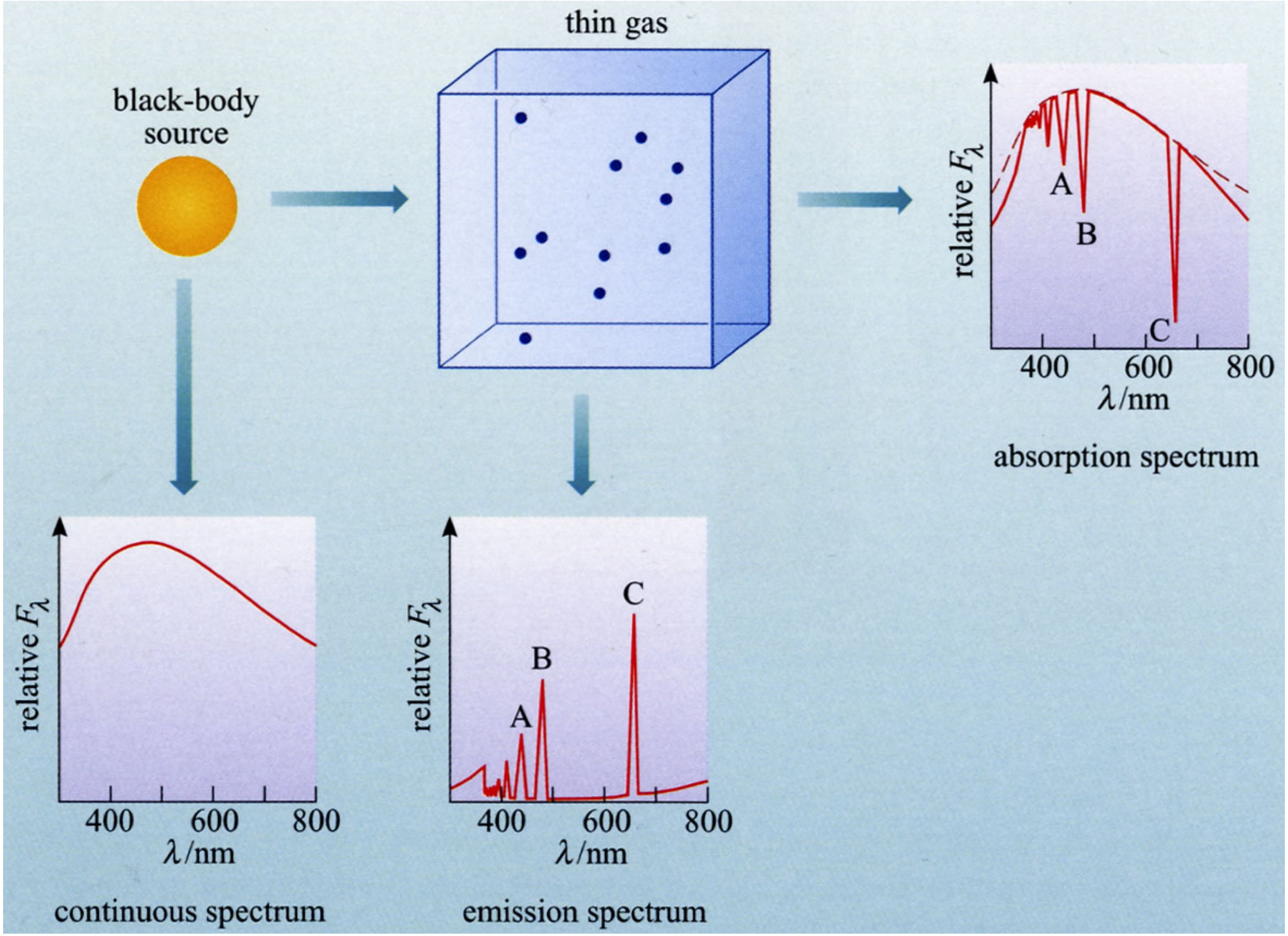
Structure and Evolution of Stars

Lecture 3: Spectral Classification and the Hertzsprung-Russell Diagram

- Absorption lines in stellar atmospheres and historical spectral classification
- The MK (Morgan-Keenan) spectral classification scheme – primary dimension, photospheric temperature
- The origin of absorption line widths and the secondary dimension of the MK spectral classification – luminosity class
- The observational and theoretical HR-diagram
- HR-diagram for stellar clusters – isochrones

Spectral Classification

- Historically, the stellar classification scheme originated from a classical botanical classification of stellar spectra based on the relative strength of various absorption lines in stellar spectra – alphabetical scheme; A,B,C…
- Absorption line spectrum arises due to cooler atmosphere overlying hotter source of continuum radiation
- Only later was it realised that the key physical property that determined the form of the absorption line spectrum was the surface temperature of the stars
- Enormous simplification of scheme and identification of key property of stars – surface temperature



black-body source
thin gas
relative F_λ
A
B
C
400
600
800
λ/nm
absorption spectrum
relative F_λ
400
600
800
λ/nm
continuous spectrum
relative F_λ
A
B
C
400
600
800
λ/nm
emission spectrum

