The Hertzsprung-Russell Diagramm

1. Classifications of stars

The spectrum of the brightest star, our Sun, shows several dark gaps perpendicular to the flow of it's colours (figure 1). These so called **spectral absorption lines** where discovered in 1802 by the English scientist William Wollaston. By 1815, the German optician Joseph von Fraunhofer (1787 - 1826) (figure 2) mapped more than 300 absorption lines. Table 1 shows some of the strongest lines with their names given by Fraunhofer. For example the *H* and *K* lines correspond to the singly ionised *Ca II* (3968 Å und 3934 Å), the strongest lines in the solar spectrum (see table 1 and figure 1).

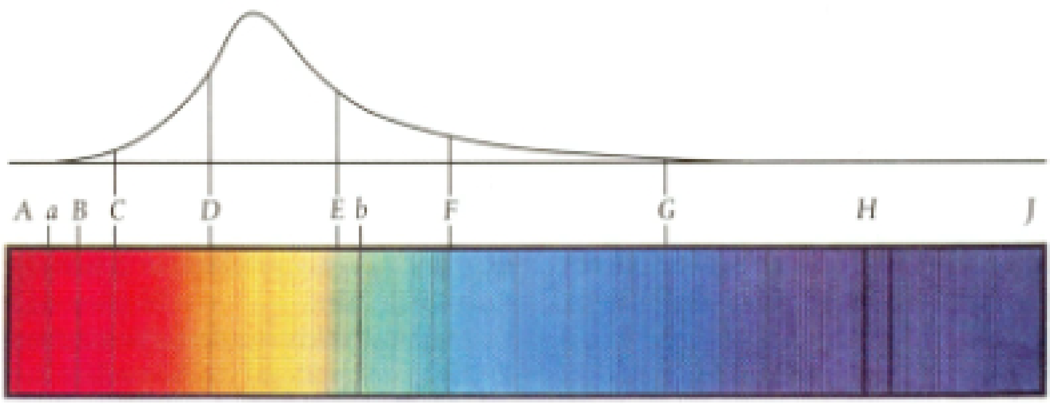

Figure 1: Spectrum of the Sun with it's absorption lines. [SuW]

Name	λ (Å)	Origin
A	7594	terrestrial O_2
a	7165	terrestrial H_2O
B	6867	terrestrial O_2
C	6563	$H\alpha$
D	5890, 5896	*Na I*
E	5270	*Fe I*
b	5167, 5173, 5184	*Mg I*
F	4861	$H\beta$
G	4300	*CH*-band
H	3968	*Ca II*

Table 1: Fraunhofer designations for some absorption lines. The first three are formed by the passage of the sunlight through the Earth's atmosphere. [JK]

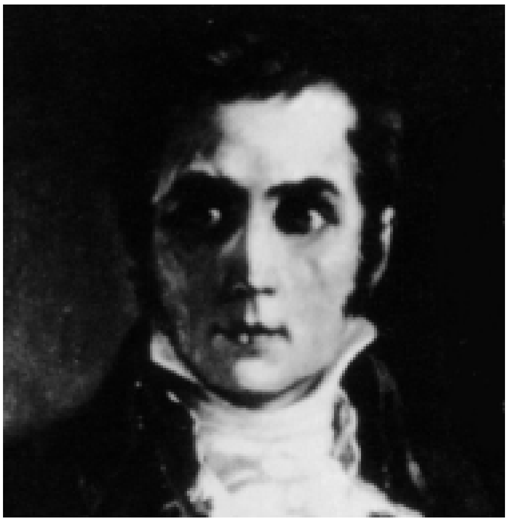

Figure 2: Joseph von Fraunhofer (1787 - 1826) [SV]

By the 1820s he examined a variety of first magnitude stars with a simple prism spectrograph and was able to recognize typical differences between the spectra of these stars. The significance of these lines was discovered some 35 years later in the physics laboratory of the University of Heidelberg by Robert Wilhelm von Bunsen (1811 - 1899) and Gustav Kirchhoff (1824 - 1887) (figure 3). They were working on the problem of identifying chemical elements by the light they emitted when heated to incandescence. Fraunhofer had already noted that a pair of bright lines produced by sodium had dark counterparts in the solar spectrum. Bunsen and Kirchhoff worked systematically to identify a number of other elements whose bright lines could be matched to the wavelengths of the dark solar lines. Their work lead to the Kirchhoff laws, the foundation of the **spectral analysis**:

1. An incandescent solid or gas under high pressure will produce a **continuous spectrum**.

2. A low density gas will radiate an **emission-line spectrum**.

3. Continuous radiation viewed through a low density gas will produce an **absorption-line spectrum**.

The wavelength of the lines, whether absorption or emission lines, depend on the chemical composition of the gas, and the relative strengths of the lines depend on temperature, density and the relative abundances of the different atoms or ions.

