# How Astronomers Discovered that All Stars are not the Same and then Used Light to Learn to Measure the Temperatures of Stars

This text is a modified and shortened version of Chapter 7 from David A. Weintraub (2010)

Two-and-a-half millennia ago, the Greek philosopher Aristotle convinced all other scholars that the Earth was the center of the universe and that all stars were exactly the same distance from Earth. A hundred years later, the great Greek astronomer Hipparchus concluded, given Aristotle's ideas about the universe, that only one reason could explain why some stars were bright and others faint: they must differ in brightness because some stars are intrinsically brighter than others. *He made a reasonable assumption for his time, and his ideas were accepted for the next 2,000 years. But he was wrong.*

By the eighteenth century, Aristotle's ideas were no longer tenable. Aristotle's idea that the Earth was the center of the universe and that all stars were exactly the same distance from Earth had been replaced by the heliocentric cosmology first put forward by Polish astronomer Nicolaus Copernicus in 1543.

While astronomers would remain unable to measure the distances to any stars until the fourth decade of the nineteenth century, in the 1700s they were in universal agreement that the stars in the heavens were at many varied distances from the Earth. Consequently but without good reason, eighteenth-century astronomers inverted the assumptions made by Hipparchus; they decided that all stars are identical in all properties except for their distances. Therefore, bright stars were understood to be bright simply and only because they were presumed to be closer than faint stars. *Like Hipparchus, they drew the most sensible conclusions given the knowledge that had. But they were wrong*.

## Not equally bright

William Herschel, professional musician and self-taught astronomer, conducted the most important astronomical research done in the eighteenth century. He did so with a 19-inch diameter, 20-foot long telescope he built in his garden in Bath, England. Though Herschel is well-remembered for discovering the planet Uranus, he gave most of his attention to his studies of stars. In addition to assuming, like everyone else at that time, that all stars were identical in all their intrinsic properties, Herschel also assumed that stars were equally spaced, one from another, with that mean distance presumed to be the (unknown) distance from the Sun to either Sirius or Arcturus, both of which are among the brightest and nearest stars. This assumption was just that, an assumption, and was based on no actual knowledge of the physical distances between the stars. He would soon prove his own assumption wrong.

As part of his research plan, Herschel worked extensively on measuring the positions of *double stars*, these being pairs of stars that appeared near to each other in the sky. He assumed such double stars were seen when two stars, one much more distant than the other, happen to lie in similar directions in the sky.

After twenty years of study, he discovered that the angle in the sky between several of these faint-bright star pairs had changed in continuous and predictable ways. The changing positions of the stars in these faint-bright star pairs revealed that these pairs of stars were *binary* star systems — he coined the term 'binary star' in 1802 — with each such system being a set of two stars obeying Newton's law of gravity and orbiting a common center and lying at essentially identical distances from the Earth and Sun. This discovery means that both faint and bright stars could exist in the same binary system. *Herschel had demonstrated conclusively that all stars are not identical*. Some are intrinsically faint while others are intrinsically bright. At the dawn of the nineteenth century, astronomers were forced to recognize that stars differed in both intrinsic brightness and distance.

**Not identical in color**

As early as the second century CE, the great Greek astronomer Ptolemy reported that six stars — known to us as Aldeberan, Antares, Arcturus, Betelgeuse, Pollux, and Sirius — are yellowish in color, whereas other stars were white. Yet Aristotle's laws of physics demanded that all stars were intrinsically identical in color; they only differed, he said, in brightness. These yellow stars, Ptolemy concluded, gained their color due to effects caused by starlight passing through Earth's atmosphere, not due to intrinsic color differences among the stars. *Like Hipparchus, Ptolemy made a reasonable assumption for his time, but he was wrong.*[1]

In the late 1770s, William Herschel took notice of the differences in colors of stars and in 1798 conducted a study of six stars and found that Aldeberan, Arcturus, and Betelgeuse were more red and orange than were Procyon, Sirius, and Vega, which more uniformly showed all the colors from red to violet. Herschel, unwilling to conclude that the colors were intrinsic properties of the stars, speculated incorrectly that the colors indicated something about the motions of the stars. At the time of Herschel's death in 1822, no satisfactory explanation for these color differences had been found. In the decade after Herschel's death, however, Russian astronomer Friedrich von Struve noted the contrasting red, blue, and green colors he saw in binary star systems, which made clear that the large differences in colors for stars were intrinsic to the stars and not due to atmospheric effects or their motions.

**Distinct spectra**

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[1] Hipparchus's and Ptolemy's ideas about stars were wrong. Does that mean they were incompetent scientists? What important aspect of science can we understand from the changes in our understanding of stars, as described in this reading?

The 19 February 1672 issue of *Philosophical Transactions* includes a letter from Isaac Newton on the colors of light. This paper, which established his reputation as a natural philosopher[2], presents his work on optics in which he established that white light is composed of a *spectrum*[3] of colors, from violet to red.

