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

Petri Käpylä Ivan Milić
pkapyla,milic@leibniz-kis.de

Institut für Sonnenphysik - KIS, Freiburg

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Why the Sun and the stars?

- The aim of this course is to show you how the Sun and stars "work". That is, what physical principles determine their structure, evolution, observable characteristics and phenomena taking place inside.
- It is a mostly theoretical / computational course - but we will make connections to the observables (today, for example).
- Stars are building blocks of the universe (stars make up galaxies, which make up the large-scale structure).
- Stars generate magnetic fields, host planets, create elements heavier than Helium, trigger creation of other stars - and are, in general, very cool thing to research.
- The Sun gives Earth *a lot* of energy, determines the space weather conditions and, from a more fundamental aspect - gives us insight into how other stars function.

Who are we and what do we do?

- We come from Institute for Solar Physics - KIS.
- KIS conducts fundamental research on the Sun and similar(ish) stars, develops instruments and computer codes and operates telescopes and the science data center (SDC).
- In practice, our institute works mostly on:
  - High-resolution observations of the solar "surface" phenomena.
  - Diagnosing physical properties of the solar surface, most importantly the magnetic fields.
  - Understanding the convection in Sun and other stars.
  - Reproducing solar and stellar interiors and surface phenomena using numerical simulations.
- And the two of us... Present and discuss 5 mins.

How will this course work

- Lectures once per week (2×45 min): 12 lectures + 1 general practice session at the end, before the exam.
- Hands-on exercises once per week (2×45 min): calculations / derivations on the blackboard or numerical calculations / data manipulation in *python*
- 4 Homeworks (HW) covering similar material to handson. You will have 2-weeks per homework.
- So, it would be good if you had an access to a computer, in order to complete the HW. Would be nice to type it up and send it as pdf. Reach out if there are issues.

Grading

- Attendance - 10% - this is to motivate you to come.
- Homework - 40%
- Final exam - 60%
- That's right - you can score more than 100% - this gives you some flexibility.
- There is no "curve grading".
- Whenever there is an issue - ask. You can reach out to us via e-mail or even phone :-)

Literature/materials

- “An introduction to the theory of stellar structure and evolution”, Dina Prialnik, 2007, CUP
- “The Sun: an introduction”, Michael Stix, 2002, Springer
- When needed: research papers and texts. It would be good to familiarize yourself with some services:
- One is ADS - a searchable database of astronomical papers
- The other is github - a repository for codes
- Finally, there is overleaf - an online manuscript editor / manager

To summarize

- Whatever you can't find, are unsure about, or don't understand - ask!
- The goal is to learn new things and hopefully have some fun.
- You are welcome to come see our institute, talk to us about science, ask us for research projects, etc.
- Do you have any questions? (Use this time to collect the contacts and establish a mailing list).
- Note: currently KIS IT is down due to the move. Slides are at a public github.

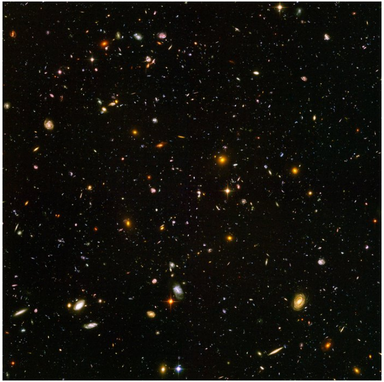
Astrophysics

Astrophysics is (literally) physics of stars. It also studies: planets, small bodies, galaxies, interstellar and intergallactic medium, etc. It gives us an opportunity to apply almost all fields of physics, to understand these specfic objects. It involves concepts from many other sciences:

- Physics: quantum, atomic, molecular, nuclear, thermodynamics, fluid dynamics, magnetohydrodynamics, relativity.
- Chemistry, biology.
- Applied mathematics, optics, photonics, solid state (detectors, etc).
- Also involves/overlaps with: cosmology, celestial mechanics, particle physics...