Figure 3: Robert Wilhelm von Bunsen (1811 - 1899) and Gustav Kirchhoff (1824 - 1887) [SV]

In the Bohr description, the atom is formed by a nucleus and electrons on different orbits. An electron can only move in orbits with very specifically allowed radii that are dependent upon the kind of atom or ion. Normally, the electron resides in the lowest possible state, the ground state. If radiation with a continuous spectrum and sufficient energy hits the electron, it rents a specific amount of energy to the electron to jump to an upper state. As this energy is missing, we observe an absorption line in the continuum. The position of this line in the spectrum depends on the energy given to the electron. If now an electron is in an upper state, it tries to get as soon as possible to a lower state. By doing this, it returns the energy as electromagnetic radiation and a bright line, an emission line appears in the spectrum. Famous series of lines are those of the Hydrogen atom: Lyman, Balmer, Paschen, … series (see table 2 and figure 4). The Lyman series for example can be observed in the UV-light and correspond to transitions to/from the ground level; the Balmer series in the visual light and correspond to transitions to/from the second level.

Name	λ (Å)	Origin
Hα	6563	2 ↔ 3
Hβ	4861	2 ↔ 4
Hγ	4340	2 ↔ 5
Hδ	4101	2 ↔ 6

Table 2: Some transitions in the Balmer series. These series are characterised by transitions to /from the second level.

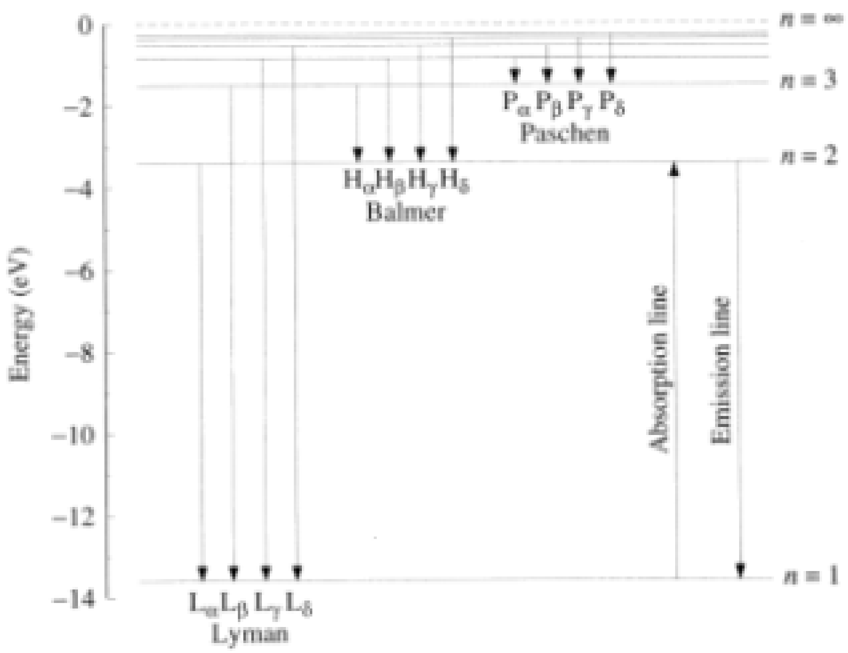

Figure 4: Energy level diagram for the Lyman, Balmer and Paschen series. [CO]

After this short excursion to the origins of emission and absorption lines, we will return to the stars and their spectra. As previously told, Fraunhofer discovered some similarities in the spectra of different stars. Some stars as Pollux show a spectrum similar to that of our sun with strong *Ca II* and *Fe II* lines, others as Sirius or Vega show strong absorption lines of hydrogen, others, as Mira show very complicated spectra due to molecular absorption lines (see figure 5).

