Theoretical Astrophysics I: Physics of Sun and Stars
Lecture 10: The Sun

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

Institut für Sonnenphysik - KIS, Freiburg

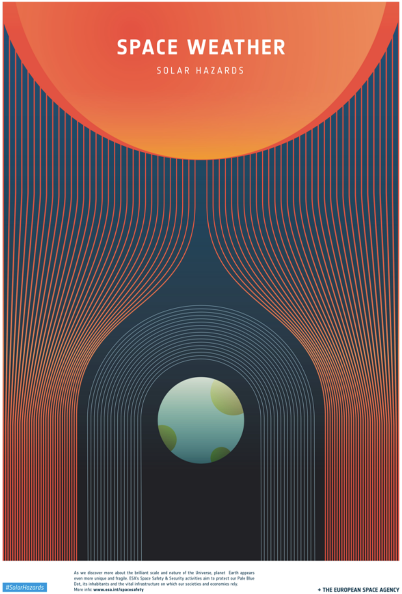
June 25, 2024

Recap

- We talked about the interior of the stars, their spectra and their evolution.
- We now have a rough understanding about what the stars do (they shine).
- Now we turning to an obvious example of a star: The Sun.
- We will discuss a group of somewhat disjointed topics about the Sun - the goal is to present you the solar science but also to outline what makes the Sun unique.
- **Probably nothing - Sun is a fairly ordinary star. But for science - it is absolutely priceless.**

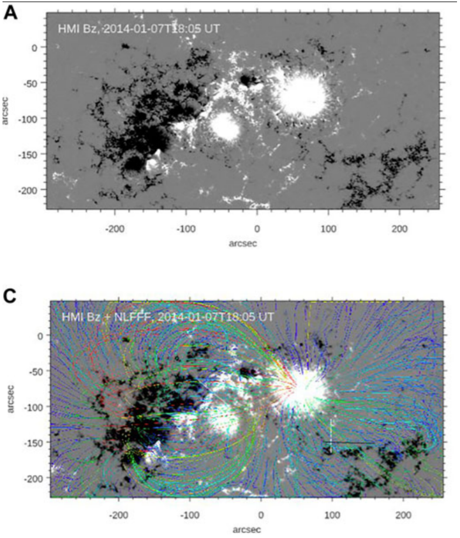
Why is the Sun important?

- Obviously, sunlight is important for sustaining life.
- But also, increased emission of high energy photons due violent explosive processes can be threatening for life on Earth.
- Magnetic fields of the Sun interact with our magnetic fields (geomagnetic storms).
- There are also occasional bursts of charged particles emerging from the Sun and reaching the Earth.
- All this is called: **space weather**.



Why is the Sun important?

- On the other hand - Sun is (almost) the only star that we can resolve.
- Perfect testbed for testing our theories about stellar structure, evolution, stellar atmosphere theory.
- Also for plasma physics, turbulence, reconnection, magnetohydrodynamics.
- Understanding the interaction between Sun and the Earth is the key to understanding exoplanets.
- Overall - understanding Sun better allows us to apply this knowledge (and the techniques to other fields of astrophysics).



Credits: Yurchyshyn et al., 2022

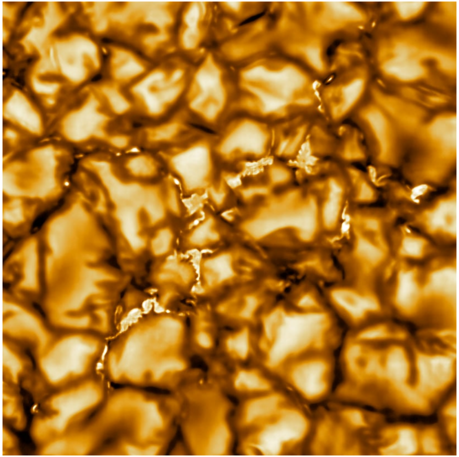
Relationship between solar physics and astrophysics

These are some of the overlaps or common interests:

- Spectroscopy/spectropolarimetry: essential to probe physical conditions in the solar/stellar/planetary atmospheres.
- Helio(astro)seismology: probing the interior regions of Sun and stars.
- Stellar structure and stellar atmospheres: Sun was the first test for these theories.
- Solar and stellar activity: flares, chromospheric events, prominences, etc. also happen on other stars.
- Physics of hot and ionized plasmas: conditions in solar transition region / corona are similar to the conditions in AGN enviroments, HII regions, and other nebulae.
- **And probably more that I am simply not aware of :-)**

How well can we really see the Sun?

