How we Know That Stars Are Balls of Gas Burning Billions of Miles Away

Bill Menke, November 25, 2023

Pumbaa [a warthog]: Ever wonder what those sparkly dots are up there?
Timon [a meercat]: Pumbaa, I don't wonder, I know.
Pumbaa: Oh. What are they?
Timon: They're fireflies. Fireflies that got stuck up on that big bluish-black thing.
Pumbaa: Oh, gee. I always thought they were balls of gas burning billions[1] of miles away.
Timon: Pumbaa, with you, everything's gas.
from *The Lion King* (1994, lyrics by Tim Rice)

Although I am writing this essay on a notebook computer, my smartphone is on the table, too. I use it to look up source material, so I don't have to keep rearranging windows on my computer's small screen. It is my information-gathering tool.

Before moving on to stars, I mentally detour to the subject of smartphones, and ask, "How many person years of effort went into the design of such an amazing device?" Mine is a rather murky question, because so much stuff is crammed into my phone, and each component has a different design pathway and a distinct history. I'll focus on just the micro-processor, which was designed by a company called ARM Holdings, founded in 1998. It is said to employ about 10,000 designers, if you include not only people who work on high-level design, but also the folk who do more routine design work and others who do verification and testing. So, hundreds of thousands of person-years of effort probably underpinned the design of the microprocessor in my phone, especially if you consider that today's design couldn't have been accomplished without carrying over knowledge gained during the design of earlier models.

Given that the micro-processor is only one of the many components inside my cell phone, a ballpark estimate of a million person-years does not seem unreasonable to me. I find wrapping my mind around such a number to be very difficult. I try to imagine myself working solo for a million years, figuring out how to make a phone, step-by-step. I finally finished the micro-processor; now I'll design the camera ... But that's not how it works. There is a kind of depth to a team of 10,000 designers that fundamentally transcends what a lone person might be able to accomplish.

Interestingly, there are about 10,000 professional astronomers in the world today. Furthermore, astronomy has been around for a long time, much longer than ARM Holdings. A good time to pick for the start of modern astronomy might Kepler's, the early Seventeenth Century. Of course, the number of professional astronomers was very small then; only in the mid-Twentieth Century did the count swell to thousands. Even so, something close to a million person-years of effort has been devoted to understanding stars and other astronomical phenomena.

An early astronomical success was the use of parallax to measure the distance from the Earth to various celestial bodies. We use parallax in our daily lives to judge distance. A nearby object (say, a finger held out in front of my face), viewed alternately by the left eye or the right, appears in slightly different positions when judged against a more distance scene (say, the wall of my living room). The visual system in my brain estimates the position of the finger, utilizing the rule that the displacement is greater for nearby objects than for distant ones. Parallax is only effective for objects up to a few yards away, because the separation between my eyes is only a few inches.

Astronomers use a telescope in place of an eye, and with two measurements made six months apart, get an eye-to-eye separation of the diameter of the Earth's orbit around the Sun. Back in the mid-Nineteenth Century, astronomers succeeded in using parallax to measure the distance to three nearby stars (Alpha Centauri, 61 Cygni and Vega). This number has grown to about a hundred thousand. Most were made by highly-automated orbiting telescopes, not by those 10,000 professional astronomers (though a few were members of the satellite design team).

Distance is important in astronomy for a variety of reasons, but especially because it is needed to understand how bright stars actually are. A light, such as from as a fire, can appear bright for two reasons, its proximity (such as a candle on the table) or because a lot of combustion is taking place (as in a bonfire on a distant hilltop). Once distance is measured using parallax, the true luminosity of the star can be inferred. Such measurements have shown that our own Sun is not a particularly bright star, but does fall within the broad range of brightnesses of typical stars.

Telescopes can also see a star's color. I own a little telescope, one with a four-inch mirror. I remember how surprised I was, the first time I used it, when I observed that many stars are lovely shades of green, red and blue, in addition to yellow, like our sun. The color is an indication of their surface temperature and works the same way as the color of hot glowing objects here on Earth. “Red hot” is about 1500F, much cooler than our sun, which is 9800F. Blue stars are even hotter.