Uniqueness of astrophysics

- In the lab we can control the parameters of the experimental set-up to see how results change.
- In astrophysics this is impossible. We can only observe. Some of the first objects we observed were the Sun and stars.
- But the physical laws are universal: 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 pecularities, 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

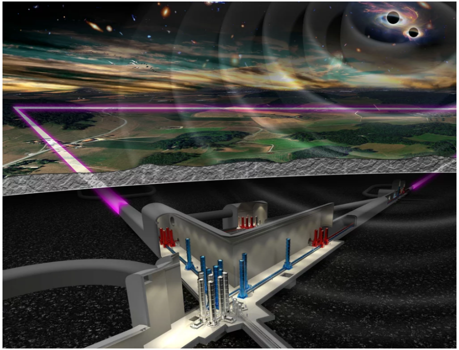
Remote sensing

- 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 electromagntic 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

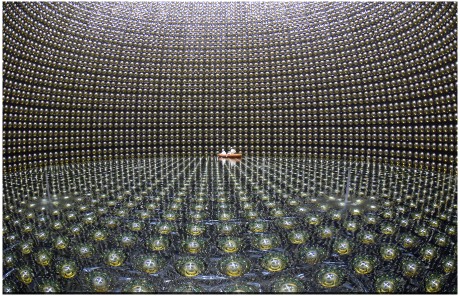
- Existence of the neutrino first postulated by Pauli (1930) to conserve energy and momentum during β-decay. First detection by Reines & Cowan (1956). Nobel in 1995.
- Neutrinos are produced in the interior of stars as a consequence of nuclear reactions (i.e. p-p chain)

$$\boxed{4\,{}^{1}H^{+} + 2e^{-} \rightarrow {}^{4}He^{2+} + \nu_e + 27.63\ \mathrm{MeV}}$$

- 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 Superkamiolande 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 th 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 $\mathrm{W/m^2}$. How much energy does Sun produce per second? (Ask for any constants you need).

The light and the electromagnetic spectrum

- 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).
- Answer:

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

Effective temperature

$3.846 \times 10^{26}\mathrm{W}$ 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 $T = 5777\,\mathrm{K}$.
- What temperature would this be?
- What does this question even mean?

Departures from the ideal case

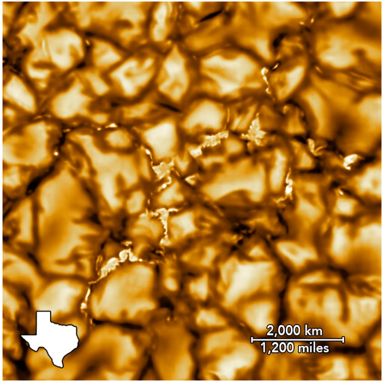
We made a series of approximations in the process of inferring this temperature.

- 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 on scales from seconds to billions of years.
- **This course is about all these aspects**



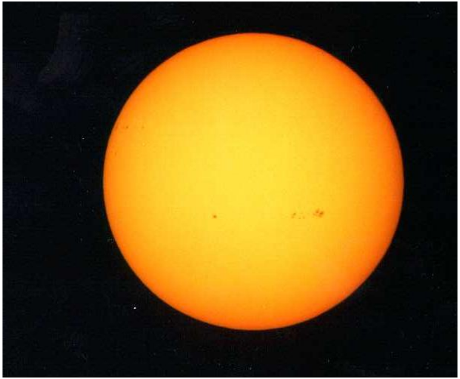
Credits: NSO/AURA/NSF/DKIST

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 the stellar atmosphere help?

Why study the stellar atmospheres?

- Are there ways to probe the stellar interior? Can the stellar atmosphere help?
- Stellar structure determines the structure of the atmosphere, and $T_{\rm eff}$.
- 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 leaves an observable imprint on its surface.**

Understanding the stars

- **The structure of the whole star leaves 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).

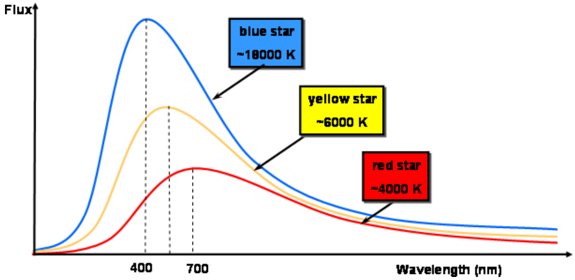


Figure: Planck curves for blackbodies of different temperatures. Credits: University of Swinburne

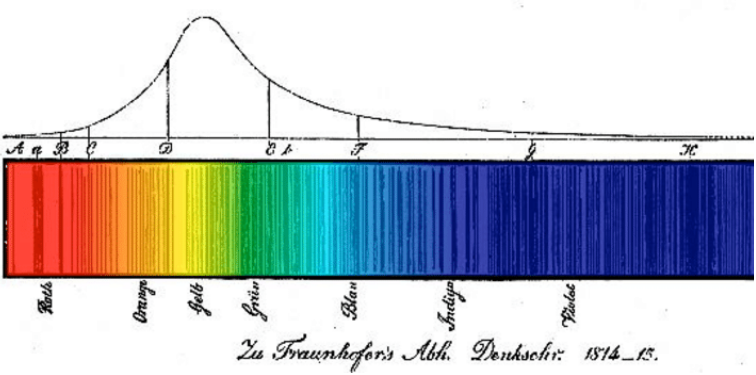
A side quest

- 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.

