1

Background

We study stellar spectra, including both lines and continua, because we are interested in the nature of the star's atmosphere. The behavior of the atmosphere is controlled by the density of the gases in it and the energy escaping through it. These in turn depend on the mass and age of the star and to a lesser extent on chemical composition and angular momentum. Stellar atmospheres are the connecting links between the observations and the rest of stellar astrophysics. In this way two philosophies arise. One is the study of the atmosphere for its own sake and the other is the use of the atmosphere as a tool to connect our observations to other parameters of interest. This book should be useful for students of both philosophies.

The topics brought together to form this chapter are background material which the reader will need. The more advanced reader can profitably skim through to Chapter 2.

What is a stellar atmosphere?

A stellar atmosphere is a transition region from the stellar interior to the interstellar medium. One way to quantify this description is to look at the change in average kinetic temperature with height as observed in the Sun. Figure 1.1 shows the solar temperature profile with the four basic sections labeled, sub-photosphere, photosphere, chromosphere, and corona. For an observer of stellar atmospheres, one concept is very important: the major portion of the visible stellar spectrum originates in the region marked "photosphere." A study of the visible-light spectrum is essentially a study of the photosphere. Higher layers are typically studied in the shorter and longer wavelengths with instruments on satellites, rockets, or balloons, and by radio

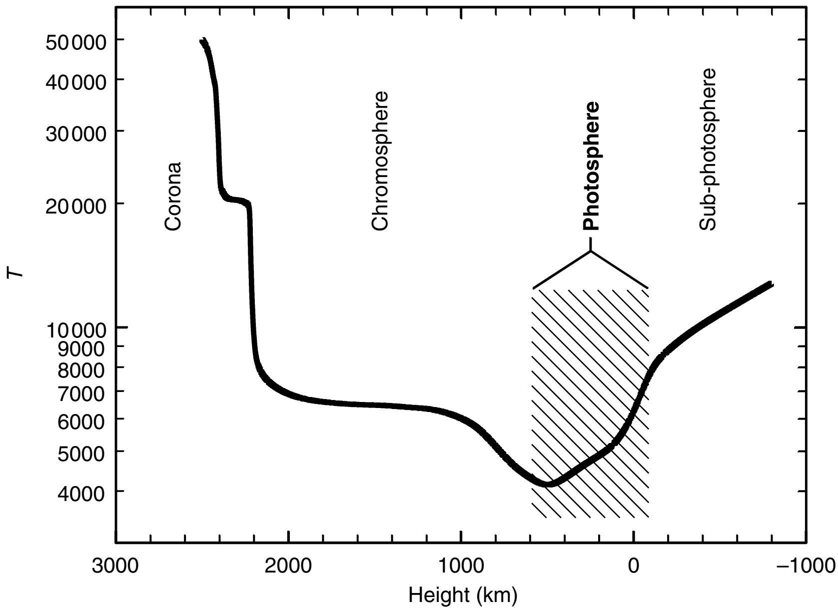

Fig. 1.1. The temperature distribution in the outer layers of the Sun is shown as a function of the geometrical depth in kilometers. The center of the Sun is toward the right. The photosphere is indicated by the shaded region. The visible-light spectrum comes from the photosphere. Adapted from Vernazza *et al*. (1973).

telescopes.

In the Sun, the photosphere is of the order of 1000 km thick, as illustrated in Fig. 1.1. The geometrical extent of the photosphere in other stars differs inversely with the surface gravity defined by

$$g = g_{\odot}\frac{\mathfrak{M}}{R^2}, \tag{1.1}$$

where $g_{\odot}$ is the surface gravity of the Sun ($2.740 \times 10^4\,\mathrm{cm/s^2}$ or $2.740 \times 10^2\,\mathrm{m/s^2}$) and the mass, $\mathfrak{M}$, and radius, R, of the star are in solar units (see Appendix A). The thickness also depends upon the opacity of the gases comprising the photosphere.

