6 Absorption Lines in Stellar Spectra

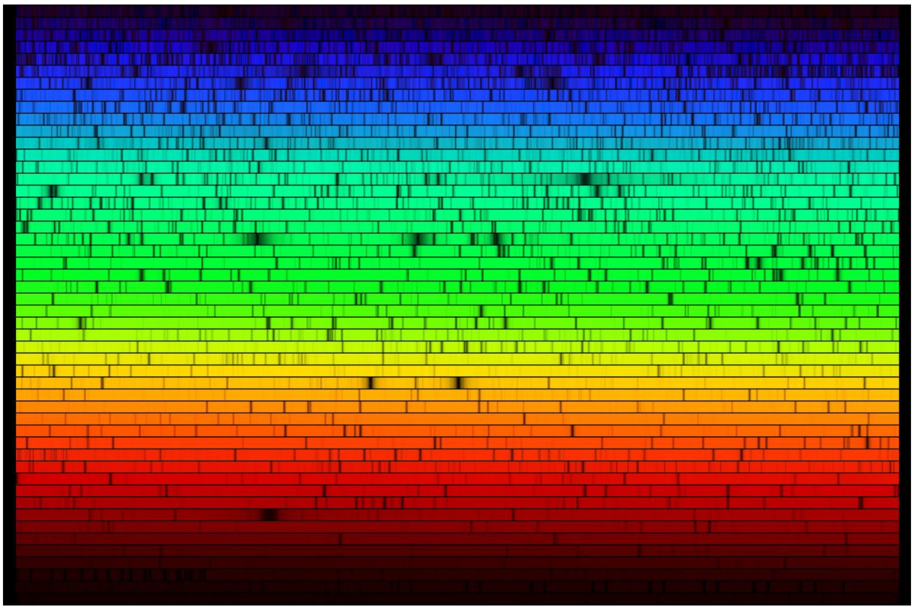

Figure 6.1 The Sun's spectrum, showing the complex pattern of absorption lines at discrete wavelength or colors. [NOAO/AURA/NSF]

In reality stars are not perfect blackbodies, and so their emitted spectra don't just depend on temperature, but contain detailed signatures of key physical properties like elemental composition. The energy we see emitted from a stellar surface is generated in the very hot interior and then diffuses outward, following the strong temperature decline to the surface. The atoms and ions that absorb and emit the light don't do so with perfect efficiency at all wavelengths, which is what is meant by the "black" in "blackbody". We experience this all the time in our everyday world, which shows that different objects have distinct "color", meaning they absorb certain wavebands of light, and reflect others. For example, a green leaf reflects some of the "green" parts of the visible spectrum – with wavelengths near $\lambda \approx 5100$ Å– and absorbs most of the rest.

For atoms in a gas, the ability to absorb, scatter and emit light can likewise

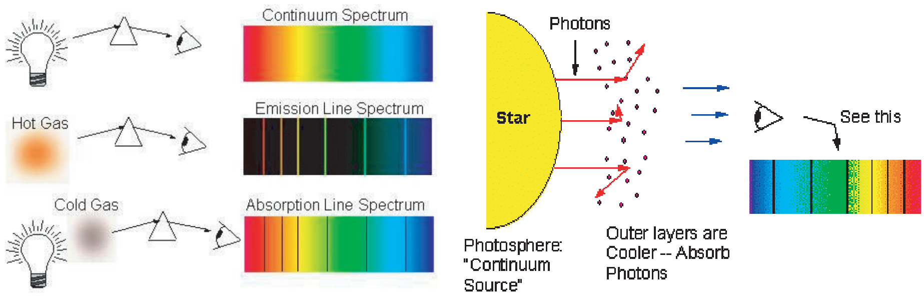

Figure 6.2 Illustration of principals for producing an emission vs. an absorption line spectrum. The left panel shows that an incandescent light passed through a prism generally produces a featureless continuum spectrum, but a cold gas placed in front of this yields an absorption line spectrum. That same gas when heated and seen on its own against a dark background produces the same pattern of lines, but now in *emission* instead of absorption. The right panel shows heuristically how the relatively cool gas in the surface layers of a star leads to an absorption line spectrum from the star.

depend on the wavelength, sometimes quite sharply. Just as the energy of light is quantized into discrete bundles called photons, the energy of electrons orbiting an atomic nucleus have discrete levels, much like the steps in a staircase. Absorption or scattering by the atom is thus much more efficient for those select few photons with an energy that closely matches the energy difference between two of these atomic energy levels.