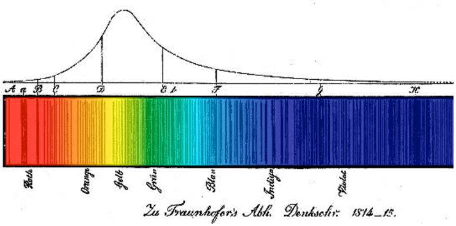
Solar spectrum is NOT a blackbody spectrum



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



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- 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

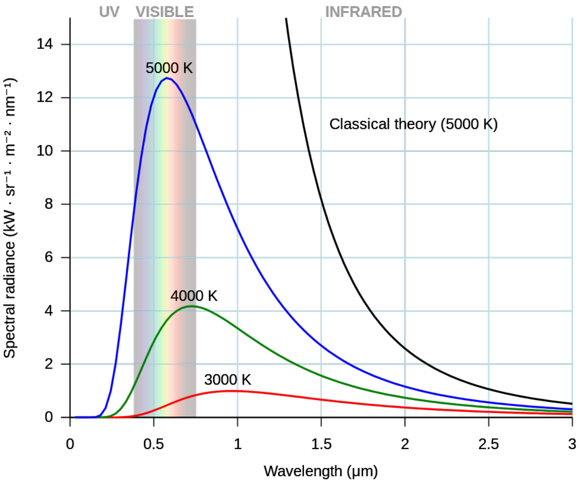
- Kirchoff (again) reckognized the importance of an universal law that connects emission and absorption properties of a medium in an equilibrium state. - *"... It is of utmost importance to derive this law theoretically"*.
- We had some pieces - Stefan-Boltzmann law that we just talked about...
- ... 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 approaces to derivation were made (for example one by Bose and Einstein).

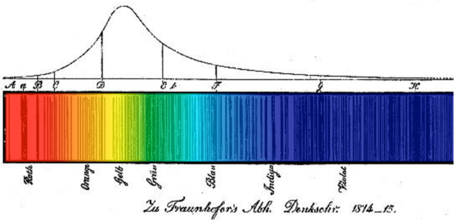
$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1} \quad (3)$$

- 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



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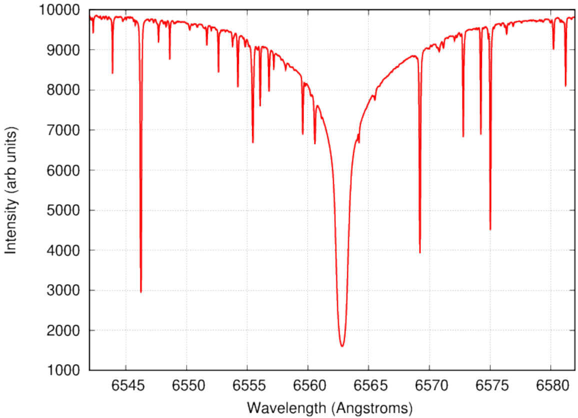
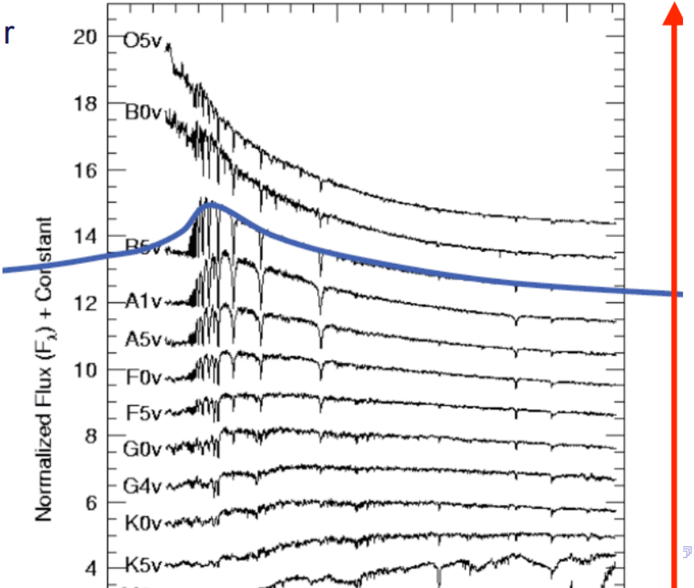
Today we can do better than 200 years ago ...



