# Chapter 2
# Stars in Their Youth

## The Hertzsprung–Russell Diagram

Perhaps the most important diagram in stellar astronomy is what is known as the Hertzsprung–Russell diagram (H–R diagram). It is a plot of the luminosity of a star versus its surface temperature (also known as the effective temperature). Most stars you see in the sky when plotted in this diagram fall into a diagonal band known as the *main sequence*. What is shown in Fig. 2.1 is a theoretical H–R diagram.

An important property of all stars that fall into this band is that they may be regarded as chemically homogeneous, and are converting hydrogen to helium in their cores. In a real sense, all the stars along this sequence have 'recently' formed out of the interstellar gas. For this reason, this main sequence is often referred to as the *zero-age main sequence* (ZAMS). This phase, during which hydrogen is being fused into helium, has such a long duration that most stars visible in the sky are likely to be in this phase (since stars spend most of their lives in this phase, the probability of catching them in this phase will obviously be the greatest). If all the stars found in the main sequence are chemically homogeneous and are converting hydrogen into helium in their core, one may ask what distinguishes them. The most important factor that determines the location of a star *within* the main sequence is the *mass of the star*. Notice that in Fig. 2.1 the more massive stars have a higher luminosity, as one would expect from Eddington's theory.

The solid lines in Fig. 2.1 are loci of constant radii. Thus a $1M_\odot$ *zero-age star* has a radius very nearly equal to $1R_\odot$. You may think this is a bit shady. Would one not expect a $1M_\odot$ star to have a radius precisely equal to $1R_\odot$? Well, the *present* radius of the Sun is what we call $1R_\odot$. The $1M_\odot$ star in Fig. 2.1 is a *zero-age* star. The Sun descended on the main sequence nearly 5 billion years ago and its radius had changed somewhat during this period. Similarly, a $10M_\odot$ zero-age star has a radius somewhat less than $10R_\odot$. This would suggest that the radius is roughly proportional to the mass. More careful consideration shows that in the lower part of the main sequence

G. Srinivasan, *Life and Death of the Stars*, Undergraduate Lecture Notes in Physics, DOI: 10.1007/978-3-642-45384-7_2, 

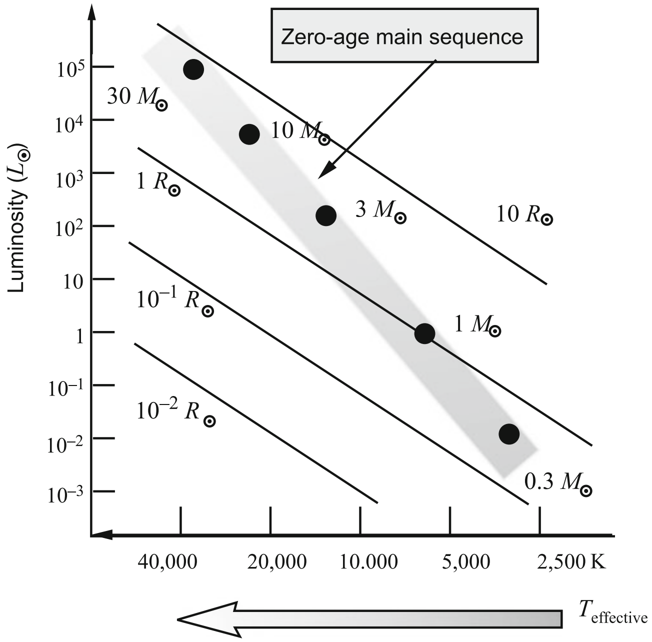


**Fig. 2.1** The diagonal band shows the location of the main sequence in the theoretical Hertzsprung–Russell diagram. This famous diagram is a plot of the luminosity versus the surface temperature (also referred to as the *effective temperature*) of stars. *Notice that the effective temperature increases from right to left!* The points indicate the theoretical location of stars of various masses when they begin their lives

$$R \propto M, \tag{2.1}$$

while in the upper part of the main sequence (that is, for the more massive stars)

$$R \propto M^{0.6} \tag{2.2}$$

is a better approximation. The above relation between the radius and the mass, taken together with the theoretical mass-luminosity relation will tell us how the surface temperature will depend on the mass. We saw in Fig. 1.5 that $M^{3.5}$ gives a reasonable fit to the observational data on luminosity. But this is over the whole range of masses. In the range 1–10 $M_\odot$ the data is better fit by an exponent 4, that is

