Stellar Evolution

During the first million years, or so, of the life of a star with a mass comparable to that of the Sun, the star loses a good fraction of its solar mass as material in a wind. As this period of high loss mass ends, the star settles into the relatively quiescent period of what is called the main sequence phase of evolution.

As with many chemical reactions, nuclear reactions have energy barriers: these are due to the (electrostatic) repelling forces between nuclei, and high temperatures (of the order of at least ten to twenty million degrees) are required for nuclei to overcome these electrostatic barriers between them and approach one another closely enough (10^{-14} m separation) to fuse. Hence, nuclear "burning" occurs only in the hot central regions of the stars and not in the cooler outer envelopes. A star remains in its main sequence phase until it burns most most of the Hydrogen in its hot central region to form Helium. At the end of the main sequence phase, the star has a core composed mostly of Helium. [Note: by "burning" is not meant the process of oxidation, which you have met in chemistry, eg. $2Mg_{(s)} + O_{2(g)} \longrightarrow 2MgO$].

If Hydrogen burning ceases, how is the stability of the star affected? The core temperature falls, reducing the pressure. The star is no longer against its own gravity, so it begins to collapse. As it does so, there is a loss of gravitational potential energy, which gives rise to an increase in thermal kinetic energy.

While the core is collapsing, Hydrogen can still

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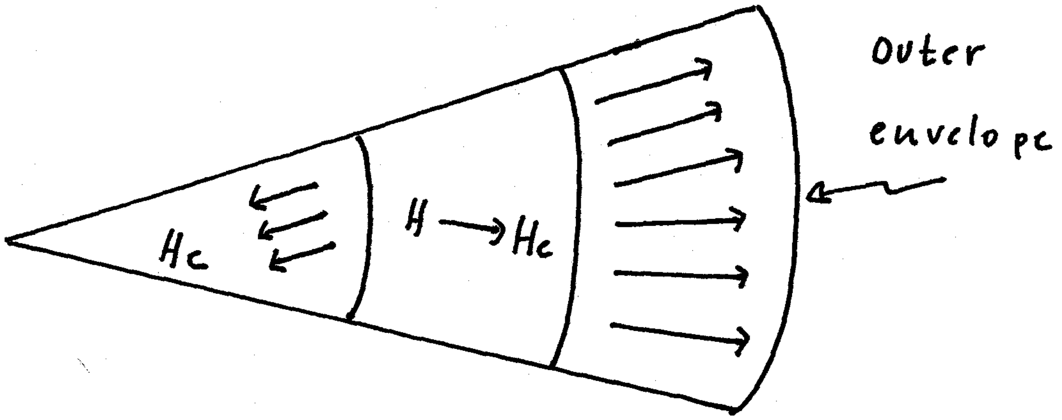
burn in a shell around the core, where the Hydrogen density and temperature are both high enough. The effect of this Hydrogen <u>shell burning</u> is dramatic: the source of energy is moving away from the centre, and this increases the pressure in the outer parts of the star — this causes the star to swell. This large expansion reduces the density of the outer parts of the star and the surface temperature also falls because of the expansion.

A star that has undergone such an expansion is called a <u>red giant</u>. Its colour becomes red as a result of its reduced temperature. Red giants are extremely luminous: their surface temperatures are relatively low (~ 3000K), but their surface areas are huge. One of the best-known red giants is the star Betelgeuse, in Orion. Its radius is greater than that of the orbit of the Earth around the Sun. The star has now left the main sequence, with a core composed mostly of Helium; it moves upwards and to the right on the H-R diagram.



Mass, Luminosity and main sequence lifetime

The time a star spends on the main sequence depends on the amount of Hydrogen available for fusion to Helium. It seems reasonable to assume that a main sequence lifetime depends on its Mass. Let this lifetime be t.

That is,

$$t \propto M \quad ①$$

If Hydrogen-burning reactions proceeded at the same rate in all main sequence stars, the most massive stars would have the longest main sequence lifetimes.

However, nuclear reactions do not proceed at the same rate in all stars. The more luminous the star, the greater is the rate at which the energy is being released — and so the greater the rate at which it is converting nuclear fuel. The luminosity, L, must be proportional to the rate at which fuel is being converted.

So,

$$t \propto \frac{1}{L} \quad ②$$

Combing ① and ②

$$t \propto \frac{M}{L} \quad ③$$

The effect of mass on core temperature and the strong temperature dependence of nuclear fusion rates means that the luminosity of a star is strongly dependent on its mass. This mass-luminosity relationship, calculated using theoretical models of stellar processes, can be approximated as:

$$L \propto M^5 \quad ④$$

This is for stars similar in mass to the Sun (up to $1{\cdot}5 M_\odot$)

$$\frac{M}{L} \propto \frac{M}{M^5} \quad \left[\text{Combining ①, ②, ③ and ④}\right]$$

$$\left.\begin{array}{l} t \propto M \\ t \propto \dfrac{1}{L} \\ L \propto M^5 \end{array}\right\} \Rightarrow t \propto M^{-4} \quad ⑤$$

Similar relationships apply to more massive stars, only the power laws are slightly different.