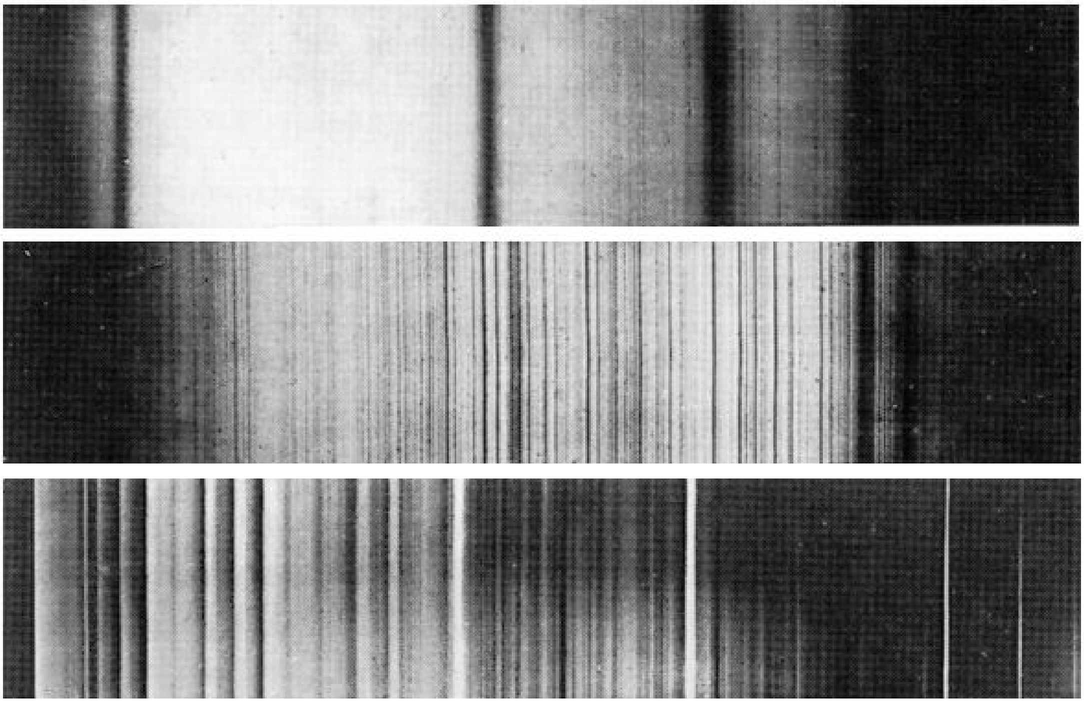

Figure 5: Original classification spectra, made with an objective prism and an 11-inch telescope in the 1890s. Spectra (from top to bottom) of
Sirius (*A*-class) with it's strong hydrogen lines,
Capella (*G*-class) with it's strong *Ca*, *Fe* and other metal lines,
Mira (*M*-class) with absorption bands due to molecules (*TiO*). [JK]

During the mid 1800s, astronomers tried to define a classification scheme to bring some order to the increasing number of spectra (f. ex.: father Angelo Secchi classified the spectra as type *I* – *V*, see table 3). But with better instrumentation, the details in the spectra became more and more abundant. Edward C. Pickering (1846 – 1919) and his assistant Williamina P. Fleming (1857 -1911) labelled in the 1890s the spectra with capital letters, beginning with the letter *A* for the broadest hydrogen absorption lines. The whole work, based on photographic spectra, was financed by Henry Draper, the first person to photograph stellar absorption lines. The first catalogues, which use *A* through *Q* (see table 3) were published in 1890 in the *Harvard Annals*.

Secchi	Draper (Harvard)	
I	*A*	strong hydrogen lines
	B	like class A, but with the addition of the 'Orion lines' (later determined to be *He I*)
	C	doubled hydrogen lines
	D	emission lines present
II	*E*	Fraunhofer *H* and *K*, and Hβ lines are seen

	F	similar to class *E*, but with all hydrogen lines present
	G	the some as *F* but with additional lines
	H	the same as *F* but with a drop in intensity in the blue part of the spectrum
	I	like *H* except with additional lines
	K	bands visible in spectrum
	L	peculiar variations of *K*
III	*M*	Secchi's third type
IV	*N*	Secchi's fourth type
V	*O*	spectra with mainly bright lines (Wolf-Rayet)
	P	planetary nebulae
	Q	all other spectra

Table 3: The Secchi-types and original Draper classes. [JK]