Orion nebula – star-formation region: emission-line spectrum from gas
NASA

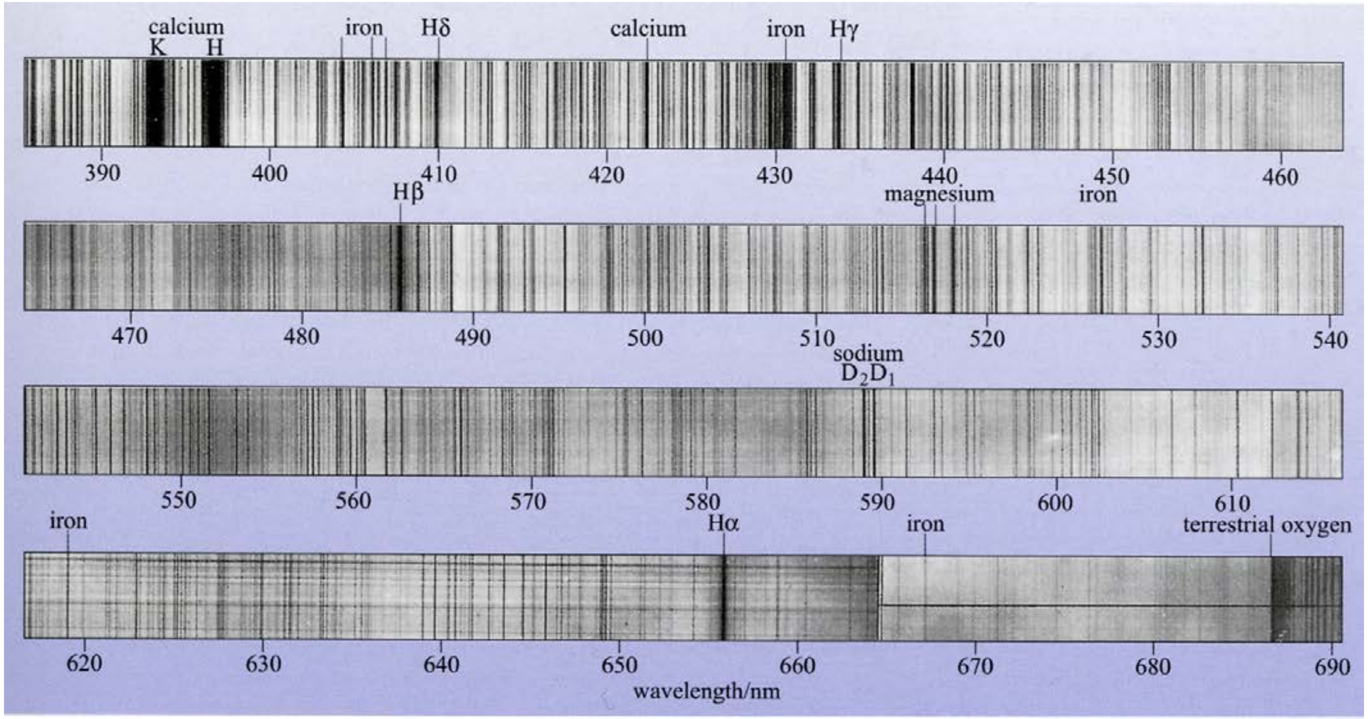


Figure 1.28 A black and white image of the solar spectrum. Note that for convenience of display, the spectrum has been cut into sections and consecutive sections have been stacked vertically in sequence. (The horizontal streaks on the spectra are artefacts.) (Kitt Peak National Observatory)

Instructive to consider why presence of absorption lines so sensitive to temperature

Energy level diagram for H

Balmer absorption seen in A-stars due to promotion of electron in n=2 level to levels n=3, 4, 5…

For low T, electrons in n=1 level – no Balmer lines

For high T, Hydrogen is ionised – no Balmer lines

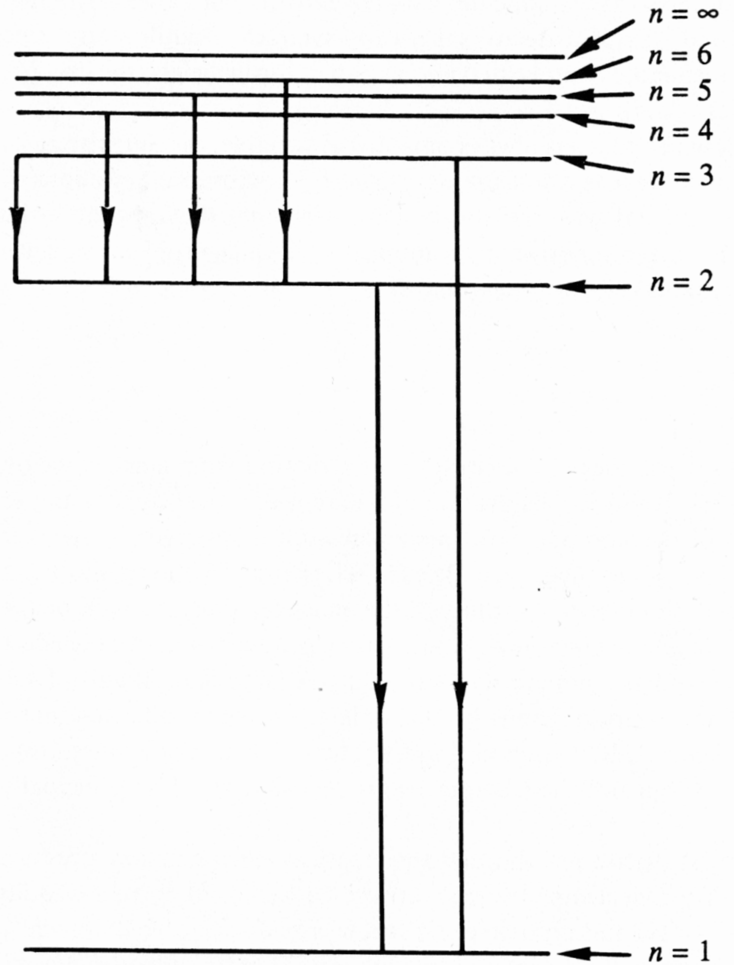


Fig. 16. Energy levels and emission spectral lines in hydrogen. The Hα emission line is produced by electrons moving from the $n = 3$ level to the $n = 2$ level. Transitions to the $n = 1$ level produce the Lyman series in the ultraviolet.