The evidence for this is quite apparent if we examine carefully the actual spectrum emitted by any star. Although the overall "Spectral Energy Distribution" (SED) discussed above often roughly fits a Planck Black-Body function, careful inspection shows that light is missing or reduced at a number of discrete wavelengths or colors. As illustrated in figure 6.1 for the Sun, when the color spectrum of light is spread out, for example by a prism or diffraction grating, this missing light appears as a complex series of relatively dark "absorption lines".

Figure 6.2 illustrates how the absorption by relatively cool, low-density atoms in the upper layers of the Sun or a star's atmosphere can impart this pattern of absorption lines on the continuum, nearly Black-Body spectrum emitted by the denser, hotter layers.

A key point here is that the discrete energies levels associated with atoms of different elements (or, as discussed below, different "ionization stages" of a given element) are quite distinct. As such the associated wavelengths of the absorption lines in a star's spectrum provide a direct "fingerprint" – perhaps even more akin to a supermarket *bar code* – for the presence of that element in the star's atmosphere. The code "key" can come from laboratory measurement of the line-spectrum from known samples of atoms and ions, or, as discussed in §A.1, from theoretical models of the atomic energy levels using modern principles of quantum physics.

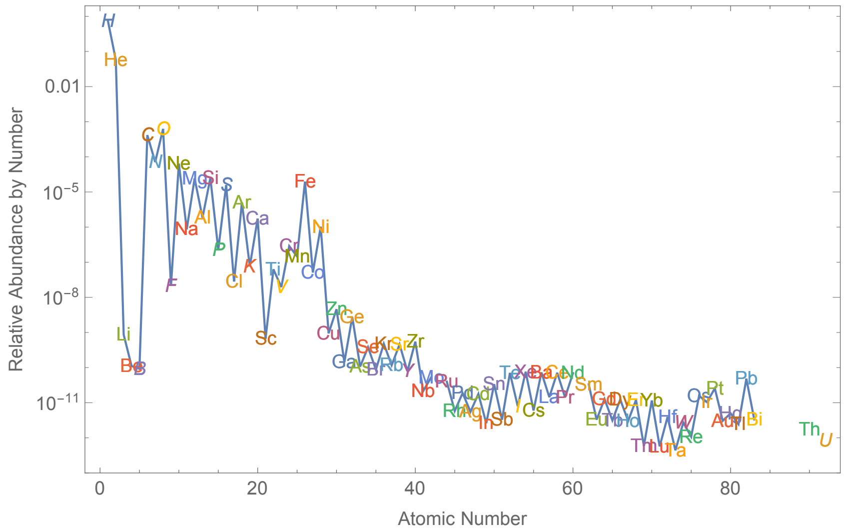

Figure 6.3 Number fractions of elements, plotted on a log scale vs. atomic number, with data points labeled by the symbols for each element.

6.1 Elemental composition of the Sun and stars

With proper physical modeling, the relative strengths of the absorption lines can even provide a quantitative measure of the relative *abundance* of the various elements. A key result is that the composition of the Sun, which is typical of most all stars, is dominated by just the two simplest elements, namely *Hydrogen* (H) and *Helium* (He) – which make up respectively 90.9% and 8.9% of the atoms, with all the other only about 0.2%. Figure 6.3 gives a log plot of these number fractions vs. atomic number.

The corresponding *mass* fractions are $X \approx 0.72$ and $Y \approx 0.26$ for Hydrogen and Helium. All the remaining elements of the periodic table – commonly referred to in astronomy as "metals" – make up just the final two percent of the mass., denoted as a "metalicity" $Z \approx 0.02$. Of these, the most abundant are Oxygen, Carbon, and Iron, with respective mass fractions of 0.009, 0.003, and 0.001.

Like all the planets in our solar system, the Earth formed out of the same material that makes up the Sun (§23). But its relatively weak gravity has allowed a lot of the light elements like Hydrogen and Helium to escape into space, leaving behind the heavier elements that make up our world, and us (§24). Indeed, once the H and He are removed, the *relative* abundances of all these s elements are roughly the same on the Earth as in the Sun!

