400A - Introduction

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Materials: chapter 1 of Onno Pols' lecture notes.

Introduction to the course

Figure 1: Word cloud of the students' expectations for what they are going to learn in this class (Spring 2025 semester).

Who am I?

My name is Mathieu Renzo, I have been an assistant professor here at Steward since last year. Before, I was a postdoc in New York city (at the Flatiron institute and Columbia University), and before that I did my PhD at the University of Amsterdam in the Netherlands – but I am originally from none of these places!

The topic of this course is stellar evolution, which is my research field. More specifically, I work on the evolution of massive stars in binary systems. These are the stars that end their lives in *supernova explosions*, that can outshine briefly an entire galaxy. During these explosions some of the most exotic objects in the universe are formed, neutron stars or black holes (especially if the explosion fails!). The massive star progenitor of these objects are found most often in binary systems, meaning there are two stars orbiting each other, and they can, as they evolve, interact and exchange mass and sometimes merge. My research is strongly embedded in the topic of this course (stellar evolution) and touches on explosion physics, X-ray binaries, gravitational waves, etc. I will try to connect the course material to all these topics whenever possible!

Also, my research field (and more broadly the scientific topic of this course) is *very computationally oriented*. Throughout the course, I will try to highlight what is the result of computer models based on necessary (but often grossly oversimplifying) approximations and what is more solidly grounded in observations. We will do this by having computational exercises, that's why I asked about your confidence in your ability to make plots in the survey. We will start the course by going over the physical foundations, but I will also ask you to use your own computer models too.

Aim of the course

To understand the structure and evolution of stars and their observational properties using known laws of physics.

Expectations

This is a core course during your 4^{th} year, so you are approaching the academic threshold beyond which you will be **expected** to carry out independent work (either in your thesis, in the future as graduate students or highly skilled professionals).

My idea for this course is to not only provide *content* regarding stellar physics and evolution, but also to help you develop skills as independent researchers for your future (whether in academia or elsewhere).

For this reason also *I will not check your attendance*. However, during the lectures I will present things in a way that complements the textbook(s), and you will more likely have a better understanding if you attend. Also, as we'll discuss in a moment, in-class participation will count for up to 20% of your final grade, so if you want more than a B you should come **and actively participate**.

An important thing to keep in mind as we go through the semester is to have a growth mindset: we are all here to learn and improve ourselves! Grading will particularly reward improvement, so a failure at some point (of one homework) is just an opportunity for improvement – not a career stopping tragedy.

Similarly, I expect everyone in the class to treat each other with respect and kindness. We don't all come from the same background, we don't all need to be at the same exact level to learn from each other. Ultimately, you are here to learn some science and *science is a team effort*. It has been proven many times over that diverse teams achieve better results. Start practicing this now: if someone is struggling with some material that you think you have under control, help them. They are not slowing you down, but giving you an opportunity to verify and deepen your knowledge by engaging with them and the difficulties they may be experiencing. You may soon be the one in difficulty yourself and give them a chance to "repay". In the end we will all be better thanks to this dynamics.

Stellar evolution is also a very vast topic, and there is too much to cover in only one semester, with many bleeding edge developments. So I will ask **you** to teach your peers some of the topics that don't fit within the main part of the course. You will also evaluate (and be evaluated) by your peers. This is because the ability of giving constructive and helpful feedback is important in science and beyond: you will work with others and need to help them improve, and you will receive feedback yourselves for the rest of your careers whatever they may be. We will do this through a project, that we will discuss later.

Discuss syllabus

Figure 2: Link to syllabus

Let's start finally talking about stars!

What is a star?

- Historical definition: *flickering light source in the sky with no intrinsic motion* (where flickering excludes planets, and no intrinsic motion excludes planets *and* other solar system objects such as comets and asteroids).
- More modern definition: *self-gravitating amount of gas that at some point is sufficiently hot for nuclear fusion.*

Note that the requirement of nuclear fusion is **extremely new**: only about 100 years old! A lot can be learned about stars without knowing anything about nuclear fusion, which we will treat, but much later in the course.

N.B.: Definitions often try to "pidgeon-hole" nature into specific categories, but often nature is more elusive. In the case of the "modern" definition of star above, there is the boundary case of Brown Dwarfs, which are self-gravitating amount of gas that early in their life may do some deuterium burning. This burning does not release a lot of energy (the deuterium nucleus, a proton and a neutron bound together, has very low nuclear binding energy), thus these objects sit at the boundary between planets and stars.

What determines the properties of a (single) star?