$$L \propto M^4. \tag{2.3}$$

Using $R \propto M$ and $L \propto M^4$, together with $L = (4\pi R^2)\sigma T_{\text{eff}}^4$, we get

$$T_{\text{eff}} \propto M^{1/2} \tag{2.4}$$

on the main sequence. We know that the effective temperature of the Sun is 5,800 K. Using this to deduce the proportionality constant in (2.4) we can deduce that a $10M_\odot$ star will have a surface temperature of about 20,000 K. To put it differently, while the Sun is a *yellow star*, a $10M_\odot$ star will be a *blue star*. Remember Wien's displacement law? The wavelength at which the black body spectrum has a maximum depends upon the surface temperature of the black body.

The moral of the story is this: *High-mass main sequence stars are more luminous and intrinsically bluer than low-mass main sequence stars.*

## Energy Generation in the Main Sequence

As mentioned above, the most distinguishing feature of the stars on the main sequence is that they are converting hydrogen into helium in their cores. In the Chap. 1 we outlined the extraordinary conjecture by Eddington. But it took nearly twenty years to work out the details. The first breakthrough in solving the problem of how stars liberate energy came in 1938 when **C. F. von Weizsäcker** discovered a nuclear cycle, now known as the *carbon–nitrogen–oxygen (CNO) cycle*, in which hydrogen nuclei could be fused using carbon as a catalyst. However, von Weizsäcker did not work out the rate at which energy could be produced in the stars using this CNO cycle or how this rate would depend on the temperature that obtains in the stars.

The credit for this must go to **Hans Bethe**, the acknowledged master of nuclear physics. In 1938, Bethe had just completed a set of three monumental review articles in nuclear physics. These were known as *Bethe's Bible.* The first textbooks in nuclear physics were published only several years after the end of World War II. Until then, physicists all over the world learnt their nuclear physics from these pedagogical and authoritative articles by Bethe. In the 1930s, physicists were not concerned with problems in astronomy. They were more interested in atomic and molecular spectra, and nuclear physics. It was George Gamow who sensitized physicists about the unsolved problems concerning stellar physics by convening a small conference in Washington, D.C. Hans Bethe and many of the leading physicists were at that conference. Within a few months of this, Hans Bethe had worked out, in great detail, the synthesis of helium in stars and published his results in a landmark paper entitled, *Energy production in stars* (1939). Bethe considered two processes. One of them has come to be known as the **p–p chain** in which one builds helium out of hydrogen. This is the process that is important for stars like the Sun, and stars of even lower mass. The other process is the **CNO cycle** discovered earlier by von Weizsäcker, and is the dominant process for stars more massive than the Sun.

We have discussed both these processes in detail in ***What Are the Stars?*** Here, we shall briefly recall the steps involved in these reactions by reproducing the relevant figures from there.

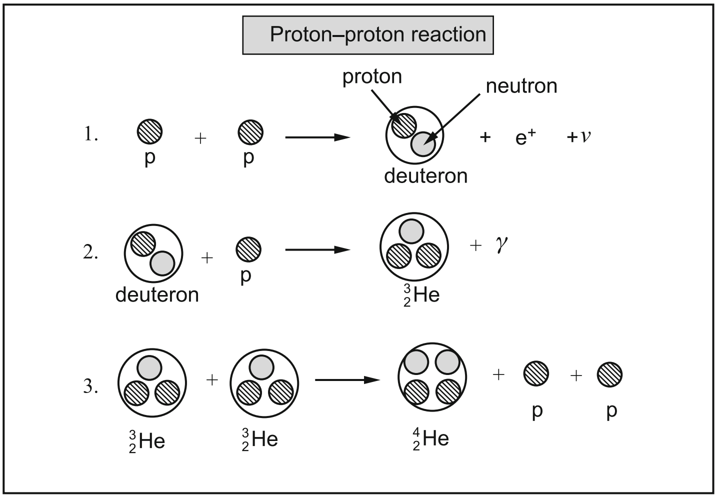


**Fig. 2.2** The synthesis of protons into helium nucleus. This is the *main branch* of the p–p chain reaction, and accounts for 85 % of the energy generation. The remaining 15 % is through alternate branches, which we shall not discuss here

## *The p–p Chain Reaction*

Figure 2.2 summarizes the main channel in the proton–proton chain.