6.2 Stellar spectral type: ionization abundances as temperature diagnostic

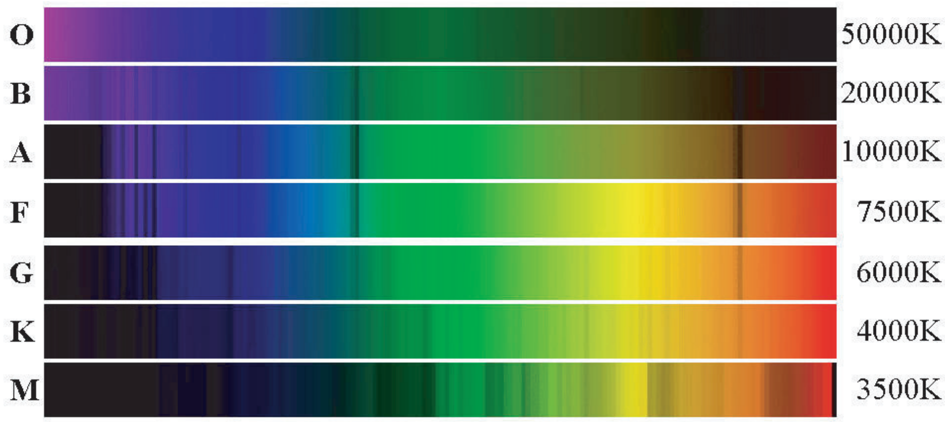

Figure 6.4 Stellar spectra for the full range of spectral types OBAFGKM, corresponding to a range in stellar surface temperature from hot to cool. [NOAO/AURA/NSF]

Another key factor in the observed stellar spectra is that the atomic elements present are generally not electrically neutral, but typically have had one or more electrons stripped – ionized— by thermal collisions with characteristic energies set by the temperature. As such, the observed degree of ionization depends on the temperature near the visible stellar surface. Figure 6.4 compares the spectra of stars of different surface temperature, showing that this leads to gradual changes and shifts in the detailed pattern of absorption lines from the various ionizations stages of the various elements. The letters "OBAFGKM" represent various categories, known as spectral class or "spectral type", assigned to stars with different spectral patterns. It turns out that type O is the hottest, with temperatures about 50,000 K, while M is the coolest[1] with temperatures of about 3500 K. The sequence is often remembered through the mnemonic[2] "Oh, Be A Fine Gal/Guy Kiss Me". In keeping with its status as a kind of average star, the Sun has spectral type G, just a bit cooler than type F in the middle of the sequence.

In addition to the spectral classes OBAFGKM that depend on surface temperature T, spectra can also be organized in terms of *luminosity* classes, convention-

[1] In recent years, it has become possible to detect even cooler "Brown dwarf" stars, with spectral classes LTY, extending down to temperatures as low as 1000 K. Brown dwarf stars have too low a mass ($< 0.08 M_\odot$) to force hydrogen fusion in their interior (see §16.3). They represent a link to gas giant planets like Jupiter (for which $M_J \approx 0.001 M_\odot$).

[2] A student in one of my exams once offered an alternative mnemonic: "Oh Boy, Another F's Gonna Kill Me".

ally denoted though Roman numerals I for the biggest, brightest "supergiant" stars, to V for smaller, dimmer "dwarf" stars; in between, there are luminosity classes II (bright giants), III (giants), and IV (sub-giants).

In this two-parameter scheme, the Sun is classified as a G2V star.

Finally, in addition to giving information on the temperature, chemical composition, and other conditions of a star's atmosphere, these absorption lines provide convenient "markers" in the star's spectrum. As discussed in §9.2, this makes it possible to track small changes in the wavelength of lines that arise from the so-called Doppler effect as a star moves toward or away from us.

In summary, the appearance of absorption lines in stellar spectra provides a real treasure trove of clues to the physical properties of stars.

