

Lecture 1: Course Introduction and History of solar and stellar research

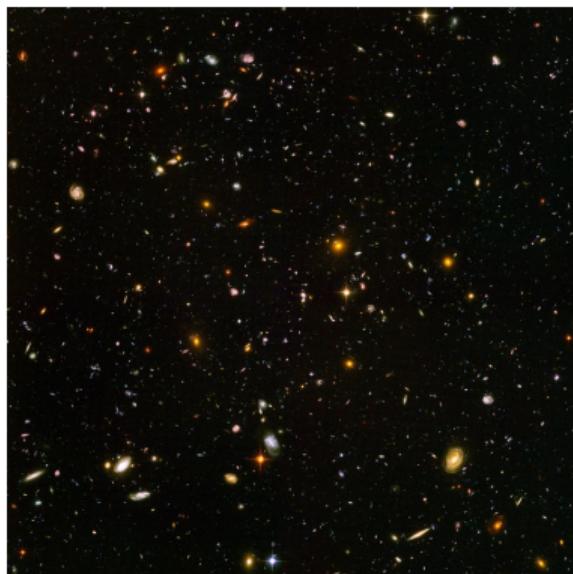
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Uniqueness of astrophysics

- ▶ In the lab we can control the temperature, pressure, voltage, etc. of the experimental set-up to see how results change.
- ▶ In astrophysics this is impossible. We are sentenced to looking at the objects as they are. Understanding this is especially important for stars.
- ▶ But knowledge goes both ways: what we learn through theory, experiment and observations is applicable everywhere.
- ▶ There is also such thing as “laboratory astrophysics” - [What do you think that is? \(1-2 mins\)](#)



Hubble Ultra Deep Field: credits to NASA

Numerical experiments

- ▶ There are also *numerical* experiments.
- ▶ We know, for hundreds of years, that most equations cannot be solved analytically.
- ▶ They are not peculiarities, they describe real-life problems. [Can you come up with any?](#)
- ▶ To solve these, we use numerical simulations. These are computer codes that solve systems of integral and differential equations, and try to describe the structure and evolution of the objects.



Mare nostrum supercomputer, Barcelona.
Credits: bcs.es

Remote sensing

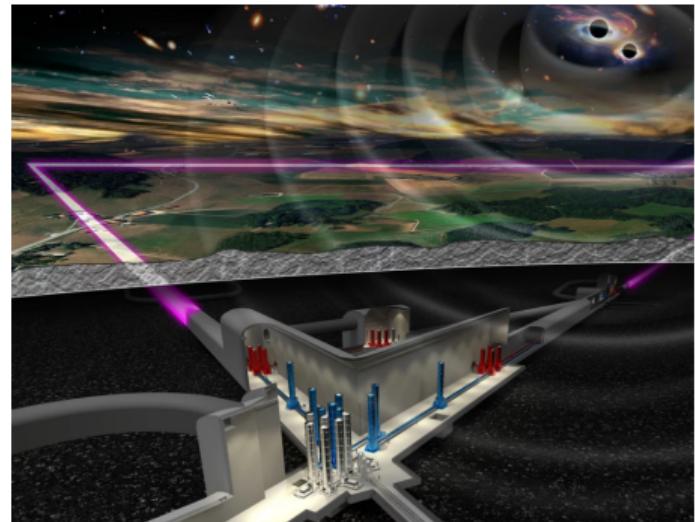
- ▶ Another problem is that we cannot measure the physical parameters directly. We have to measure whatever the object is emitting:
 - Gravitational waves
 - Neutrinos
 - but mostly electromagnetic waves (**light**)
- ▶ This problem is tackled in more depth in another course: "Experimental Astrophysics: Remote Sensing", that will take place in the winter semester 2024/25.



Engraving after a picture by J.A. Houston, ca. 1870. Courtesy of The Granger Collection, New York

Gravitational wave astronomy

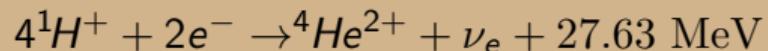
- ▶ Just like moving charges emit electromagnetic waves, moving masses emit gravitational waves (GW)
- ▶ They cause the space-time to fluctuate
 - The tiny variations in distance can be detected
- ▶ The LIGO experiment uses interferometry to detect tiny variations in the distance between two perpendicular arms.
- ▶ First successful detection: 2016. Nobel in 2017.



