VII. Observation of the Sun and the Stars

In the next section we will start our investigation of the stars. We will start with our sun, since the sun is

- A typical star and thus a very good example for all other stars
- The closest star and thus can be studied in detail
- The energy source of our solar system

What do we know about the sun? As we will see, the exact knowledge of the parameters of the sun will be very helpful in comparisons with the other stars. We get the right "astronomical meter stick, the right mass normal" etc.

However, we will immediately compare our knowledge of the sun with observations of stars. In order to categorize the stars and to relate them to the sun we have to collect some observational material about stars first. What is easy for the sun to determine, i.e. the distance and the size, seems insurmountable at first glance: the stars are so far away that we only see them as points, even through the most powerful telescope. Which parameters of the stars can we observe under these circumstances?

Slide VII.2

1. Luminosity, Distance and Size

We have to start by making clear what we mean with a few important quantities. When we talk about the apparent magnitude (or brightness) of stars, we mean their brightness as seen in the night sky. This is not to be confused with the absolute luminosity of a star, which refers to the total light output or the rate at which it emits energy. The latter is an intrinsic property of the star, and this is what we will be primarily interested in.

A) Magnitudes

We see bright stars and stars which are less bright. This obvious observation led to a classification of the stars in the sky according to their apparent magnitude (or their brightness in the sky). The Greek astronomer Hipparcos introduced this classification. He divided the visible stars into 6 classes. His original classification was based on the sensitivity of the eye. This led to a scale in which each step in brightness (i.e. one step in magnitude) means an increase by a factor of about 2.5. To make things simple the modern scale has been set such that a step of 5 magnitudes is a factor of 100 in light intensity.

The brightest stars are magnitude 0 and 1 (first class stars), the faintest that we can still see with our eyes are magnitude 6 (sixth class stars). Note:

View VII.1
a higher number means less bright!! (Magnitude scale)

We can measure the light intensity or the amount of radiation from a source (if star or light bulb or whatsoever) with a radiometer. Demo Candle, Flashlight

For a star such an instrument is mounted at the position of the eyepiece and then used in a similar way. View VIII.2

Let us explore what the determination of this light intensity or the apparent magnitude means:

1) If I measure the light of different sources the amount of light is different. So we may have stars with a different luminosity in front of us, i.e. their total light output is different.

2) If I measure the light from the same source but at different distances, the value varies also. Thus we may have stars at different distances. Demo Flashlight View VII.3, a

3) In addition, if there is matter in between, such as interstellar gas and dust, as we just discussed previously, the light is reduced by interstellar extinction. Demo Filter

The latter problem is a bit tricky, because we need to correct for an unknown amount of absorbing material between the star and us. However, from the reddening of the starlight, which alters the star spectrum in a different way than does a variation of the star temperature we can deduce how much matter is between the star and us. Then we can apply this information to correct the results of our measurement. We will revisit this effect in more detail later.

This still leaves us with the ambiguity of luminosity and/or distance variations. In order to obtain the physically meaningful parameter of the star, the luminosity, we must know its distance from the Earth.

B) Distance: \( r = 150 \text{ Mio km} \quad = \quad 1 \text{ Astronomical Unit (AU)} \)

For the Sun the distance can be derived through Kepler's 3rd law, after determining the distance to other planets with the Parallax method. Why do we use Kepler's 3rd law again? As the Sun is a huge gas ball, it is not so easy to determine its distance directly. It is much easier and more precise to measure the distance of any planet from the Earth and then get the distance Earth-Sun through Kepler's 3rd law. For example, the distance to Mars was determined by applying the parallax method. Sketch