In essence, the more massive the star, the shorter its main sequence lifetime.

It is often useful to relate the main sequence lifetime of a star to its luminosity.

For low-mass stars,

$$M \propto L^{\frac{1}{5}} \quad \left[\text{from equation ④}\right]$$

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Look again at ④:

$$L \propto M^5$$

or

$$M^5 \propto L$$

$$\Rightarrow \underline{\underline{M \propto L^{\frac{1}{5}}}}$$

So, $\frac{M}{L} \propto \frac{L^{\frac{1}{5}}}{L}$

Hence,

$$\underline{\underline{t \propto L^{-\frac{4}{5}}}} \quad \text{—— ⑤}$$

These relationships between mass, luminosity and lifetime, have important implications. First, since very hot luminous, blue-white main sequence stars (O and B spectral classes), with effective surface temperatures > 10^4 K have relatively short lifetimes, any that is now observed must have formed recently, so all main sequence stars of this sort are "young".

Second, the stars which spend longest on the main sequence are those of least mass. These are the cool, red stars (K and M spectral classes), with surface temperatures < 5000 K. It is common to find references to "young" blue stars and "old" red stars. This does <u>not</u> mean that stars start off hot and blue and cool as they age: merely that all blue main sequence stars must be young, since they do not "live" very long, and that all old main sequence stars are red.

The <u>converse</u> is not true: it is perfectly possible for a "newborn" star to be red and cool —— indeed, if a main sequence star has a low mass, it <u>must</u> be cool and red, regardless of its age.

In a cluster (globular) of stars which all formed together, the most massive stars will be the end of their main sequence lives. In an old cluster, the only stars remaining on the main sequence will be the cool, red low-mass stars. The age of the cluster is thus equal to the main sequence lifetime of the most massive stars remaining on the main sequence.

Such stars can be identified from the <u>main sequence turn-off point</u>, found by plotting the stars on an HR diagram. The ages of some globular clusters, thus estimated, are comparable with the age of the Universe (a few times 10^{10} years).