Future Einstein Telescope (artist impression).
Credits: NIKHEF

Neutrino astronomy

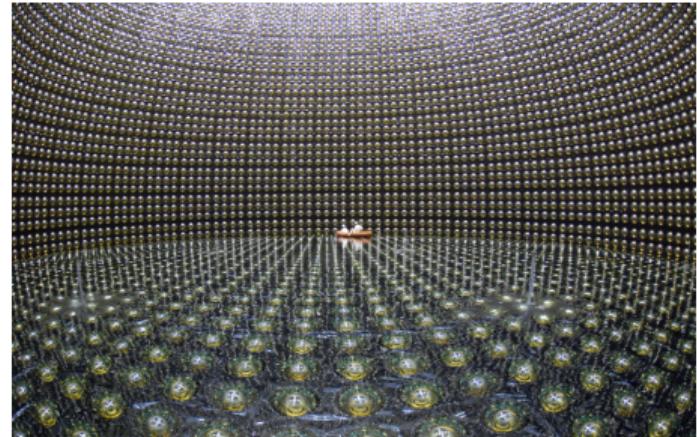
- ▶ Existence of the neutrino first postulated by Pauli (1930) to conserve energy and momentum during β -decay. First detection by Reines & Cowan (1956). Nobel in 1995.
- ▶ Neutrinos are produced in the interior of stars as a consequence of nuclear reactions (i.e. p-p chain)



- ▶ Also produced during supernova explosions.
- ▶ There is also the cosmic neutrino background: dates from 1 sec after the Big Bang.
- ▶ The cosmic microwave background, was produced some 380,000 years later.

Solar Neutrino Problem

- ▶ According to the Standard Solar Model, the Sun's core has a temperature of about $T \approx 1.5 \times 10^7$ K.
- ▶ At this temperature, the Sun should be producing a given number of neutrinos per second.
- ▶ Experiments such as the Superkamiokande, detect only one third.
- ▶ Does this mean that the temperature in the Sun's core is lower ? Is the Standard model wrong?
Strong debate in the 90's.
- ▶ In fact, we detect only a third because Superkamiokande detects only ν_e , but as neutrinos having **small mass**, they change flavours (ν_e , ν_τ , ν_μ) as they travel - Neutrino oscillations! (Nobel prize in 2015).



Credits Inst. Cosmic Ray Research, University of Tokyo

The light and the electromagnetic spectrum

- ▶ The reason why we see *anything* is because the light is coming from that object to our eyes or detectors (camera chip, etc..)
- ▶ We see the planets and moons because they reflect the light, but we see the Sun and other stars because they **emit** the light.
- ▶ That means there is energy generated in these objects that allows them to radiate.
- ▶ **Solve the following problem:** *Total solar irradiance* (radiative energy per second per square meter at the top of the Earth's atmosphere) is 1361 W/m^2 . How much energy does Sun produce per second? (Ask for any constants you need).

The light and the electromagnetic spectrum

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- ▶ Solve the following problem: *Total solar irradiance* (radiative energy per second per square meter at the top of the Earth's atmosphere) is 1361 W/m^2 . How much energy does Sun produce per second? (Ask for any constants you need).
- ▶ Answer:

$$\frac{dE}{dt} \equiv L_{\odot} = \mathcal{E}4\pi d^2 = 1361 \text{ W m}^{-2} 4\pi (149 \times 10^9 \text{ m})^2 = 3.846 \times 10^{26} \text{ W} \quad (1)$$

Effective temperature

3.846×10^{26} W is a lot of energy. What would roughly have to be the temperature of the Sun, so it would radiate this amount of energy?

Stefan-Boltzmann law

- ▶ The simplest way for us to relate the emitted energy to the temperature is through the Stefan-Boltzmann law.
- ▶ The emissivity (emitted energy per unit surface in the outgoing direction) is equal to:

$$\epsilon = \sigma T^4 \tag{2}$$

- ▶ Then, the luminosity (emitted energy per second) of such object is: $L = 4\pi R^2 \sigma T^4$.
- ▶ If you substitute the numbers, you will get $T = 5777$ K.
- ▶ What temperature would this be?
- ▶ What does this question even mean?

Departures from the ideal case

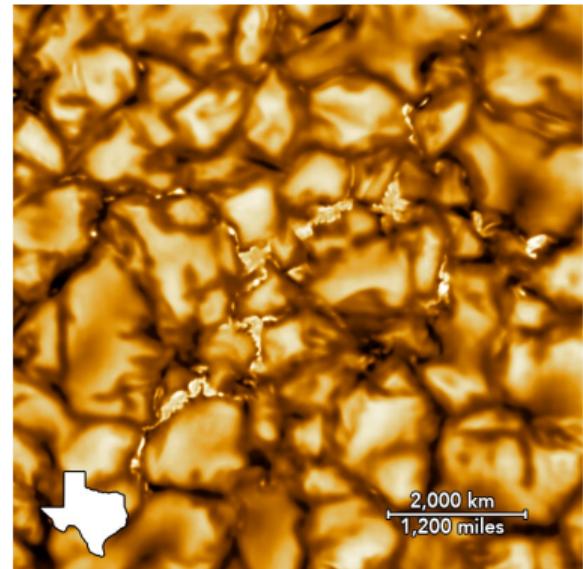
We made a series of approximations in the process of inferring this temperature.

