PHY20003 ASTROPHYSICS

Lecture 17 Stellar Classification and Evolution

17.1 Spectral Classification

All spectra of stars show absorption lines, where atoms and ions in the stellar photosphere absorb the radiation coming from deeper layers.

Stars like the Sun show many absorption lines due to both neutral and lightly ionised atoms (including many lines from metals).

Some stars show evidence of only light elements, such as hydrogen and helium.

Cooler stars show evidence of absorption by molecules in their atmospheres (these molecules are dissociated in hotter stars).

The first classification of stars was done based on the strength of the Hydrogen lines in the stellar spectra:

$$\text{A}, \text{B}, \ldots\ , \text{O}$$
$$\text{Strong} \rightarrow \text{Weak}$$

It was later realised that the absorption lines in stars denoted a temperature sequence, and therefore that the types should not be sorted in alphabetical order, but that the sequence (from hot to cool) is:

$$\text{O} \;\; \text{B} \;\; \text{A} \;\; \text{F} \;\; \text{G} \;\; \text{K} \;\; \text{M}$$

Oh Be A Fine Guy/Girl/Gerbil, Kiss Me

A description of the different spectral classes is shown in Table 17.1.

This spectral classification is further subdivided by a number between 0 and 9, where 0 is used for the hottest stars, and 9 is used for the coolest stars within a spectral class.

Table 17.1: Spectral classes of stars, including their temperatures and the main features visible in their spectra.

Class	***Temperature***	***Spectral Features***
O	>30,000 K	Ionised Helium, weak Hydrogen
B	10,000 K – 30,000K	Neutral Helium, Hydrogen, ionised metals (predominantly CNO)
A	7,500 K – 10,000 K	Hydrogen features are the strongest, Helium disappeared, singly ionised metals
F	6,000 K – 7,500 K	Weaker hydrogen, neutral and singly ionised metals
G	5,000 K – 6,000 K	Ca II is the most prominent, weak hydrogen, neutral metals
K	3,500 K – 5,000 K	Neutral metals, very weak hydrogen, some molecules (CH & TiO)
M	<4,000 K	Strong molecular absorption (TiO/VO dominate).

Variations in the absorption line widths, correlate with a star's luminosity and absolute magnitude, M_V. Therefore, each star can be assigned a Luminosity class.

There are 5 main luminosity classes, as listed in Table 17.2.

Table 17.2: Luminosity classes of stars.

Class	**Name**
I	Supergiant
II	Bright giant
III	Giant
IV	Subgiant
V	Dwarf

The full classification of a star consists of a letter denoting the spectral class, followed by a number based on the temperature within the spectral class, and finally a roman numeral for the luminosity class (there are sometimes other letters added to this to indicate stars with strange properties).

Some examples of the spectral classification:

Vega (α Lyrae) is a A0V star

Aldebaran (α Tauri) is a K5III star

The Sun and α Centauri A are G2V stars

α Centauri B is a K1V star

Betelgeuse (α Orionis) is a M1Ia star

Proxima Centauri is a M5.5V star

Infrared surveys later discovered a class of sub-stellar objects that are cooler than M dwarfs. These stars show spectral features from complex molecules, including water, in their atmospheres. They are given a spectral classification of L or T, and are not massive enough for sustained hydrogen fusion. Collectively these stars are known as brown dwarfs.

17.2 Star Formation

Currently, there is no complete theory of star-formation that can account for all the details. The difficulty lies in the wide range in sizes, densities and temperatures encountered throughout the process. However, the general features can be well described. Stars form in giant interstellar clouds, which collapse (Sect. 17.2.1), when the core gets hot enough, fusion will start (Sect. 17.2.2), and as time progresses this will stabilise, and the star becomes a main sequence star (Sect. 17.2.3).

17.2.1 Collapse

The collapse of an interstellar gas cloud under its own gravity is the first stage of star formation. Initially, this collapse will result in gravitational free-fall of any material.

Consider a cloud of mass M with an initial radius R and density ρ_0. To calculate the free-fall time, we follow a test particle falling in radially from the outer edge of the cloud towards the centre, so that it follows an elliptical orbit of semi-major axis $a = R/2$. We then have

$$M = \frac{4\pi}{3} R^3 \rho_0 = \frac{32\pi}{3} a^3 \rho_0$$

Kepler's 3rd law states that

$$\frac{P^2}{a^3} = \frac{4\pi^2}{GM}$$

Solving for P^2 we get

$$P^2 = \frac{12\pi^2 a^3}{32G\pi a^3 \rho_0} = \frac{3\pi}{8G\rho_0}$$

The free-fall time, t_{ff}, is half of the period:

$$t_{ff} = \left(\frac{3\pi}{32G\rho_0}\right)^{1/2}$$

Typical densities in molecular clouds are $\sim 10^4$ hydrogen atoms cm^{-3}, giving $t_{ff} \sim 10^5$ years.

As the cloud collapses, its density will increase and temperature in the core rises, leading to the next important stage.

17.2.2 Ignition

As the core heats up, a point is eventually reached where the temperature and pressure are high enough for nuclear fusion to occur. The basic fusion process in (pre-)main sequence stars results in four hydrogen nuclei fusing together into a single helium nucleus through the proton-proton (PP) chain. This process releases a significant amount of energy. There are several different PP chains. Here we focus on the PP1 chain, which starts with hydrogen atoms, and, through the intermediate production of deuterium (${}^2_1D \equiv {}^2_1H$) and helium-3, produces helium-4:

$$ {}^1_1H + {}^1_1H \rightarrow {}^2_1D + e^+ + \nu_e $$
$$ {}^2_1D + {}^1_1H \rightarrow {}^3_2He + \gamma $$
$$ {}^3_2He + {}^3_2He \rightarrow {}^4_2He + {}^1_1H + {}^1_1H $$

For the Sun, the PP1 chain dominates, but for hotter stars, other routes, including the CNO cycle can dominate the fusion process, although all routes in a main-sequence star result in four hydrogen nuclei fusing into a single helium nucleus, and releasing energy.

The central temperature of a star depends on its mass.

An object with a $M_* < 0.08 M_\odot$ will not have a core hot enough for the fusion of hydrogen. These objects will slowly cool down and shrink, once the initial collapse is halted by the thermal pressure of the gas. These “failed stars” are known as brown dwarfs (BDs).

Older BDs have lithium in their atmosphere, while “true stars” do not. Young stars will show some lithium in their spectra, but this disappears as they age (the lithium abundance can be used to age young stars).

17.2.3 Stabilisation

The beginning of nuclear fusion in the core of the stars creates an increase in the optical luminosity of the star that literally blows the remaining gas surrounding the forming star away.

Such new-born stars are easily seen in nearby star-formation regions and are known as *T-Tauri star*.

When the radiation pressure from the nuclear reactions in the core of a stars balance the gravitational collapse, the star reaches the main sequence.

While on the main sequence, the nuclear fusion in the core acts as a thermostat, if the reaction rates become too low, the temperature will decrease causing the star to shrink. This raises the pressure and temperature in the core and thereby increasing the fusion rate. On the other hand, if the reaction rate becomes too high, the radiation pressure from the core will cause it to expand, cooling down and decreasing the nuclear reaction rates.