Chapter 8

Star properties

Our understanding of star properties is based on analysis of the light we receive from them. By 'light' we mean not only visible radiation but, very importantly, radiation that the human eye cannot see, such as x-rays, ultraviolet light, microwaves, radio waves, etc. In interstellar space, all these forms of radiation travel at the same speed, the speed of light, and collectively they form the *electromagnetic spectrum*.

Even at the speed of light, there is a significant lag between the time the radiation was emitted from the star and the time when the radiation is detected by Earth-based observers. For example, it takes about 8 min for light leaving the surface of the Sun to reach Earth. It takes over 4 years for light leaving Proxima Centauri, our nearest neighbor star, to reach us. In other words, what we see today is how Proxima Centauri was 4 years ago. In a way this time lag is an advantage because by looking farther into space astrophysicists are essentially looking back into the past and see stars and galaxies that are at different stages of their evolution. The images from nearby stars and galaxies represent how the Universe is 'now'. The images from more distant objects tell us how the Universe looked when it was younger. Understanding the evolution of stars and the Universe is one of the most exciting areas of research and is beyond the scope of this book. This chapter will provide a qualitative description of the principles of some of the methods used to measure some star properties.

8.1 The color and temperature of stars

Stars like the Sun obtain their energy from the hydrogen fusion that takes place deep in their interior. Fusion is a nuclear reaction that fuses four hydrogen nuclei to make a nucleus of helium, releasing energy and other particles in the process. Stars that obtain their energy from hydrogen fusion are called *main sequence stars*. Fusion can take place only in the core of the star, where the temperature is several million degrees and the pressure is about a trillion times larger than the atmospheric

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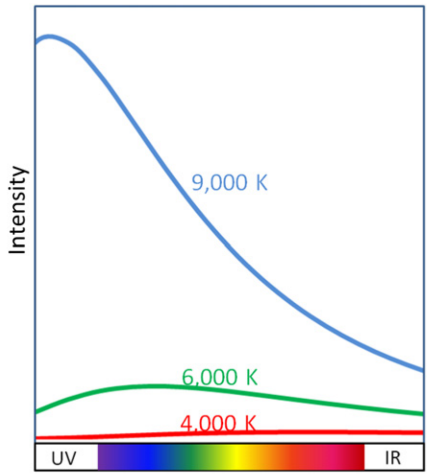

Figure 8.1. The continuous spectrum at three temperatures. Note that at higher temperatures the relative amount of blue increases.

pressure on Earth. These numbers are estimates, because the interior of a star cannot be observed directly.

What we perceive as the surface of a star is the opaque layer below the star's atmosphere, the so-called *photosphere*. The average temperature of the Sun's photosphere is about 5800 K[1]. The photosphere emits the sunlight (starlight) we see and the color of the light emitted depends on the temperature of the photosphere. From everyday experience we know that as a solid object becomes hot, it emits radiation (heat, which is infra-red light) and if the temperature of the object increases further it emits more and more heat, and may begin to emit visible light (it becomes red hot). The filament in an ordinary incandescent light bulb is even hotter than red hot, it is yellow to white hot.

Hot solids emit all colors of light, but at different proportions, depending on the temperature. What our eye perceives depends on which color dominates. If the light emitted contains red, green and blue in a certain balance, the human visual system perceives white light. If there is slight excess of red and less blue, we perceive yellow. As the excess of red increases, we see orange, orange-red, etc. The color distribution of the light emitted by a hot solid is the *continuous spectrum*. Figure 8.1 shows the continuous spectrum for three different temperatures. Note that as the temperature increases, the overall intensity is significantly increased. Note also that the increase is more dramatic in the blue.

If the temperature is low, below 4000 K, the emitted light is red. As the temperature is increased, the color becomes orange-red and at above 5000 K the color becomes golden-yellow, like the color of the Sun. Hotter stars (7500 to 10 000 K) look white, and even hotter stars look blue or blue-violet. As a general rule, the more red the star appears, the lower its surface temperature. The more blue the star

[1] The temperatures are given in the kelvin scale (K) which is equivalent to degrees centigrade (°C) + 273.