In the following years, several of the classes were dropped or rearranged. A large contribution is due to Antonia Maury and Annie Jump Cannon (1863 - 1941). We find the remnants of the early Draper classification in our modern classification with the following classes: *O B A F G K M* (see table 4). The rearrangement of the different classes was done especially by Annie Cannon and respects the fact, that this new sequence represents a temperature sequence. The physical basis of the presence or absence and the relative strength of the spectral lines was although not understood. *O* stars have a high, *M* stars a low surface temperature. She classified some 200 000 spectra between 1911 and 1914; the results were collected into the Henry Draper Catalogue. But again, as instrumentations improve, the classes were subdivided by adding a decimal. For example, our sun is a star of the *G2* class. (For more details see f. ex. Stars and their spectra by J. B. Kaler)

Type	Characteristic	Main sequence temperature
O	hottest blue-white stars with few lines strong *He II* absorption lines, sometimes emission lines *He I* absorption lines becoming stronger	28 000 – 50 000 K
B	hot blue-white stars *He I* absorption lines strongest at *B2* *H I* (Balmer) absorption lines becoming stronger	9 900 – 28 000 K
A	white stars Balmer absorption lines strongest at *A0* becoming weaker later *Ca II* lines becoming stronger	7 400 – 9 900 K
F	yellow-white stars	

	Ca II lines continue to strengthen as Balmer lines continue to weaken neutral metal absorption lines (*Fe I*, *Cr I*)	6 000 – 7 400 K
G	yellow stars *Ca II* lines continue becoming stronger *Fe I*, other neutral metal lines becoming stronger	4 900 – 6 000 K
K	cool orange stars *Ca II*, *H* and *K* lines strongest at *K0*, becoming weaker later spectra dominated by metal absorption lines	3 500 – 4 900 K
M	coolest red stars spectra dominated by molecular absorption bands, especially *TiO* neutral metal absorption lines remain strong	2 000 – 3 500 K

Table 4: The Harvard classes with some later developments. [CO][FK]

2. The Hertzsprung-Russell Diagramm

From the numerous spectra, astronomers recognized that *O* stars at the one end of the Harvard sequence tended to be brighter and hotter than the *M* stars at the other end. One theory of stellar evolution (later recognized as wrong) suggested, that stars begin their life as hot *O* stars with a large mass. During their live they should loose mass through stellar winds and become cooler as they age.

To prove this theory, the Danish engineer and amateur astronomer, Ejnar Hertzsprung (1873 -1967) (see figure 6) investigated the relation of the absolute magnitude of stars and their spectral class. In 1905 he published the discovery of a relation between these two quantities in tabular form. In addition to this discovery, he recognized, that stars of *G* or later classes had a range of magnitudes, despite having the same spectral classification. Hertzsprung termed the brighter stars **giants**, as two stars having the same temperature, the more luminous star must be the larger one.

Figure 6: Ejnar Hertzsprung (1873 -1967) [SV]

Meanwhile, at Princeton University, Henry Norris Russell (1877 -1957) independently came to the same conclusion as Hertzsprung. Russell used the same term to describe the luminous stars and the term **dwarf stars** for their dim counterpart. In 1913 Russell published the diagram shown in figure 7.