1. **Mass**
2. Chemical composition
3. Presence of other stellar companion(s)
4. Rotation
5. Magnetic fields

- **Q**: what is a star made of? Can you think of a star made of something else? Mention Cecilia Payne-Gaposchkin.

Observations

- Photometry
- Spectroscopy
- Astrometry
- Asteroseismology (either through photometry or spectroscopy)
- Neutrinos

Parallax

In astrophysics (and in stellar physics in particular) we still use quantities and units that have mostly a historical justification (one could say for "backward compatibility" to borrow software development language).

The yearly apparent motion on the sky of stars (w.r.t. to farther stars that are too far to exhibit this behavior) due to the orbit of the Earth around the Sun is called *parallax*. A commonly used unit of distance in astronomy is the *parsec* = distance of a star with a parallax of one arcsecond:

1 pc $\simeq 3\times10^{18}$cm $\simeq 2 \times 10^5$ AU $\simeq$ 3 light years

This is a measure of distance that can be used for stars with relatively small distances to the Solar system.

Proper motion and radial velocity

We can also see how stars move in the sky, but we need two different techniques to measure the velocity *on the plane of the sky* (so called proper motion), and *towards* or *away* from us (so called "radial velocity", as in the radial direction in a sphere centered on the observer).

But even before considering those, we need to remove all the apparent motions due to the Earth rotation:

Figure 3: Long exposure picture showing circular tracks along the north direction. These are just the reflected motion due to the rotation of the Earth. Note the stars have different colors! Credits: G. Inchingolo.

We also have to remove the apparent motion due to the orbit of the Earth around the Sun, and the motion of the Sun and solar system across the Galaxy (which includes a component of "peculiar motion", that is a deviation from the galactic rotation curve).

Once all that cleaning is done, we can see the intrinsic projected motion of a star on the sky, so called *proper motion* (sometimes indicated with μ or pm). All that requires is a long timeline (since $\mu \simeq \arcsin((\mathrm{v}_{\parallel} \times \Delta\ \mathrm{t})/\mathrm{d})$ with $\mathrm{v}_{\parallel}$ transverse velocity (i.e., on the plane of the sky), Δ t time baseline and d distance of the star, and a reference frame.

N.B.: The proper motion is an *angle on the plane of the sky per unit time*. Converting proper motions to physical velocity requires knowing the distance d, which is usually hard! Moreover, d is very large typically (d $\gg$ 1 pc), so measuring μ requires long time baselines and very accurate instruments.

For the motion orthogonal to the plane of the sky, that is the motion away/towards the observer, that is the so called *radial velocity* (RV) through the Doppler shift of spectral lines (we will talk more about these later in the course). These sometimes can be periodic and thus caused by either pulsations of the stellar atmosphere or Keplerian orbital motion around a (possibly unseen) com-