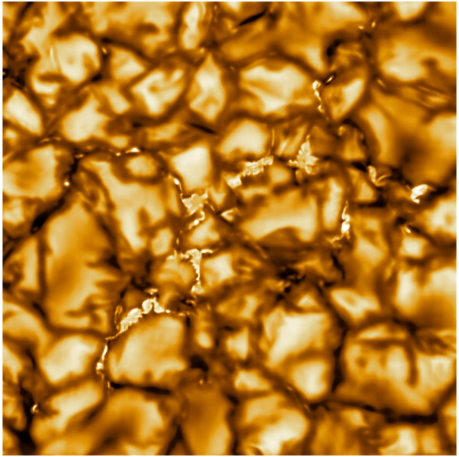
- Right: solar granulation captured by DKIST solar telescope (4m, credits: NSO/NSF/AURA)
- Many questions for you:
- How big would you say is one pixel at the image?
- How many photons does one pixel emit per second?
- How many of these photons reach the DKIST telescope?



Credits: NSO/DKIST/NSF/AURA

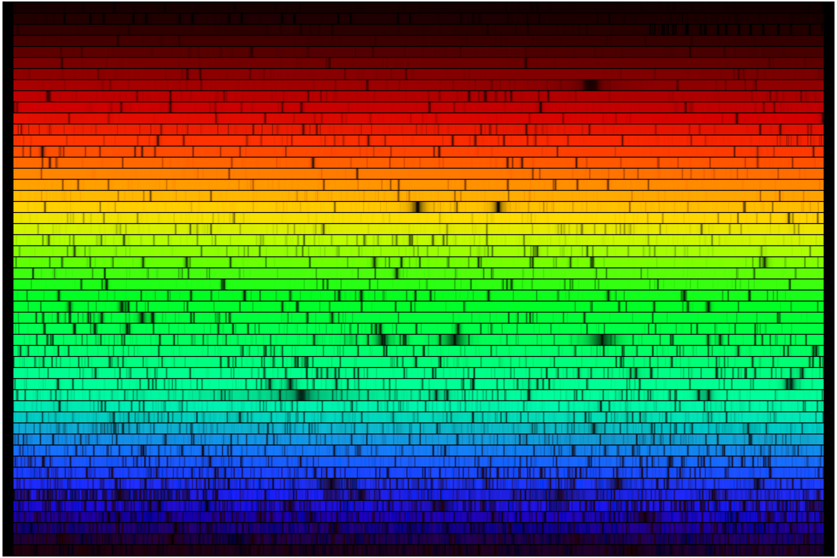
How well can we really see the Sun?

- Right: solar granulation captured by DKIST solar telescope (4m, credits: NSO/NSF/AURA)
- Many questions for you:
- Diffraction limit of this telescope in visible is around 30 km, so these pixels should correspond to around 15 km.
- Apply blackbody law and multiply with the surface of one pixel, number should be huge!
- Apply the blackbody law and find the intensity, then multiply with the solid angle corresponding to surface of DKIST mirror seen from the Sun, number should be much smaller.



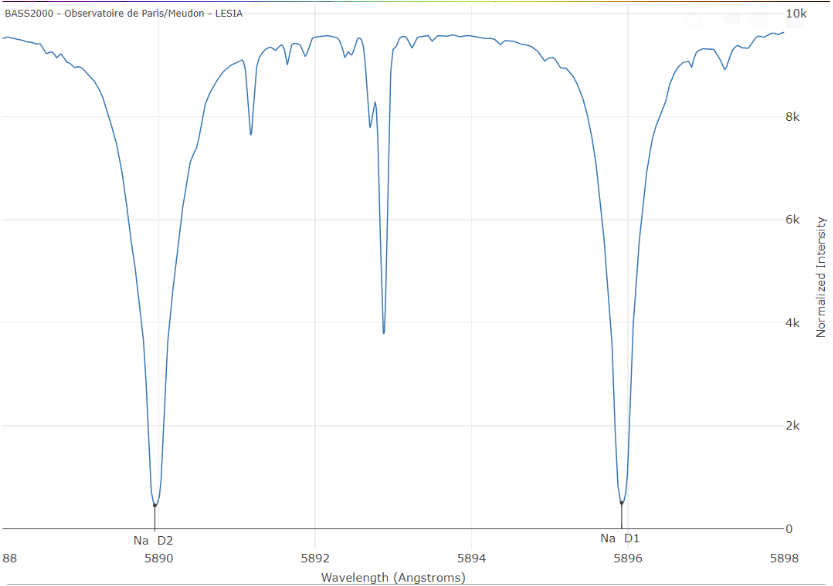
Credits: NSO/DKIST/NSF/AURA

Solar spectrum



Solar Spectrum. Credits: N.A.Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