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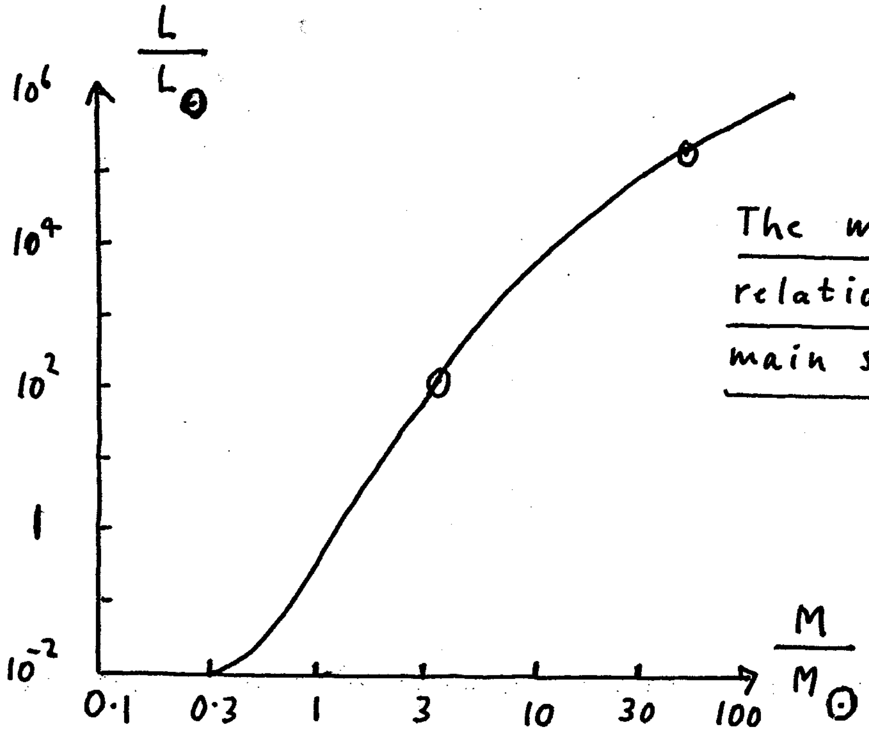
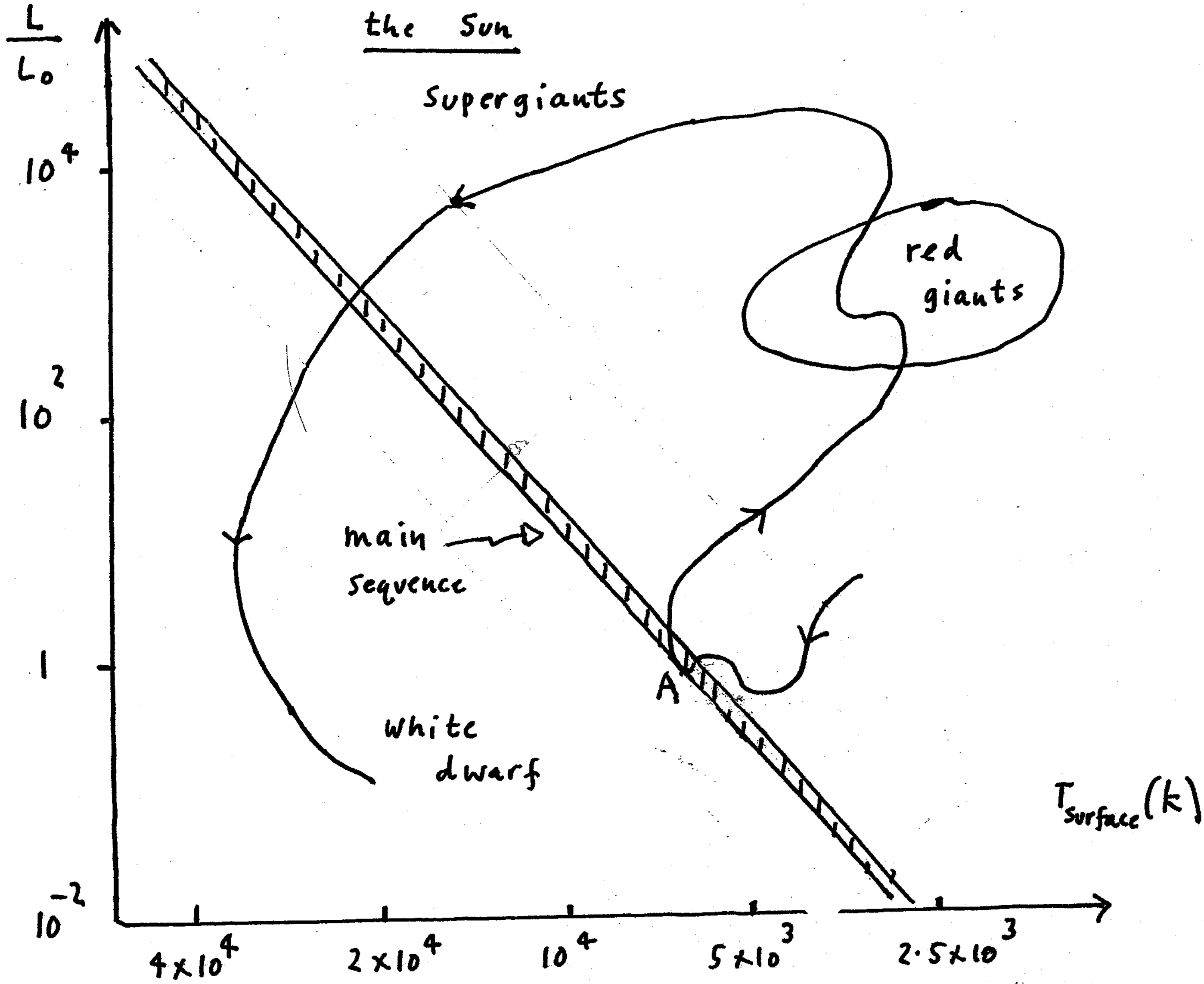


The mass-luminosity relationship for main sequence stars.