Hotter objects not only emit more blue light than do colder ones, they emit more light-energy, overall. The exact formula was worked out in the late-Nineteenth Century and can be used to infer the diameter of a star, and more broadly, to show that the color of a star is consistent with its luminosity. Our sun and the other stars really are shining because they are hot – very hot.

Newton, usually portrayed as a physicist, was intensely interested in astronomy and directed a tremendous amount of mental energy to understanding the motion of objects, such as planets and stars, through space. His work in the late Seventeenth Century showed the connection between the mass of a star, the gravity that it produced, and the time it takes other objects to complete an orbit around it. This relationship allows one use the length of the year and the distance of the Earth from the Sun to the determine the mass of the Sun. Not surprisingly, the Sun is very massive – about 330,000 times the mass of the Earth.

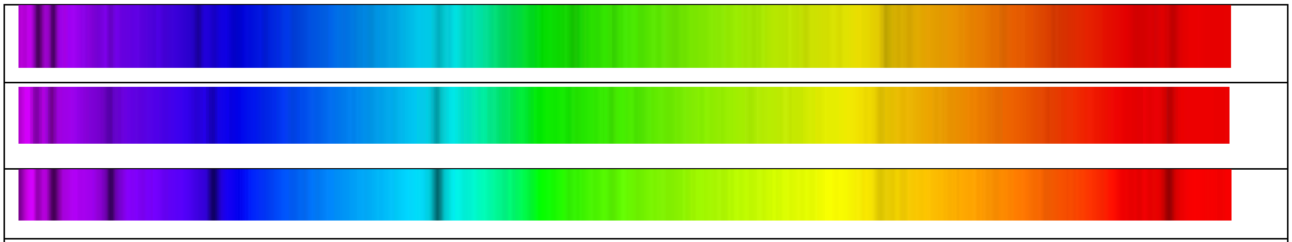
Surprisingly, the mass of some other stars was worked out in the late Eighteenth Century, too. Though telescopes of that age were not powerful enough to see planets orbiting distant stars, they could see stars orbiting other stars – which are called binaries. I could see many of such binary star system using my little telescope, for they are very common, comprising about 85% of star systems. They appear as double-dots of light, like a colon on a printed page. Consequently, the mass of very many stars has been measured, with the finding that the mass of stars spans a wide range, with our Sun being at the low end. Only in the later Twentieth Century were planets orbiting distant stars detected. Some thousands of these “exoplanets” are now known.

One of the factors that helped astronomers understand stars is that stars turn out to be comparatively simple. Early in the early Nineteenth Century it was recognized that the color, luminosity and diameter of most stars (including our Sun) can be predicted accurately from their mass, alone. About 90% of stars are among this "main sequence" of stars. The rest depart from this pattern for reasons that I'll mention towards the end of this essay.

The rotation rate of the sun can be measured by tracking sunspots. The length of solar day is found to be shorter at the Sun's equator – 24 days – than at its poles - 38 days, a pattern that no solid object can mimic. Furthermore, telescopic images of the surface show it to be in seething constant motion. The average density of the Sun, as inferred from its mass and diameter, is only a little higher than water and much less than rock, so the notion that it is entirely a very large ball of very hot gas is a plausible one. Furthermore, as balls of seething gas are not likely to have much internal structure, the gaseous nature of stars might be part of the reason why many such balls act similarly to comprise the main sequence pattern. This existence of this pattern would be especially easy to understand if main sequence stars were all of the same composition. Then, stars really would differ only because of their mass.

The key to identifying the composition of the Sun (and, later, other stars) was discovered at the very beginning of the Nineteenth Century, when a pattern of dark lines was detected in the spectrum of sunlight (which otherwise is a continuous rainbow of colors). Initially, the reason for the pattern was unknown, but in the mid-Nineteenth Century, physicists experimenting in the laboratory with hot glowing gases discovered that they, too, emitted light with a characteristic pattern of spectral lines. Astronomers quickly recognized that the two phenomena were connected. However, another half-century would pass before the type and percentage of each gas was determined.

In the plot below, I reproduce modern measurements of the spectrum of the Sun, Procyon and Altair (all main sequence stars).