Solar spectral lines example



Sodium D lines in the solar spectrum. Credits: BASS2000

Spectral lines: bound-bound processes

- Finally, we can talk about the absorption and emission between two bound states.
- This gives rise to the spectral line processes.
- There, the opacity varies dramatically with wavelenght. We often write:

$$\kappa_\nu = \kappa_0 \phi_\nu \tag{1}$$

- ϕ_ν is the **line absorption profile**. It varies very quickly with the wavelength.

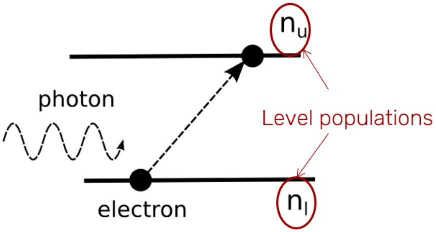
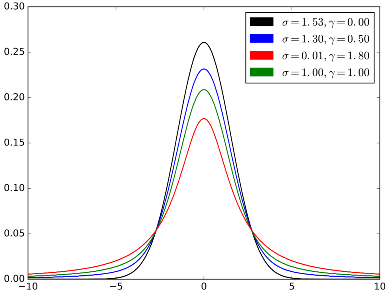


Figure: The photon gets absorbed via bound-bound process. Excited atom then can deposit the energy back into the gas, or emit a new photon, similar to the old one.

Spectral lines: line absorption profile

- In theory, spectral lines should be δ-functions. In reality, delta function does not exist of course:
- First, there is an uncertainty in the energy, leading to a finite width of the energy levels.
- Then, there is perturbation of the energy levels by the environment.
- Then, the particles are moving and thus shifting their absorption profile toward blue and toward red, according to Maxwell velocity distribution, projected onto the line-of-sight:

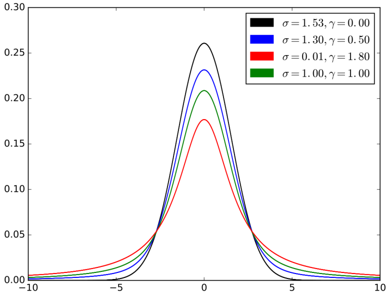
$$p(v) = \frac{1}{\sqrt{\pi} v_D} e^{-v^2/v_D^2} \tag{2}$$



Credits: Wikipedia

Spectral lines: cross-section

- Similarly to the continuum processes, we can always write the opacity as something like:
$$\kappa_0 = \frac{1}{\rho} n_{\mathrm{lower}} \sigma_0 \qquad (3)$$
- Where this σ_0 depends on the nature of the transition.
- It can vary by orders of magnitude (strong spectral lines vs "forbidden" spectral lines).
- What else determines the strength of a spectral line?



Credits: Wikipedia

Spectral lines: cross-section

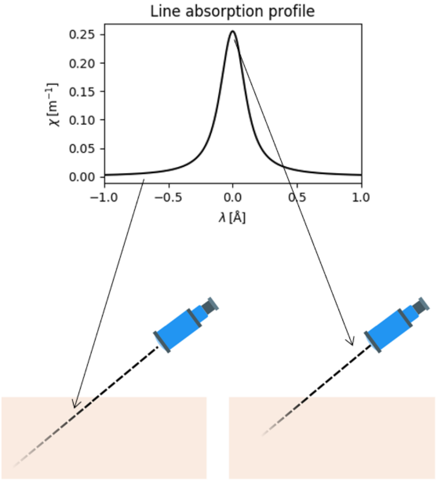
- What else determines the strength of a spectral line?