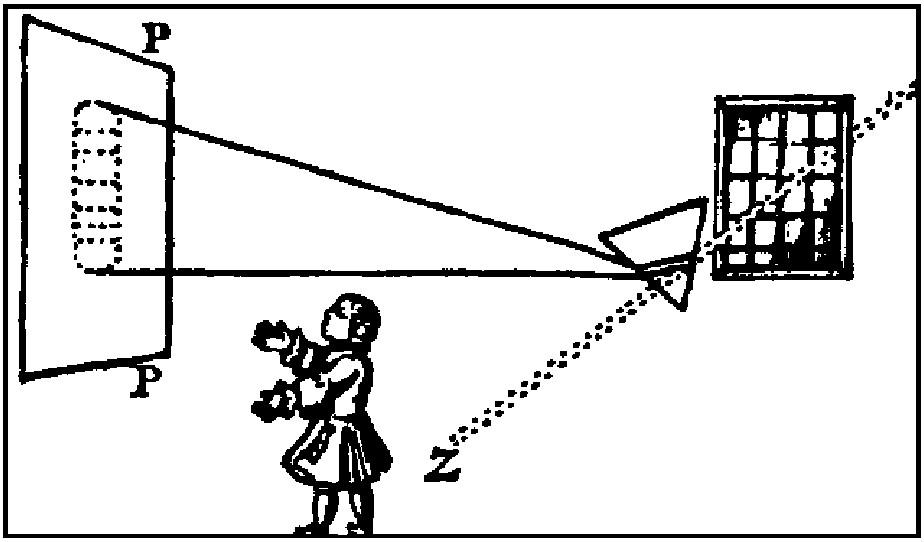


Figure 7.1: Newton's experiment with white light, in which he showed that white light form the Sun can be dispersed into a rainbow of colors. Cartoon from Voltaire's *Eléments de la Philosophie de Newton,* published in 1738.

In 1802 the English chemist William Wollaston and in 1814 the German glass maker Joseph Fraunhofer independently discovered dark lines in the spectrum of the Sun. Wollaston noted seven lines; Fraunhofer identified hundreds of lines, which he was convinced were intrinsic to the Sun. Six years after his initial discovery, Fraunhofer wrote about his discovery that the spectra of the two stars Castor and Sirius also showed dark lines, but the lines in their spectra were different from those seen in the solar spectrum.

By 1840, Herschel's ideas about identical stars had given way to an understanding of stars in which they differed in intrinsic brightness, color, and spectral features as well as distance. Astronomy was about to give way to astrophysics.

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[2] The word ‘scientist’ was coined by British philosopher William Whewell in 1834. Before that time, the people we would identify as scientists were known as ‘natural philosphers.’

[3] A spectrum is produced by sending a stream of light through a prism.

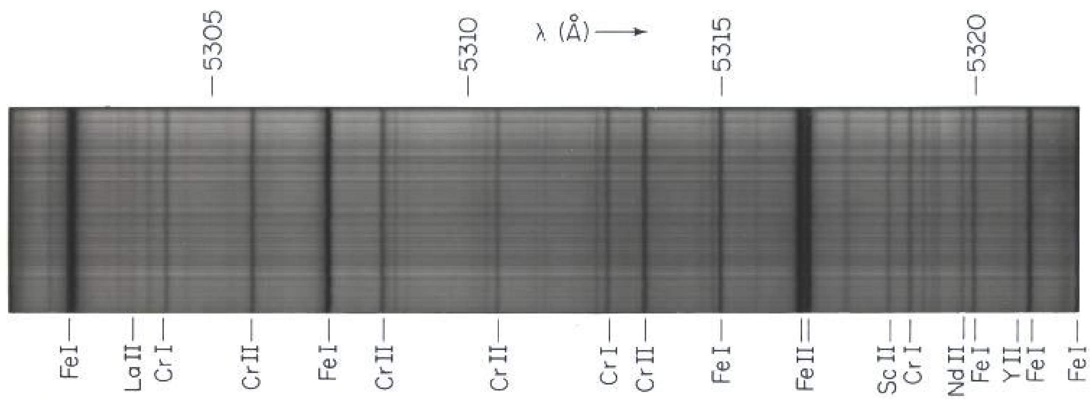



Figure 7.2: A modern spectrum showing the kinds of dark lines originally seen by Fraunhofer and Wollaston in their spectra, obtained early in the early nineteenth century. The labels at the top indicate the wavelength of light (in units of Angstroms); the labels at the bottom indicate which elements are responsible for which lines.

**What is light?**

Light, of course, is absolutely fundamental to astronomers since that is what we measure when we observe celestial objects. And in 1800, astronomers and physicists used the term ‘light’ to describe the spectrum of colors humans could see with their eyes. That concept was incomplete.

Light is energy as it is transported through space. When light travels through space, it sometimes bounces (reflects) off surfaces, just like a tennis ball bouncing off the ground, and behaves like a solid particle; at other times and in other circumstances, for instance when light passes through a slit or bends around a corner, this traveling packet of energy we call light behaves like a wave. Physicists invented the name *photon* for these light packages that travel through space and that sometimes exhibit particle-like and other times wave-like properties.