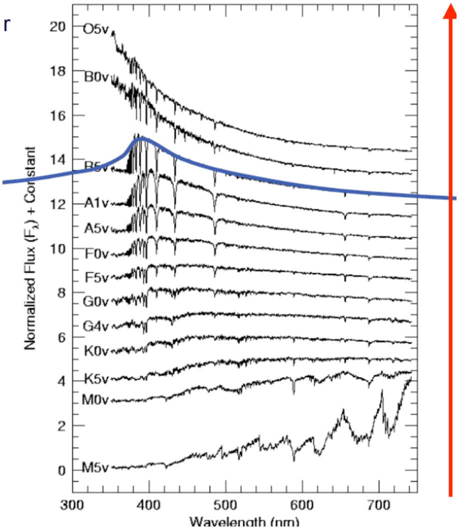
Hα spectral line in solar spectrum: notice all the weak spectral lines around!

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?

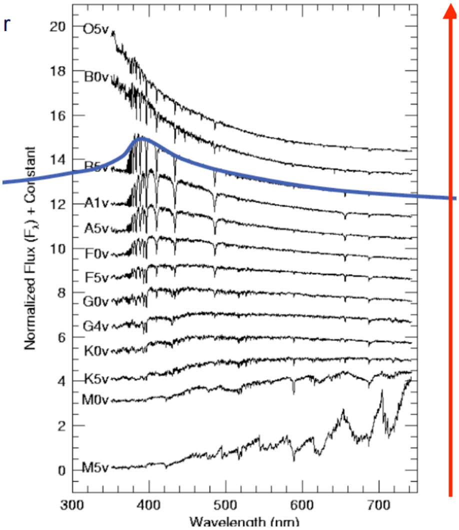


Credits: Adam Burrows, Princeton

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?

It is the temperature! It determines the ionization and excitation of the particles and thus their absorption/emission properties.



Credits: Adam Burrows, Princeton

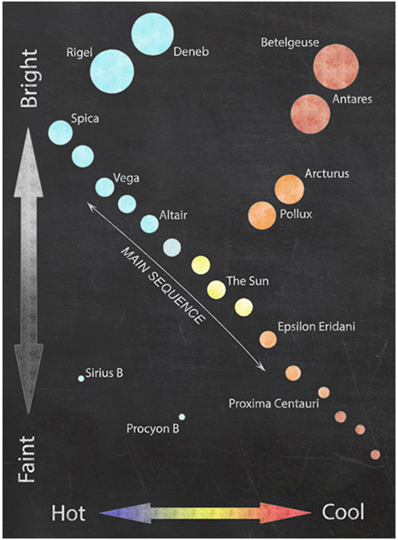
The Harvard Spectral Classification

Class	T_{eff} [K]
O	$\geq$ 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

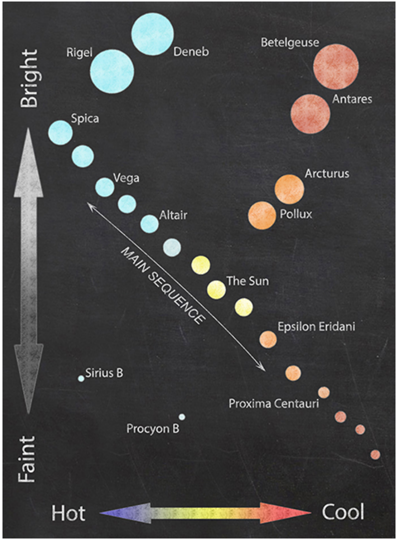
- There are three groups of stars.
- For one (main sequence) the color and brightness are somewhat correlated.
- Other is very hot but faint - white dwarves
- The last is cool but bright - (red) giants (there are also other giants).
- It will turn out these are *phases* in stellar evolution.