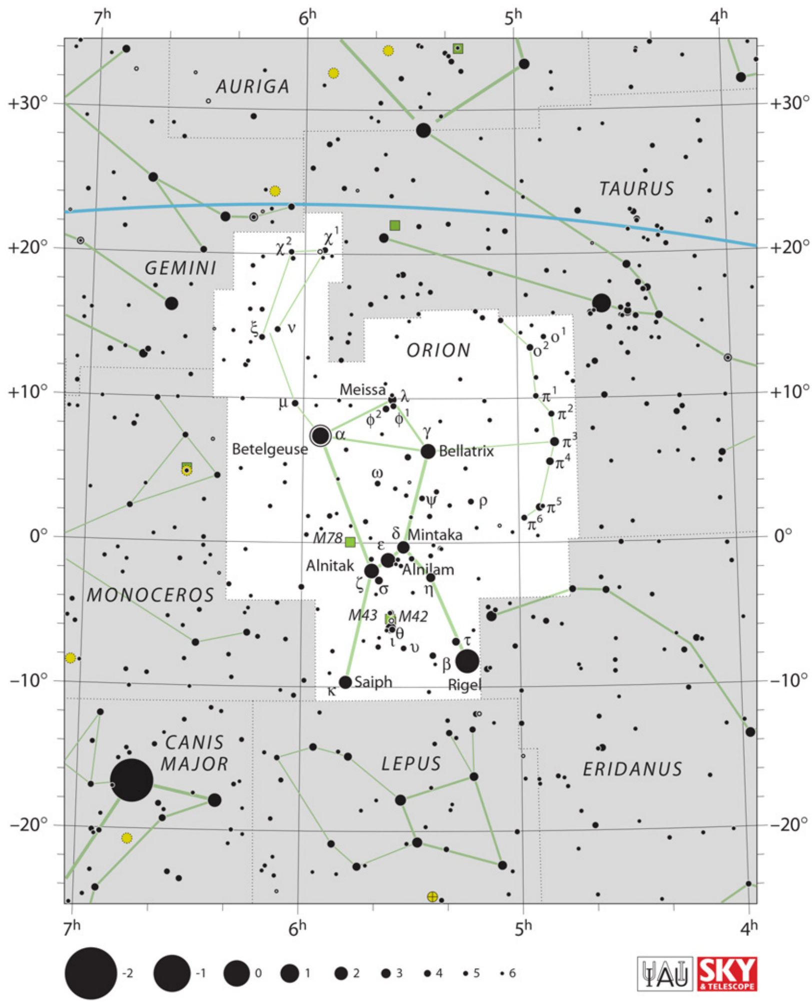

Figure 8.2. A star map of the constellation of Orion. Credit: International Astronomical Union and *Sky and Telescope*.

appears, the hotter its surface. Analysis of the continuous spectrum of the light emitted by a star provides one way of determining the surface temperature of the star. Note that there is a temperature range where green is in highest proportion. This is the temperature range where all the colors are in a certain balance such that to the human eye the star appears white, not green.

For the brighter stars the color is easily detectable. Figure 8.2 shows the star map in the constellation of Orion which is visible in the evening from mid-December to mid-April. The brightness of the stars is indicated by the size of the dots. In Orion the brightest stars are Rigel and Betelgeuse. Their color is distinctly noticeable. Rigel is blue-white (i.e. hot) and Betelgeuse is red (i.e. cool). The three stars Alnitak, Alnilam and Mintaka are distinctly blue, and together form *Orion's Belt*. These stars are very hot.

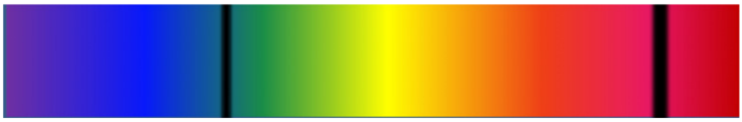

Figure 8.3. The absorption spectrum of the hydrogen atom.