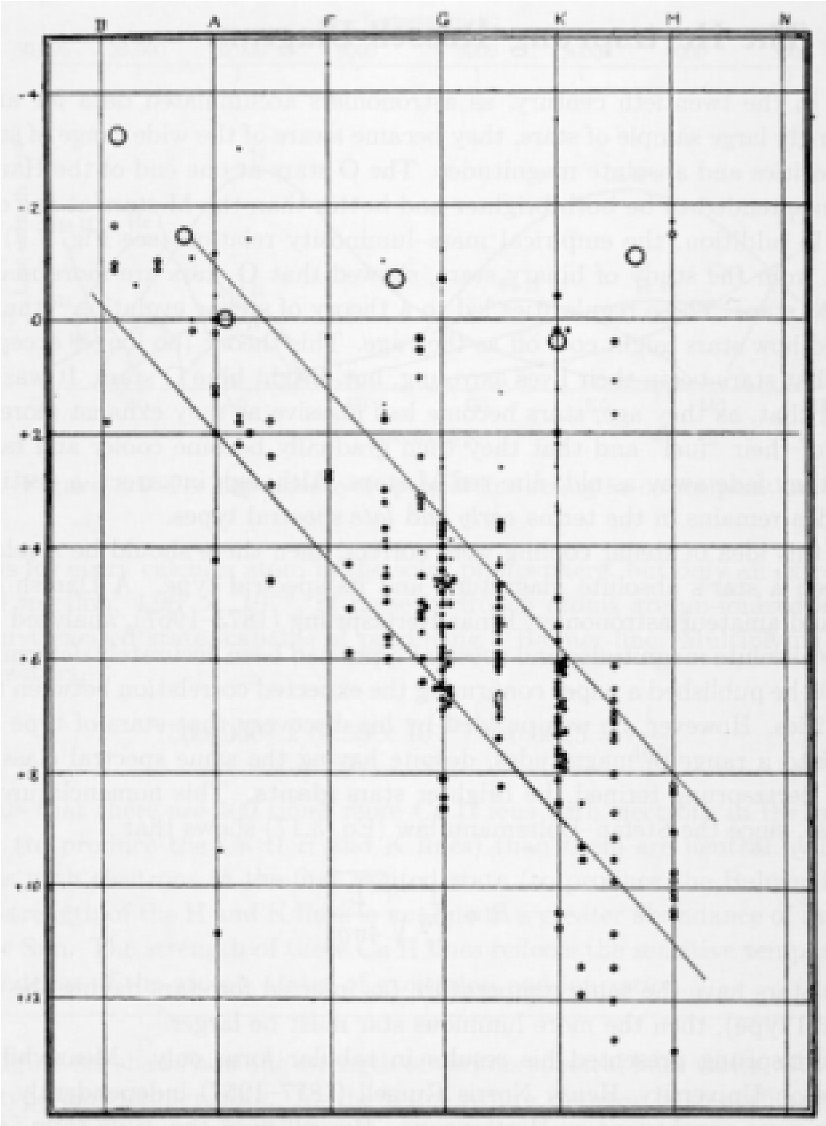

Figure 7: Russell's first diagram, with spectral types listed along the top and absolute magnitudes on the left-hand side. [CO]

Most stars are in a band in the HR-diagram that consists of hot, bright O-stars at the upper left hand corner and the cool, dim stars at the lower right hand corner. This band, where most stars can be found is called the **main sequence**.

The original HR-diagram can also be modified to represent the luminosity in dependence of the temperature (see figure 8). The main sequence is not a line but has a finite width, due to small differences in the chemical composition and evolution of the star while being on the main sequence.

As the radius of a star depends on its luminosity and temperature (Stefan-Boltzmann's law), the radius can also be represented in the HR-diagram as diagonal line. Stars on the main sequence that are hotter than our sun must have a larger radius, stars that are cooler have a smaller radius. Besides the stars on the main sequence, we can find the giants (ex. Taurus $45R_{\odot}$), supergiants (Betelgeuze 700 … 1000 $R_{\odot}$).

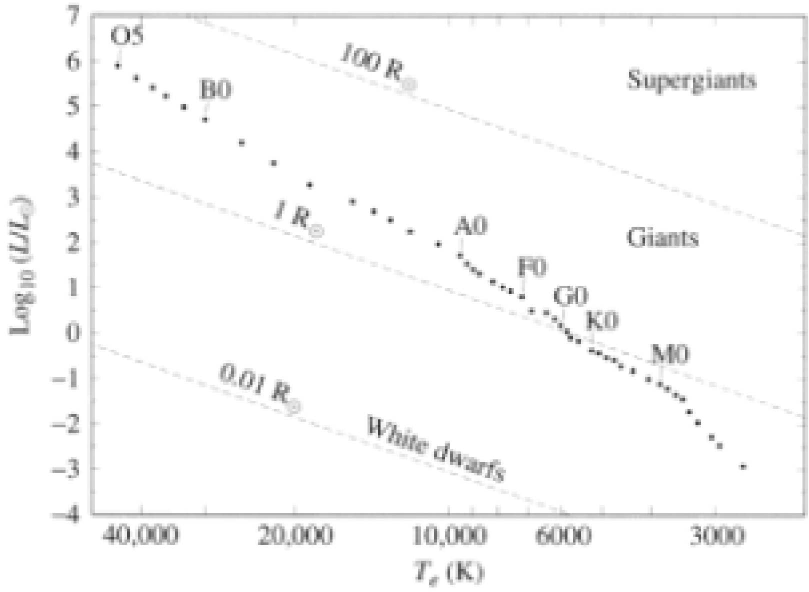

Figure 8: Lines of constant radius on the HR-diagram. [CO]

The position of a star on the HR-diagram and its later evolution is almost only determined by one factor: the mass. The most massive stars (*O*-stars) can have masses up to 60 solar masses (even 100 solar masses seem possible). On the other side, the sequence is bounded by light-weight *M*-stars with masses down to 0.08 solar masses.

