Stellar Characteristics and Evolution

By Constantine Thomas

The most important factor that defines a star's characteristics is its mass. The second most important factor is its age. The third is metallicity (how much stuff the star contains that isn't hydrogen or helium) These determine the star's luminosity, temperature, chemistry, spectral type, and size, and it all links together in a rather complicated way.

Spectral type is the familiar OBAFGKM classification, which is further divided into numbers from 0-9. So you can have a G2 star, or an M5 star, or a B0 star. This is **NOT** an evolutionary track - stars don't start off as an O0 and end up as an M9. It is important to realise that the spectral type is a reflection of the chemistry of the star's surface/atmosphere, which is in turn generally defined by its effective temperature (the temperature of the uppermost surface layers) and metallicity. O stars are bluest in colour, A and F stars are white, G is yellow, K is orange, and M stars are red. There are other types too (W, C, S) but these are pretty rare.

Size is the second part of the star description: these are measured in roman numerals, as follows:

Ia	Bright supergiant
Ib	Supergiant
II	Bright Giant
III	Giant
IV	Subgiant
V	Main Sequence
VI	Subdwarf
VII	White Dwarf

Stars are described by putting these together. So a G2 V star is a yellow main sequence star (e.g. our sun), an M1 Ib is a red supergiant (e.g. Betelgeuse), and so on.

The main sequence is where the star spends most of its life, and its length is directly related to the star's mass – a star with solar metallicity and mass similar to Sol will be an early G V star (i.e. G0 - G5 V) that spends about 10 billion years on the Main Sequence - our star is about 4.6 billion years old now, so we're about halfway through Sol’s Main Sequence lifespan. A star with 0.9 solar masses will be a late G V star (G5 V - G9 V) that spends 15 billion years or so on its Main Sequence. A star with 1.25 solar masses will be a late F V star (F5 - F9 V) that spends only about 4 billion years total on its Main Sequence. Thus, it is possible to find first generation stars that are less massive than Sol that date from the earliest eras of the universe (the age of the universe is between 13 and 14 billion years old). It is also possible to find less massive stars that formed only a few million years ago, since star formation is an ongoing process.

Conversely, it is not possible to find a five billion year old main sequence star that has three solar masses (e.g. a B V star), since these complete their entire life cycles in a few hundred million years at most – instead we would find a stellar remnant (probably a white dwarf) left behind after it reached the end of its life billions of years earlier.

There is also a big spread in the distribution of stars in the galaxy, roughly as follows: 71 % of all stars are M V, 14% are K V, 10% are G V, 4% are F V, about 1% are A V, and about 0.1% are O or B V (or their evolved forms). So M V stars are by far the most common stars in the universe.

STELLAR EVOLUTION EXPLAINED

Star (and their attendant planets, if there are any) condense out of a protostellar nebula, a vast cloud of gas and dust that may be hundreds of AU in diameter initially. The cloud flattens into a disk due to its own rotation, spinning around a growing central mass of hydrogen and helium. Eventually this mass reaches a critical value, and nuclear fusion begins in its core - this marks the birth of the star. Binary star systems may form if two large masses grow to ‘critical mass’ in the nebula. During this formation period the planets coalesce in orbit around the protostar, and when the star ‘ignites’ the planets are mostly formed. However, although most of the gas and dust is blown away by the solar wind as the star enters what is known as the **T Tauri stage**, large planetesimals still remain in the system. These are eventually mopped up by the larger bodies - evidence from the impact record in our solar system indicates that planets don’t really stop forming (and growing) until a few hundred million years after the star ignites!

As soon as the star ignites, it begins its **Main Sequence (Size V)**, where it spends the majority of its life. Over the course of its main sequence life however, the luminosity of the star increases as more of its hydrogen is converted to helium by nuclear fusion in the core. As a result, the luminosity of the star at the end of its main sequence stage is over twice the luminosity it had when it formed. It is also larger and hotter than it was initially, which means that the spectral type of the star also changes with age.