$$\kappa_0 = \frac{1}{\rho} n_{\rm lower} \sigma_0 \tag{4}$$

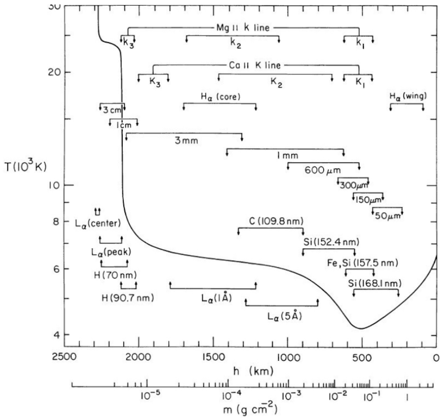
- The number density of the lower level of the transition! Recall the Boltzmann equation:

$$n_{i,j} = n_j \frac{g_i e^{-E_i/kT}}{Q_j} \tag{5}$$

- Here n_j is the total population of that ion, and Q_j is the partition function.
- So, to have a strong line, we need an abundant element, with appropriate ionization state at a given temperature.

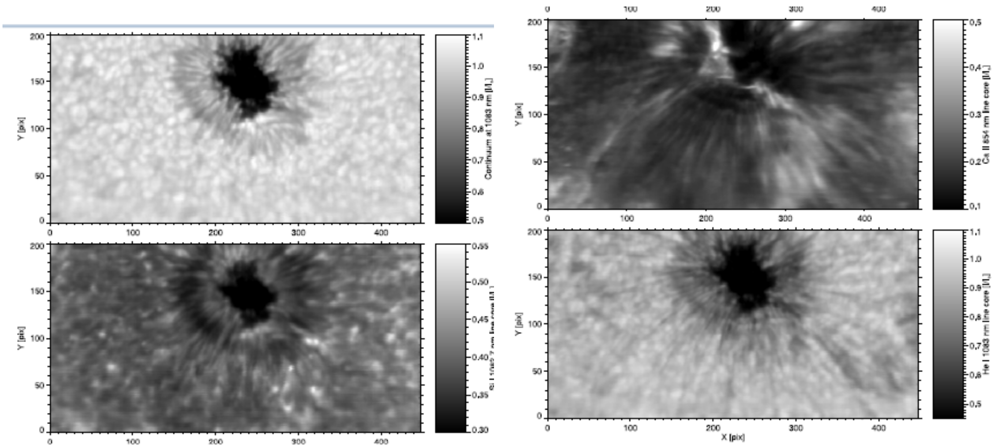


- Stronger line - larger opacity - we see higher layers. We can define something called "height of formation."
- This height gives us a rough idea what layers we see when we observe a specific wavelength in spectral line.
- Remember that different wavelengths in the same spectral line still probe different heights.
- So, even by probing one line only we can do the "tomography" of the solar atmosphere.



Credits: Vernazza et al. 1981

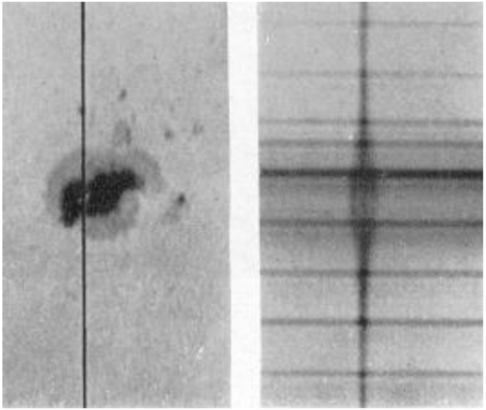
Spectral lines: 3D information



Credits: GRIS team

Spectral lines: Zeeman effect

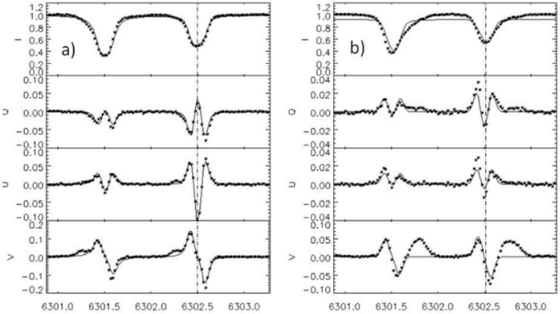
- Around 1920, George Ellery Hale observed the spectrum of a nickel line in the Sun.
- When his spectrograph slit (what is this?) crossed the Sunspot - spectral line split.
- Not long ago, Pieter Zeeman got a Nobel prize for discovering exactly that.
- This was the first “direct” (not literally direct...) proof that Sunspots harbor magnetic fields!
- From the amount of splitting, one can infer the magnetic field.