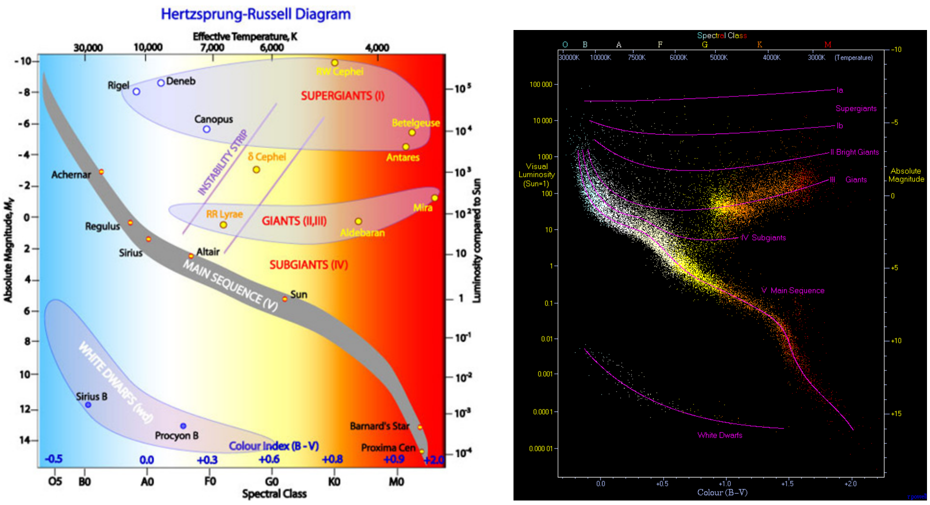

Figure 6.5 *Left:* Hertzsprung-Russel (H-R) diagram relating star's absolute magnitude (or log luminosity) vs. surface temperature, as characterized by the spectral type or color, with hotter bluer stars on the left, and cooler redder stars on the right. The main sequence (MS) represents stars burning Hydrogen into Helium in their core, whereas the giants are supergiants are stars that have evolved away from the MS after exhausting Hydrogen in their cores. The White Dwarf stars are dying remnants of solar-type stars. *Right:* Observed H-R diagram for stars in the solar neighborhood. The points include 22,000 stars from the Hipparcos Catalogue together with 1000 low-luminosity stars (red and white dwarfs) from the Gliese Catalogue of Nearby Stars.

6.3 Hertzsprung-Russell (H-R) diagram

A key diagnostic of stellar populations comes from the *Hertzsprung-Russel* (H-R) diagram, illustrated by the left panel of figure 6.5. Observationally, it relates (absolute) magnitude (or luminosity class) on the y-axis, to color or spectral type on the x-axis; physically, it relates luminosity to temperature. For stars in the solar neighborhood with parallaxes measured by the *Hipparchus* astrometry satellite, one can readily use the associated distance to convert observed apparent magnitudes to absolute magnitudes and luminosities. The right panel of figure 6.5 shows the H-R diagram for these stars, plotting their known luminosities vs. their colors or spectral types, with the horizontal lines showing the luminosity classes[3].

The extended band of stars running from the upper left to lower right is known as the *main sequence*, representing "dwarf" stars of luminosity class V. The reason there are so many stars in this main-sequence band is that it represents the long-lived phase when stars are stably burning Hydrogen into Helium in their cores (§18).

The medium horizontal band above the main sequence represents "giant stars" of luminosity class III. They are typically stars that have exhausted hydrogen in their core, and are now getting energy from a combination of hydrogen burning in a shell around the core, and burning Helium into Carbon in the cores themselves (§19).

The relative lack here of still more luminous supergiant stars of luminosity class I stems from both the relative rarity of stars with sufficiently high mass to become this luminous, coupled with the fact that such luminous stars only live for a very short time (§8.4). As such, there are only a few such massive, luminous stars in the solar neighborhood. Studying them requires broader surveys extending to larger distances that encompass a greater fraction of our galaxy.

The stars in the band below the main sequence are called *white dwarfs*; they represent the slowly cooling remnant cores of low-mass stars like the Sun (§19.4).

This association between position on the H-R diagram, and stellar parameters and evolutionary status, represents a key link between the observable properties of light emitted from the stellar surface and the physical properties associated with the stellar interior. Understanding this link through examination of stellar structure and evolution will constitute the major thrust of our studies of stellar interiors in part II of these notes.

But before we can do that, we need to consider ways that we can empirically determine the two key parameters differentiating the various kinds of stars on this H-R diagram, namely *mass* and *age*.

6.4 Questions and Exercises

Quick Question 1: On the H-R diagram, where do we find stars that are: a.) Hot and luminous? b.) Cool and luminous? c.) Cool and Dim? d.) Hot and Dim?

Which of these are known as: 1.) White Dwarfs? 2.) Red Giants? 3.) Blue supergiants? 4.) Red dwarfs?

[3] The more recent `GAIA` satellite has provided an even more extensive H-R diagram representing more than 4 million stars within 5000 pc. See `https://sci.esa.int/web/gaia/-/60198-gaia-hertzsprung-russell-diagram`.