Jim’s Stellar Corner

Main Street

by. Jim Kaler

We delight in reading of stars that are dead or dying, of supergiants, supernovae, white dwarfs, neutron stars, and black holes. The main sequence of ordinary stars seems to hold less interest. It’s composed entirely of stars whose cores are converting the most abundant element, hydrogen, into helium. The main sequence begins at a low stellar mass of about eight percent solar, where the density and temperature of the interior core are raised just high enough by gravitational compression (into the low millions of kelvins) to run the proton-proton (p-p) chain. Two protons travelling fast enough to overcome their electromagnetic repulsion collide and stick via the “strong force,” one turning into a neutron to produce heavy hydrogen (deuterium). The deuterium then picks up another proton to make light helium, the process finishing when two light helium nuclei merge to make ordinary helium, with the release of two protons. As a result, 0.7 percent of the mass is lost to make energy via Einstein’s relation $E=mc^2$, mostly through the release of high energy gamma rays that gradually make their way to the stellar surface to be released as optical photons. Nuclear fusion provides the outward force that keeps the star from collapsing by means of its own self gravity. The result is the great stability that is responsible for the main sequence. As mass is increased, so is the internal temperature and fusion rate, and stars both brighten and heat at their surfaces. It’s a dramatic effect, luminosity on the average increasing with the 3.5 power of the mass. Double the stellar mass and the luminosity increases by about a factor of 10. On the Hertzsprung-Russell (HR) diagram, with luminosity expressed as absolute magnitude plotted against spectral class (OBAFGKM), the hydrogen-fusing stars define a thin curved band of stars that for historical reasons are called “dwarfs.” The classes, which are decimalized (the Sun is a G2 star), are derived from the appearance of the stellar spectra. Measured temperatures run from 50,000 Kelvin in class O through 10,000 at A, 6500 at G, to 3000 at M. With some exceptions main sequence stars all have pretty much the same chemical compositions. The appearance of the spectrum depends mostly on temperature, which controls the ionization level. As they age, dwarfs slightly change temperature and luminosity, which spreads the main sequence into a band and provides an opportunity to measure the star’s age.

At class M, with masses of a few tenths that of the Sun and the stars are cool, the outer layers are rich in molecules, particularly titanium oxide. Called “red dwarfs,” they are so dim that none is visible to the naked eye. Yet they are by far the most abundant kind, constituting 70 percent of the stars from O through M. The best known is Proxima Centauri, the closest star to the Earth, an M5.5 dwarf only 4.25 light years away. Part of a triple that includes Alpha Centauri (third brightest star in the sky), it’s only 11th magnitude, but has its own planet at least 1.3 times as massive as Earth that orbits every 11.2 days. Only 0.05 Astronomical Units away from Proxima, it’s in the star’s “habitable zone” where we might find liquid water and life.

However red dwarfs, including Proxima, generate strong magnetic fields through convection and rotation, and have the habit of flaring. The events are rather like flares on the Sun, which are caused by reconnecting magnetic field lines. But rather than being localized, a flare on an M dwarf involves the whole star, which can greatly increase the luminosity across the spectrum and that would not seem conducive to life. The planet’s rotation is probably locked to the orbital revolution, so you could always go to the far side, where there is no light and, unless there is an atmosphere, it’s really cold. Another of interest, Barnards’s Star in Ophiuchus, holds the speed record for motion across the line of sight at 10.4 seconds of arc per year. Over your lifetime you can watch it move!

Alpha Centauri, about which Proxima orbits every 3/4 million years or so, is itself a double with an 80-year period. Higher up the main sequence, Alpha consists of a G2 dwarf much like the Sun and a K1 dwarf 90 percent the solar mass that by itself would rank as the 21st brightest star. Like the Sun, the outer layers of K dwarfs exhibit magnetic spots and spot cycles. The most famed is the K5-K7 pair whose distance was first measured in 1838, 61 Cygni. Flare stars occupy the lower end of class K as well. A large fraction of G dwarfs also have sunspot or activity cycles at least similar to that of the Sun.

As stellar mass and core temperature increase, so do the rates of nuclear reactions, which far offset the increasing fuel supply. As a result, the greater the stellar mass the shorter the star's lifetime. The Sun has a main sequence life of 10 billion years, of which we have used about half. Below around G8, the lifetime hits the age of the Galaxy of some 13 billion years. Barring catastrophe, every red dwarf ever made is still alive.

The fun starts in the middle of class F. As interior temperatures climb, the proton-proton chain is replaced by the much more efficient "carbon cycle," in which ordinary carbon acts as a nuclear catalyst in a multi-step process to bring four protons together into a helium atom, creating nitrogen, energy, even oxygen along the way. The solar wind drags the Sun's magnetic field lines outward. Still attached to the Sun, the field lines gently put the brakes on rotation. Magnetic activity slows as well, old G and K stars far quieter magnetically than new ones, giving another way of estimating age. In mid F, the outer convective stellar envelope and the magnetic fields begin to wane. The braking effect disappears, and at this "rotation break," with little to slow them down, hotter stars spin faster. The Sun's equatorial rotation speed is about two kilometers per second. In class B, where temperatures climb to more than 20,000 kelvins and luminosities go into the hundreds of Suns, stars spin madly, up to 400 kilometers per second, rotating so fast they flatten out. A good number of the rapidly spinning B dwarfs develop surrounding disks that radiate strong emissions of hydrogen. Because the disks are unstable, these "Be" stars can rapidly change their apparent brightnesses; Gamma Cassiopeiae and Delta Scorpii have approached first magnitude.

In class F we see the entry of the "metallic-line (Am) stars," that peak in class A. If the star is rotating rapidly, the atoms of the various chemical elements are stirred and the surface composition is roughly solar. But if the star is spinning slowly and there is little mixing, some elements sink under the force of gravity, while others are pushed upward by radiation pressure. Elements like europium can be enhanced by tens of thousands of times, the process making classification quite uncertain. Weird powerful magnetic patches add to the phenomenon. The magnetic "Ap," (also called Alpha-2 Canum Venaticorum) stars can have patchy magnetic fields thousands of time greater than the Sun in addition to odd chemical abundances.

As the mass of the star increases, so does the mass of the core that will ultimately become a stable white dwarf that is supported by its electron pressure. At the ultimate divide of 8 to 10 solar masses, in class O, the core fuses to iron. No further energy can be gained by fusion, and the core collapses to a neutron star or black hole, which in turn blows the star up as a supernova. The main sequence tops off at around 120 solar masses, where the lifetime is just a few million years.

At the other end, where the core temperatures drop too low to allow thermonuclear fusion we find the "brown dwarfs," the coolest of which cannot be seen with the eye and have no visual magnitudes at all. At a lower limit of 13 Jupiters, not even the stars' natural deuterium can be fused and we enter the realm of planets. Are some exoplanets really brown dwarfs? Are some brown dwarfs escaped planets? These questions go to those of star and planet formation and thus even to the formation of life itself.