East of Orion is the constellation of Canis Major and the brightest star in the constellation is Sirius (not labeled). Sirius is the brightest star in the night sky and is white, i.e. not as hot as the stars in Orion's belt. West of Orion is the constellation of Taurus. The brightest in Taurus is Aldebaran (not labeled) and its color is orange, i.e. cool, but hotter than Betelgeuse. For dimmer stars the color is not detectable by the human eye.

8.2 The spectral classification of stars

Another method of determining the surface temperature relies on analysis of the absorption of light by the *chromosphere*, the bottom layer of the star's atmosphere that is immediately above the *photosphere*. The basic idea is that if the temperature is very high, only the simplest atoms (hydrogen and helium) can be in a state that absorbs light. As the temperature becomes lower, more atomic species can be in a state that absorbs light. The color of light[2] absorbed by each atomic species is very *characteristic* of the atom. The pattern of the absorbed color bands is the so-called *absorption spectrum*, and this is the basis of *absorption spectroscopy*, a powerful method of chemical analysis. Figure 8.3 shows a qualitative absorption spectrum for the hydrogen atom if the temperature is high.

Note that the two dark lines are characteristic of the atom, in other words, if these two lines are present in the spectrum of a star, then there must be hydrogen in the chromosphere of the star and the temperature must be high. If the temperature is low, hydrogen may be present but the lines will not show up in the absorption spectrum. Therefore, the absorption spectrum contains information about the temperature of the chromosphere of the star. In terms of the absorption spectrum, stars are classified in seven main *spectral types*: O, B, A, F, G, K and M. The O type is the hottest and the M type is the coolest. Each type includes ten subdivisions, with 0 the hottest and 9 the coolest of the given spectral type. For example, for type A, we have A0, A1, A2, …, A9, which is followed in order of decreasing temperature by F0, F1, …, F9, then G0, G1, etc. In terms of spectral type, the Sun is a G2 star.

Table 8.1 lists the main spectral types with the corresponding temperature, color and a star representative of that spectral type.

8.3 Other information contained in the absorption spectra of stars

Analysis of the absorption spectrum can also provide information about the motion of stars. From everyday experience we know that the pitch of the siren we hear from fire trucks depends on their motion: if the siren is approaching the pitch becomes higher and if the siren is receding the pitch becomes lower. The same applies to light.

[2] The color is indicated by the so-called wavelength of light.

Table 8.1. The main spectral types of stars, with temperature range and color.

Spectral type	Temperature (K)	Color	Representative star
O	Above 25 000	Blue–violet	Na'ir al Saif, O9
B	10 000–25 000	Blue–white	Rigel, B8
A	7500–10 000	White	Sirius, A1
F	6000–7500	Yellow–white	Procyon, F5
G	5000–6000	Yellow	Sun, G2
K	3500–5000	Orange	Arcturus, K2
M	Below 3500	Red	Betelgeuse, M2

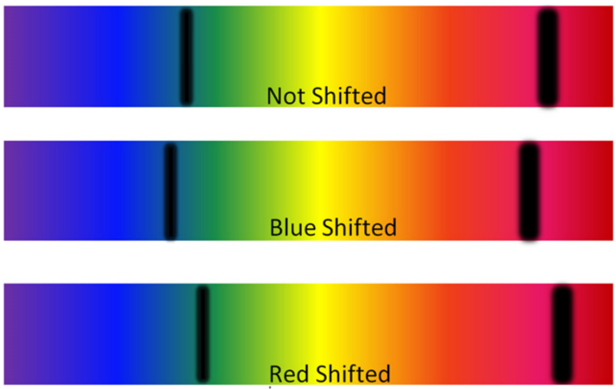

Figure 8.4. Qualitative absorption spectra of hydrogen showing the shift due to motion.