Nowadays much more accurate values are obtained using radar. Slide VII.3

We have measured the distances in the solar system with the parallax method and we will make our first step towards the stars with the same method. The non-observation of a parallax of stars, namely their apparent motion in the sky during the Earth's orbit around the sun, posed a big scientific problem to Copernicus' model, but Copernicus himself pointed out that the stars may be so far away that the effect is not observed. He was right! The first star parallax was not observed before 1837, when Bessel determined the first distance of a star. He measured the parallax with the orbit of the Earth as the baseline (largest baseline possible) View VIII.4
The position of a relatively close star in the sky with respect to other stars is determined twice half a year apart. Then we get a very small angle under which somebody from that star would see the diameter of the Earth's orbit. With the diameter (2 AU) we can compute the distance in the well-known way. For the nearest star (α Centauri) the parallax angle is 1.52 seconds of arc or for orbit radius (1 AU) 0.76 arcsec. Now we see why the distance of the Earth from the sun is so important in astronomy that it got its own name. We use it as a pathfinder to the distance of the stars. Astronomers even built one distance unit for the stars on it:

1 Parsec (parallax second) is the distance from which the radius of Earth's orbit (1 AU) is seen under an angle of 1 arcsec (a Dime seen from a distance of 1 Mile)

At this point we should reemphasize another widely used unit for the distance of stars:

1 Light-year: It is the distance that light travels in 1 year.
1 Parsec = 3.26 Light-years

This is a very skinny triangle, and the method works up to ≈ 100 parsec, if telescopes on Earth are used. This is still the immediate neighborhood of our sun. To measure larger distances we have to resort to other methods, but all of them will build upon this first step. Therefore, attempts have been make this basic measurement with higher precision in space, for example, with the ESA Mission *Hipparcos* that has expanded the reach of the method to > 1000 Parsec.

**C) Size:** \[ D = 1.39 \text{ Mio km} = 2 \text{ Solar Radii (R}_S\text{)} \] Slide VII.4

The size can be derived from the angular size of the using again the skinny triangle method: With the knowledge of the distance \( r \) of the sun and the angular size: 0.5°, under which we see the sun in the sky.

\[ \rightarrow D = 0.5/360*2° * 1.5*10^8 \text{ km} \]

The stars are so far away that they appear as a point even through the most powerful telescopes. Therefore, a direct size determination is not possible. We will derive it later, when we have collected more information about the stars.

**D) Luminosity**

Knowing the apparent magnitude and the distance, we can now determine the luminosity (or the total light and energy output) of the stars in the neighborhood of the sun.

**Energy flux of the Sun:** \( L = 4*10^{26} \text{ Watt} \)

For the sun we can derive the total energy flux directly. We can measure the energy flowing through an area of 1 m² at the distance of the Earth. You want to know this for example, if you build a solar collector for hot water or electricity.

The value is ≈ 1400 Watt/m² (known as the solar constant). On every square meter over the complete sphere with a radius of 1 AU (the distance of the Earth) we would measure the same energy flux. Think of this sphere like the huge Dyson Sphere that the Star Trek (next generation) crew encountered in one of its sequels. This sphere was built around a star at the distance of a planet. Thus the sphere would collect all the energy from that star.
Multiplying the 1400 W/m² with the number of square meters on the surface of this sphere, we arrive at the total energy flux of \( L = 4 \times 10^{26} \text{ Watt} \), which we call the luminosity of the sun \( L_s \).

Let's look at this from a different angle. This is an incredible amount of energy flux from the sun, of which the Earth only intercepts a tiny fraction:

\[ F_{\text{Earth}} = 1400 \text{ W/m}^2 \times 6,400,000 \text{ m}^2 \times \pi = 1.8 \times 10^{17} \text{ W} \]

This total that the earth receives is still an enormous amount. It is equivalent to the output of 180 million good sized nuclear power plants (currently we have \( \approx 450 \) of them on Earth). It comprises more than 10,000 times the total energy currently used by humankind!!