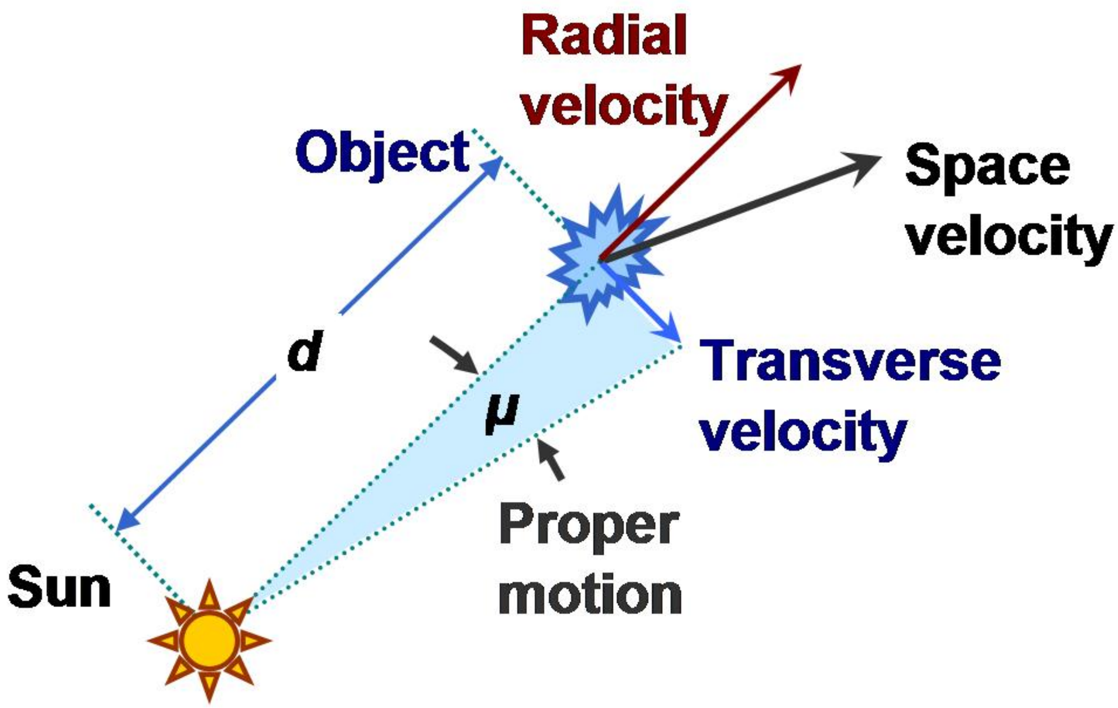

Figure 4: Schematic representation of the proper motion

panion star, or they can be constant (on timescales much shorter than the period of the orbit of the star around the Galactic center) and thus reveal intrinsic motion. In general, one does not look at just one spectral line, but a "series" of lines (e.g., the series coming from all the transitions of electrons across energy levels of a specific ion).

Magnitudes

The magnitude scale is a logarithmic scale first introduces by Hipparchus, who clearly was only able to do naked-eye observations. This explains why a logarithmic scale: the sensory responses are often logarithmic (see Weber-Fechner's law). The magnitude scale was formalized by Pogson 1856.

The magnitudes measure the energy flux from a point-like source (like a distant star) and it is a differential measure relative to some standard source. Hipparchus was comparing the visual brightness of various stars visible in the sky. This is still the basis of (some) magnitude systems. In reality. typically magnitudes are provided integrating over a range of frequencies (photometry!) accounting for the response of a filter as a function of wavelength T(λ):

$$m = -2.5 \log_{10}\left(\frac{\int T(\lambda) F_\lambda d\lambda}{\int T(\lambda) d\lambda}\right) + m_0 \quad , \tag{1}$$

where m_0 is the reference magnitude, F_λ is the monochromatic flux of the source, and the factor of -2.5 is chosen so that the magnitudes measured this way roughly agree with Hipparchus'. *An increase of 5 magnitudes corresponds to an increase in flux of a factor of 100.*

The *bolometric* magnitude is the magnitude across all wavelengths for an idealized perfect detector ($T(\lambda) = 1 \; \forall \; \lambda$). If the distance of a source is known, we can then infer its intrinsic luminosity from this.