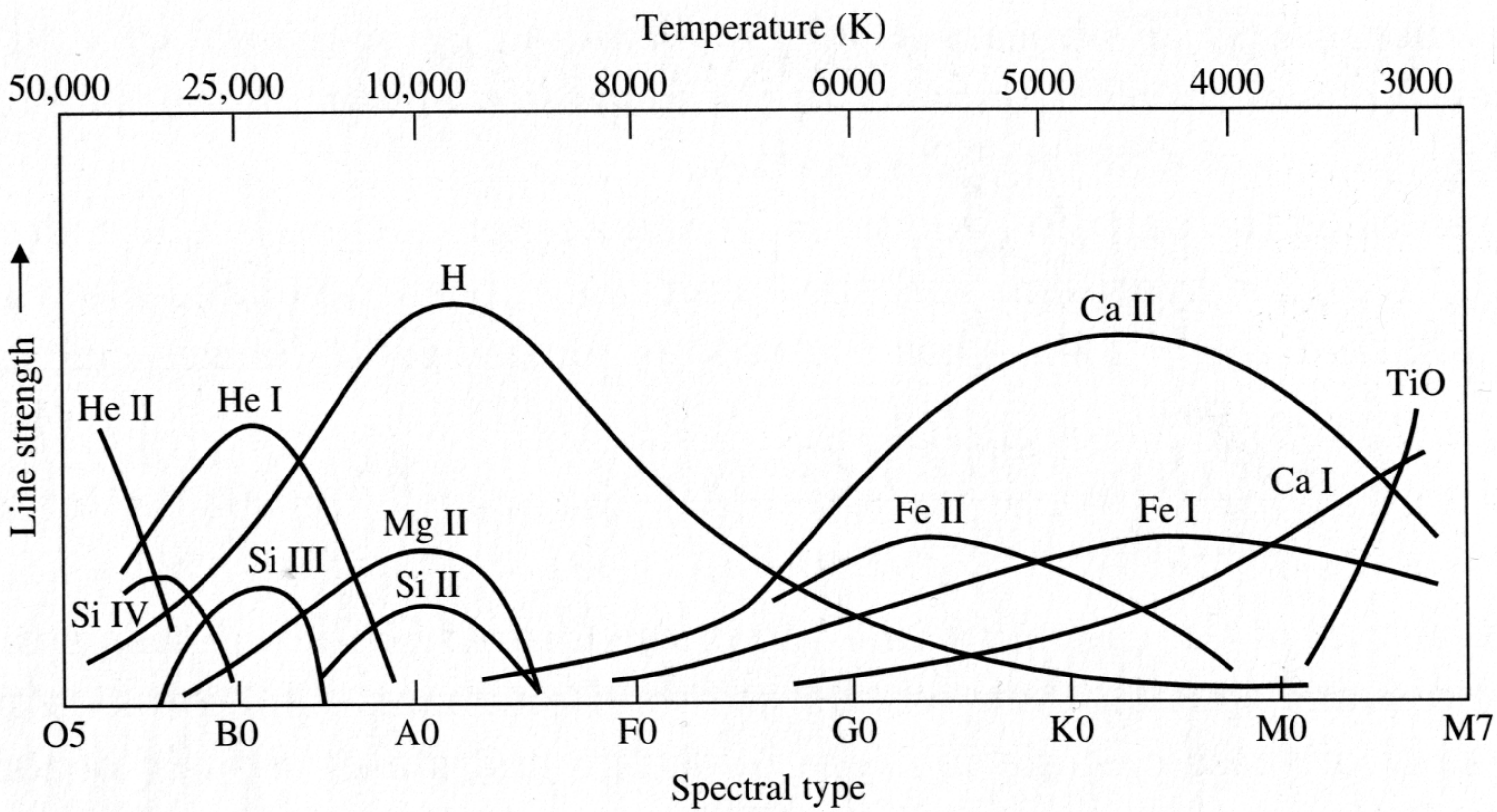
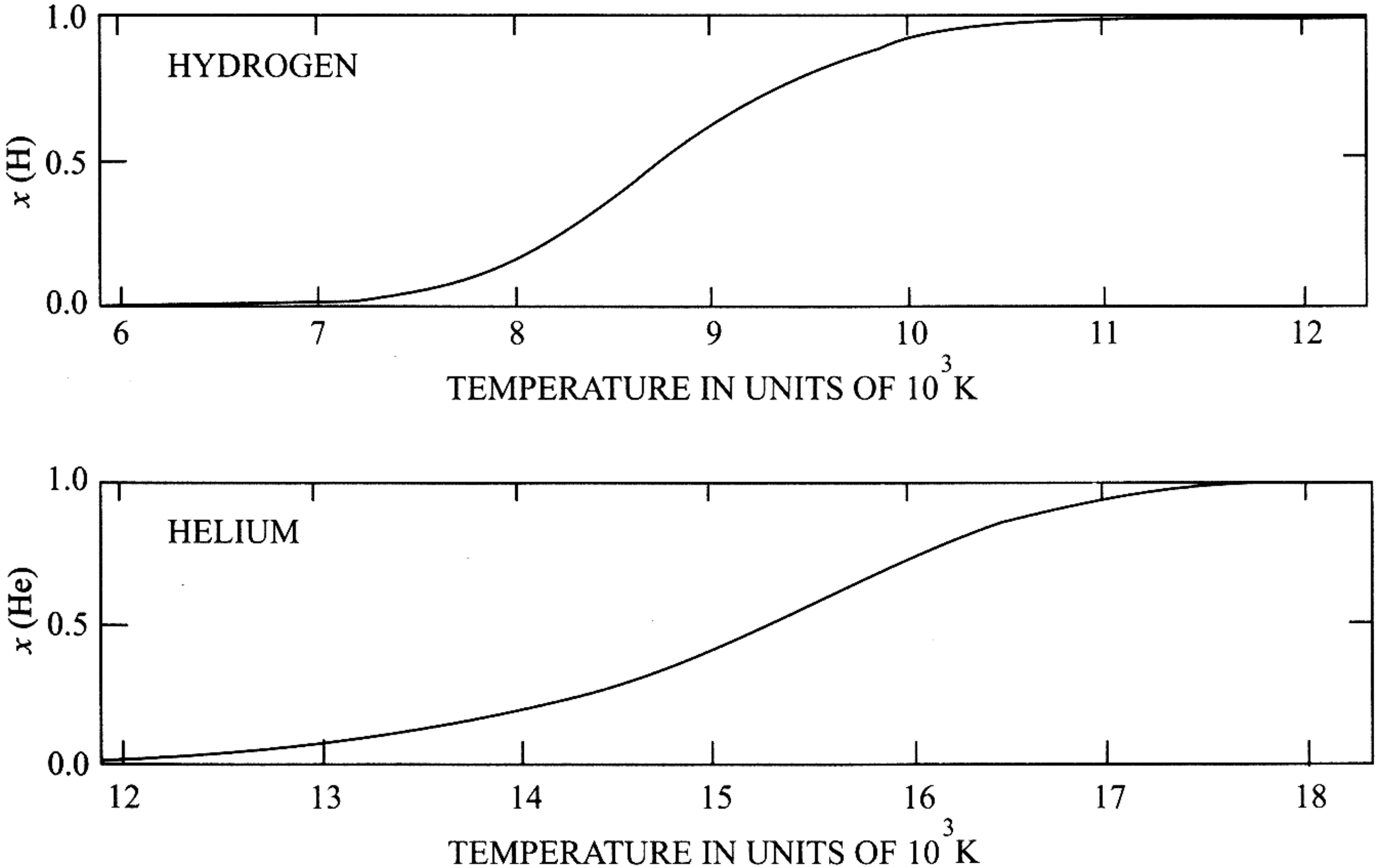


Figure 8.9 The dependence of spectral line strengths on temperature.



The fractional degree of ionization of hydrogen and helium as a function of the temperature in a gas with a free electron concentration $n_e = 10^{19}\ \mathrm{m}^{-3}$

Table 3.2 Stellar spectral types, photosphere temperatures and prominent lines.

Spectral type	Temperature[a] /K	Most prominent lines (see Figure 3.23)
O5	40 000	ionized helium and other ionized atoms
B0 B5	28 000 15 500	neutral helium, hydrogen
A0 A5	9900 8500	hydrogen, some ionized metals
F0 F5	7400 6600	hydrogen, ionized calcium, iron and other metals
G0 G5	6000 5500	ionized and neutral calcium, iron, and other metals, hydrogen
K0 K5	4900 4100	neutral iron, calcium and other metals
M0 M5 M8	3500 2800 2400	titanium oxide, neutral calcium