Thus, if wisely used, it should be enough for our energy demands, although it doesn't add up economically yet. You may answer: well we want to grow our economy. Therefore, the sun may not be enough in the future. I bring this argument up also to show to you that there is a limitation for mankind. There may still be some room for growth, but not forever. We live on a limited world that is in energy balance: The Earth gets energy from the sun and radiates heat into space in exactly the way the sun does. If we would introduce an energy source on Earth, which provides us with all the energy we may think we need for unlimited growth, the Earth has to become hotter to get rid of the energy. (A hotter body radiates more heat!) If the artificial energy production is only 1.3% of the solar energy flux, the temperature on Earth will increase by \( \approx 1 \text{ centigrade} \) in order to stay in balance. Such an increase would be another threat that humanity can create in addition to the CO₂ greenhouse effect. Thus the energy usage has to stay at a small fraction of the solar energy flux. Fortunately, we are still far away from this limit. But this should tell us that it is not useless to think of solar energy as a major source for humankind!!

Going farther away, we can employ the same method to stars. The luminosity of a star is equal to its total energy emitted. The calculation of this quantity is exactly the same as we used for the sun. Remember: we need the energy flux through one square meter on the Earth and the surface of the sphere with a radius of 1 AU (the distance of the Earth from the sun) for the determination of the sun’s luminosity. Likewise, the measured brightness (or apparent magnitude) of a star provides us with the energy flux through one 1 m². Now we have to calculate the surface of the sphere with a radius of the distance of the star from us. This is an incredibly huge sphere, but we can calculate this. We find indeed that there are stars with a total luminosity comparable to the sun, but also stars with much larger and much smaller luminosity. There are stars that emit much more (*1,000,000) than the sun and many which emit much less (1/1000).

What determines the luminosity of a star? Firstly, the size of a star has an influence on the luminosity: a larger area of the same brightness emits more light.

2) Spectroscopic Measurements

What is the parameter that determines the brightness of the sun's or the star's surface? This brings us back to the temperature of a star.

A) Temperature: Sun: \( T = 5500 \text{ K} \)

The temperature of the sun can be derived from the solar radiation, i.e., from the color of sunlight, as we have talked about in connection with light.
The sun has the maximum intensity at yellow/green (our eyes work best for this color). This is no accident, but on purpose, in order to make use of the sun's radiation in the most efficient way. The stars have different colors

- **hot stars:** blue, UV.
- **sun:** yellow.
- **cool stars:** red.
- **very cool stars:** (protostars) IR.

In this sense also planets and cloud tops radiate in infrared (without getting light directly from the sun)!! You can get this flavor, if you remember standing near a concrete building in a summer night. You feel the heat radiated by this concrete! This is infrared radiation, which we can't see, but we can measure it!

However, gaseous nebulae, such as the Orion nebula do not radiate in this way. *Slide VII.5* Physicists call radiation, whose reason is the heat of a body, **thermal radiation** or more precisely **blackbody radiation**. In this sense the **Sun** is the most perfect "black body" in the solar system. Now you may ask, what does black mean? You thought you knew what black means, a color. However, **black is no color**, it is the absence of color! This observation means: **No light is reflected** by a blackbody. Black cardboard looks black, since it does not reflect light, or more precise since it does not reflect much light.

_Demo Box_

This fabric seems even blacker to us, it reflects even less light. But what is this black dot, which is even blacker than the fabric? It is just a hole cut into the cardboard of this box. The light, which strikes it, gets trapped in the box. Thus this hole is the most ideal black body here!! It does not reflect light at all. Now you may think, well, the box is just black inside, and that makes it even better.

Surprise, surprise!!! The walls are white! I didn't trick you. The hollow structure is good enough to make it a black body! It does not even need to be black to be a black body!! In this sense the sun is a black body: If there were another brighter star out there, shining at the sun, the sun would not reflect its light at all! It still would only turn out its own thermal radiation, its own light! You can compare this with an everyday life analogy: The heater elements of the kitchen stove look almost black. But when you forget to turn them off after removing the cooking pot, they glow red, since they are hot now. However, they did not change their color. In the light of your kitchen light bulb they still look black.