The second physical variable strongly affecting the nature of the atmosphere is its characteristic temperature. Typically the temperature drops by somewhat more than a factor of two from the bottom to the top of the photosphere (Fig. 1.1), and instead of choosing a temperature at some depth to characterize the temperature parameter, it is customary to use the effective temperature. The effective temperature is defined in terms of the total power per unit area radiated by the star,

$$\int_0^\infty \mathfrak{F}_\nu \mathrm{d}\nu = \sigma T_{\mathrm{eff}}^4, \tag{1.2}$$

where the total radiant power per unit area is given by the integral and $\sigma = 5.670\,40 \times 10^{-5}\,\mathrm{erg/(s\,cm^2\,deg^4)}$ or $5.670\,40 \times 10^{-8}\,\mathrm{W/(m^2\,deg^4)}$. Here $\mathfrak{F}_\nu$ is the flux leaving the stellar surface, which is defined formally in Chapter 5. Equation (1.2) has the form of the Stefan–Boltzmann law, which we will meet in Chapter 6, making T_{eff} the temperature of a black body having the same power output per unit area as the star. However, the distribution of power across the spectrum may differ dramatically from a black body at the same effective temperature.

The total power emitted by the star is termed the luminosity. Luminosity is related to the effective temperature through the surface area, namely,

$$L = 4\pi R^2 \int_0^\infty \mathfrak{F}_\nu \mathrm{d}\nu = 4\pi R^2 \sigma T_{\mathrm{eff}}^4, \tag{1.3}$$

for a spherical star of radius R.

Traditionally and of historic necessity, the more empirical parameters of magnitude, spectral type, and color index have been used to describe stellar surface gravity and temperature.

Spectral types

One of the most powerful ways to analyze starlight is through spectroscopy, i.e., looking at the amount of light as a function of wavelength. The portion of the stellar spectrum emitted by the photosphere is an absorption-line spectrum. The absorption lines are narrow dark regions, of which there are many, and are sometimes called Fraunhofer lines after Joseph Fraunhofer who first saw them in the solar spectrum. The relative strengths and shapes of the absorption lines are used to classify a star by effective temperature and photospheric pressure, a process referred to as assigning a spectral type. A spectral type consists of a capital letter followed by an Arabic number representing the fraction toward the next letter class, followed by a Roman numeral. The letter represents the temperature classification and the Roman numeral denotes the pressure classification. Spectrograph dispersions of $\sim$100 Å/mm, giving $\sim$2 Å resolution, are found to be best for classification. Higher resolution resolves details of line profiles giving unwanted complications; lower resolution does not adequately separate individual lines. The traditional approach uses photographic records, called spectrograms, that are centered in the blue region of the spectrum where photographic emulsions are most sensitive, but electrical detectors work equally well or better. Line strengths and ratios are estimated visually by comparing an untyped spectrogram with standards. Establishing a grid of standard stars is a major undertaking with deep historical roots (see Huggins & Huggins 1899, Draper 1935, Garrison 1984, Keenan 1985, 1987, Hearnshaw 1986). Figure 1.2 shows a set of standard spectra in order of decreasing effective temperature. Those spectra toward the cool end of the sequence are referred to as "late-type" spectra, and those on the hot end as "early-type" spectra. In principle the spectral classification separates the observed (normal) stars into about 60 temperature steps. These range (hottest to coolest) from O2 to M8 through the standard (temperature) sequence: O, B, A, F, G, K, M with ten subdivisions per letter group. But some subclasses are rarely used. For example, the main subtypes for the cooler stars are G0, G2, G5, G8, K0, K1, K2, K3, K4, K5, M0, M1, M2, M3, M4, M5, M6, M7, and M8. In a few cases, half intervals are given full weight as a subclass, for example, O9.5 and B2.5. Statistically smooth relations exist between these main subtypes and other temperature indicators such as