- ▶ First we assumed that the solar radiance is constant in time (*excellent approximation*)
- ▶ Then we assumed that the emission is isotropic (*this is not a good approximation but see below*)
- ▶ Then we assumed that the solar surface is homogeneous (*on small scales it is not, but let's discuss this for a while*)
- ▶ Finally, we assumed that the Sun emits like a blackbody to infer the called effective temperature - 5777K.
- ▶ Let's discuss a bit what this concept means - 5 mins

Real situations

The Sun (and other stars) depart severely from these assumptions:

- ▶ Stars are inhomogeneous in all 3 dimensions (especially radially).
- ▶ They emit non-Plankian spectra, in a generally anisotropic manner
- ▶ And they also change and evolve on scales from seconds to billions of years.
- ▶ **This course is about all these aspects**



Credits: NSO/AURA/NSF/DKIST

The concept of stellar atmosphere

- ▶ Energy is generated in the cores of stars and transported outwards (in multiple ways)
- ▶ As we move away from the stellar center - the medium becomes less opaque, at some point the photons can escape the star. Then they contribute to the total stellar luminosity that we ultimately detect.
- ▶ The **layer** of the last emission is referred to as $\tau = 1$ layer, where τ is the so called **optical depth**.
- ▶ As the stars are made of plasma - we don't have an obvious surface. $\tau = 1$ layer serves as a loose definition of a solar surface (observationally).
- ▶ Next week, we will describe a star using equations of stellar structure - we will again have to make a definition of solar surface.

The concept of stellar atmosphere

- ▶ The physical location of $\tau = 1$ depends on the density of the medium and how the photon interacts with the medium - **described by the opacity.**
- ▶ Solar plasma has different opacity at different wavelengths - photosphere has different physical location.
- ▶ Also, when we look at the Sun under different angles, we see different depths.
- ▶ This is the so called limb-darkening.



Why study the stellar atmospheres?

- ▶ The stellar light gives us direct information about the stellar surface (the photosphere).
- ▶ Are there ways to probe the stellar interior? Can stellar atmosphere help?

Why study the stellar atmospheres?

- ▶ Are there ways to probe the stellar interior? Can stellar atmosphere help?
- ▶ Stellar structure determines the structure of the atmosphere, and T_{eff} .
- ▶ Stellar atmosphere oscillates because of the processes in stellar interior.
- ▶ At the surface, we measure the magnetic fields generated in the interior.
- ▶ Neutrinos produced in the core leave the star directly.
- ▶ **The structure of the whole star leave an observable imprint on its surface.**

Understanding the stars

- ▶ **The structure of the whole star leave an observable imprint on its surface.**
- ▶ We measure these observable imprints.
- ▶ We can observe *a lot* of stars - so we can have accurate statistics.
- ▶ **We devise theoretical models that try to describe the stellar structure and the evolution and compare the outputs of these models both to the measurable properties of individual stars and to the statistical distributions.**

Luminosity vs the color

- ▶ Effective temperature describes the total luminosity of the star.
- ▶ We used a blackbody to approximate solar *surface*.
- ▶ Now, different temperatures imply different colors (i.e. different spectral distributions).

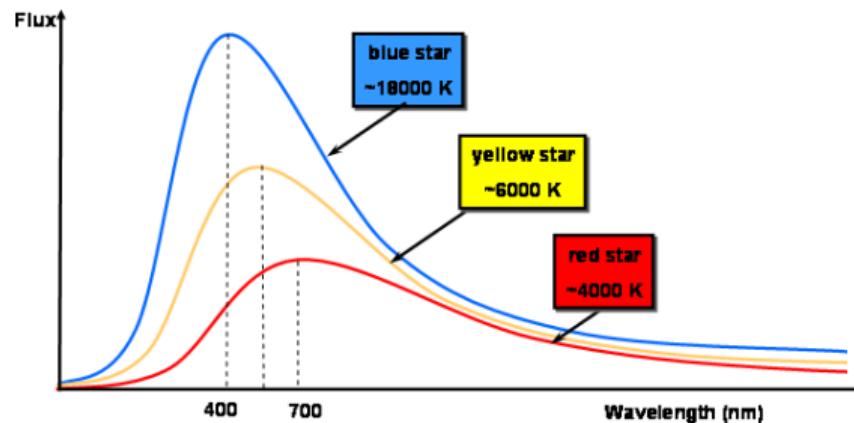


Figure: Planck curves for blackbodies of different temperatures. Credits: University of Swinburne