## *The CNO Cycle*

The other route for the synthesis of helium is the Carbon–Nitrogen–Oxygen cycle, first discovered by C. F. von Weizsäcker. The details of this were worked out by Hans Bethe in 1939. The CNO cycle requires the presence of some carbon, nitrogen or oxygen which act as catalysts in chemical reactions.

Here also, like in the p–p chain, four protons are fused into one helium nucleus, releasing roughly the same amount of energy as before (25 MeV per $^4$He nucleus produced).

All nuclear reactions are sensitive to temperature. Fusion of nuclei is made possible by quantum mechanical tunnelling through the repulsive coulomb barrier. Given the like charges of the two colliding nuclei, the probability of such a tunnelling depends very sensitively on the kinetic energy of the particles. And this, in turn, depends upon the temperature of the stellar plasma (Figs. 2.3 and 2.4).

The p–p chain is the least temperature-sensitive of all the fusion reactions. The CNO cycle is much more sensitive to temperature. This has the consequence that the p–p chain dominates at lower central temperatures ($T_c < 15 \times 10^6$K). At higher

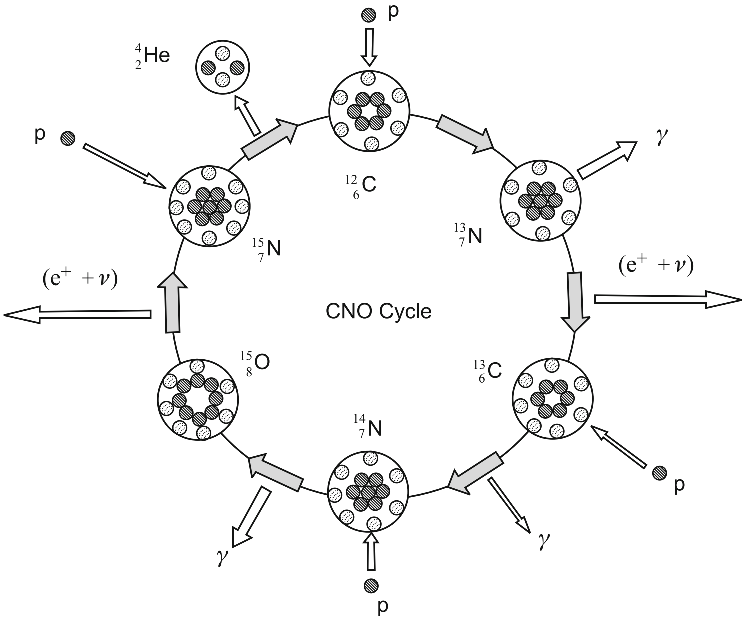


**Fig. 2.3** A pictorial representation of the CNO cycle. The *bigger circles* represent the nuclei indicated. The small *hatched circles* are the protons and the *small circles* with *dots* are the neutrons

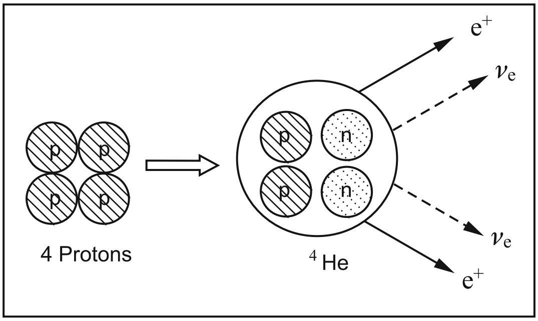


**Fig. 2.4** In both the p–p reaction chain and the CNO cycle, four protons are involved in forming a helium nucleus. For every helium nucleus that is synthesized, *two positrons* and *two electron neutrinos* are emitted

central temperatures the CNO cycle dominates over the p–p chain. This is shown in Fig. 2.5.

Going back to the main sequence sketched in Fig. 2.1, for stars more massive than the Sun the CNO cycle is the main process of energy generation, while for stars less massive than the Sun the p–p chain is the main channel.