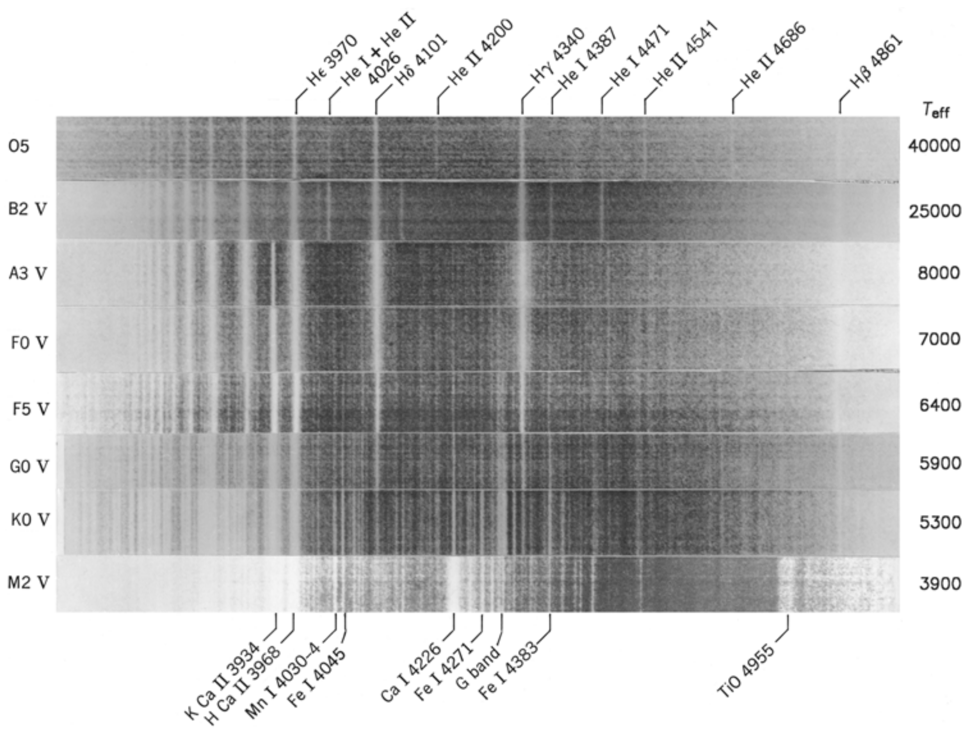

Fig. 1.2. The spectral temperature classification is illustrated by these samples of standard spectra from Abt *et al.* (1968). Notice how the hydrogen lines reach maximum strength in the A stars, high excitation lines are seen in O and B stars, while most spectral lines increase their strength with cooler temperatures.

color indices (see below). The other subclasses are sometimes used; a star classified as G1 is judged to lie between G0 and G2, for example. The spectral type of the Sun is G2 V by definition. The effective temperature associated with each spectral type is discussed in Chapter 14.

Spectral classification of very cool stars, also called brown dwarfs (see Geballe *et al*. 2002, Leggett *et al*. 2002), includes extension to classes L (2200–1300 K) and T (1300–800 K) as well as side branches: R stars parallel K stars, but show carbon-molecular bands; N stars parallel M stars, but show very strong carbon-molecular bands; S stars parallel M stars, but have the usual titanium oxide bands overshadowed by those of zirconium oxide (see Hearnshaw 1986).

Pressure sensitive features in the spectrum show markedly less variation, and only about a dozen classes are recognized. It is an observed fact that luminosity (the total power output of the star) and pressure are strongly correlated, and the pressure classification is universally referred to as the luminosity classification. The luminosity class designations in order of decreasing luminosity are 0, I, Ia, Ib, II, III, IV, and V. The names associated with these numerals are: 0 hypergiants, I supergiants, II bright giants, III giants, IV subgiants, and V dwarfs. Sometimes subdwarfs are denoted as class VI. Luminosity effects are illustrated in Fig. 1.3 and discussed in detail in Chapters 13 and 15. Sometimes the suffixes listed in Table 1.1 are used to supply additional information.

