energy at the same rate as now for the past $4{\cdot}5 \times 10^9$ years. We now also believe that many other stars are about 10^{10} years old and these enormous ages immediately focus our attention on the source of the stellar energy. In the case of the Sun, we can multiply the solar luminosity $L_\odot = 3{\cdot}8 \times 10^{26}$ WATTS (W) by its minimum radiating lifetime ($4{\cdot}5 \times 10^9$ years) to arrive at the total energy emitted at least during the lifetime of the Earth. This turns out to be a staggering $5{\cdot}5 \times 10^{43}$ JOULES (J).

We can then ask what energy sources could satisfy the above requirement. The simplest case is to consider the thermal energy of the Sun; the heat output from the slow cooling of hot, central regions. As these regions cool then for a sphere of gas (the Sun) to maintain gas pressure to balance the weight of the outer layers, the central region must contract somewhat. The entire star then also contracts. Lord Kelvin performed a calculation of the above process, now frequently referred to as Kelvin-Helmholtz contraction. He found that the total amount of heat the Sun could have accumulated in contracting to its present radius is just the present GRAVITATIONAL POTENTIAL ENERGY of the Sun. If this is the total available energy, we may calculate the solar lifetime (using thermal energy) by dividing this by the solar luminosity. This turns out to be only 30×10^6 years, nearly 150 times less than the known age.

With our current preoccupation with the 'energy crisis' on our globe, alternative sources immedately spring to mind. Two major categories are fossil or chemical energy and nuclear energy. Coal is one form of fossil fuel and it is interesting to calculate the lifetime of a coal-burning Sun. As all chemical forms of energy yield roughly the same output for each unit consumed, this calculation will also serve for oil- and gas-burning Suns. Let us allow the Sun to be composed of 90 per cent coal! We know the coal-burning power output and so we can figure out how long the Sun can last burning at the required rate necessary to produce the present luminosity. The result is a disaster as it turns out to be a mere few thousand years, short by a factor of a million. We must, therefore, turn to nuclear energy.

The gradual understanding of the structure of the atom and radioactivity combined with Einstein's principle of equivalence of mass and energy, showed the enormous energy release possible from nuclear reactions. From this famous Einstein relation of $E = mc^2$, where E is the energy, m the mass and c the velocity of light, it is seen that if only a small quantity of mass is converted into energy, the output is tremendous. For instance, the solar luminosity can be supplied by the complete conversion of 4×10^9 kg of matter into energy every second. Although this is a sizeable amount of material it is utterly negligible compared to the total mass of the Sun.

For most of a star's lifetime its energy comes from the conversion of hydrogen into helium. Four hydrogen nuclei (protons) are fused to form one helium nucleus, with the emission of energy in the form of neutrinos and gamma-rays. The direct process, the **proton-proton chain**, occurs above 10^6K, and another using carbon as a CATALYST, the carbon-nitrogen-oxygen or **CNO cycle**, above about 2×10^7K. In the later stages of evolution 3 helium nuclei may be fused to give one carbon nucleus in the **triple-alpha process**, at temperatures above about 2×10^8K. (Alpha-particles are heluim nuclei.) At even higher temperatures oxygen-, magnesium-, and silicon-burning may occur. The process cannot continue beyond iron, however, and all heavier elements are believed to have been formed in the brief instants when massive stars explode as supernovae (page 63).

The life histories of stars

We have discussed the nuclear power stations of stars and how they shine, so let us now explore their life histories, that is stellar evolution. Three time scales of stellar evolution may be distinguished – the dynamical, thermal and nuclear. In our present context, the latter is defined to be the time taken for nuclear processes inside the star to change the chemical composition significantly. For a star on the main sequence it is the time required to convert all the hydrogen in its centre into helium. The time scale is proportional to the mass, M, divided by the luminosity of the star. We know from the mass-luminosity law that the luminosity of a normal star is proportional to about M^4. Therefore, we see that although a massive star begins with more fuel, it consumes it much faster, and as the **nuclear time scale** varies as $1/M^3$, the more massive (more luminous) stars have much shorter lifetimes on the main sequence. It emerges that this is the longest portion of any star's life and for stars of $20\ M_\odot$ the nuclear (main sequence) lifetime is a mere million years compared with 10^{10} years for stars of solar mass.

This is a vital clue in accounting for varieties of H–R diagrams which we get for different star clusters. Figures 3·10 and 3·11 show H–R diagrams for two types of star cluster in our Galaxy. The first depicts the Hyades, an open (galactic) cluster, and the second is M3, a globular cluster (see page 169). Astronomers believe that all the stars in a cluster

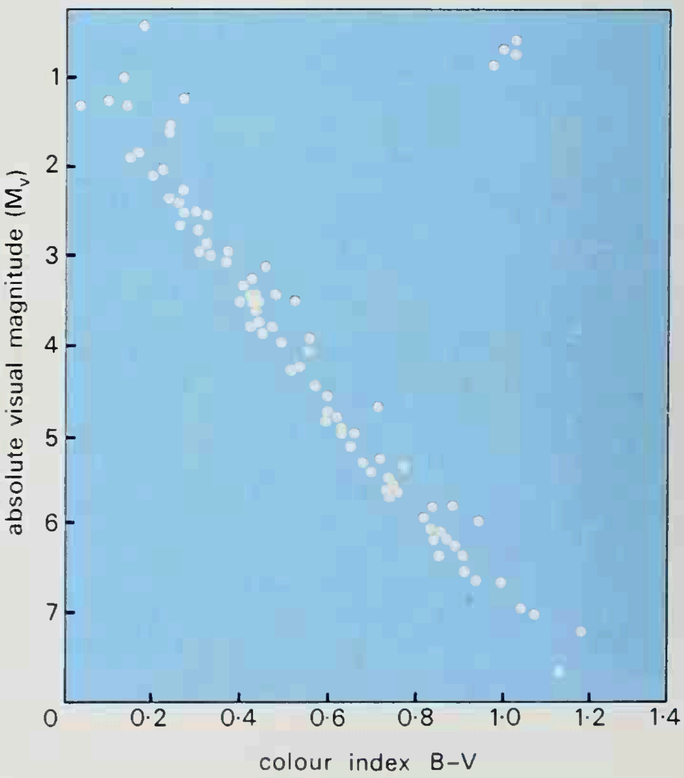

Fig. 3·10 far right: H–R diagram for the Hyades star cluster. The colour index (B-V) is the difference in apparent magnitudes in the blue and visible regions and is a measure of stellar temperature. The main sequence for the Hyades is seen to be well defined. This diagram for this particular cluster is most important for the determination of cosmic distances.