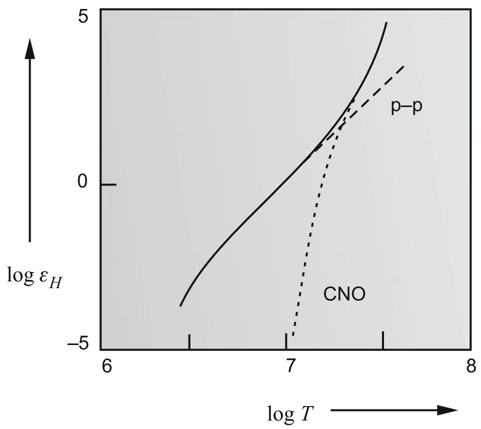


**Fig. 2.5** The energy generation rate $\varepsilon_H$ (erg. $g^{-1}$. $s^{-1}$) as a function of temperature. The *dashed lines* show the contributions of the p–p chain and the CNO cycle. The *solid line* is the total energy generation

## Convection in Stars

Convection is a rather important phenomenon in stars. I refer the interested reader to the companion volume, ***What Are the Stars?*** for a comprehensive discussion of why convection occurs. Here, we shall merely state that *a fluid in a gravitational field will become unstable to the onset of convection if the temperature gradient exceeds a critical value*. This critical value is known as the *adiabatic temperature gradient*; this is the rate at which the temperature of a blob of fluid will decrease if it is transported upward (that is, against gravity) in an adiabatic manner.

In Eddington's theory, stars are assumed to be in radiative equilibrium; the outward flowing heat is transported by the outward flux of radiation itself. There is no convection. But this assumption is not necessarily valid everywhere in a star. What do modern calculations tell us regarding this?

Let us first consider stars in the lower part of the main sequence, namely the low mass stars. They have cores which are in radiative equilibrium. As a consequence of the relatively low temperature sensitivity of the p–p reactions, there are no steep gradients in the rate of energy generation in the central region and, therefore, no steep temperature gradients. But the outer layers of low mass stars tend to be convective. The outer layers of these stars tend to be cooler. This, in turn, increases the opacity of the outer regions. The presence of new species of ions, such as the *negative ion of hydrogen* (hydrogen atom with two electrons!) results in a dramatic increase in the opacity. This results in very steep temperature gradients, leading to convection. In the Sun, for example, the outer 200,000 km (roughly one-third of its radius) is fully convective. In stars of even lower mass, the convective region can penetrate right down to the core.

The situation is exactly opposite in the upper part of the main sequence. In more massive stars, the outer regions are in radiative equilibrium. Their high surface temperature ensures that there are no steep temperature gradients in the outer layers. But their cores tend to be fully convective. This is because of steep temperature

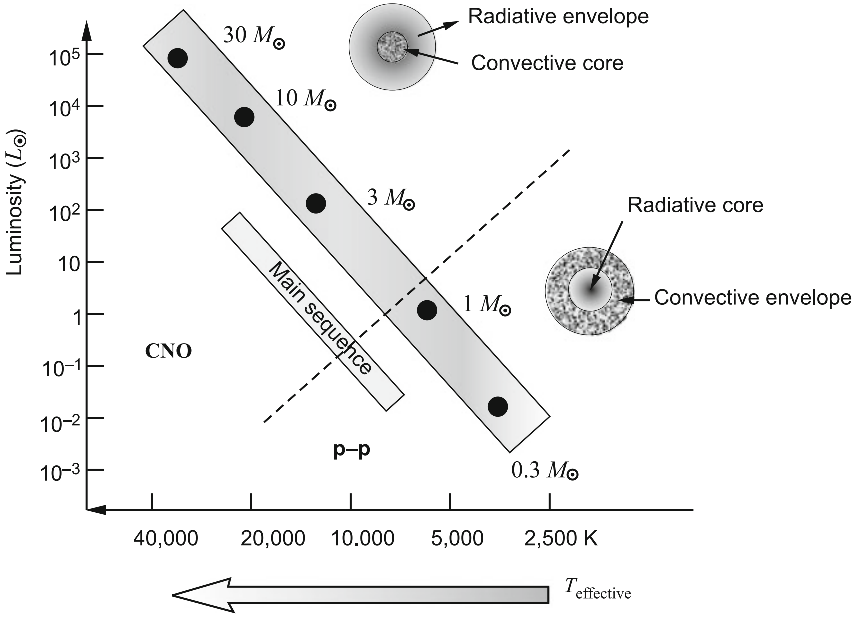


**Fig. 2.6** This figure summarizes some important differences between the stars in the *upper part* of the main sequence and the *lower part*; the boundary is roughly around one solar mass

gradients in the core. The reason for this is the following. Remember that in these stars the CNO cycle is the dominant energy generation mechanism, and this process is very sensitive to temperature. Therefore, *the energy production more centrally concentrated, leading to steep temperature gradients*.