The sun is dense. Thus the photons undergo many collisions with matter before escaping (like what is happening in our box). As a consequence, photons "know" about the temperature. The **total radiation and distribution over wavelength** depends only on $T$. We have a peaked spectrum in wavelength, which obeys 2 laws, which we make ample use of in astronomy:

**a) Wien's Law:**

\[
\text{temperature} \times \text{wavelength(max.)} = \text{constant}
\]

A star with twice the temperature has the maximum intensity at half the wavelength.

The sun's spectrum is in between
View VII.5

From measuring the wavelength at maximum intensity, we find the temperature of any star!! This will be very important when we move on. You may have already noticed that the curves of the spectra get higher and higher with temperature. This means that the radiation becomes more intense. This is:

2) Stefan Boltzmann's Law:

\[
\text{Energy Flux} = \text{constant} \times T^4
\]

Let's look at it with the same figures again:

A star with twice the temperature has an intensity which is increased by a factor of 16 (2x2x2x2 or \(2^4\))

The sun's spectrum is in between

View VII.6
From *Wien's Law* we can determine the temperature for each star independent of its distance. This result is very important as the energy flux, which is emitted from the star's surface, also varies with temperature via *Stefan-Boltzmann's Law*.

**B) Size of a Star**

From measuring the total intensity, we also find the temperature of any star!! Of course we also need to know the area which is emitting the light to compute the total light emission or the total energy flux. For the sun we know already the size of its sphere. Thus we can easily compute the area from which we get the light, it is the disk of the sun we see. If the sun was larger and it still had the same temperature it would emit more light. For example, a star with twice the diameter of the sun (same T) will have 4 times the surface area and thus emit 4 times as much light or energy. Thus, if we know the temperature and the size of a star, we can calculate the total light emission. This will also be very important when we move on. Or if we know the total energy flux (or luminosity) of a star and its temperature, we can now determine the size of the star.

That a body (star) maintains a constant temperature also means that it must either receive or produce as much energy as is radiated away, since this energy is lost. It must stay in balance!

To really make use of this technique it is important to have another independent way to get the temperature, since as we have noted dust in interstellar space may change the color of a star. Indeed there is another feature in the spectra of the sun and the stars which not only gives us another way to measure temperatures, but also to find the composition of the material.

**C) Composition: 75% H, 23% He, 2% the rest, heavy elements.**

In order to understand what scientists do about this (and this is again a technique which we use for all other stars also) let me continue with another Demonstration. The spectrum of light does not always look so smooth. The German optician *Fraunhofer* found dark lines in the spectrum of the sun. He recognized that these lines represent the fingerprints of the elements the sun is made of. Unfortunately, it is not possible to show you the dark lines in this large class. But I can show you the opposite effect. In this lamp the light is produced by mercury vapor. The vapor cloud is not thick enough to create a blackbody. Thus we see the pattern of individual atoms emitting light. You see the 3 possibilities for a light spectrum. From observations *Kirchhoff* put forth the following rules:

1) A **hot, dense glowing object** emits a *continuous spectrum*.

2) A **hot gas** cloud emits light of certain wavelength, **bright lines**, depending on its elements.

3) A **cold gas in front of a hot dense object absorbs light** of certain wavelength, and **dark lines** appear in the spectrum.

Each atom, ion, molecule absorbs or emits with its own set of wavelengths.
Why do elements emit light only at certain wavelengths?

An atom consists of its **nucleus** with **positive electric charge** and **negative electrons** in its shell. The electrons are attracted by the electric force, similar to a planet that is affected by the gravity force of the sun. In order not to fall into the nucleus the electrons orbit around the nucleus and compensate the attraction by the centrifugal force. An electron closer to the nucleus has less energy than farther away. If an electron changes into an orbit closer to the nucleus it must loose energy, i.e., it emits a burst of light, a **photon**. We have already learned that the energy of the photon is equivalent to the wavelength of the light.