As mentioned above, Hertzsprung wondered if there might be some differences in the spectra of stars on the main sequence and giants of the same spectral class. Detailed analysis of the spectra revealed that there exists a subtle difference in the relative strength of the spectral lines.

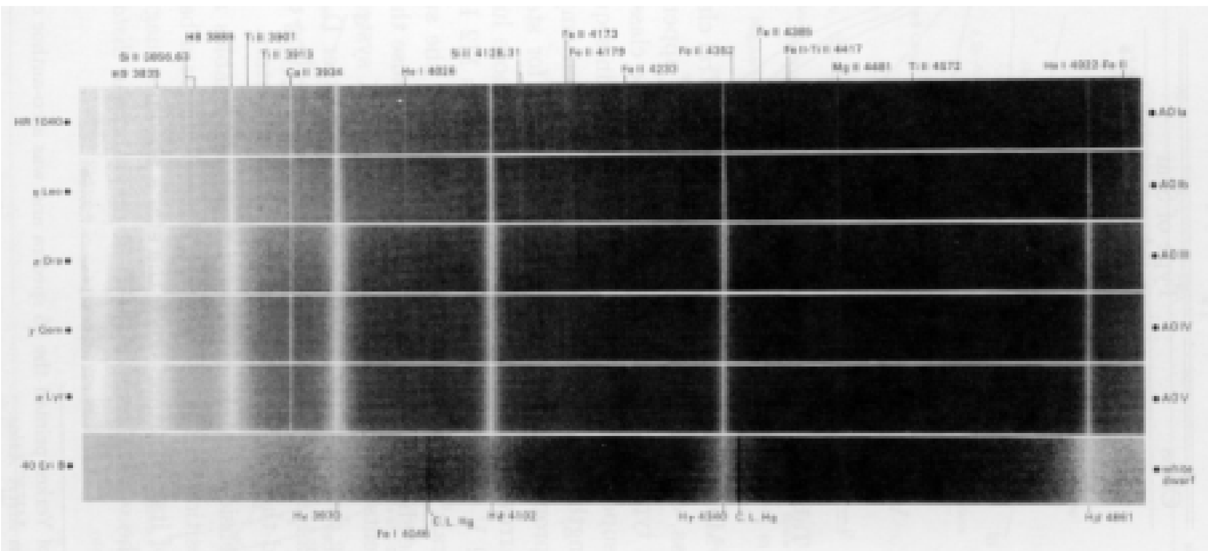

Figure 9: A comparison of the strength of the hydrogen Balmer lines in types *A0 Ia*, *A0 Ib*, *A0 III, A0 IV, A0 V,* and a white dwarf, showing the narrower lines found in supergiants (from: *An Atlas of Representative Stellar Spectra* 1978). [CO]

Stars of the same spectral class can have different luminosities. A further system, the Morgan-Keenan (M-K) system, was introduced to make the distinction between the different **luminosity classes** (1943; *Atlas of Stellar Spectra* by W.W. Morgan and P. C. Keenan). These luminosity classes range from *I* for supergiant stars to *VI* for subdwarfs (table 5). By a detailed analysis of a stars spectra and it's absorption lines, it is possible to classify it in this *M-K* system. Our sun is a *G2 V*, Betelgeuse a *M2 Ia* star. In figure 9 are shown *A*-class stars of different luminosity classes. Supergiant stars are characterised by narrow lines. These lines broaden as one gets to less luminous stars. The cause of this effect is due to atmospheric pressure. All spectral lines have a natural width in wavelength. This width can be increased by the pressure of the stars atmosphere. At high pressure, more collisions occur between the different atoms and cause perturbations of the electronic energy levels. These levels then become smeared out, and that allows an electron to absorb light slightly away from the line centre. Consequently, the higher the pressure (as f. ex. on white dwarfs), the broader the lines; the lower the pressure (giants, supergiants) the narrower the lines. Besides atmospheric pressure, star rotation and turbulences on its surface influence the line width too.