Eventually, all the hydrogen in the star’s core is converted to helium. At this point, the star leaves the Main Sequence and enters its **Subgiant (Size IV)** stage - it starts to burn hydrogen in a shell around the inert ‘Helium Ash’ core. The star grows in size and luminosity while its effective temperature decreases - this ‘reddens’ the star, shifting it towards the M end of the spectrum. All the while, the core is gradually increasing in size as more of the star is converted to helium. Subgiants are stars in transition, between core hydrogen burning and core helium burning. Subgiants represent the star moving off the MS and right (and up) toward the M end of the HR Diagram.

As the star's core grows, it becomes more massive. Eventually, the core becomes so massive that it collapses into what is known as a degenerate state. When this happens, H-shell burning continues around the core, but the star expands in size and luminosity dramatically, moving up and toward the M end of the spectrum and becoming a **Giant (Size III or II)**. As the core collapses, its temperature increases until it becomes so high that Helium fusion can begin. The degenerate state of the core allows the fusion reaction to engulf the entire core in a matter of minutes, and the core temperature increases even more - this is called the "Helium Flash", and marks the end of the **Red Giant Branch** phase. It should be noted that this 'flash' is misleadingly named - the star doesn't visibly change in luminosity at the surface when this occurs.

When the core temperature becomes high enough through the He-burning, the core expands and cools and becomes non-degenerate again. The star then settles down on a "**Horizontal Branch**" (or "Helium Burning Main Sequence") and contracts and dims, burning Helium in its core and Hydrogen in shell around core at the same time. Because Helium is being burned in the centre of the star, a Carbon core now forms and grows. The star is now a **size III Giant**, larger and brighter than it was in its main sequence phase, but dimmer and smaller than it was at the Helium Flash. The spectral type and luminosity is not constant however, and some stars can evolve though a large spread of spectral types while in the Horizontal Branch.

Eventually, the Helium in the core is exhausted and converted to carbon. The core becomes degenerate and collapses, and the star expands again. At this point the star is evolving along the "**Asymptotic Giant Branch**" - the final giant phase - alternately burning Helium and Hydrogen in shells around the dead degenerate carbon core. AGB Giants are generally larger and more luminous than RGB giants, and some are even large enough to be considered as **Size II** (here defined as a star whose luminosity is greater than 700 Sols) rather than Size III. However, the helium-burning shell is not very stable - this causes the star to pulsate in both size and luminosity. As time goes on these pulsations get more and more severe (stars in this stage are sometimes known as the "Mira Giants"), becoming so great that the star actually starts to shed significant amounts of mass into space. Eventually, the star's outer layers are blown off completely, producing a planetary nebula and leaving behind an Earth-sized **White Dwarf (size D, or VII)** - what was once the stellar core of degenerate carbon, glowing white hot. Since it is not creating any more energy through nuclear fusion, the white dwarf cools down over trillions of years to become a cold lump of degenerate matter - a Black Dwarf.

This evolutionary sequence applies to stars between about 0.8 and 5 solar masses. More massive stars have a much more rapid lifespan, and evolve through more spectral types in their Horizontal Branch stage. Very massive stars become Supergiants (Ia, Ib) as they burn even the Carbon in their cores to more massive elements such as Neon, Magnesium, Silicon and Iron. These stars end their lives in titanic **supernova explosions** that leave behind neutron stars, pulsars, or black holes. These stars will not be discussed here, since they are extremely rare and too short-lived to have planets - they would originally have been the massive early B-type and O-type main sequence stars.

Stars with less than about 0.8 solar masses have extremely *long* main sequence lifespans - measured in the tens to thousands of **billions** of years. None of them have had time to evolve beyond their main sequence phase in the age of the universe, and most have not changed significantly in average luminosity since they were formed. Stellar models indicate that low mass stars will not evolve into giants at all - instead, they fuse helium until their core grows to consume the entire star, resulting in an inert '**Helium Dwarf**' after trillions of years have passed.