If the star is approaching, the absorption spectral lines move towards the blue end of the spectrum (*blue shift*) and if the star is receding the shift is towards the red end of the spectrum (*red shift*). A qualitative diagram of the shifted lines is given in figure 8.4. This shift of the spectral lines is called the *Doppler shift* and can be used to determine the speed of motion along the line of sight to the star. Note that the important quantity is the distance between star and observer: if the distance is becoming smaller, we have blue-shift, and it does not matter if the observer is moving towards the star or the star is moving towards the observer. In other words, there is only *relative motion* and there is no *absolute motion*. The Doppler shift is a very powerful method and was used to establish the *expansion of the Universe*, as well as the discovery of *exoplanets*.

In addition, the analysis of the absorption spectrum provides information about the pressure of the stellar atmosphere. If the pressure in the star's atmosphere is low, the absorption lines are sharp. If the pressure is high, then the absorption lines are broad. The two spectra in figure 8.5 show the effect of pressure on the width of the spectral lines.

The atmospheric pressure of a star is determined by the strength of gravity at the surface of the star. Stronger gravity will make the pressure higher and can result if the material in the star is densely packed. For stars, this means that the mass is

Figure 8.5. Qualitative absorption spectra of the hydrogen atom showing the effect of pressure on the width of the dark absorption lines. The dark absorption lines in the top spectrum indicate low pressure in the star's atmosphere. The dark lines are wider in the bottom spectrum indicating high pressure in the star's atmosphere.

packed in a smaller volume. Similarly, low pressure indicates low surface gravity, a lower density and therefore a larger volume, which means a larger radius. Thus by analyzing the width of the absorption lines, we can obtain some idea about the density and the size of the star itself.

The absorption spectra can also tell us about the magnetic field of the star, its rotation and also detect the existence of other stars or planets that may be orbiting the star. The discussion of these fascinating topics is beyond the scope of this book.

8.4 Luminosity and luminosity classes

From Earth, the Sun appears to be the brightest object in the sky because the Sun is close to Earth. Other stars may emit a lot more light than the Sun, but they appear dim because they are so far away. The situation is similar to light bulbs. For example, a 60 watt (W) light bulb may appear dazzlingly bright if it is located close by, while a 1000 W street light may appear quite dim if it is 1 km away. The terms *luminosity* or *intrinsic brightness* are used to characterize the rate of energy emission. The luminosity is a characteristic quantity of the star and therefore independent of the distance of the star, in the same way that a 100 W light bulb outputs 100 W independent of where it is.

Star luminosities are usually expressed using the Sun's luminosity as a unit. The luminosity of a star is determined by two quantities: the surface temperature and the size of the star. The higher the temperature, the more energy is emitted from each part of the surface. Also, the larger the star, the more surface there is. The luminosity or intrinsic brightness of stars is also expressed in terms of the *absolute magnitude*. The absolute magnitude scale is discussed in detail in appendix D.

The size–temperature combinations for different stars can be used to classify stars in terms of their luminosity. For example, *white dwarf* stars are much smaller than the Sun, but their surface temperature is much higher than the Sun. As a result, white dwarfs have very low luminosities. For example, Sirius, the brightest star in the sky, has a companion star that is a white dwarf, Sirius B. Sirius B is about the size of the Earth, but its surface temperature is over 20 000 K compared to the Sun's 5800 K. In spite of its high temperature, Sirius B is 10 000 dimmer than the Sun.

In contrast to white dwarfs, *red giant* stars have a lower temperature than the Sun, but are much larger. The result is that red giants have higher luminosities.

For example, Aldebaran, the brightest star in the constellation of Taurus, is a red giant. Its surface temperature is about 4000 K but its radius is over 40 times larger than the Sun's radius. As a result of its larger size, Aldebaran is over 500 times more luminous than the Sun.

Although white dwarfs are smaller than the Sun in size, this does not mean that the mass of the white dwarfs is much smaller than the Sun's mass. Actually, the mass of a white dwarf can be larger than the mass of the Sun. The difference is that the mass of a white dwarf is packed in a smaller volume, more densely. In fact the material that makes the white dwarfs is so dense that on Earth a spoonful of this material would weigh 1 ton! The reverse is true for red giants. They can be 10 times larger than the Sun, but have less mass than the Sun. In red giant stars the material is loosely packed. The difference in the star's density, and therefore atmospheric pressure, can be demonstrated by the width of the dark lines in the absorption spectrum as discussed in section 8.3. Red giants have narrower absorption spectral lines (which means lower pressure) while white dwarfs have broader spectral lines (which means higher pressure). Red giants and white dwarfs are stages in the evolution of main sequence stars (see section 8.1) after they have depleted the hydrogen in their core.