Class	Type of star
Ia-O	extreme, luminous supergiants
Ia	luminous supergiants
Ib	less luminous supergiants
II	bright giants
III	normal giants
IV	subgiants
V	main-sequence (dwarf) stars
VI, sd	subdwarfs
D	white dwarfs

Table 5: Morgan-Keenan Luminosity Classes

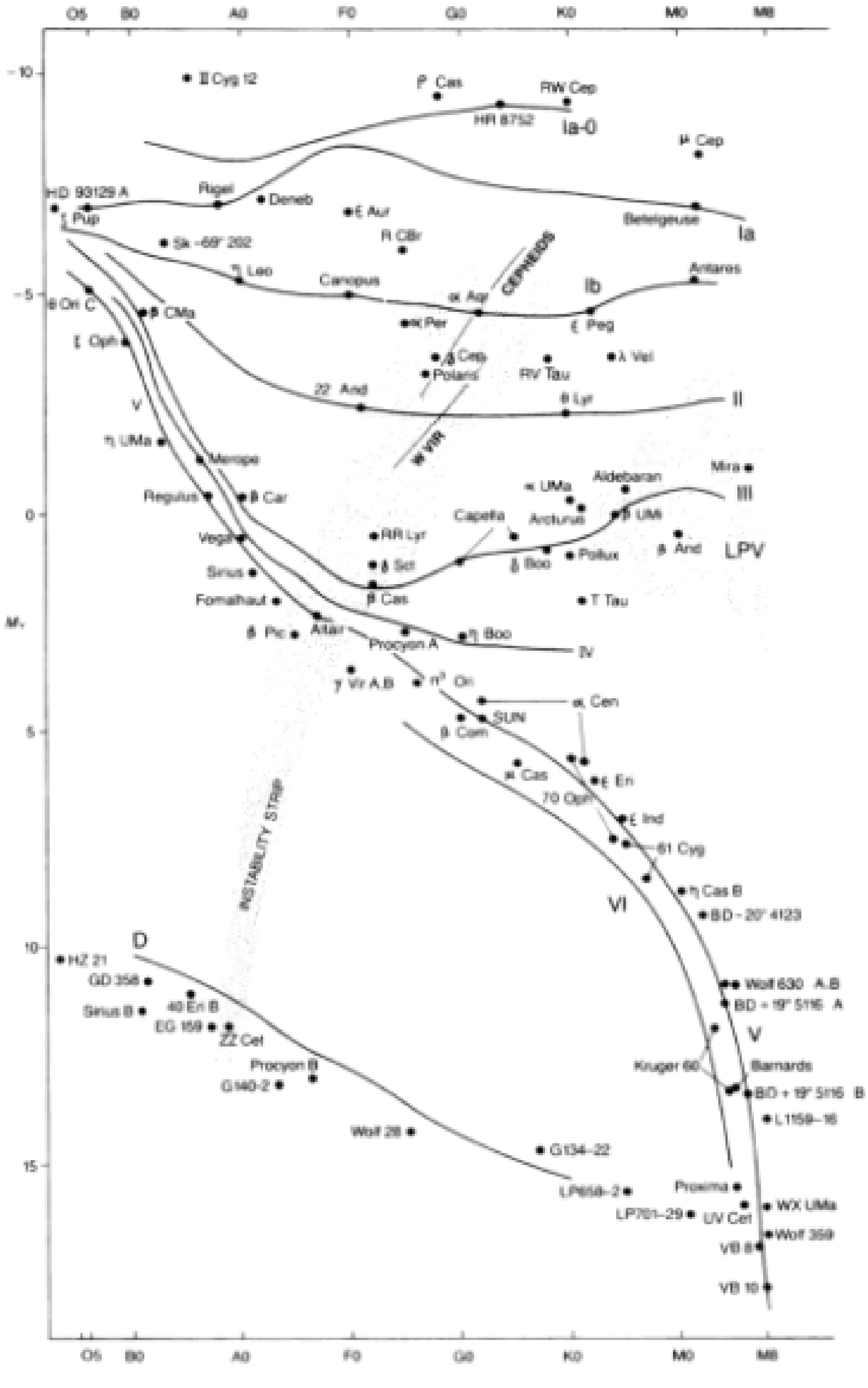

Figure 10: Luminosity classes on the HR-diagram. [CO]

One question remains to be answered. Although our sun is mostly formed by hydrogen (the sun surface has about 500 000 *H*-atoms for each *Ca*-atom!), it's absorption lines from neutral hydrogen are dominated by the *Ca II* lines. On the other side, stars such as Vega, show very strong *H* lines.

