3 Stars: A Basic Overview

Stars are "balls of gas burning billions of miles away." Most of astrophysics that we will study in this class relates to star: observing them, making models to understand their interior processes, and studying their dead remnants, natal gas clouds, or stellar clusters with hundreds to trillions of members.

3.1 *Types of Observations*

The two main ways we observe stars (or almost anything else) are **photometry** and **spectroscopy**. To understand either of these, we first need to understand the spectra of stars: how much light they emit at different wavelengths. If you disperse light from the Sun or a hot incandescent bulk through a prism, you see a rainbow: light from shorter-wavelength blue/violet out to longer-wavelength orange/red. If you disperse light from a red LED or a laser, you would see that all of their light comes out at just a tiny range of wavelengths — essentially just a single color rather than a wide range (we call such single-colored light **monochromatic**).

For the dispersed Sunlight, we see the rainbow because our eyes are only sensitive to wavelengths from roughly 400–650 nm. But if we had panchromatic eyes we would see that the Sun (and all stars) emits lights over a broad range of wavelengths. Fig. 4 shows the amount of light coming from several different types of stars, indicating that considerable amounts of light are being emitted at invisible wavelengths.

Spectroscopy

Spectroscopy is the making of measurements such as those shown in Fig. 4, i.e. how much light do we see at each particular wavelength. Spectra are obtained by dispersing light through an optical element such as a prism, diffraction grating, or similar devices.

Each particular spectrum has its own characteristic **spectral resolution** R, which describes how well very narrow features in the spectrum can be resolved. Spectral resolution is typically defined as $R = \lambda/\Delta\lambda$, where $\Delta lambda$ is the width of the narrowest spectral feature that can be measured. If R is very low (say, < 100) then all but the broadest features are 'smoothed over' and washed out. Fig. 4 has R of a few thousand and many spectral features are visible in the spectrum. Typical spectrographic instruments will have $R = 10^3 - 10^4$, but some can go higher (or lower).

By measuring the location (i.e., the wavelength) of particular lines in an object's spectrum, we can learn something about what the object is made of, what temperature it is, and (through the Doppler shift, Eq. 5) how fast the object is moving toward us or away from us. E.g. the spectral line seen at 0.6563μm is the well-known Hα electronic transition line. Seeing it clearly indicates that hydrogen is in a star; unfortunately (for us), the lack of an elemental line (as in the M0V spectrum shown, which lacks Hα) may or may not indicate that that particular element is absent in the star.

Photometry

Photometry is the measurement of average brightness (usually very broad) spectral ranges. It often corresponds to (though is rarely described as) ultra-low-spectral resolution; a typical photometric bandpass would have $\Delta\lambda/\lambda \sim$ 20%. The common *V* (for visual) bandpass spans roughly 500–570 nm; many standard photometric bands (such as *V*) have single-letter names, and some of these are indicated on the OoMA handout and in the bottom of Fig. 4. If one measured the photometry of the stars in that figure, the measurements would essentially average the spectra down into just five points (one per indicated bandpass).

So obviously photometry is a cruder tool than spectroscopy: you typically wouldn't bet the farm that a star showed an Hα line (or not) juts based on photometry alone. On the other hand, astronomical targets are much fainter than the Sun and accurately measuring their faint, dispersed spectra can often be challenging; in contrast, it's comparatively easy to measure an object's

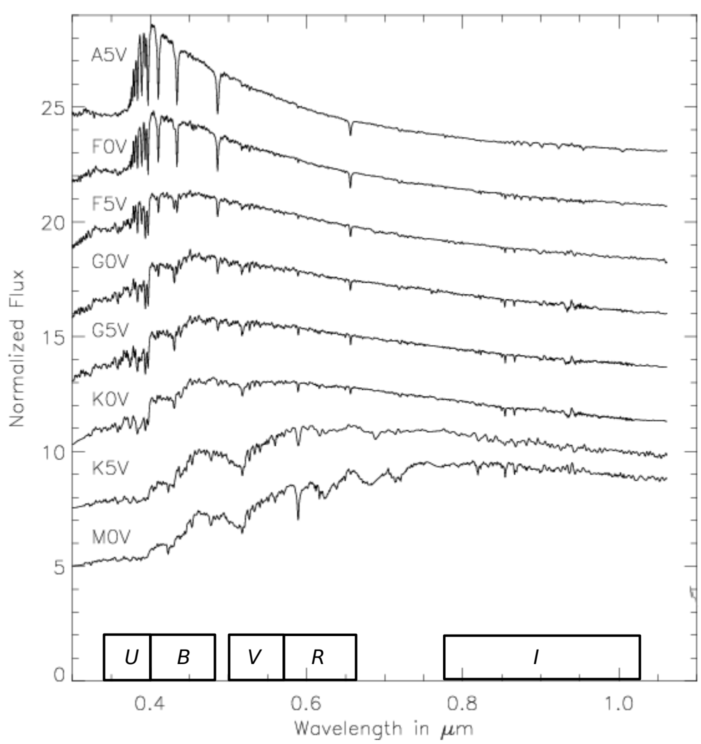

Figure 2: Optical-wavelength spectra of main-sequence stars across a range of spectral types. Wavelength is plotted in μm (10^{-6} m), so the range plotted corresponds to 300–1100 nm. The Sun is a G2V star, and so would be somewhere between the G0V and G5V spectra shown. Shown at bottom are the approximate spectral ranges of some common optical-wavelength photometric bands.

photometric properties. So much of early astronomy was built on photometry, with spectroscopy coming later.