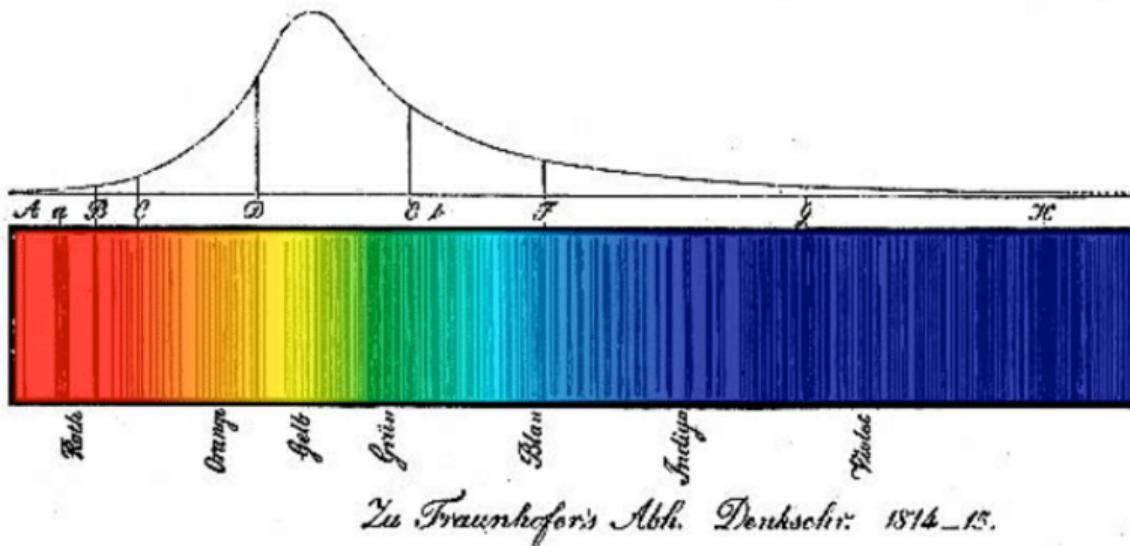
A side quest

- ▶ Can someone convince me that a star **cannot** be a blackbody? - 2-3 mins

Stars are not black bodies!

- ▶ Star needs to transport energy outwards. For that a gradient of temperature is needed - not a blackbody.
- ▶ Harder question is can stellar photosphere be a blackbody?
- ▶ In theory - yes, no fundamental law would be broken if it was.
- ▶ In practice - it can't. Different wavelengths *always* have different opacities and thus sample different depths.

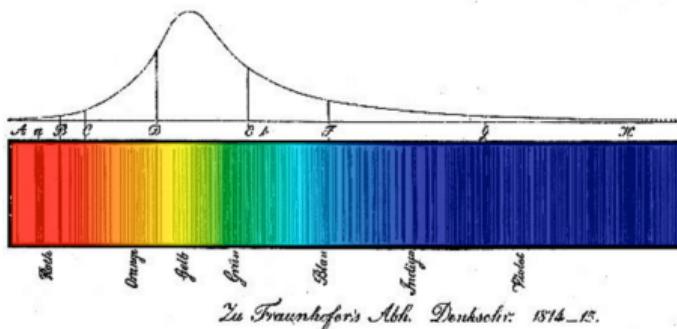
Solar spectrum is NOT a blackbody spectrum



Credits: Fraunhofer (1814)

- ▶ Wollastone (1802) and Fraunhofer (1814) discovered dark lanes in the solar spectrum,
- ▶ These lines represent loss of light at specific wavelengths - solar atmosphere is much more opaque at these wavelengths. Why?

Solar spectrum is NOT a blackbody spectrum



Credits: Fraunhofer (1814)

- ▶ These lines represent loss of light at specific wavelengths - solar atmosphere is much more opaque at these wavelengths. **Why?**
- ▶ Kirchoff and Bunsen (1860's) related them to chemical elements.
- ▶ Birth of quantum mechanics: Bohr's model can explain hydrogen lines. **Energy jumps between discrete energy levels.**
- ▶ Discovery of Helium by Janssen (1868) in the solar spectrum.