The speed of light in a vacuum (a region with no particles of mass) is about 300,000 kilometers per second. Light will travel slightly more slowly through air or glass or water, and in a particular medium, longer wavelength photons will travel slightly faster than shorter wavelength photons.

Photons are characterized by their wavelength, frequency, and energy. The wavelength is the distance from one wave crest to the next. Given that all light waves travel at identical speeds in a vacuum, if one kind of light has a large wavelength while another has a very short wavelength, very few of the large wavelength waves but a great many of the short wavelength waves will pass a given point in a fixed amount of time. The number of waves passing a fixed point in a single second is the frequency (measured in units of waves per second or cycles per second). The wavelength and frequency are inversely related to each other such that the wavelength multiplied by the frequency is equal to the speed of light. Since the speed of light in a vacuum is a constant, a photon with a large wavelength has a small frequency and one with a small wavelength has a large frequency. The energy carried through space by each photon is directly proportional to the frequency, or, equivalently, inversely proportional to the wavelength. Thus, higher frequency (shorter wavelength) photons carry more energy than lower frequency (longer wavelength) photons.

When we see colors, our eyes are detecting and measuring light with different wavelengths. Our eyes happen to be fairly inefficient systems --- our eyes typically respond to only about three percent of the photons they collect --- for detecting a very limited range of wavelengths or colors, the ones that encompass the visible light spectrum, from violet to red.

Until 1800, scientists assumed that the rainbow of colors evident to human eyes encompassed all the possible colors; however, in 1800, Herschel showed that light will heat up thermometers and that a thermometer set just beyond the red end of a visible light spectrum, where our eyes see absolutely no light, also will heat up. Herschel had discovered that the spectrum of light does not end at the low energy end of the spectrum that represents the long wavelength limit of light perceptible to human eyes; instead, the spectrum continues beyond the red, beyond where our eyes can see color, into a region known as the infrared. After learning about Herschel's experiment[4], the German chemist Johann Wilhelm Ritter used the same experimental technique in 1801 to discover light beyond the violet, light that our eyes cannot detect and which is known to us as ultraviolet light.

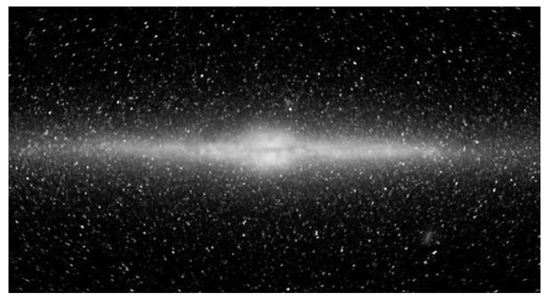
We now understand that the *electromagnetic spectrum* extends from the very highest energy photons, known as *gamma rays*, to the slightly less energetic *x-rays*, then to the *far ultraviolet* ('far' from visible light), the *near ultraviolet*, *visible light*, the *near infrared* (‘near’ to visible light), the *far infrared*, *microwaves*, and at the very low energy (and long wavelength) end, *radio waves*. Since our eyes are unable to detect any colors except the narrow range we call visible light, we need other materials to detect other kinds of light. Human bones, for example, are good X-ray detectors: dense bones stop X-rays so that the X-ray image taken by the radiologist shows a negative image of the bone. Melanin molecules in human skin cells are excellent detectors of ultraviolet light, and water molecules are very efficient at detecting infrared photons and microwaves. Of course, human bone and skin as well as water molecules are not very good materials for making quantitative measurements of the brightnesses of stars and galaxies, let alone taking images of the sky, so astronomers have learned how to design and build a broad range of detectors[5] that are capable of detecting light from astrophysical sources across the entire electromagnetic spectrum.

[4] https://www.americanscientist.org/article/herschel-and-the-puzzle-of-infrared

[5] CMOS detectors are now built into modern smartphones; CMOS detectors are far more efficient at detecting the colors of visible light than the human eye.

For reasons similar to those that cause different materials to be more or less effective at detecting different wavelengths of light — for example, the composition, density and temperature of those materials — astrophysical sources can look very different when observed at different wavelengths.

Figure 7.3: Left: the Milky Way seen in visible light (image courtesy of Serge Brunier) shows regions that are very bright (from the accumulated light from millions of stars) and other regions that include numerous



patches of darkness (where dusty, interstellar clouds block the light of the stars). Right: the Milky Way seen in infrared light (image courtesy of E. L. Wright, The COBE Project, DIRBE, and NASA) glows brightly throughout, and the light is mostly from the heated clouds of interstellar dust.

When viewed in X-rays, the Crab Nebula looks like a spinning disk with a jet emerging from that disk while in ultraviolet light it looks like a bubble filled with glowing filaments. By using telescopes designed to measure different wavelengths of light, astronomers can learn about the physical processes in stars, galaxies, and interstellar space that produce those kinds of light, and astronomers using myriad kinds of telescopes to study a single object at many wavelengths can learn about the many different kinds of astrophysical phenomena that occur beyond the Earth.