**high energy <-> short wavelength**

But this could be any amount of energy or any wavelength. The Danish physicist **Niels Bohr** made the connection in 1913:

1) **Only certain orbits** with certain energies are **allowed for the electrons** in an atom. This seems to be there without reason? There should be a reason for this constraint, and there is. Let me just give you the flavor for those of you who want to see a little bit more. I won't ask this in a test: We have seen that light behaves as a wave and also as a moving particle, right? Nature is beautiful, and we find beautiful symmetries in it! Like light, any moving particle behaves in a similar way: It is also a wave. Only such orbits are allowed for which the wave of the moving electron fits into the circumference, like a standing wave. It does not fit, the wave would travel away, and this means emitting light.

2) The electron can only **jump between** these **specific orbits** and thus emits light with **certain wavelengths**.

   If the electron goes to a lower orbit, we get light emission (bright lines).
   If the electron captures light and then goes into a higher orbit, we call this light absorption (dark lines)

   We can use this effect:

   **a) to find out what’s there? (H, He, etc.).**

   Which set of lines determines the elements, for example:

   **Hydrogen alpha** line = **red**. (most abundant element)
   (Hydrogen at 10,000K or near a star at 10,000K.) e.g.
b) to measure abundance
from the relative intensity of lines can be used to get the composition of the sun
We can use both: Slide VII.10
absorption lines: material in front of a "black body", for example, the sun's lower atmosphere
and
emission lines: thin material radiating by itself, for example, the sun’s upper atmosphere

We can apply exactly the same technique to get the composition of stars. It turns out that there is population of stars with about the same composition as the sun, called

Population I: 75% H, 23% He, (2%) some heavy elements, which seems to be "recycled" material
In addition, there is also a population of stars, which has much less heavy elements, called

Population II: 77% H, 23% He, very few, but some heavy elements

This seems to be "more primitive" material before much heavy elements were "cooked". The universe was born with H and He only except for little Li, Be. Heavy elements were only made inside stars. Thus there was a puzzle for many years:

Where were the true "first" stars (with H, He only)?
Only recently (2003) the first stars of such a kind have been found. They will provide us with valuable insight into the early days of our universe, because that is the time they have been formed.

Finally, which lines of an element are emitted depends on the energy input. It is much easier to make metals emit spectral lines than H and He. Thus from a cool star we see many metal lines, whereas the hotter ones emit mainly H and He lines. Using this information we can get a star temperature independent of interstellar absorption.

3. Stellar Mass and Density

A) Solar Mass: \[ M = 2 \times 10^3 \, \text{kg} \] = 1 Solar Mass \( (M_\odot) \)

The mass of the sun is derived from Kepler's 3rd Law applied to the planets of the solar system, but in Newton's interpretation. The constant in Kepler's Law describes the mass in the center, which causes the planets to orbit around it. We know

\[ \frac{\text{Distance}^3}{\text{Orbital Period}^2} = \text{Constant} \times \text{Mass} = \text{Speed}^3 \times \text{Orbital Period} \]

The Constant in this relation is a universal constant throughout the entire universe!! Thus, if we know the mass for one orbiting system, we can compute all masses! We have weighed the Earth, and we know the Distance and orbital Period of the Moon! We can calculate the
gravitational constant. Now we use the distance and orbital period of the Earth around the Sun, and we get the sun's mass.

B) Binary Stars and Star Masses

In order to determine star masses, we need a second body in the system, which we can see. Therefore, this only works out for binary star systems. By a binary star we mean 2 stars which are tied together by gravity. There are also accidental (apparent) binaries so-called optical doubles, stars, which are very close in the sky, but are at very different distances (such as Mizar and Alcor in the Big Dipper). Mizar itself is a real gravitationally bound binary. If we can see the stars moving separately, this is called a visual binary.

If the distance of the stars from the Earth is known, we can determine their distance from each other in the same way as we measured planet sizes. From their motion we get the orbital period. Again we can determine both masses.