Spectra of light from the Sun (top), Procyon (middle) and Altair (bottom), showing spectral lines (dark vertical bars) superimposed on the overall "rainbow of colors" spectra. The most prominent lines are due to hydrogen.

One can immediately see that the pattern of lines is very similar between these three stars, implying that these three stars have similar compositions. The patterns of many different gasses are superimposed, so working out the presence and abundance of each gas is a bit of a chore (but made a name for a certain Ph.D. student[2] of the 1920's). The results indicate that the two major elements in stars is hydrogen and helium, the two lightest gasses, with smaller amounts of most of the other elements.

How objects made of hydrogen and helium gas came to be so hot was mystery to early astronomers. Several hypotheses, including chemical combustion, in-fall of meteorites, and gravity-driven contraction were ruled out on various grounds. The possibility that the heat source operated in antiquity but was no longer active was dismissed, too. Only after the mid-Twentieth Century discovery of nuclear fusion (and its application to the Hydrogen Bomb) was the source of energy apparent: hydrogen was fusing to helium in the central part of the sun, where the temperatures and pressures are enormously high. Physical evidence of the nuclear fusion is the sun's interior was uncovered in the late 1960's, when instruments on Earth detected sub-atomic particles called neutrinos that are produced in fusion reaction. Neutrinos are only weakly absorbed by surrounding matter, so most of those that are produced within the Sun escape it to space, with as small percentage heading towards the Earth. Their inertness also makes them notoriously difficult to detect.

A star's hydrogen lasts a long time, but eventually runs out. Other nuclear fusion reactions take over. Helium begins to fuse, and when its gone, the heavier elements, too. These stars have different compositions and different properties than hydrogen-burning stars, and account for the 10 percent or so of stars that are off the main sequence.

The notion that the energy source of stars is nuclear fusion explains another enigmatic astronomical phenomenon, the supernovae. Very rarely (about once every 40 years, in our galaxy) a star is destroyed in a colossal explosion. They tend to be the largest stars, for they are the hot ones that quickly burn through all their nuclear fuel. When its fuel is exhausted, the star collapses, for it can no longer generate enough heat to resist its own inward-pulling gravitational attraction. The collapse heats up and blows away the outer part of the star (which is the explosion that we see) and creates a very small star largely composed of sub-atomic particles called neutrons. The nuclear reactions that produce such a neutron star also produces an extremely intense burst of neutrinos. The first such burst was detected in 1987, from a supernova in the Large Magellanic Cloud, a satellite galaxy orbiting our own Milky Way galaxy.

The evidence is very strong that stars are distant balls of fusing mostly-hydrogen gas, similar in all essential respects to our own Sun. Some of the techniques that were employed during its collection – like parallax and luminosity – connect very strongly with our day-to-day experience and are easy for us to understand as robust (in the sense of foolproof). Astronomical orbits are somewhat outside our personal experience, but reliably applied by the folk who operate communication satellites and guide interplanetary probes (that really do arrive at Mars, as planned). Atomic spectra are outside our personal experience in a different way. We employ glowing gasses in street lighting, recognize that it's pretty harsh to our eyes, but rarely wonder why. But its designers know that the reason: the light consists of just a few spectral lines, and not the rainbow of colors that our eyes are used to. And while atomic fusion might be esoteric, we all grew up in the shadow of the Bomb and know that fusion reactions are very powerful, indeed. However, a very diverse set of techniques was employed to understand stars. Its collection required the expertise a large, tremendously diverse group of astronomers, other scientists and engineers. No one person figured out that stars are distant balls of fusing mostly-hydrogen gas. It was an accomplishment achieved by tens of thousands of people working over five hundred years. It's not something that you or I could do solo, starting from a state of complete ignorance, even had we to devoted our careers to it.

Footnote 1. Pumbaa is vasty understating the distance to the stars. A billion miles only gets you to the vicinity of the planet Saturn, which is in our solar system. The nearest star, Alpha Centauri, is about twenty trillion miles away.

Footnote 2. Cecilia Payne, a graduate student at Harvard University.

Reference for the spectra in the figure: Walker, R. (2013) Spectroscopic Atlas for Amateur Astronomers: A Guide to the Stellar Spectral Classes, Version 4.0, https://doi.org/10.1017/9781316694206.