A theoretical evolutionary track of a star similar to the Sun

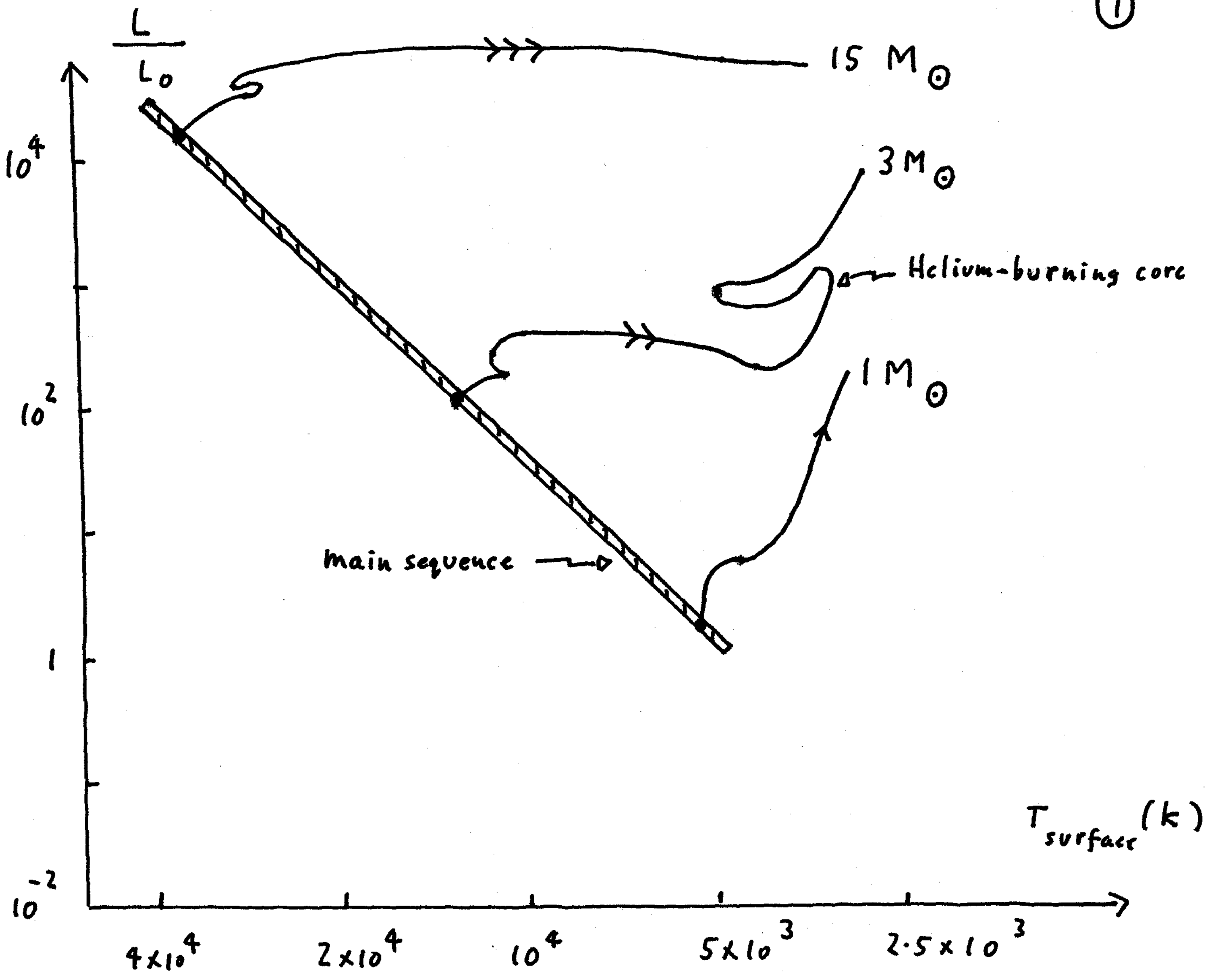


The mass of a protostar (immediately after condensation from the stellar medium) determines its subsequent evolution. The mass remaining as a condensed stellar core determines its nature.

After leaving the main sequence, a star undergoes a succession of gravitational contractions, each leading to internal heating and the initial of further nuclear fusion reactions.

The more massive the star, the higher the temperature that can be achieved in its interior and the more massive the nuclei which can be synthesied (synthesized?). A star which has a main sequence similar to the Sun becomes a red giant and probably ends by shedding a planetary nebula and becoming a white dwarf. A star with a main sequence mass about eight times that of the Sun becomes a supergiant and explodes as a supernova, leaving an extended supernova remnant and a neutron star (that might be observed as a pulsar) or a black hole.

Helium can also burn through nuclear reactions, and the product of Helium burning (fusion) is carbon, because the primary helium burning reaction involves the simultaneous collision of three Helium nuclei that form a complex which is stabilized by the loss of energy to form the carbon. The electrostatic repelling force(s) between Helium nuclei is greater than that between Hydrogen nuclei, and Helium burning takes place at higher temperatures than Hydrogen burning. These higher temperatures are initially reached in the stellar core by the gravitationally-induced contraction of the core, since rapid contraction of a gas results in its heating.



Despite the uncertainties about exactly what happens when a star sheds some mass and leaves a compact remnant, the mass of a star is the main factor which determines its fate.

The end can be quite sudden : perhaps there is a blast of radiation from the core, which hurls these outer layers of Hydrogen into space. The core cannot become hotter, because it has lost its overcoat, and so it cools —— and collapses. Its brightness dwindles as it shrinks. The density of its material becomes enormous, as the star becomes a white dwarf. There is no power to restore it.

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2013, March 12