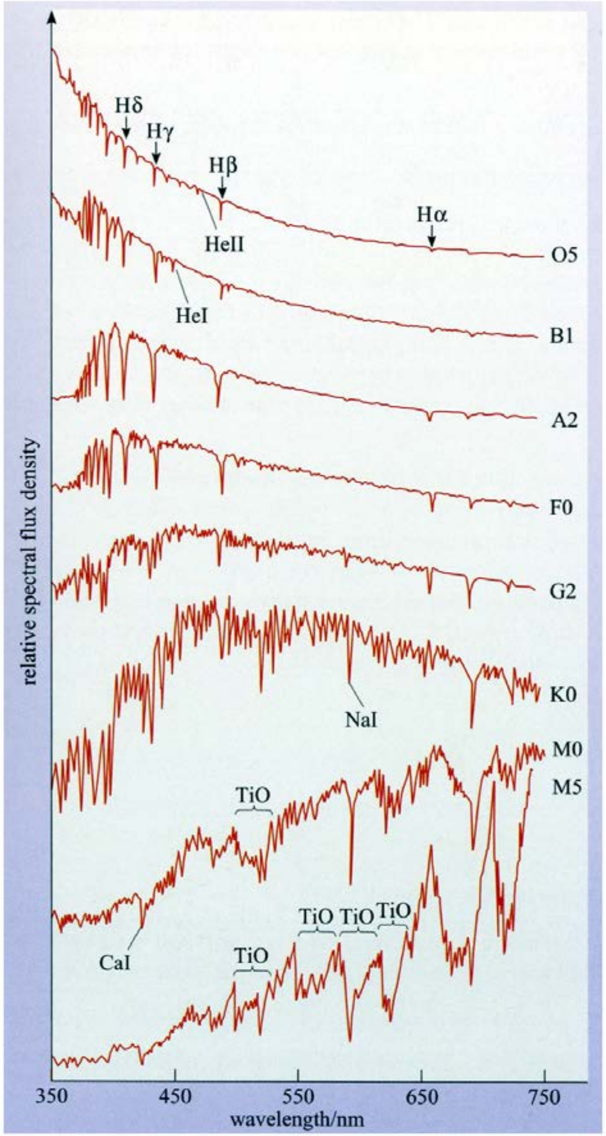


Figure 3.26 The stellar absorption spectra given in Figure 3.25 are more usually presented as graphs of relative flux density versus wavelength for ease of identification of the prominent absorption lines. The spectra have been plotted without spectral flux density scales and displaced vertically for clarity. (Kaufmann and Freedman, 1998)

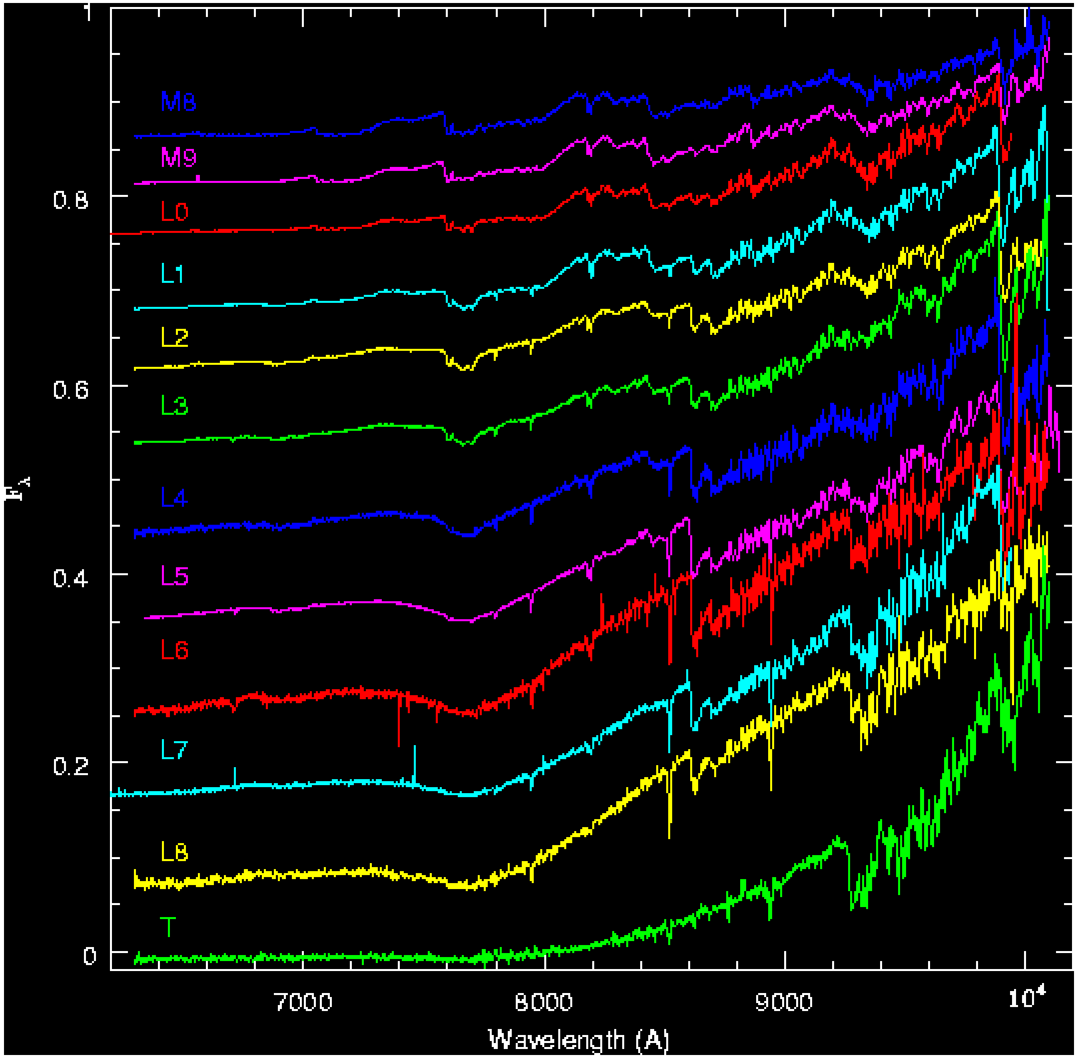
Temperature-based scheme, O, B, A, F, G, K, M now standard with each class sub-divided into 10 sub-classes, 0,1,2…

The Sun has spectral class G2

In recent years, new observations allow detection of the faintest stars and brown dwarfs, resulting in extension of the scheme to include types L and T

Recent observations have extended sequence through "L" and "T" dwarfs – "Brown Dwarfs". Brown Dwarfs are essentially "failed"-stars due to low mass.

Broad structures evident in spectra due to the presence of molecular species in the low temperature atmospheres of the "stars". Plot from Neil Reid (STScI)



Absorption Lines: what else can be learned?

- The strength of a spectral line is measured by its Equivalent Width (EW). The width (in Angstroms, nm…) of a rectangular line extending all the way to the continuum level that has the same area as the spectral line. Absorption lines with different widths or depths can have the same Equivalent Width.
- What determines the width of an absorption line?
- Three principal factors:
  - Natural Broadening
  - Doppler Broadening
  - Pressure Broadening