Before classification can begin, the observer must acquire spectrograms of the standard stars using the same equipment and technique intended to be used with the program stars. The first step in classification is to identify the lines

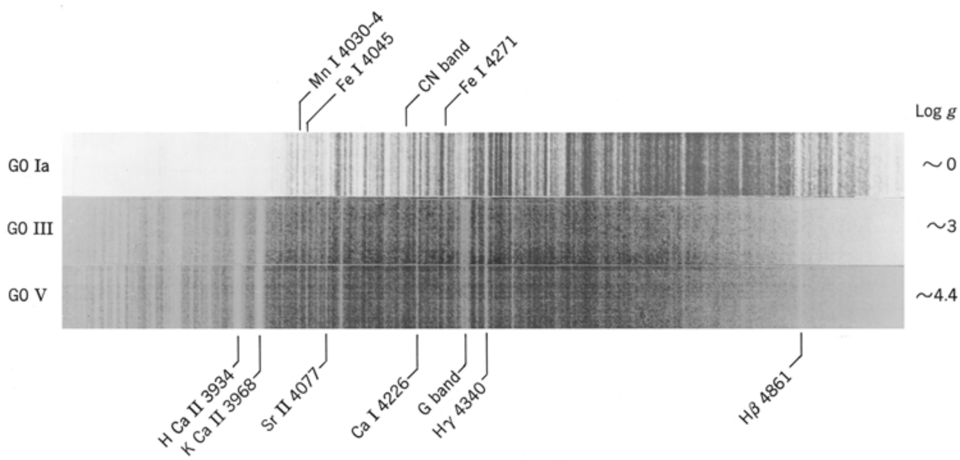

Fig. 1.3. Luminosity classification is illustrated by these samples of standard spectra from Abt *et al*. (1968). The lines are generally stronger in higher-luminosity stars. Note also specific changes as in the ratio of Sr II $\lambda 4077$ compared to H_δ, the strong line just to the right of $\lambda 4077$.

Table 1.1. *Spectral classification.*

Temperature criteria	
O4–B0	He I λ4471/He II λ4541 increasing with type
	He I + He II λ4026/He II λ4200 increasing with type
B0–A0	H lines increase with type
	He I lines reach maximum at B2
	Ca II K line becomes visible at B8
A0–F5	Ca II K/H_δ increasing with type
	Neutral metals become stronger
	G band visible starting at F2
F5–K2	H lines decrease
	Neutral metals increase
	G band strengthens
K2–M5	*G* band changes appearance
	Ca I λ4226 increases rapidly
	TiO starts near M0 in dwarfs, K5 in giants
Luminosity criteria	
O9–A5	H and He lines weaken with increasing luminosity
	Fe II becomes prominent in A0–A5
F0–K0	Blend $\lambda\lambda$4172–9 increases with luminosity (early F)
	Sr II λ4077 increases with luminosity
	CN λ4200 increases with luminosity
K0–M6	CN λ4200 increases with luminosity
	Sr II increases with luminosity
Suffix notation	
e	Emission lines are present
f	He II λ4686 and/or C III λ4650 in emission; mostly for O stars
k	Ca II K line when unexpected, e.g., interstellar in hot stars
m	Metallic; metal lines are stronger than normal
n	Nebulous; lines are broad and shallow; usually high rotation
nn	Very nebulous!
p	Peculiar; spectrum is abnormal
q	Queer; unusual emission; evolved from Q novae designation (archaic)
s	Sharp; lines are sharp, usually for early-type stars with low rotation
v	Variable; spectrum changes with time
w	Wolf–Rayet bands present (archaic)
Old prefix notation	
c for supergiants; g for giants; d for dwarfs	

whose strengths serve as the criterion for classification. The required lines can be identified by their position relative to lines in the comparison spectrum or to the few prominent features of the stellar spectrum itself. Iron and titanium are commonly used comparison spectra. In the stellar spectrum we easily recognize the hydrogen lines from class O to F5, and the less conspicuous lines can be referred to them. H_β remains distinguishable as the most intense line at the long-wavelength end of the spectrogram (Fig. 1.2) as late as K0. From F5 to M, the

G band near the center of the spectrogram and the H and K lines on the short-wavelength end can be used as guideposts.

