercise 2. Observing a star

We observe a star with a telescope to find:

- Apparent magnitude $m = 5$
- Maximum emission at $\lambda = 4000\ \text{Å}$
- Parallax $p = 0.174''$

Find the effective temperature of the star, their distance (in parsecs), their absolute magnitude, their luminosity (in solar luminosities) and the radius of the star (both in solar radii and arc-seconds).

Bonus content: Cosmology