Credits: Mount Wilson Observatory

Spectral lines: Polarization

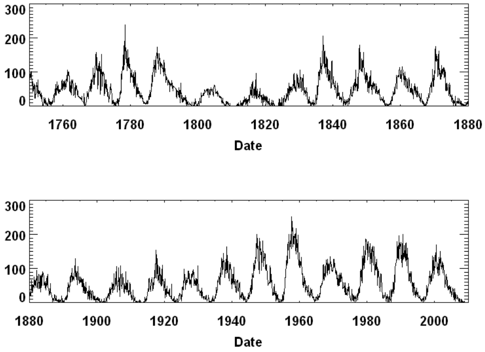
- Today we use spectral line observations to infer the full magnetic field vector.
- The magnetic field polarizes the light at the wavelengths corresponding to a spectral line.
- Different sub-transitions have different polarizations.
- They get split in the wavelength so the polarization does not cancel.
- More about this in the next semester!



Credits: Borrero & Ichimoto (2011)

Counting sunspots

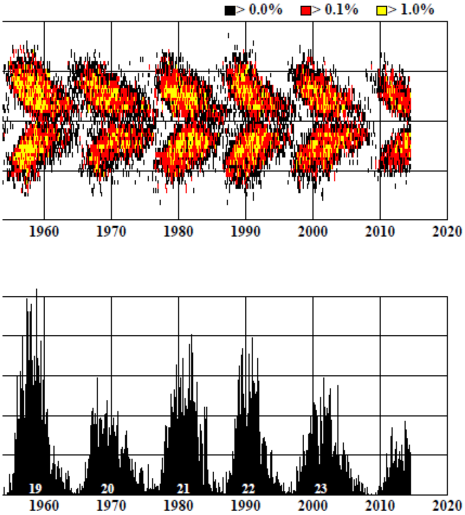
- Even before people have proven that the sunspots are magnetic, they have been counting them.
- First one was Horrebow, from roughly 1750.
- Schwabe discovered a regularity and Wolf introduced so-called Wolf's number (mid 1800s).
- When you look at it now - it's obvious, the Sunspots vary with a period of **11 years**.
- This is the famous **solar activity cycle**.
- Sunspots are magnetic formations, so this means the solar magnetic configuration changes with cycle.



International sunspot number, credits: spaceweather.com

Butterfly diagram

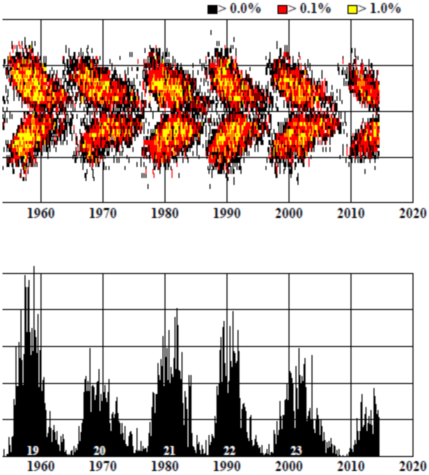
- The next step would be to follow the location of the sunspots on the disk.
- Can you tell me how the spots move over the cycle?



Credits: NASA/MSFC Hathaway

Butterfly diagram

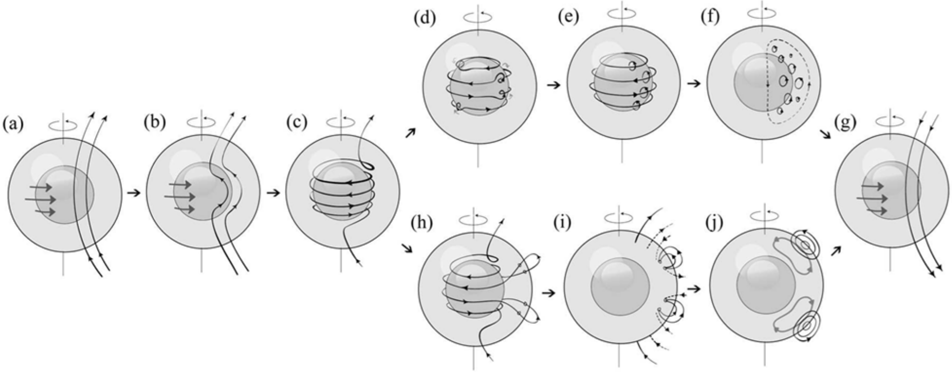
- The next step would be to follow the location of the sunspots on the disk.
- The spots appear on higher latitudes.
- Over the cycle they move more toward the equator.
- Eventually there are no more sunspots.
- The butterfly diagram is a reflection of what happens on the inside.