Depending on the luminosity, stars are classified in five luminosity classes. The luminosity classes are indicated by a roman numeral from I to V.

Luminosity classes:

I. Supergiants
II. Bright giants
III. Giants
IV. Subgiants
V. Main sequence stars or dwarf stars

In luminosity class V, the term 'dwarf' does not include white dwarfs. White dwarfs are designated by the symbol D. This classification has been extended to include more classes, for example, class 0 hypergiants to indicate stars more luminous than class I, and class I is subdivided into Ia for bright supergiants and Ib for supergiants.

A star is completely characterized by its spectral type and its luminosity class. For example the Sun is a G2V (V means main sequence); Sirius B is a DA2 (D means white dwarf); Arcturus is a K2III (III means giant).

The star information is summarized in the so-called HR diagram[3]. The various luminosity classes are outlined in figure 8.6. Stars at the left end of the diagram are the hottest stars. Stars on the right end of the diagram are the coolest stars. The vertical axis is the luminosity expressed in solar luminosities. Stars towards the top of the diagram are over 100 000 times more luminous than the Sun. Stars at the bottom have luminosities that are 100 or more times less luminous than the Sun. The background colors in the diagram represent the approximate color of each spectral class. As discussed earlier, the color of a star relates directly to the surface temperature of the star.

[3] The HR diagram is named after Ejnar Hertzsprung and Henry Norris Russell.

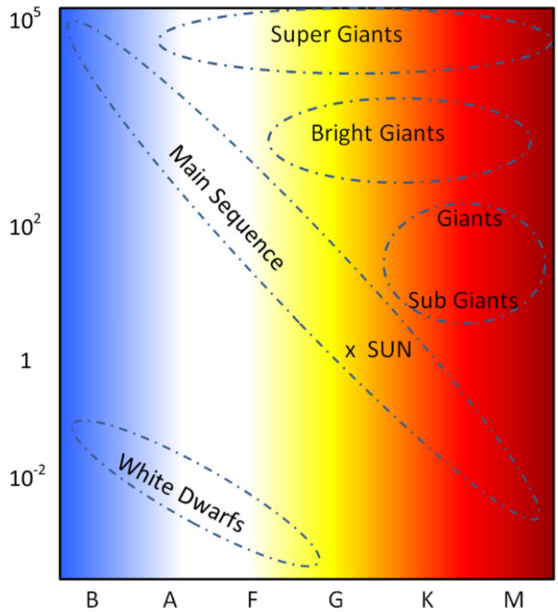

Figure 8.6. A qualitative HR diagram. The vertical axis indicates luminosity in terms of the Sun's luminosity. The background indicates color of the star. The axes of HR diagrams can be labeled in many ways. For example, the horizontal axis can indicate temperature instead of the spectral class[4].

8.5 The apparent brightness and the inverse square law

The apparent brightness, or simply *brightness*, refers to the amount of light we receive from a star. What determines the apparent brightness of a star is its distance from the observer and the star's intrinsic brightness or luminosity. A star may look bright because it emits lots of light, or because it is close to us, or both. The energy radiated by a star (which is what the luminosity tells us) spreads over larger and larger areas in all directions the farther it travels from the star. Therefore, the amount received by the observer on Earth depends on the rate the energy is emitted by the star, but also on the distance of the star from Earth. The dependence on distance follows the *inverse square law*, which states that the apparent brightness of a star depends on the inverse of the distance squared. Consider for example two identical stars (i.e. two stars of the same luminosity). If one of the stars is 10 times farther, it will not appear 10 times dimmer; instead it will appear 100 times dimmer, i.e. the brightness changes by a factor of $1/10^2$. The apparent brightness of stars is usually expressed in terms of the *apparent magnitude*. The apparent magnitude scale is discussed in detail in appendix D.