The spectrum is first classed roughly. Does it have few lines, many lines, or does it show molecular bands? This rough classification is refined in successive steps. It is generally considered unwise to attempt an immediate accurate classification. Table 1.1 gives examples of the classification criteria from the atlases of Keenan and McNeil (1976) and Morgan *et al*. (1978). The earlier atlas by Morgan *et al*. (1943) is similar (see also Johnson & Morgan 1953). Although these special features are singled out, it is the appearance of the whole spectrum that is ultimately compared with the standards. Some care must be exercised, especially with early-type stars, because high rotation (see Chapter 18) can wash out weaker classification lines. Most modern spectral types are on the Morgan–Keenan system (MK) or a close derivative of it. A review of spectral classification is given by Morgan and Keenan (1973) and there is also a symposium dealing with this topic (Garrison 1984). Additional classification information can be found in a comprehensive objective-prism survey by Houk and Cowley (1975). Early O star classification is discussed by Walborn *et al*. (2002). Most catalogues of stars list spectral types, e.g., *The Bright Star Catalogue* (Hoffleit & Warren 1996) and the *Geneva Photometric Catalogue 1988* (Rufener 1988).

Magnitudes and color indices

The brightness of a star is often expressed in magnitude units defined by

$$m = -2.5 \log \int_0^\infty F_\nu W(\nu)\, \mathrm{d}\nu + \text{constant} \tag{1.4}$$

in which the amount of light or flux of the star, F_ν, is recorded in the spectral interval specified by $W(\nu)$. The visual magnitude, often denoted by m_v or V, has a spectral window, $W(\nu)$, centered on the yellow–green wavelengths. The constant is arbitrary and usually adjusted to suit an adopted set of standard stars. Notice that the minus sign in Eq. (1.4) implies smaller magnitudes for brighter stars. The bright star Vega, for example, has a visual magnitude of 0.03 according to Hoffleit and Warren (1996). Should we wish to include radiation at all wavelengths, $W(\nu) = 1$ everywhere, and the corresponding magnitude is the bolometric magnitude. Even for this case, there remains an arbitrary zero-point constant.

Standard magnitude systems have been set up. The first was the *RGU* system of Becker (1948, Becker & Stock 1954). The most commonly encountered systems are: the *UBV* system (Johnson & Morgan 1953, Nicolet 1978) and its extension to longer wavelengths in the *RIJKLMNH* magnitudes (Johnson 1966, Johnson *et al*. 1966, Morel & Magnenat 1978, Landolt 1992), the *uvby* system