Credits: the Open University

HR diagram: basics

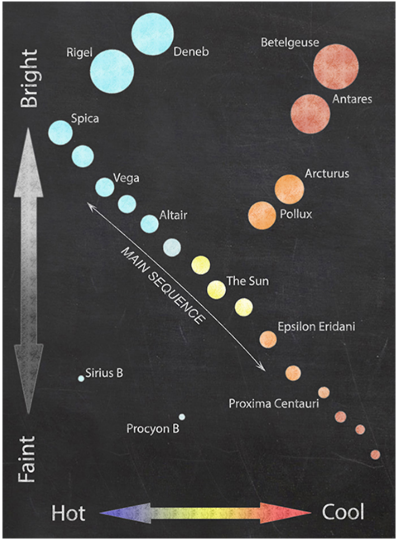
- It will turn out these are *phases* in stellar evolution.
- We **can't** observe stars as they evolve and age.
- But we can observe a lot of stars and try to infer things.
- It is like aliens observed us very briefly: they would need some time that small, weak humans are a first stage in a lifetime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



Credits: the Open University

HR diagram: questions

- Why are the color and the brightness of the stars on the main sequence correlated?
- In which order these evolutionary stages take place?
- What determines when and how the star changes between these stages?
- What are the fundamental differences between these phases?



Credits: the Open University

How can we infer other stellar parameters?

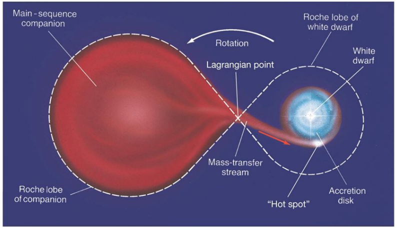
- We saw that we can estimate luminosity from the apparent brightness (irradiance) and distance.
- And that we can infer the effective temperature from the color.
- Combined, these two give us the radius (an estimate of).
- Write down the equations again if necessary.
- What about the mass? Physical composition? Magnetic field? Rotation rate?

Stellar masses

- Are extremely important, yet extremely hard to infer.
- The only accurate opportunity to infer the mass is to observe the star in a dynamical interaction.
- For example in a binary system.
- These binary stars are very important, a big fraction of the stars are in binary (or multiple systems).
- The stars can also interact with each other.

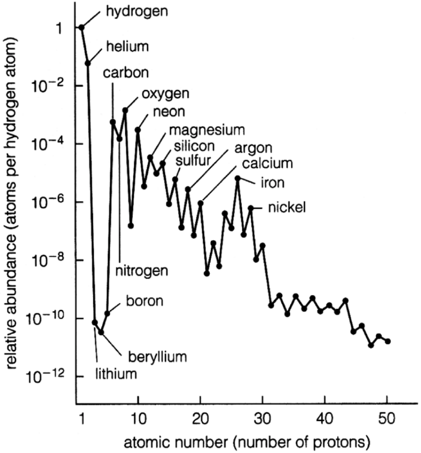
Life after Death for White Dwarfs

A white dwarf that is part of a semidetached binary system can undergo repeated explosions!



Element abundances in the Universe

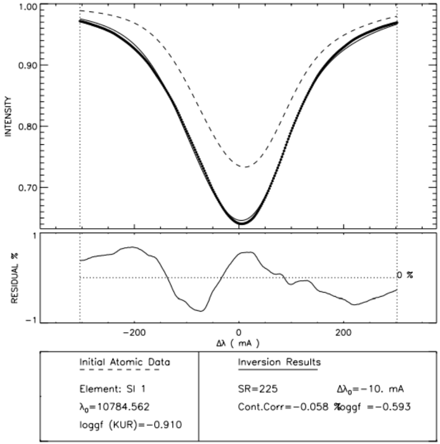
- Most of these elements were generate in stars.
- But they also have implications for generation and evolution of other stars?
- Let's have a relaxed discussion on importance of heavier elements.



Credits: Goldschmidt 1938

These abundances are inferred from the spectra

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



Credits: Borrero et al. 2003

Question to think about

- We said that the effective temperature of the Sun is 5777 K.
- We also said that this temperature is not constant, but must be increasing inward, in order to drive energy flux outward.
- What is the temperature in the core?
- What is the source of energy?

Answer

- The temperature at the core is $\approx 1.5 \times 10^7$ K. And the source of energy is nuclear fusion of H in He.
- How do we know? It took us some time.
- First one to even think about this was Eddington. (Maybe check this paper by H. Kragh).
- The previous idea was graviational contraction.
- The temporal scale for such a process is the **Kelvin-Helmholtz timescale**.

Kelvin-Helmholtz timescale

- Let's do an order of magnitude estimation:

$$t_{\mathrm{KH}} = \frac{GM^2}{RL} \tag{4}$$

- For the Sun this amounts to 30 million years.
- We knew back then already that Earth is billions of years old.
- It had to be something else!