However, there is still a way to get the star masses, even if we cannot separate the two stars by measuring the speed of the stars and the orbital period.

\[ \text{Speed}^2 \times \text{Period} = \text{Constant} \times \text{Mass} \]

This is Kepler's 3rd Law written in a different format, which can be applied to stars that are very close to each other. But how can we measure the speed without seeing their orbit? There is a way to measure directly the velocity of the star by using again the spectral lines.

We can use the Doppler effect to determine their speeds. Motion towards us makes their wavelength shorter (i.e. shifted to blue) and away from us longer (i.e. shifted to red)

Eclipsing binaries are very special they pass in front of each other during their orbit. They are brightest when we see them both. The light drops, more or less, when the brighter one (or the fainter one) is eclipsed by the other.
Parameters of the Sun

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Abbreviation</th>
<th>Value</th>
<th>How Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>r</td>
<td>$1.5 \times 10^8$ km</td>
<td>Parallax, <em>Kepler’s 3rd</em> Angular Size</td>
</tr>
<tr>
<td>Diameter</td>
<td>$D_S$</td>
<td>$1.39 \times 10^6$ km</td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>$L_S$</td>
<td>$3.9 \times 10^{26}$ W</td>
<td>Energy Flux at the Earth $Wien’s \ Law$</td>
</tr>
<tr>
<td>Temperature</td>
<td>$T_S$</td>
<td>$5500$ K</td>
<td></td>
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</tbody>
</table>

Composition: 75% Hydrogen, 23% Helium, 2% Heavy Elements (O, C, Fe etc.)

Mass $M_S$ $1.99 \times 10^{30}$ kg $Kepler’s \ 3rd, \ Newton’s \ Law$

Mass $= \frac{2}{3} \pi R_S^3$

C) Density: (Density of the Sun: $[ \rho ] = 1.4 \ \text{g/cm}^3 = 1400 \ \text{kg/m}^3$)

We get the density of the sun when we combine the mass of the sun and the size of the sun from above. In order to get the density of the sun we need its volume.

The volume of a cube with 1 solar radius is:

Volume (cube) $= R_s^3$

For the sphere we have to multiply by $4/3$:

Volume (sphere) $= \frac{4}{3} \pi R_s^3$

The density is: $\rho = \frac{\text{Mass}}{\text{Volume}}$

The result is 1.4 times the density of water. This is about the same as for Jupiter! However, we will see that the interior of the Sun is totally different from that of Jupiter. The densities of ordinary stars are not very far from this number, but stars on the death bed can be much different, as we will see.
**Determination of the Star Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Observation</th>
<th>Deduction</th>
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</thead>
<tbody>
<tr>
<td>Apparent Magnitude</td>
<td>Measure Brightness</td>
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<tr>
<td>Distance</td>
<td>Parallax</td>
<td>Distance</td>
</tr>
<tr>
<td>Luminosity</td>
<td>Combine: Distance and Apparent Magnitude</td>
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</tr>
<tr>
<td>Surface Temperature</td>
<td>Color of Star (Wien's Law)</td>
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<tr>
<td></td>
<td>Spectral Lines</td>
<td></td>
</tr>
<tr>
<td>Energy Flux/Area</td>
<td></td>
<td>from Temperature (Stefan-Boltzmann's Law)</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Size</td>
<td>Combine: Luminosity and Energy Flux/Area</td>
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<tr>
<td>Composition</td>
<td>Spectral Lines</td>
<td>Elements</td>
</tr>
<tr>
<td>Mass</td>
<td>Distance or Velocity and Use Kepler's 3d Law Orbital Period of Binary Stars</td>
<td></td>
</tr>
</tbody>
</table>

4. **Classification of Stars**

It is always easier and fairly convenient to remember, if you call something names. In this sense *Annie Cannon*, a Harvard astronomer put the stars into a classification scheme according to their spectra, first alphabetically. Later this was rearranged by temperature and some classes dropped out. Now we have O stars as the hottest (30,000 - 60,000 K) and M the coolest (less than 3500 K):

O(hot) B A F G(sun) K M(cool).