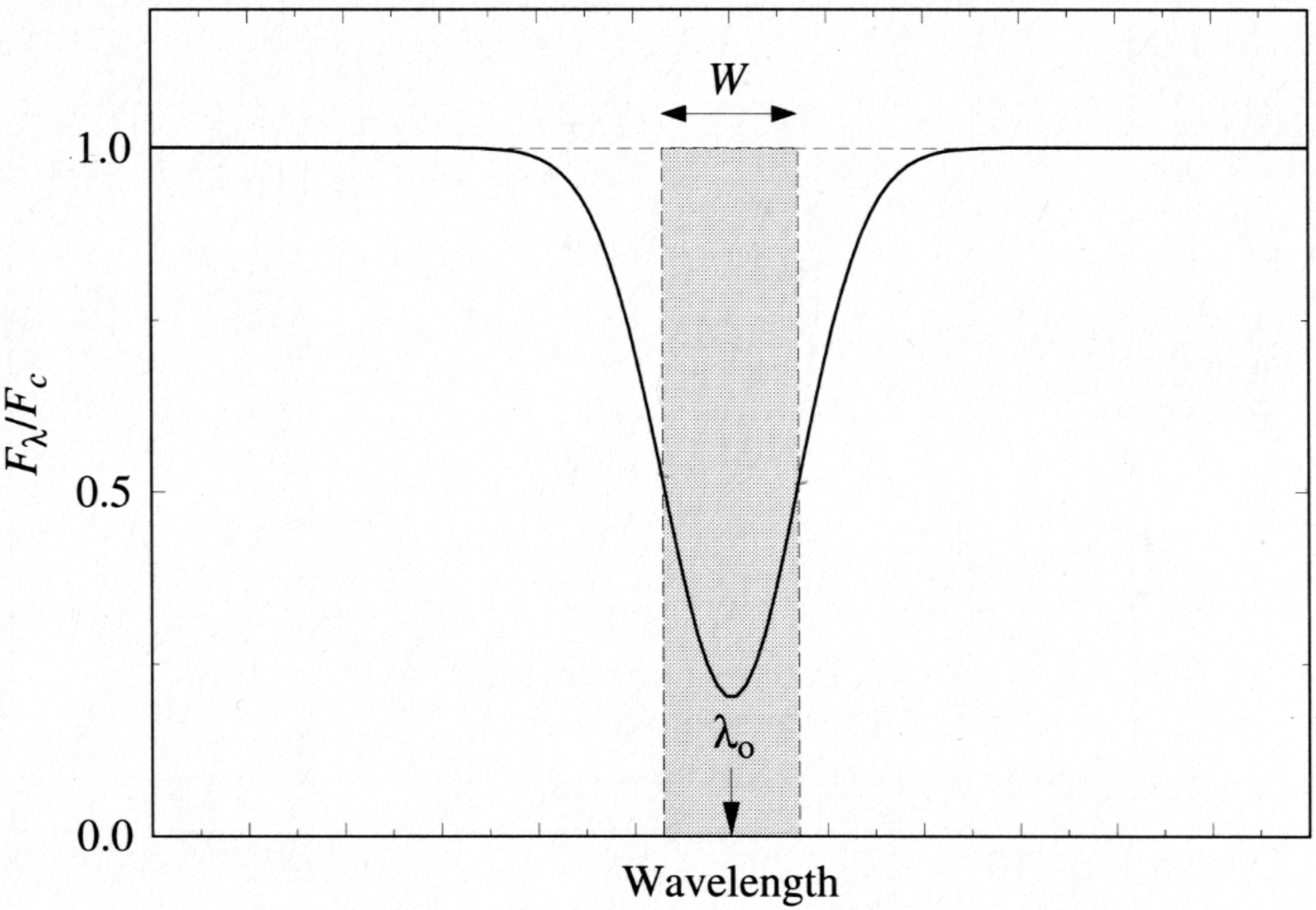


Figure 9.18 The shape of a typical spectral line.

Line Profiles: Natural Broadening

- Heisenberg Uncertainty Principle: $$\Delta E \approx \frac{\hbar}{\Delta t}$$

where Δt is the lifetime of the electron in the energy level.

Photon moving between levels has $E_{photon} = hc/\lambda$

Uncertainty in wavelength: $$\Delta\lambda \approx \frac{\lambda^2}{2\pi c}\left(\frac{1}{\Delta t_i} + \frac{1}{\Delta t_j}\right)$$

For the Hα line (6563A),

lifetimes in n=2 and n=3 states

$\Delta t \approx 10^{-8}$s and $\Delta\lambda \approx 4.6 \times 10^{-4}$A

Line Profiles: Doppler Broadening

- Atoms, mass *m*, in thermal equilibrium in stellar atmosphere
- Random motion obeying Maxwell-Boltzmann distribution, most probable speed $v_{mp} = (2kT/m)^{1/2}$
- Fractional wavelength shift $\Delta\lambda/\lambda = v/c$, thus linewidth due to thermal motions:

$$\Delta\lambda \approx \frac{2\lambda}{c} v_{mp} = \frac{2\lambda}{c}\sqrt{\frac{2kT}{m}}$$

Line Profiles: Doppler Broadening

- For the Hα line in the Sun ($T=5800K$) $\Delta\lambda \approx 0.4$Angstroms
- Approximately 1000 times larger than Natural Broadening
- Organised bulk motion of material can also produce significant Doppler broadening
  – rotation of star
  – turbulence in atmosphere

Line Profiles: Pressure Broadening

- Energy levels perturbed by collisions with other atoms or close encounters with electric field of ions
- Overall effect of ensemble of electric fields of close encounters with ions is termed “pressure broadening”
- Similarly, effect of ensemble of collisions is termed “collisional broadening”
- Pressure broadening is most important in practice
- To estimate line-width due to pressure broadening. Consider Δt_0 , the time between encounters, where $\Delta t_0 \approx l/v$ where *l* is the mean-free-path between collisons and *v* is the velocity of the particles

Line Profiles: Pressure Broadening

- mfp, $l = 1/n\sigma$, where n is the number density of particles and σ is the cross-section for an encounter that produces a significant perturbation to the energy of the electron
- Velocity, v, from the Maxwell-Boltzmann distribution, $v_{mp} = (2kT/m)^{1/2}$, and

$$\Delta t_0 \approx \frac{l}{v} = \frac{1}{n\sigma\sqrt{2kT/m}}$$

- Substituting the expression for Δt_0 into the expression for $\Delta\lambda$ derived for natural broadening, gives an estimate for the size of pressure broadening of

$$\Delta\lambda = \frac{\lambda^2}{c}\frac{1}{\pi\Delta t_0} \approx \frac{\lambda^2}{c}\frac{n\sigma}{\pi}\sqrt{\frac{2kT}{m}}$$

Line Profiles: Pressure Broadening

- For the Hα line in the Sun, T=5800K and $n=1.5\times10^{17}cm^{-3}$ the broadening $\Delta\lambda \approx 2\times10^{-4}$A which is comparable to the size of the natural broadening
- In the deep cores of the absorption lines the Doppler broadening dominates the line shape but the line-profile of pressure broadening has very extended wings and for strong lines the pressure broadening dominates the total width of the line
- The broadening Δλ depends linearly on the density of the atmosphere and this is the physical basis for the second dimension of the 2-dimensional MK spectral classification scheme

The combination of all the broadening mechanisms produces a "Voigt Profile" where the core of the line is dominated by the Doppler profile and the wings of the line by the pressure broadening profile.