Planck Law

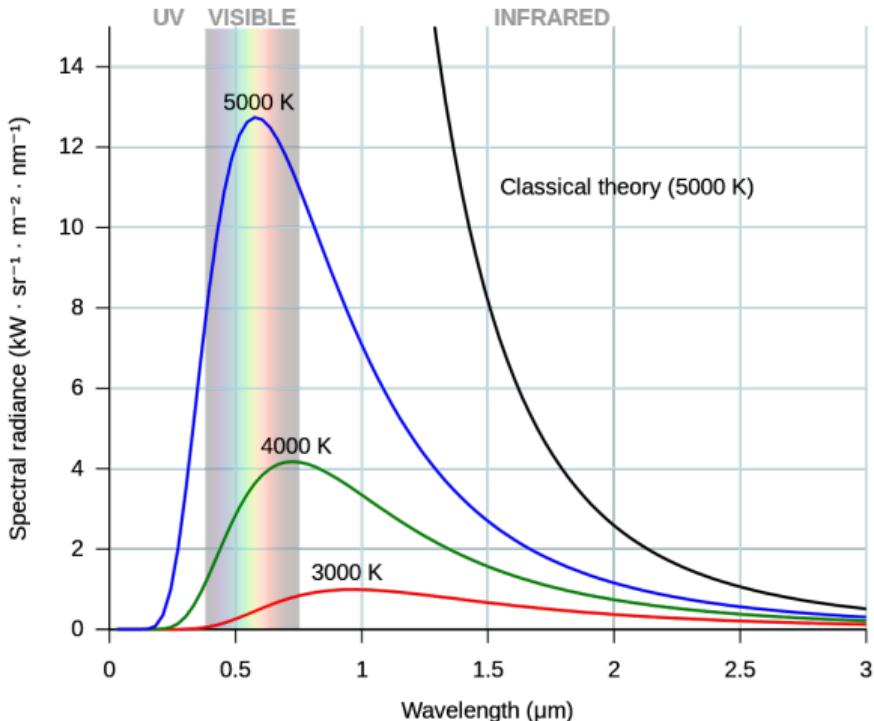
- ▶ Kirchoff (again) recognized the importance of an universal law that connects emission and absorption properties of a medium in an equilibrium state. - "... *It is of utmost importance to derive this law theoretically*".
- ▶ We had some pieces - Stefan-Boltzmann law that we just talked about...
- ▶ ... Then we had Wien's law: Emission of bodies of different temperature peaks at different wavelengths (colors).
- ▶ People also experimentally captured the dependence $B(T)$, where B is some "brightness" or essentially luminosity.
- ▶ *Interesting:* Both Boltzmann and Wien (as well as Rayleigh and later Jeans) derived the corresponding laws theoretically. **Do you know how?**
- ▶ Recommendation: "Theoretical Concepts in Physics" (Malcom Longair, 2020, Cambridge)

Planck Law

- ▶ Finally, Planck derived this law theoretically.
- ▶ After that, multiple other approaches to derivation were made (for example one by Bose and Einstein).

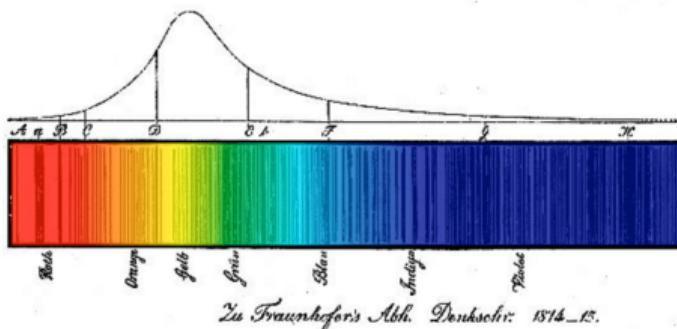
$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1} \quad (3)$$

- ▶ This equation describes the *intensity* of the light in a state where photons are in equilibrium.



Planck curves for few different temperatures.
Credits: Wikipedia

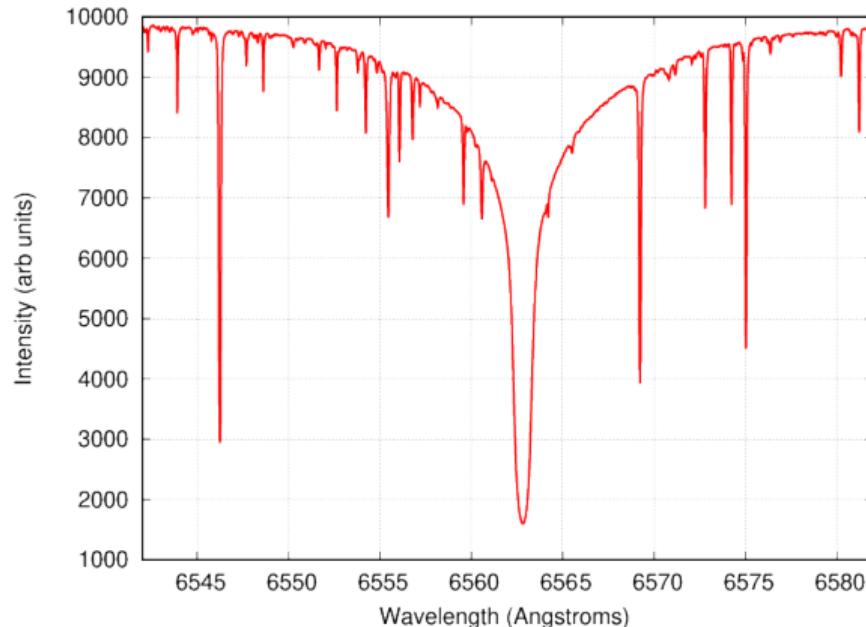
Solar spectrum is NOT a blackbody spectrum