Subdwarfs and metallicity

The Main Sequence is followed by stars with broadly similar compositions to our own sun. Although all stars are (initially) composed primarily of hydrogen and helium, they also have a small amount of "metals" in them. To be slightly confusing, "metals" actually means "anything heavier than helium" - whether it's actually metallic or not. Sol contains about 73% Hydrogen, 25% Helium, and 2% metals, and is considered to be a reasonably metal-rich star.

Metallicity is related to the "generation" of the star - stars that formed early in the universe's history generally contain less metals than those formed later on. These older, low-metallicity stars are known as Subdwarfs (Size VI). Their evolution follows a "Subdwarf Sequence" that is equivalent to and broadly similar to the Main Sequence. However, Subdwarfs are more luminous than Main Sequence stars of the same mass, and their lifespans are also somewhat shorter - Sol's main sequence lifespan is about 10 billion years, whereas the corresponding lifespan of a Subdwarf with the same mass is only about 7 billion years. Since Subdwarfs only formed during the first few billion years of the history of the universe when metal concentrations were low, this means that the more massive Subdwarfs have all either become white dwarfs or are in their giant phases today - only those with lower mass remain on the subdwarf sequence.

Low metallicity stars are rare in the galactic disk, but are more common in the galactic halo that surrounds our galaxy. Occasionally their orbits around the core take them through the galactic disk - most of the disk's population of subdwarfs come from these transient stars. (some can be found in our neighbourhood, such as Kapetyn's Star). However, it is important to note that there are star that qualify as "Main Sequence" stars, that actually have metallicities that are between those of *bona fide* Main Sequence stars and Subdwarfs - these are called "Old Disk Stars" and as their name suggests are old and metal-deficient, but not so much as to be classed as subdwarfs. This affects their lifespans and luminosities, so there is actually a continuum of stars between V and VI.

There are also stars that are extremely metal rich, probably because they were born in a stellar neighbourhood where many massive stars exploded as supernova and enriched the local medium with significant amounts of metals. In practise, these stars evolve in a similar way to subdwarfs - metal-rich stars are more luminous for a given mass with shorter lifespans than stars with solar metallicity. These stars are also rare in the galactic disk, and are usually found in the galactic core or more crowded stellar neighbourhoods. Again, some of the orbits of these stars around the core may take them through our part of the galactic disk.

The Hertzsprung-Russell Diagram

Stellar evolution is often displayed on a Hertzsprung-Russell (HR) diagram, named after the scientists who first formulated it. HR Diagrams are logarithmic graphs, plotting (log Temperature) vs. (log Luminosity) – this means that every integer is a factor of 10 higher than the integer below (e.g. LogL=0 is 1 Solar Luminosity, LogL=1 is 10 Solar Luminosities, LogL=2 is 100 solar luminosities, etc). The OBAFGKM types correspond roughly to temperature, with O being at the high end and M at the low end. As stars evolve, their temperature and luminosities change, and this change can be drawn as “evolutionary tracks” in HR Diagrams for a given star mass.

The HR diagram on the next page shows the evolutionary tracks of stars between 0.4 solar masses and 5 solar masses. The low mass stars are shown in the bottom right corner of the graph - the short lines are 0.4, 0.5, 0.6 and 0.7 (pale green) masses respectively. They are short lines on the graph because low mass stars have not had time to evolve significantly since the formation of the universe. Going up the graph toward the top-left, the next five lines are for 0.8 (dark blue), 0.9, 1.0, 1.25, 1.5 and 1.7 (red) solar masses. The last batch of lines closest to the top left corner are for 2 (turquoise), 2.5, 3, 4 and 5 (black) solar masses.

Low mass stars have low luminosities and temperatures – these are Red Dwarf (M V) stars in the bottom right corner of the HR Diagram. High mass stars have high temperatures and luminosities, and are found in the top left corner of the HR Diagram - these are the O/B/A V stars. As stars evolve, they generally end up in the top right corner of the HR Diagram, which is high luminosity and low temperature – these stars are Red Giants and Supergiants.

There are more massive stars (the most massive known star is over 300 solar masses) but these are extremely rare. Supergiants like Antares and Betelgeuse are in the 15-20 solar mass range.