The solution to this problem lies in the excitation and ionisation energies of *H* and *Ca*. The excitation energy of neutral *H* is higher than the ionisation energy of *Ca*. The difference is strong enough, so that almost all of the Ca atoms are ionised (and produce the *Ca II*-lines), whereas very few neutral hydrogen atoms (responsible for possible Balmer lines) are in an exited state. As the surface temperature rises, more *H*-atoms are found in an excited state and the *H*-lines get stronger. The most intensive *H*-lines are found on stars with temperatures of almost 10.000 K (class *A0*; f. ex. Vega). For higher surface temperatures, ionisation dominates excitation and the Balmer lines weaken.

In general, the situation can be described as follow:

At low temperatures, most of the metals will be in their neutral states; the *Fe I* and *Ca I* lines are very strong. Even though neutral hydrogen dominates everything, the temperature (energy) is too low to pump the electron of the hydrogen in an excited state. For the coolest stars, even molecules such as *TiO* can exist. As the temperature rises, metal atoms become ionised. The *Ca II* line strengthen at the expense of the neutral *Ca I* line (see figure 11). Our sun, at a temperature of about 5800 K shows strong *Ca II* and *Fe II* lines, fainter *Fe I* and *Ca I* lines and a rather faint *H I* absorption line. As the temperature reaches 10.000 K, the H-lines dominate all other lines. Only at higher temperatures, excited and ionised *Si*, *Mg*, *He*, … can be found in the stars spectra.

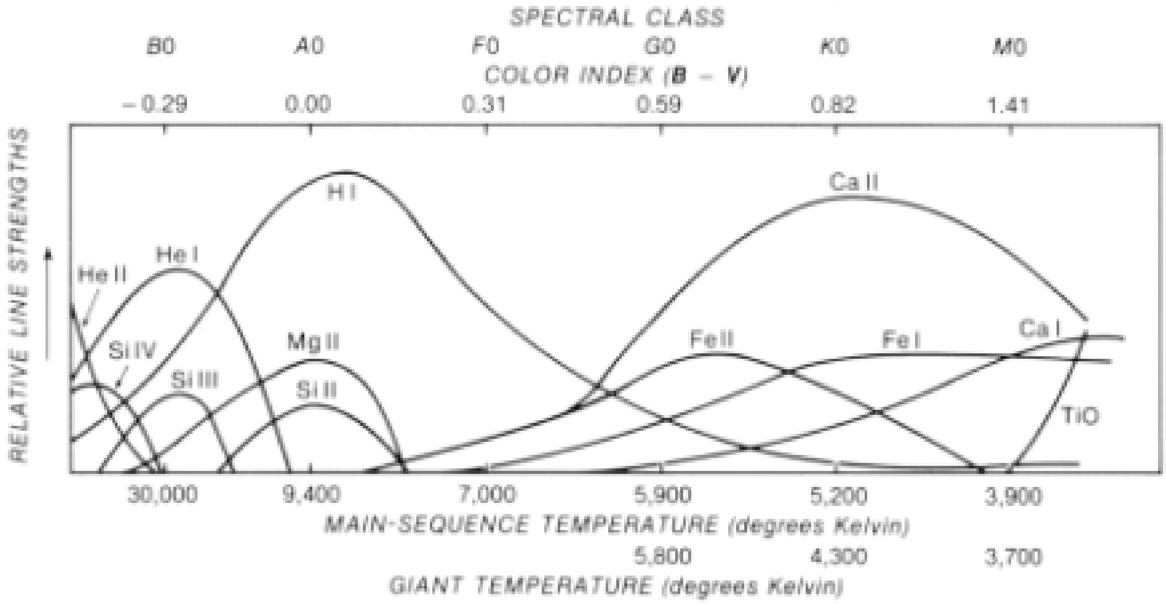

Figure 11: Line strength in dependence of the surface temperature. [JK]

Further readings:

[JK] Stars and their spectra
James B. Kaler
Cambridge University Press, 1989

[CO] An Introduction to Modern Astrophysics
B. W. Carroll, D. A. Ostlie

Addison-Wesley, 1996

[SuW] Sonne
SuW-Spezial 4, 1999

[SV] X-XXe siècle, Particules et galaxies
Cahiers de Science et Vie, 1999