The above mentioned characteristics of stars in the main sequence are summarized in Fig. 2.6.

## The Lifetime of Stars

As mentioned above, the stars on the main sequence are infant stars. The more massive among them would have formed only *recently* from interstellar gas. But some of these infants, like our Sun, were born a long time ago. We believe that that our solar system was formed roughly 4.5 billion years ago, but it is still in its infancy!

How long will the stars live? Perhaps it is more pertinent to ask how long the present act of the stellar drama will last. The main theme in this first act is the generation of energy by fusing hydrogen nuclei to form helium nuclei. This is often referred to as *hydrogen burning* in the astronomical literature.

[At this stage, let me make a parenthetical remark. After resisting for long (!), I have succumbed to the astronomers' terminology of *hydrogen burning*. This is of course a misnomer. *Combustion* or *burning* is the sequence of exothermic chemical reactions between a fuel and an oxidant accompanied by the production of heat and conversion of chemical species. The release of heat can result in the production of light in the form of either glowing or a flame. Fuels of interest often include organic compounds (especially hydrocarbons) in the gas, liquid or solid phase. A simple example can be seen in the combustion of hydrogen and oxygen, which is a commonly used reaction in rocket engines: $2H_2 + O_2 \rightarrow 2H_2O$ (gas) + heat. The result is water vapour.

But this not what is happening in the stars! *What is happening in the stars is fusion reactions, in which nuclei are fused together and vast amount of energy is released.* So do not get confused if I occasionally slip into the astronomers' jargon and use phrases like *helium burning, carbon burning*, etc.]

The time $\tau_H$ a star spends in the *hydrogen-burning* phase depends on its mass $M$. This is because the luminosity $L$ of a star (or the total energy radiated per unit time) depends on the mass of the star rather strongly. We saw in Fig. 1.5 that $M^{3.5}$ gives a reasonable fit to the observational data on luminosity over the entire mass range. Let $E_H$ be the energy that can be released by fusion of hydrogen. The lifetime of the star in this phase can be written as

$$\tau_H = \frac{E_H}{L}. \tag{2.5}$$

Let us assume for simplicity that the same fraction of the total mass of the star is consumed in this phase in all stars. We then have $E_H \propto Mc^2$ and

$$\boxed{\tau_H \sim \frac{M}{L} \sim M^{-2.5}.} \tag{2.6}$$

The Sun has already spent 4.5 billion years on the main sequence and it will be another 6.5 billion years before it begins the second act and leaves the main sequence. So *the hydrogen burning lifetime of the Sun is* $\sim 10^{10}$ *years*. The main sequence lifetime of stars of different mass can be estimated using this normalization and the scaling relation (2.6). Today, with fast computers at our disposal, one can actually calculate the lifetime by making some specific assumption about the abundance of hydrogen in the stars at the beginning of their lives. The main sequence lifetimes from such calculations is given in the table below.

| $M/M_\odot$ | 1 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|
| $\tau_H/10^7$ years | 700 | 8 | 4.9 | 3.3 | 2.5 | 2 |

## The Ultimate Fate of the Stars

Once the hydrogen in the *core* is exhausted, the curtain will come down on the first act, and the subsequent acts of the stellar drama will follow. As we shall see, the subsequent acts will be of shorter and shorter duration. *Astonishingly, for a drama that has gone on for tens of millions or billions of years, the final act will last only a day or so!* Instead of continuing with the story of the life history of stars in a logical manner, we shall straightaway come to the point when the curtains come down at the end of the last act.

As I remarked while concluding the first chapter, this book is devoted to the question 'What is the ultimate fate of the stars?' What will happen when the nuclear reactions cease either because the central region is not hot enough or because it has run out of fuel. Since no more heat will be generated, the star will be in a serious predicament when the fossil heat is also radiated away.

*Can the stars find peace?*

It turns out that astronomers were confronted with this question way back in 1924, many decades before one had a satisfactory understanding of the evolution of stars. And they came up with some extraordinary answers.

Let us therefore go backwards in time to 1924 and get a historical perspective.

http://www.springer.com/978-3-642-45383-0

Life and Death of the Stars
Srinivasan, G.
2014, XVII, 225 p. 113 illus., Softcover
ISBN: 978-3-642-45383-0