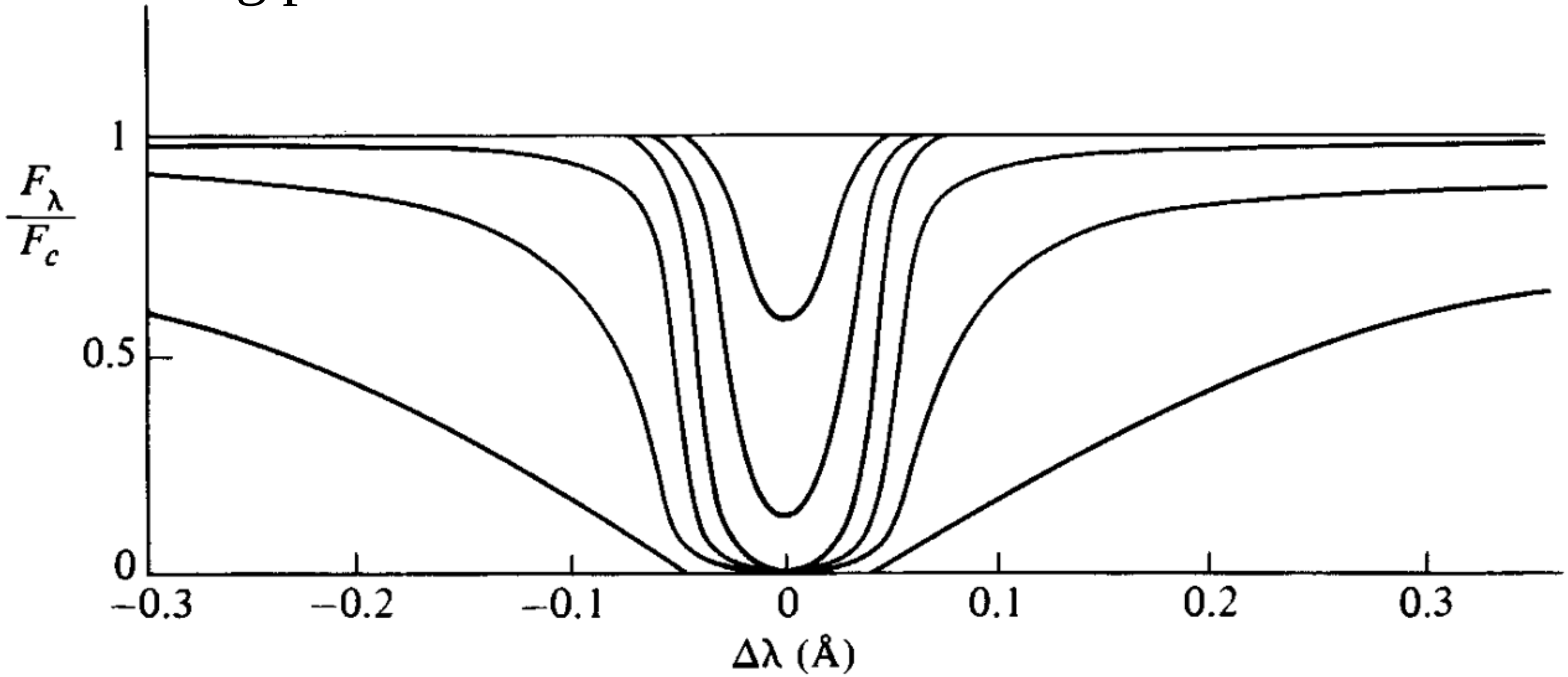
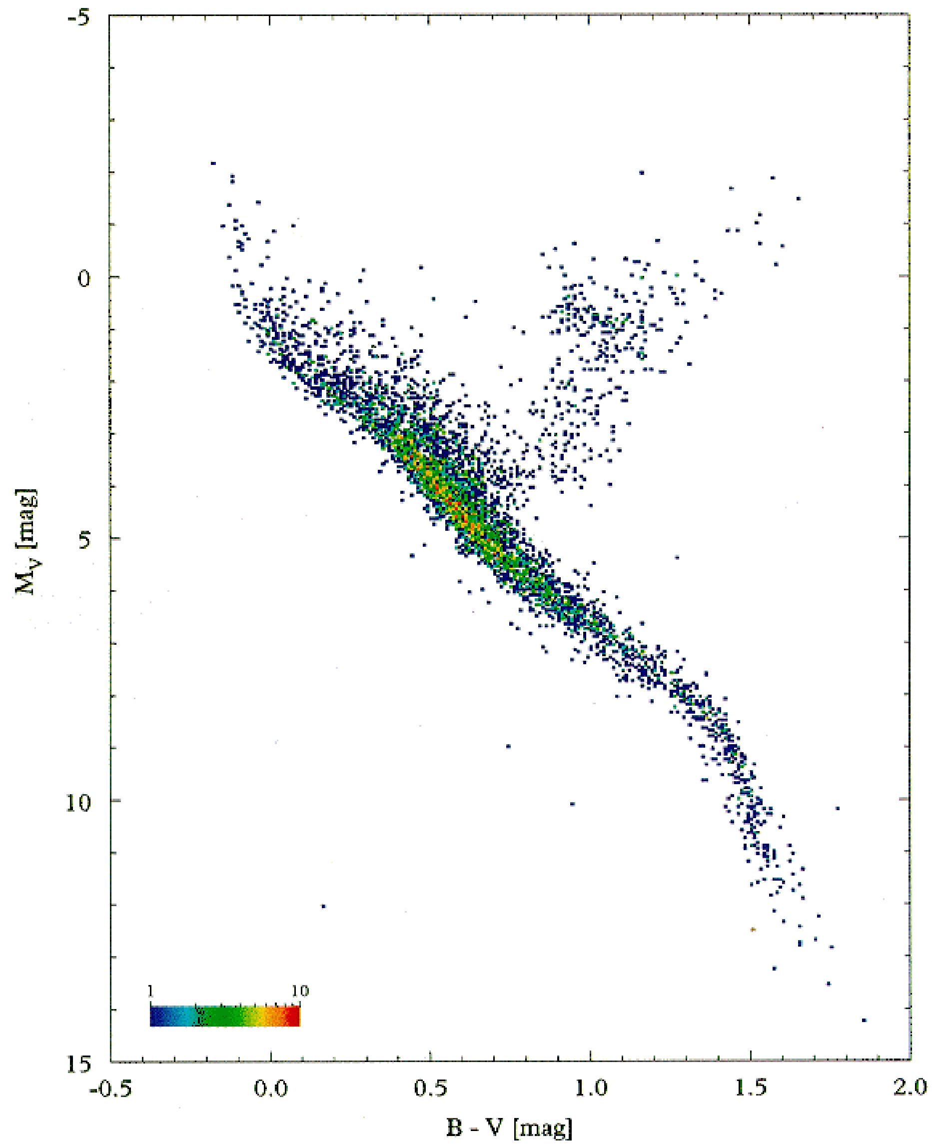


Figure 9.20 Voigt profiles of the K line of Ca II. The shallowest line is produced by $N_a = 3.4 \times 10^{11}$ ions cm^{-2}, and the ions are ten times more abundant for each successively broader line. (Adapted from Novotny, *Introduction to Stellar Atmospheres and Interiors*, Oxford University Press, New York, 1973.)