Credits: Fraunhofer (1814)

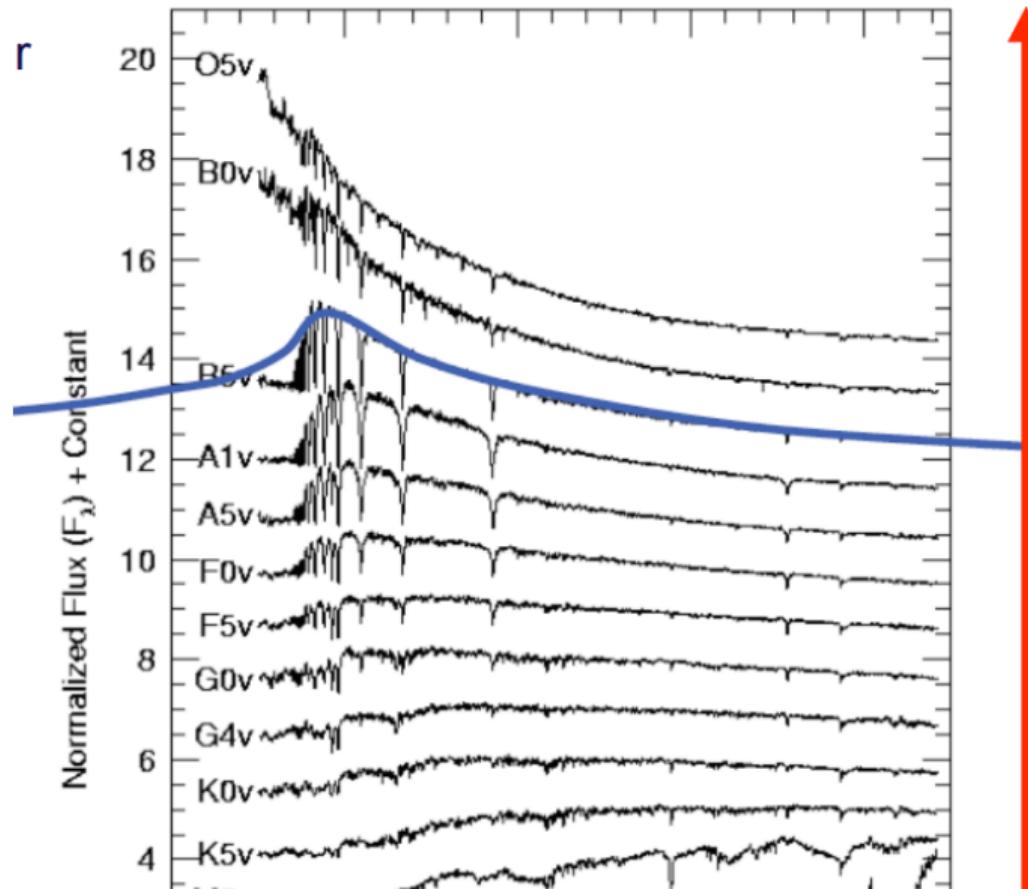
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Today we can do better than 200 years ago ...



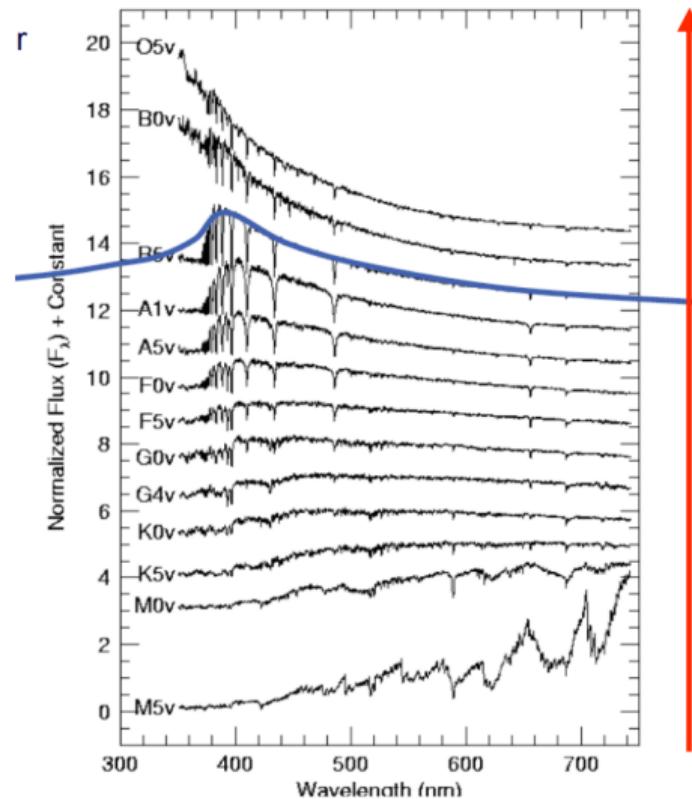
$H\alpha$ spectral line in solar spectrum: notice all the weak spectral lines around!