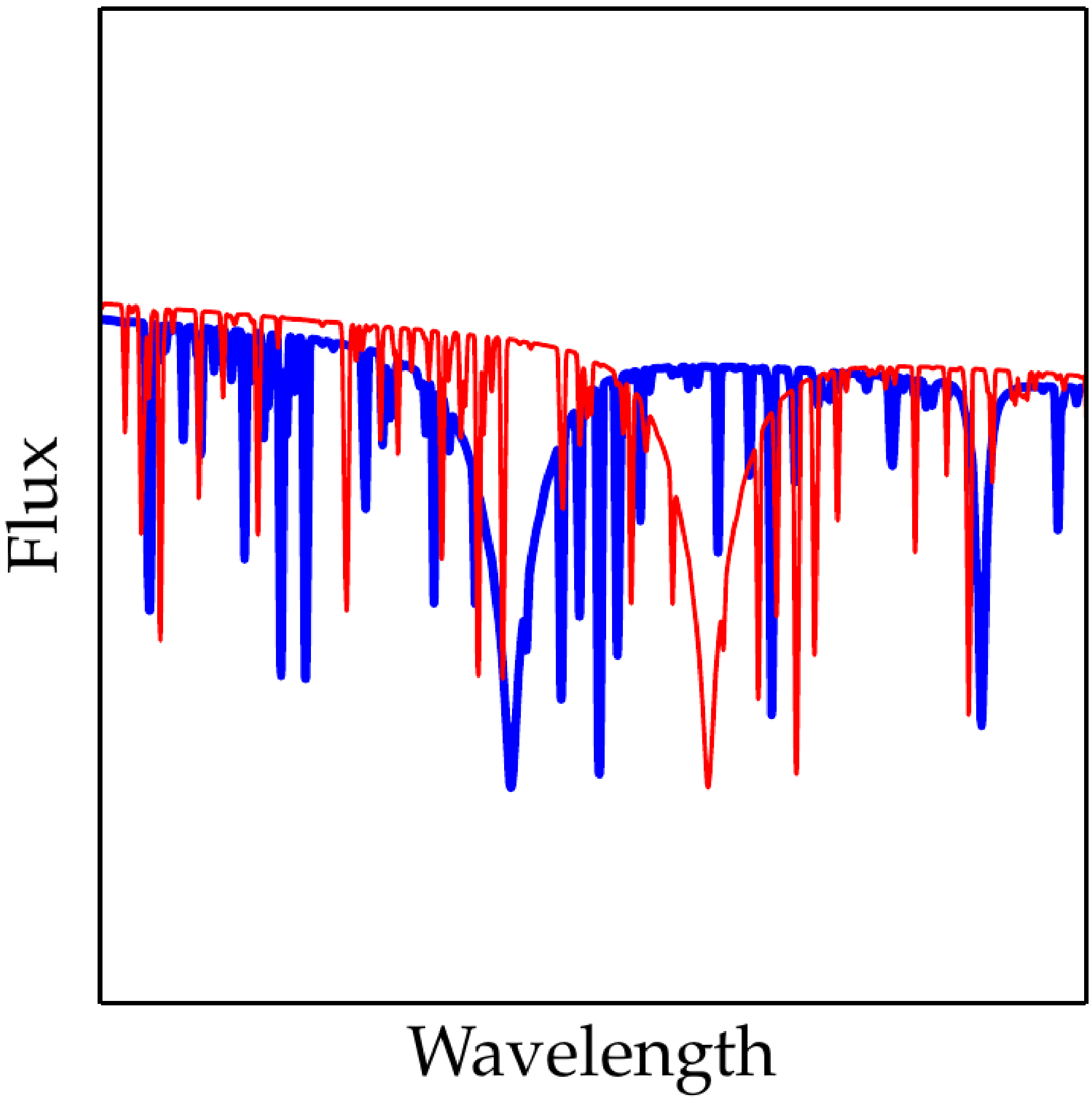

Figure 5: Schematic representation of radial velocity shifts. Credits: Y. Gotberg.

The *apparent* magnitude m we just defined is a measure of the actual photon flux received from a source (e.g., a star) on Earth, but that of course depends on how far the source is from Earth (a candle in your hand has a higher apparent magnitude than Betelgeuse in the sky!). Therefore, astronomer also introduced the *absolute* magnitude as the apparent magnitude a star would have if it were at a distance of 10pc from the Sun, thus the relation between apparent magnitude m and absolute magnitude M is

$$M - m = -2.5 \log_{10} \left[\left(\frac{d}{10\mathrm{pc}} \right)^2 \right] \tag{2}$$

where d is the distance, and it is assumed there is no absorption of light by the interstellar material.

For the reference magnitude m_0 there are multiple choices (and there are many different magnitude systems because of the $T(\lambda)$ and m_0 choices!). For instance, typically the star Vega (α Lyrae) is used as a standard and by definition its magnitude in U, B, and V band in the Vega-based magnitude system is zero. So for magnitude M=0 we have a specific (i.e., per unit frequency) radiative energy flux of 3.5×10^{-20} erg cm^{-2} s^{-1} Hz^{-1} corresponding to a photon flux of $N_\lambda \simeq 10^3$ photons cm^{-2} s^{-1} A^{-1} for the visual band.

- **Q**: why the square within the argument of the logarithm in Eq. 2?

Relevant physical scales

The star we can observe best is the closest one, the Sun ($\odot$), so a lot of quantities are scaled to those of the Sun in stellar physics and in astronomy more generally.

Solar radius: $R_\odot = 6.957 \times 10^{10}$ cm $\simeq$ $\mathbf{7\times10^{10}}$ cm $\simeq$ $\mathbf{10^{11}}$ cm

- **Q**: How many $R_\odot$ are in 1 AU?

Solar mass: $M_\odot = 1.98 \times 10^{33}$ g $\simeq$ $\mathbf{2\times10^{33}}$ g

Often, for lack of better knowledge available, we assume that the distribution of metals scales with the Solar distribution, sometimes allowing for enhancement of α particles (e.g., carbon, oxygen, neon, and all other elements that can approximately be thought of as N α particles bound together where α particle = nucleus of helium 4).

A common notation is also $[X/H] = \log_{10}[(n_X/n_H)/(n_X/n_H)_\odot]$ where n_X is the number of ions of species X and n_H is the number of protons (i.e., hydrogen positive ions!). Often, [Fe/H] can be used as a proxy for the metallicity (i.e., taking X=Fe).

- **Q**: Any idea why Fe here?

Lifetimes: ~3 Myr to $\gg$ age of the Universe ($\simeq$ 13.7 Gyr)

- **Q**: How old is the Sun? How long will it live? How do we know?