8.6 The size of stars

When viewed through telescopes, stars always appear as points. The disk seen in images is a spread of the light by diffraction (see chapter 9) and does not represent

[4] The scientific notation $10^2 = 100$, $10^3 = 1000$ and $10^{-2} = 1/100$ etc.

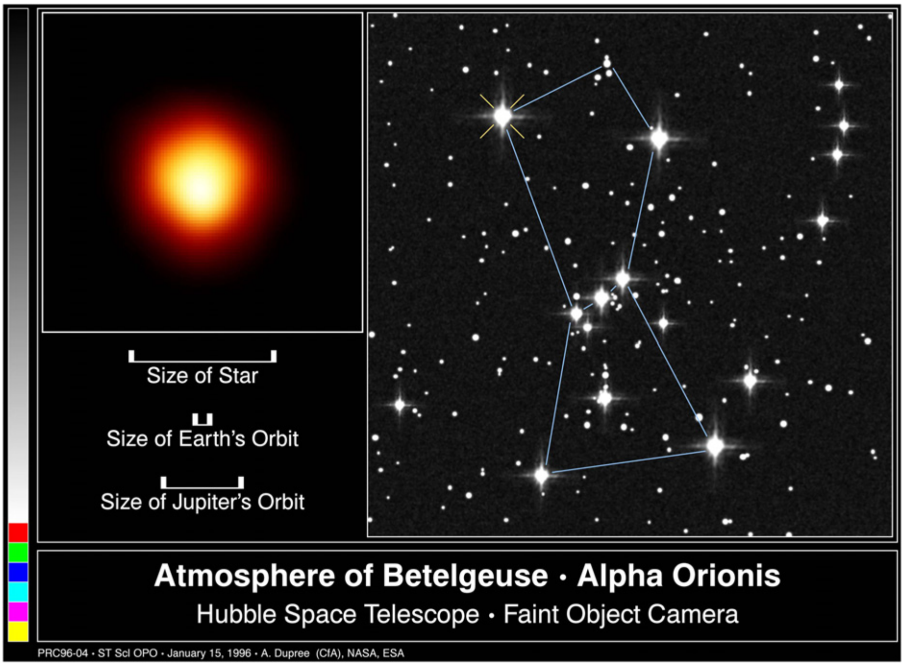

Figure 8.7. A resolved image of Betelgeuse, obtained by the Hubble Space Telescope. Betelgeuse (or alpha Orionis) is the star at the top left of the stick figure of the constellation. Credit: A Dupree (CfA), NASA, ESA, http://apod.nasa.gov/apod/image/9804/betelgeuse_hst_big.jpg.

the actual size of the star. This is true even for the best telescopes. To date, the number of star images that represent the actual size of the star (so-called *resolved* images) is fewer than a dozen. The first star to have its image resolved was Betelgeuse in the constellation of Orion, shown in figure 8.7.

The size of unresolved stars can be determined indirectly from the luminosity. The luminosity of a star depends on the temperature and the size of the star. Knowing the temperature and the luminosity allows the estimate of a star's size. If two stars have the same temperature (same spectral type) then the more luminous star must have a larger radius.

For comparison we will consider two stars of spectral type M, Betelgeuse and Menkar (the brightest star in the constellation of Cetus). The fact that the two stars are of the same spectral type means that in the HR diagram of figure 8.6 the two stars lie along the same vertical. The luminosity class of Betelgeuse is I and that of Menkar is III. Therefore Betelguese has larger luminosity, i.e. is closer to the top of the HR diagram than Menkar, so the radius of Betelgeuse must be larger than that of Menkar. The Sun's radius is commonly used as a unit for star radii. A detailed analysis of the data shows that Betelgeuse is approximately 1000 while Menkar is only 90 solar radii. In summary, this comparison shows that the radius of the stars increases as we move vertically from the bottom of the HR diagram to the top of the diagram in figure 8.6.