And we can do the same for other stars.



And we can do the same for other stars.

What is the fundamental parameter that determines the shape of the spectrum and the absence/presence of spectral lines?



The Harvard Spectral Classification

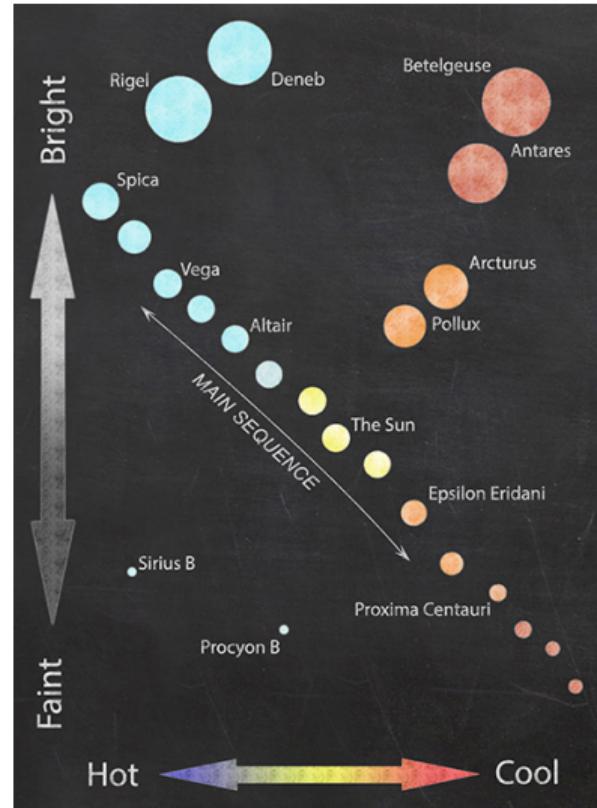
Class	T _{eff} [kelvin]
O	≥ 30000
B	10000-30000
A	7500-10000
F	6000-7500
G	5000-6000
K	3000-5000
M	2000-3000



Annie Jump Cannon. Credits: Library of Congress, US

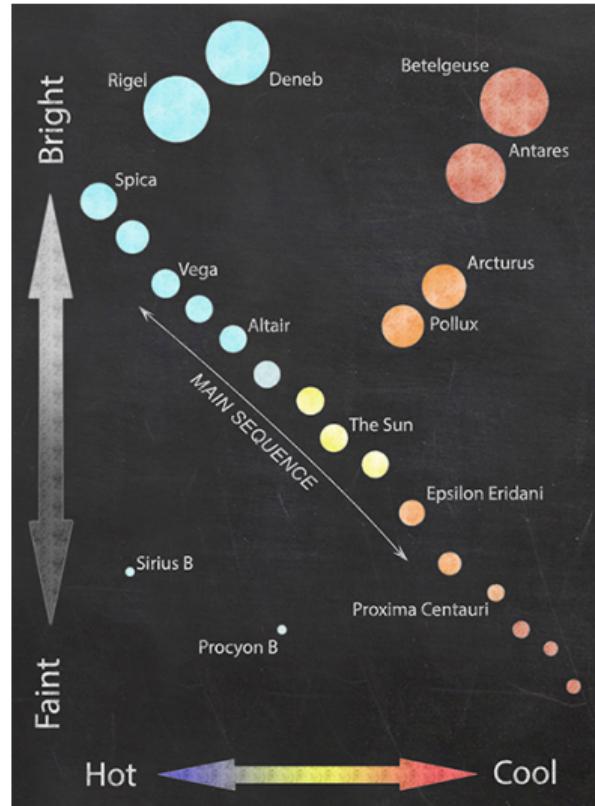
HR diagram: basics

- ▶ There are three groups of stars.
- ▶ For one (main sequence) the color and brightness are somewhat correlated.
- ▶ Other is very hot but faint - white dwarves
- ▶ The last is cool but bright - red giants
- ▶ It will turn out these are *phases* in stellar evolution.