Discuss projects

- Projects will cover topics that are important and or timely, but hard to fit in the main body of the course

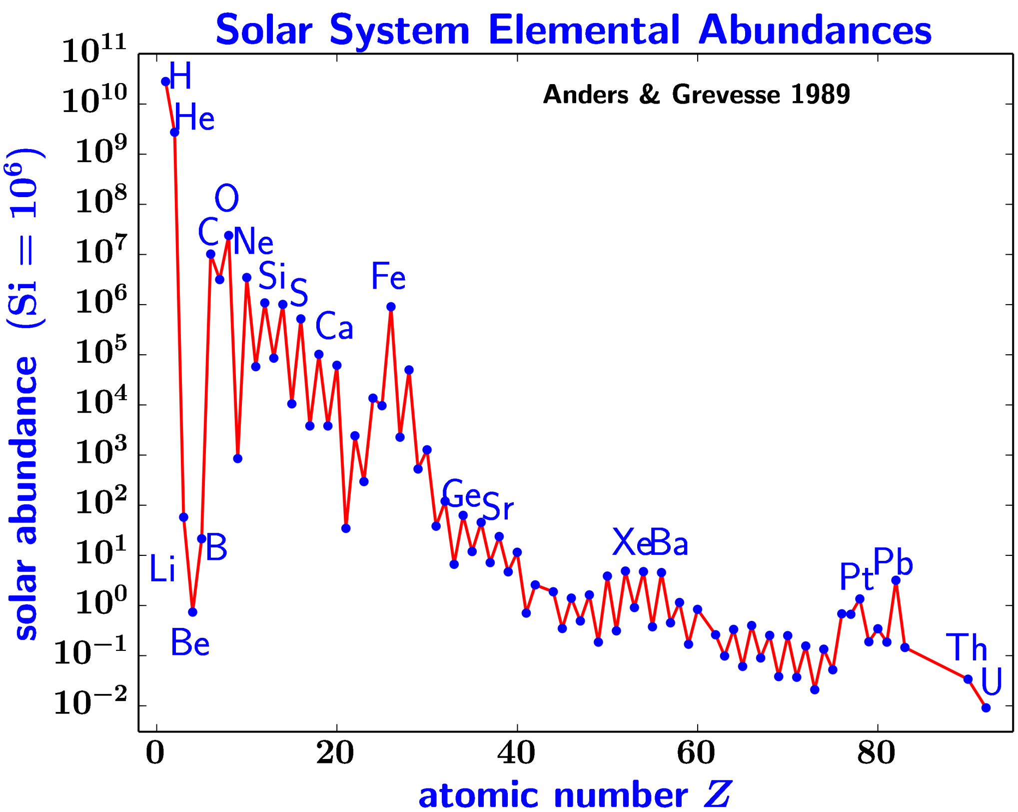

Figure 6: Solar abundance pattern from Anders & Grevesse 1989. This shows the number of atoms normalized to 10^6 atoms of Silicon as a function of atomic number A. Often, for lack of better knowledge, this (or more recent updates to it) is the abundance pattern that is rescaled when changing the metallicity in a model.

- Occasion for you to dig deeper and teach to your peers
- You should look over the proposed project, and give us a ranked list of 5 projects you'd like to do (see D2L for updated deadline).
- After receiving your preferences, we will assign to each a project trying to maximize happiness (though it may not be possible to accommodate everyone), and for each project we will assign two peer referees.
- Look over also how the grading of the project will work: in short, we will evaluate your written summary (together with 2 of your classmates!), your oral presentation in class (again, with your peers!), and how you give feedback to others.

Homework

General considerations

- As per the syllabus, homework should be your own production, though you can discuss with your peers. Science is made of collaborations, but you are expected to be able to do all the homeworks yourself.
- Always consult D2L for official deadlines. If you need an extension, it should be agreed upon at least **one day before the official deadline**.
- Throughout the course the typology of exercises and difficulty will vary. This is normal also when doing research: not every task is as easy/as hard as the next. If you encounter difficulties, keep in mind that it's only an opportunity to grow and improve!

Specific assignments for today

- Calculate the average density of the Sun and compare it with the density of something familiar on Earth.
- Start looking over the list of final projects, you will need to provide a ranked list of 5 preferences. Feel free to search the web/literature to decide. Based on this list, I will try to assign projects and peer-referees, but it may not be possible to satisfy everyone. If you want, feel free to come up with different subjects related to stellar physics as well to propose, but you need to talk to me to get them approved before they can be on your list!