This is hard to memorize, but would be useful to know. Thus there is a nice mnemonic for it:

"Oh, Be A Fine Girl (or Guy, gender neutral) Kiss Me"

A) **Hertzsprung-Russell Diagram**

If I would make diagram with your Exam scores on one axis and the percentage of lecture hours attended (given the fact that I would collect this information), I probably would get a plot like this

So there is an obvious correlation between the time spent with the subject and the accumulated knowledge in this case. These 2 parameters are not independent. In the same way we now plot essentially luminosity vs. temperature.

for observed stars.
This can be done with fairly good accuracy for stars within a distance of 100 Parsec, since here we know the distance from the parallax and thus the true luminosity of the stars. This is called an H-R Diagram after Hertzsprung and Russell who independently developed this compilation of stars. We see an obvious grouping of stars.

**Main Sequence** (It stretches through the diagram from the lower right to the upper left. It tells us for the stars: the hotter they are, the more luminous.)

In addition, we find:

- **Red super-giants, Red Giants** (in the upper right of the diagram)
- **White dwarfs** (in the lower left).

Let us concentrate for now on the main sequence, which contains most of the stars (85%). This means that stars spend most of their lives on the main sequence. The sun is a relatively small and faint star, but a typical main sequence star.

**Main sequence:** It contains few O & B stars, because they don't live long.

**Giants, super-giants:** There are only a few, don't stay there long ("senility").

**White dwarfs:** (≈10%) They are "dead" stars.

We will discuss this evolution in detail in the section X.

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### a) Size of Stars

With the luminosity and the temperature we can also determine the size of a star. After Stefan-Boltzmann we know the **energy flux/m²** for each given T. With the total luminosity we can now compute the emitting area and thus the **radius of the star**. For example the white dwarfs are hot and faint, thus they are small, whereas the red giants are huge (more than 100 times the sun's size).

### b) Spectral Parallax:

Obviously there is only 1 basic parameter, which determines the luminosity of the star (i.e., its **energy flux/area and its size**). It is the mass of the star. Thus all stars, everywhere in the universe, will behave in the same way. If we get H-R diagrams from 2 different clusters of stars
we see that the magnitude scale is shifted (we don't know their distance yet). The only difference between the stars is the distance. By aligning the main sequence we see how much brighter the stars of the one cluster are over the other. Since we know that the brightness goes down with the inverse square of the distance, we can determine the distance now.

This is a 2nd way of getting stellar distances, the **spectroscopic parallax**. Each point on the HR diagram has a spectral signature (lines). We use spectral lines and Wien's law to locate the star on the HR diagram. From the HR diagram we get the luminosity. Then the stars can be used as **standard candles**.

**Luminosity & Apparent Brightness vs Distance.**

**B) Mass Luminosity Relationship**

If we now plot the mass of main sequence stars against their luminosity, we get an interesting relationship

\[ \text{Luminosity} \propto \text{Mass}^{3.5} = \text{Mass} \times \text{Mass} \times \text{Mass} \times \sqrt{\text{Mass}} \]

which may not be so surprising after the H-R Diagram. More massive stars are brighter. Thus it is true that only one parameter, namely the mass determines the fate of the star. It is very interesting to see that a star, which is 10 times as massive as the sun, emits 3000 times more light. It is squandering, which will become important in the next section of the course.

The luminosity varies with the mass of a star as

**Luminosity** goes as  

\[ \text{Mass}^{3.5} = \text{Mass} \times \text{Mass} \times \text{Mass} \times \sqrt{\text{Mass}} \]

Because the amount of fuel is equivalent to the mass of the star itself, we see immediately that heavier, i.e. more luminous star is eating up its fuel much faster than a smaller star. A star with twice the mass is 12x more luminous, i.e. burns 12x more fuel. Therefore, it uses up the fuel 6x times faster. The Sun is 4.5 Billion years old and still shining steadily. What is the enormous energy source that still keeps it going strong after such a long time?