The main way that photometry is used is via measurements of apparent magnitudes in the various photometric bandpasses. When one talks of a star's absolute or apparent magnitude without other reference, the **bolometric** measurement is typically meant — i.e., a measurement of the star's total luminosity integrated over all wavelengths. But one can also speak of a V-band or R-band magnitude; in this case it is assumed than an apparent magnitude is being referred to (unless otherwise specified). The hot A0V star Vega has an apparent magnitude of roughly zero in all optical-wavelength bandpasses; that is, $B \approx V \approx R \approx 0$ (and so forth). Again, the classic astronomer's website for learning the magnitudes, coordinates, and many other details of a given star is SIMBAD[2].

3.2 *Basic Properties of Stars*

As we will see later in the course, it typically takes just three parameters to describe the most salient aspects of a star. But just like constructing a coordinate system (Cartesian? spherical? cylindrical?) there are multiple ways to choose your fundamental stellar parameters – and any can be converted into the others (with greater or lesser degree of accuracy).

The intrinsic stellar parameters most commonly used are mass M, radius R, and either luminosity L or the **effective temperature** $T_{\rm eff}$. This last quantity is something like the average temperature in the outer layers of the star, and it is defined as

$$(13) \quad T_{\rm eff} = \left(\frac{L}{4\pi\sigma_{SB}R^2} \right)^{1/4}$$

where σ_{SB} is the Stefan-Boltzmann constant. As often as we can, we want to avoid having to remember complicated numbers like σ_{SB} – instead, astronomers like to put things in terms of other more familiar quantities. For stars, nothing is more familiar than the Sun. So instead we can rewrite Eq. 13 as

$$(14) \quad \frac{T_{\rm eff,*}}{T_{\rm eff,\odot}} = \left[\frac{L_*}{L_\odot} \left(\frac{R_\odot}{R_*} \right)^2 \right]^{1/4} .$$

An alternative set of parameters often used in the study of **stellar evolution** (the birth, growth, and death of stars) would be the star's mass, age, and the amount of heavier-than-helium elements in the star. Since most of the universe (and stars) are made of H and He, astronomers call all elements heavier than He **metals**. Thus the relative enhancement level of these heavier elements is typically called **metallicity** (and is reported logarithmically).

If one had to pick just two key parameters, they would likely be M and either $T_{\rm eff}$ or age.

The typical range of properties for stars is:

[2] `http://simbad.u-strasbg.fr/simbad/sim-fid`

- **Mass**: From as low as 0.08 $M_\odot$ to as high as around $\sim 100 M_\odot$.
- $T_{\rm eff}$: From as low as about 2400 K to $> 30,000$ K. Many cooler objects exist; these include planets as well as **brown dwarfs** (objects with masses and temperatures between stars and planets).
- **Radius**: From as small as 0.08 $R_\odot$ (smaller than Jupiter!) to as large as $\sim 1000 R_\odot$ (much larger than the Earth's orbit around the Sun).

3.3 *Classification*

Classification is a key step toward understanding any new class of objects. When modern astronomy began, classification of the stars was a key goal — also an elusive one, until the physical processes became better understood. We're now going to begin to peel back the onion that is a Star. And the first step in peeling an onion is to look at it from the outside.

One of the first successful frameworks used photometry measurements of stellar flux density at different colors. Assuming again that stellar spectra are approximately blackbodies, the Planck function shows that we should see the hotter stars have bluer colors and be intrinsically brighter. This led to the **Hertzsprung-Russell diagram** (HR diagram), which plots absolute magnitude against color – we'll see the HR diagram again when we discuss stellar evolution.

It's fair to say that spectroscopy is one of our key tools for learning about astronomical objects, including stars. Fig. 4 shows a sequence of stars arranged from hot to cool: one can easily see the Wien peak shift with temperature, although none of the stars are perfect blackbodies. Other features come and go, determined (as we will see) mainly by stellar temperature but also surface gravity (or equivalently, surface pressure).

Through decades of refinement, spectra are now classified using Morgan-Keenan **spectral types**. These include a letter to indicate the approximate temperature, an Arabic numeral to refine the temperature, and a roman numeral to indicate the star's luminosity. The order of letters seems disjointed because stars were classified before the underlying physical causes were well-understood. The temperature sequence is OBAFGKMLTY, where the last three

Table 1: Stellar spectral types.

SpT	$T_{\rm eff}$	Spectral features
O	$> 3 \times 10^4$	Ionized He or Si; no H (or only very weak)
B	$10^4 - 3 \times 10^4$	H Balmer lines, neutral He lines
A	$7500 - 10^4$	Strong H lines
F	$6000 - 7500$	H Balmer, first metal lines appear (Ca)
G	$5200 - 6000$	Fading H lines, increasing metal lines
K	$3700 - 5200$	Strong Ca and other metals, hydride molecules appear
M	$2400 - 3700$	Molecular bands rapidly strengthen: hydrides, TiO, H_2O
L	$1400 - 2400$	A melange of atomic and molecular bands; dust appears
T	$\sim 400 - 1400$	CH_4 strengthens, dust clears
Y	$\lesssim 400$	NH_3 strengthens

typically apply to brown dwarfs (intermediate in mass between planets and stars) and the rest apply to stars. Table 3.3 briefly describes each of the alphabetic spectral types. Additional resolution is added to the system through the use of numbers 0–9, so that F9–G0–G1 is a sequence of steadily decreasing T_{eff}. Finally, the Roman numerals described in Table 2 indicate the luminosity class, which typically correlates with the stellar radius (and inversely with the surface gravity).

Table 2: Stellar luminosity classes.

Lum	name	examples
VI	subdwarf	Kapteyn's Star (M1VI)
V	dwarf	Sun (G2V), Vega (A0V)
IV	subgiant	Procyon (F5IV)
III	giant	Arcturus (K1III)
II	bright giant	
I	supergiant	Rigel (B8Ia), Betelgeuse (M1Ia)
0	hypergiant	η Carinae, Pistol Star