Credits: Hathaway, 2015

Solar dynamo - schematic picture

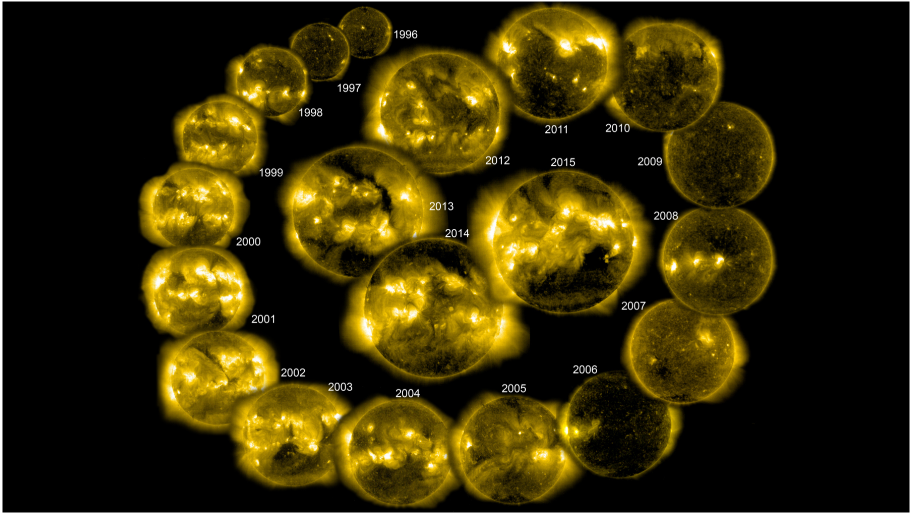
The interaction between magnetic fields and plasma flows periodically changes the topology of the magnetic fields.



Credits: Sanchez, 2013

Solar cycle - the magnetic field

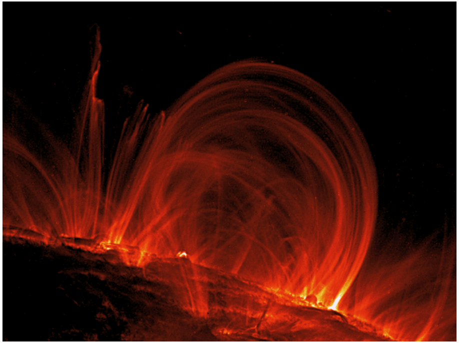
The interaction between magnetic fields and plasma flows periodically changes the topology of the magnetic fields. We can also see that in the solar corona.



Credits: SDO/AIA, NASA

Solar Corona

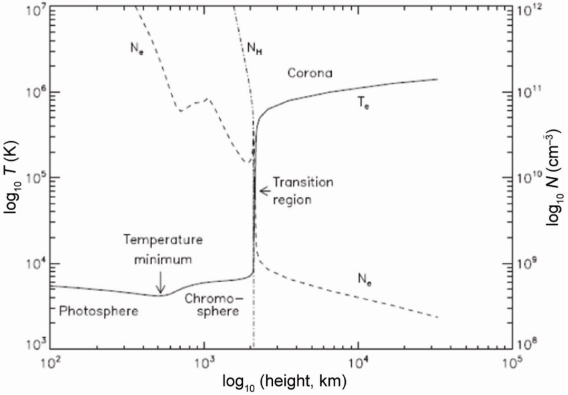
- A hot ($> 10^6$ K) very thin (low density) layer of the solar atmosphere.
- Most of the elements are ionized to a very high degree.
- Because the density is so low - the plasma follows the magnetic field.
- It is much more inhomogeneous and dynamic than the photosphere.
- The coronal magnetic field can be understood through an extrapolation of the photospheric field.