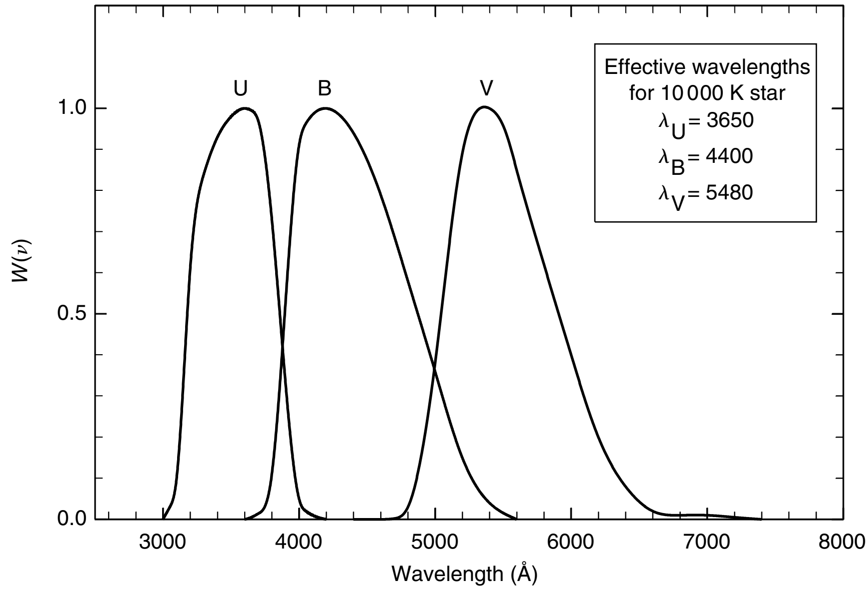

Fig. 1.4. The response functions for the *UBV* standard magnitude system are shown (from Johnson 1965). Because the bandpasses are so wide, their effective (average) wavelengths depend on the temperature of the star through the gross changes in the shape of the spectrum.

(Strömgren 1966, Hauck & Mermilliod 1980, Perry *et al.* 1987), the Geneva $UBVB_1B_2V_1G$ system (Rufener 1988, Rufener & Nicolet 1988), and the DDO system (McClure & van den Bergh 1968). The standard magnitude transmission bands are defined in terms of filter and detector response. The *UBV* response functions are shown in Fig. 1.4, for example.

By comparing the magnitudes of the same star measured in different parts of the spectrum, a measurement is made of the general shape of the spectrum. The *UBV* color indices are related to the flux and the transmission bands by

$$B - V = -2.5 \log\left(\frac{\int F_\nu W_B(\nu)\,\mathrm{d}\nu}{\int F_\nu W_V(\nu)\,\mathrm{d}\nu}\right) + 0.710 \tag{1.5}$$

$$U - B = -2.5 \log\left(\frac{\int F_\nu W_U(\nu)\,\mathrm{d}\nu}{\int F_\nu W_B(\nu)\,\mathrm{d}\nu}\right) - 1.093. \tag{1.6}$$

The constants by definition are adjusted to ensure that both indices are zero for an average A0 V star, and their value depends on the absolute photometry discussed in Chapter 10. The $B - V$ color index is a relative measure of the tem-