Hertzsprung-Russell diagram from HIPPARCOS satellite – bright, nearby stars.

What can now be deduced from the relation
$L = 4 \pi R^2 \sigma T_e^4$?



Two-dimensional Spectral Classification: Luminosity Class

- Take a vertical cut through the HR-diagram, ie, fixed Temperature, and consider the behaviour of the pressure, $P=nkT$ in stars of increasing radius
- T is constant but the density of particles, n, drops as the atmosphere of the stars becomes more and more distended
- Pressure therefore drops and the effects of pressure-broadening becomes much reduced, i.e. absorption lines become narrower as the radius of the star increases
- Absorption line width provides a measure of the "Luminosity Class" to give the 2-dimensional MK classification system based on Temperature & Luminosity

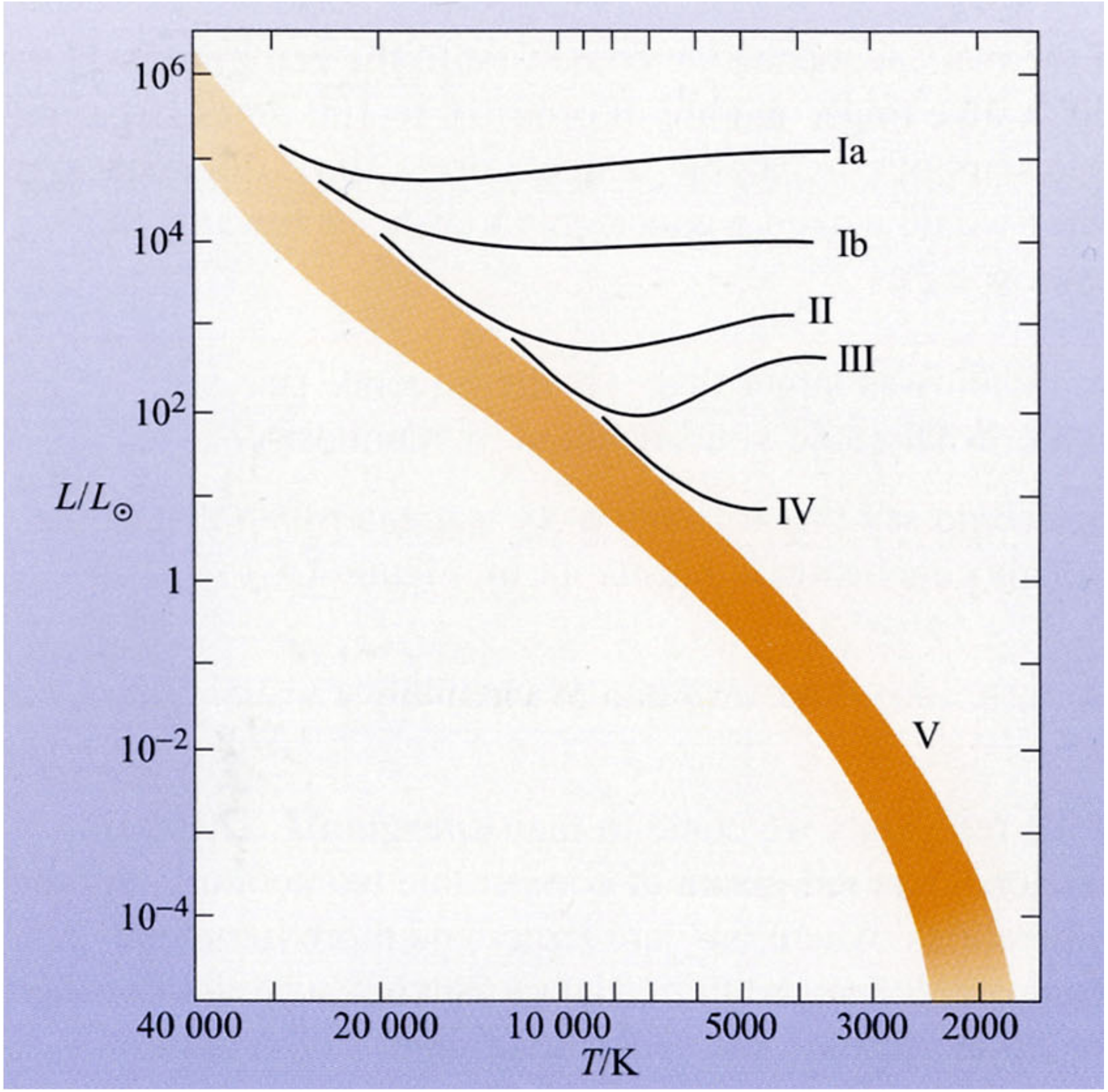


Figure 4.6 The H–R diagram indicating the approximate positions of luminosity classes I to V. Luminosity class V applies to the whole of the main sequence.

Table 3.6. *The MK luminosity classes*

The table gives a brief description of the luminosity classes and their absolute visual magnitudes at various spectral types. The letters *a* and *b* are sometimes suffixed to the classes to indicate whether a star is on the bright or dim side of the average, as for class I. Anomalously high abundances are indicated by appending the relevant chemical or molecular symbol; sometimes a '+' or '−' and a numerical index is added to the symbol to show enrichment or depletion: see Section 3.6.

		Absolute visual mag		
	Spectral type	B0	F0	M0
0 (zero)	The extreme, luminous supergiants		−9	
	The Magellanic Clouds and the Galaxy			
Ia	Luminous supergiants	−6.7	−8.2	−7.5
Ib	Less luminous supergiants	−6.1	−4.7	−4.6
II	Bright giants	−5.4	−2.3	−2.3
III	Normal giants	−5.0	1.2	−0.4
IV	Subgiants	−4.7	2.0	
V	Main sequence	−4.1	2.6	9.0
sd (VI*)	Subdwarfs			10
D, wd (VII*)	White dwarfs	10.2	12.9	

* Infrequent

Hertzsprung-Russell diagram in both observational form (Colour vs M_V or Spectral Type vs M_V) and theoretical form (T vs L)