Credits: TRACE/NASA

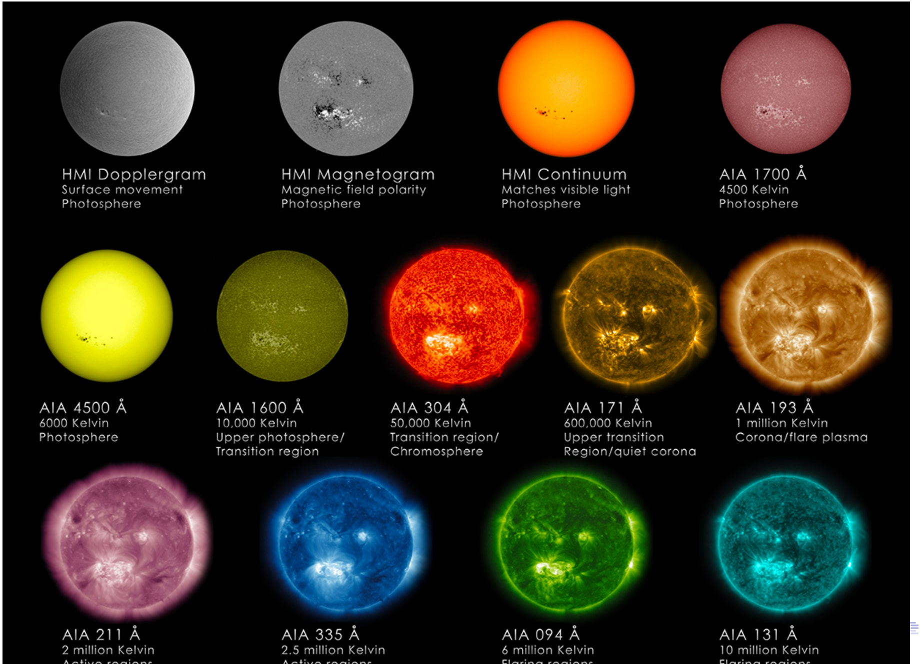
Solar Corona - 1D picture

- A hot ($> 10^6$ K) very thin (low density) layer of the solar atmosphere.
- Most of the elements are ionized to a very high degree.
- In a canonical 1D picture - there is a very narrow region where the density and temperature change dramatically - transition region.
- You can see that the density drops by more than 5 orders of magnitude, over merely 2000 km.



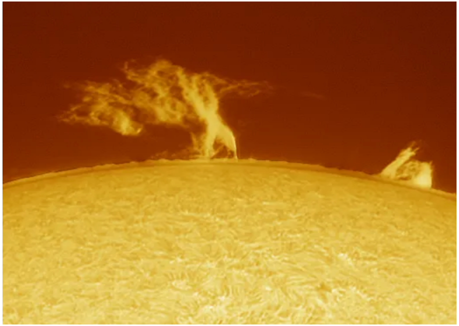
Credits: Aschwanden, 2005

Multi-wavelength view of solar corona



Coronal structures - prominences

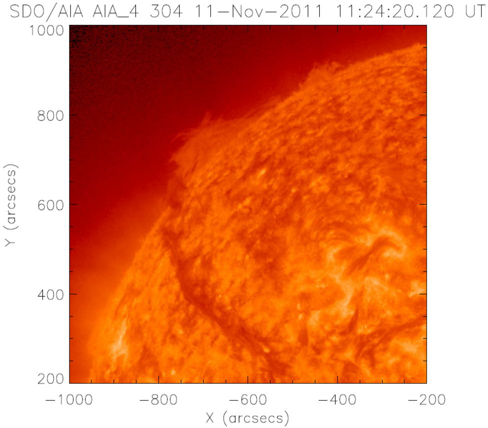
- Right: solar prominences seen "off-limb". These are dense plasma structures in the corona that scatter light from the photosphere.
- They are much cooler and denser than the corona (approx 10 000 kK).
- How are they supported? Magnetic field of course.
- They evolve, become unstable and sometimes explode and give rise to Coronal Mass Ejections (CMEs). Watch the video if there is time.



Credits: André van der Hoeven, HI-Ambacht, The Netherlands. Equipment: Lunt 60/BF1200, NEQ6, DMK21au618

Coronal structures - filaments

- We get another insight into prominences when we see them on limb.
- Then they are seen in absorption and are called **filaments**.
- Radiative transfer related: why do they look different?
- Filaments and prominences are without doubt related to the underlying photospheric magnetic field.
- Understanding and tracking the structure of filaments and prominences is very important for space weather.