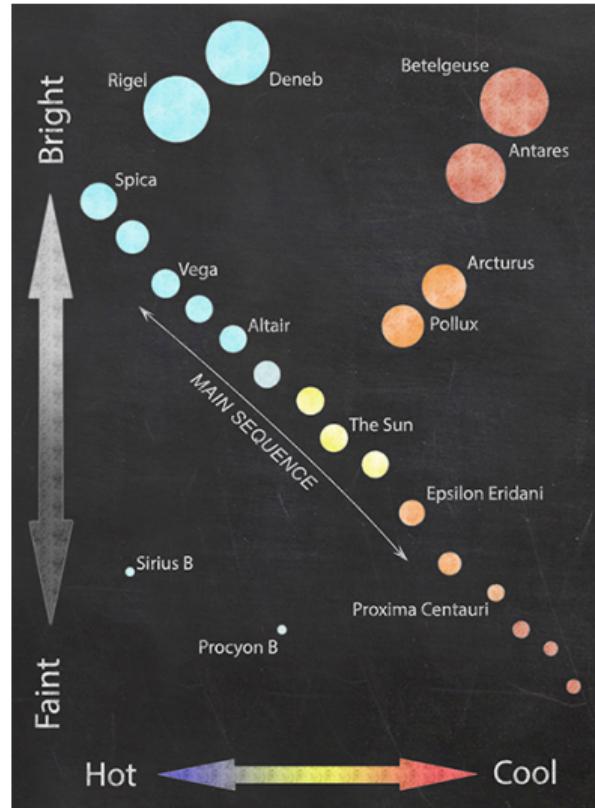
HR diagram: basics

- ▶ It will turn out these are *phases* in stellar evolution.
- ▶ We **can't** observe stars as they evolve and age.
- ▶ But we can observe a lot of stars and try to infer things.
- ▶ It is like aliens observed us very briefly: they would need some time that small, weak humans are a first stage in a lifetime of a human being.



HR diagram: questions

- ▶ Why are the stars on the main sequence correlated?
- ▶ What is the order in the evolutionary stages of these three groups?
- ▶ What determines when and how the star changes between these stages?
- ▶ What are the fundamental differences between these phases?



Credits: the Open University

Back to the HR diagram: if we know the star is on the main sequence

- ▶ Main sequence: hydrogen → helium at the star's core.
- ▶ Question: what forces are competing against each other when two nuclei fusion to form a new one inside a star ?
- ▶ If we measure the luminosity and T_{eff} we can place the star along the main sequence and determine its radius R and mass M (direction of variation of radius and mass)
- ▶ Question: which stars do you think will run out of hydrogen (by converting it into helium) faster ? large mass or small mass ?



Credits: New Jersey Institute of Technology, US

Element abundances in the Universe (i.e. also stars)

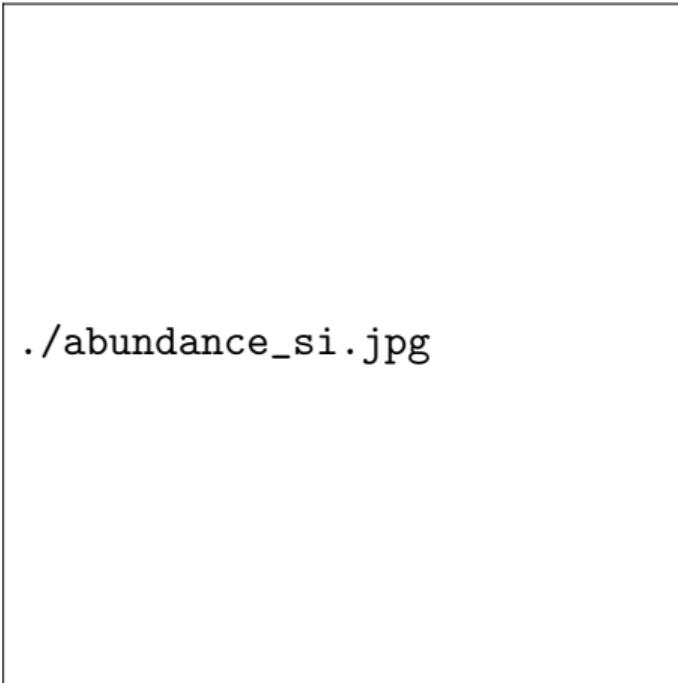
- ▶ Question: consequences for life and biological evolution
- ▶ Question: how was this figure determined ?

./The-relative-abundances-of-elements.html

Credits: Goldschmidt 1938

Of course it's the spectra!!

- ▶ Determination of the Silicon Abundance by fitting the solar spectra
- ▶ Dots: observations; dashed/solid: low/high Silicon abundance.



./abundance_si.jpg

Credits: Borrero et al. 2003