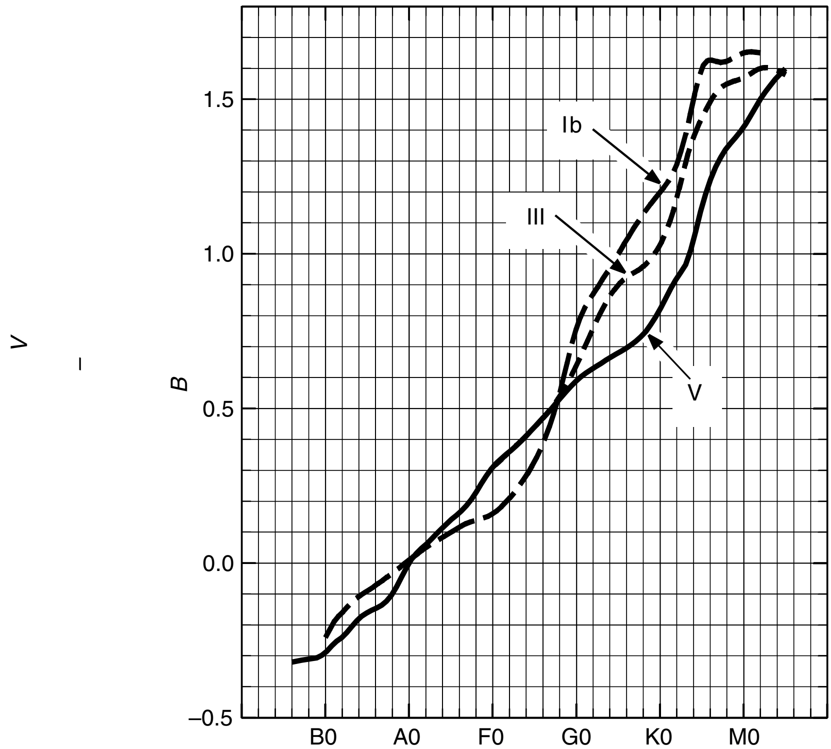

Fig. 1.5. The mean relation between the $B - V$ color index and the MK spectral type is shown based on the tabulation of FitzGerald (1970).

perature of the star through the slope of the Paschen continuum. With 0.01 magnitude precision in $B - V$, the temperature sequence can be divided into about 200 steps. Figure 1.5 relates $B - V$ and spectral type empirically. We can use this relation to estimate the $B - V$ of a star from its spectral type or vice versa.

Interstellar extinction alters the continuous energy distribution of a star, and consequently its color indices. Stars affected in this way deviate from the relation shown in Fig. 1.5. The spectral lines are unaffected by the interstellar extinction because the wavelength dependence of the extinction is negligible over the extent of an absorption line. There are, however, interstellar absorption lines, such as the calcium H and K lines and the sodium D lines, arising from the gaseous component of the interstellar material.

Interstellar extinction is a serious problem when the continuous spectrum of a star is to be analyzed because there is no really satisfactory way of correcting for the effect with the precision needed in stellar atmosphere analyses. For stars nearer than $\approx$100 pc, little or no detectable reddening is expected. Inside this relatively small volume, the shapes of stellar continua and hence color indices such as $B-V$ are independent of distance.

The $U-B$ color index is a measure of the Balmer discontinuity and makes a useful gravity indicator for early-type stars, but it is also sensitive to temperature. Indeed, many photometric indices have been defined to sense variations in temperature, gravity (or luminosity), and global chemical abundances (Philip 1979). When the stars of interest are too faint to measure with high spectral resolution, these photometric measurements can play an important role.

The Hertzsprung–Russell diagram

The mass and age of a star, and to a lesser extent its chemical composition and rotation, determine the luminosity, radius, and temperature of the star. A log–log plot of luminosity versus temperature is called an Hertzsprung–Russell or HR diagram and can take on several forms depending on exactly which coordinates are chosen. Figure 1.6 shows one example in which instead of log luminosity, absolute visual magnitude is used, and log temperature is replaced by spectral type. Because of the multi-valued relation between spectral type and $B-V$, as in Fig. 1.5, lines of constant $B-V$ for cool stars are not vertical. Similarly, if the $B-V$ were chosen for the abscissa, lines of constant spectral type would not be vertical. Most stars are found on the main sequence (class V) because this is the longest-lasting stage, during which hydrogen is converted to helium. Stars above the main sequence, luminosity classes I–IV, are "evolved" stars. Details on stellar evolution can be found in most books on stellar interiors.

The gas laws

The photospheres of stars are hot gas. Because the gas pressure is $\lesssim 10^5$ dynes/cm^2 ($\lesssim 10^4$ N/m^2) in most photospheres, the perfect gas law is exactly what we need since it holds in the limit of low pressures. We can write this law as

$$PV = nRT, \tag{1.7}$$

where P is the gas pressure of the volume of gas V at a temperature T in Kelvin. The number of moles of gas is n and the gas constant R has a value of 8.314×10^7 erg/(mol K) or 8.314 J/(mol K). More frequently we use the gas law in a slightly different form given by dividing Eq. (1.7) by V as follows. Let the number of particles per mole ($6.022\,04 \times 10^{23}$) be denoted by N_0. Then

$$P = \frac{nN_0}{V}\frac{R}{N_0}T = NkT$$