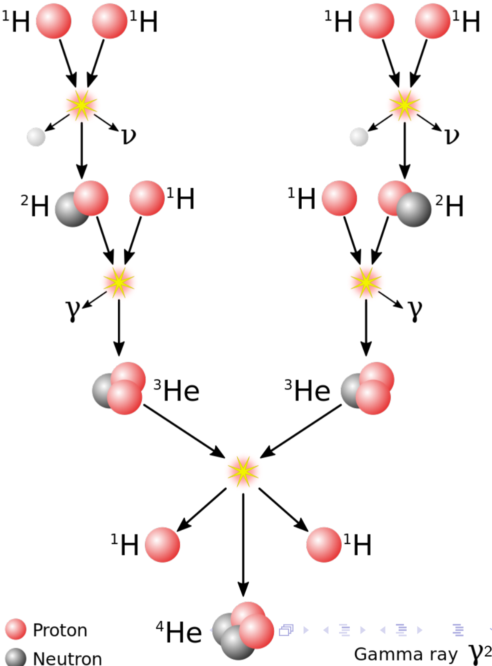
Credits: Parenti 2014, SDO/AIA

Solar neutrinos

- There is an ucommon reaction:

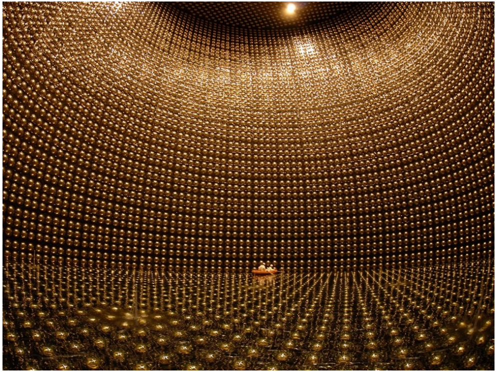
$$p^+ + e^- + p^+ = D^+ + \nu \qquad (6)$$

- Which always produces a neutrino of the same energy equal to 1.442 MeV
- These neutrinos are above the treshold of Cl detectors, and can be detected.
- The solar structure (temperature stratification) determines the flux of these neutrinos.
- Predicted capture rate was around 7 snu. 1 snu = 1 capture per second per 10^36 target atoms.



Solar neutrinos

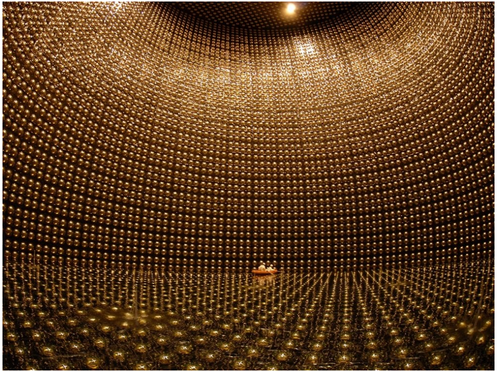
- Predicted capture rate was around 7 snu. 1 snu = 1 capture per second per $10^{3}6$ target atoms.
- Measurement from the experiments at the time (70s) were around **three times lower**, 2.1 snu.
- No standard model of the Sun predicted such a low capture rates.
- Where can the error be?



Credits: Wikipedia

Solar neutrinos

- Either solar model is wrong.
- Or our understanding of neutrino generation is wrong.
- Or our instruments are wrong.
- Or there is something else that happens with the neutrinos.



Credits: Wikipedia

Solar neutrinos

- Turns out that the neutrinos can undergo oscillations, which was theoretically predicted.
- Superkamiokande in 1998 confirmed the existence of neutrino oscillations.
- This yielded a Nobel prize for Takaaki Kajita and Arthur McDonald in 2015.
- This also meant that the models of solar interior are fine.
- It was the **helioseismology** that allowed us to scrutinize these models and confirm that they are indeed sound and that error lies elsewhere.

Credits: NobelPrize.org

Other topics and conclusions

- Of course, these are only some topics I have chosen to talk about. Some more interesting solar questions are:
- What is the nature and origin of sunspots?
- Where does the solar magnetic field come from, what is the role of the small-scale dynamo?
- How do variations in solar irradiance work and how they influence the Earth?
- What is the mechanism of the solar global dynamo and how does it relate to the flows in the Sun?
- Can we model and predict the violent solar explosions taking place in the solar atmosphere?
- Next week, you will hear from Petri about the exicting field or **helioseismology**, that played a bit role in our studies of the Sun.