Sun has spectral classification = G2V

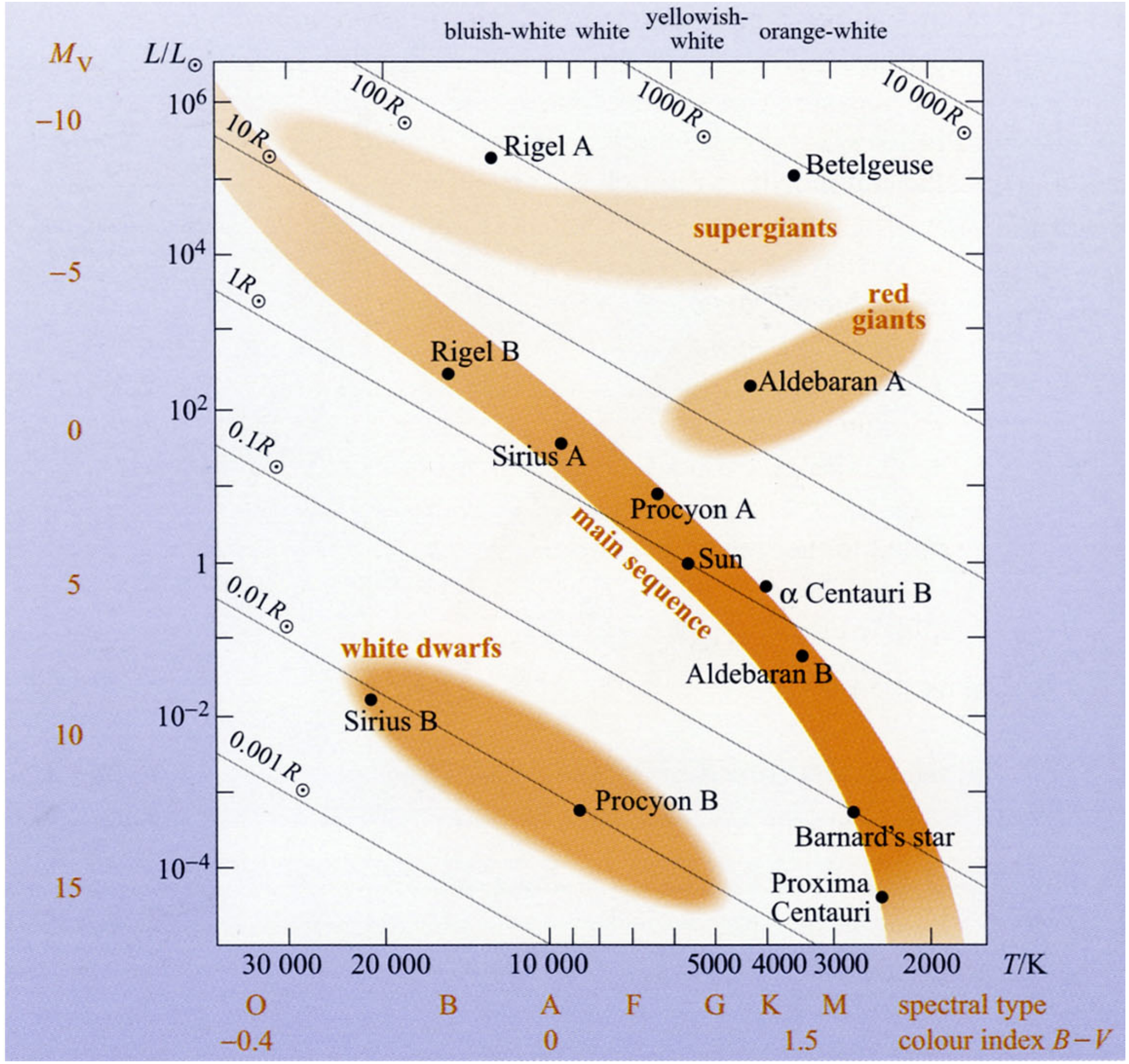


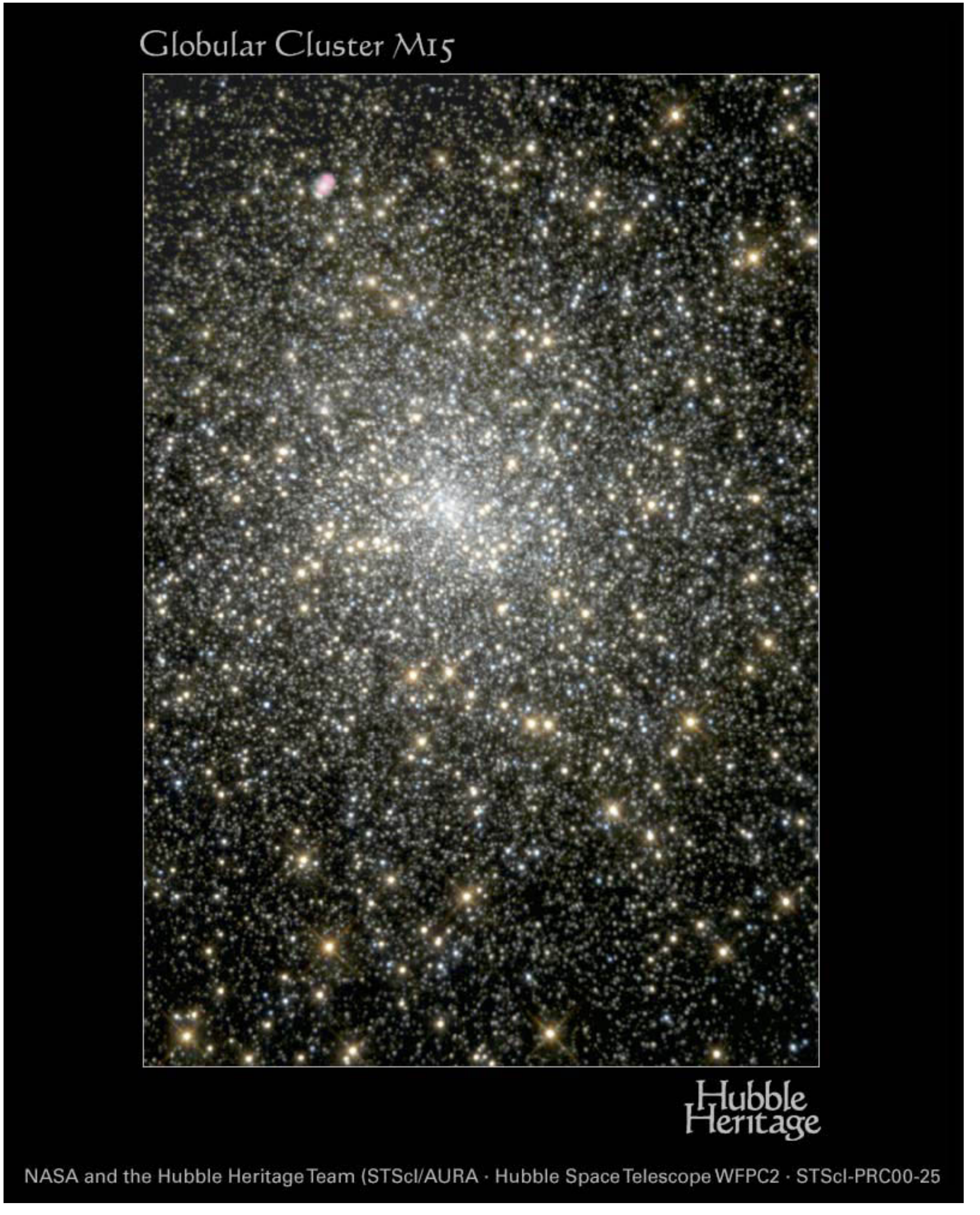
Figure 4.5 The H–R diagram in Figure 4.3, with the addition of stellar radii, and other information. (Adapted from Seeds, 1984)

Pleiades, young cluster, age $\approx 8 \times 10^7$yr

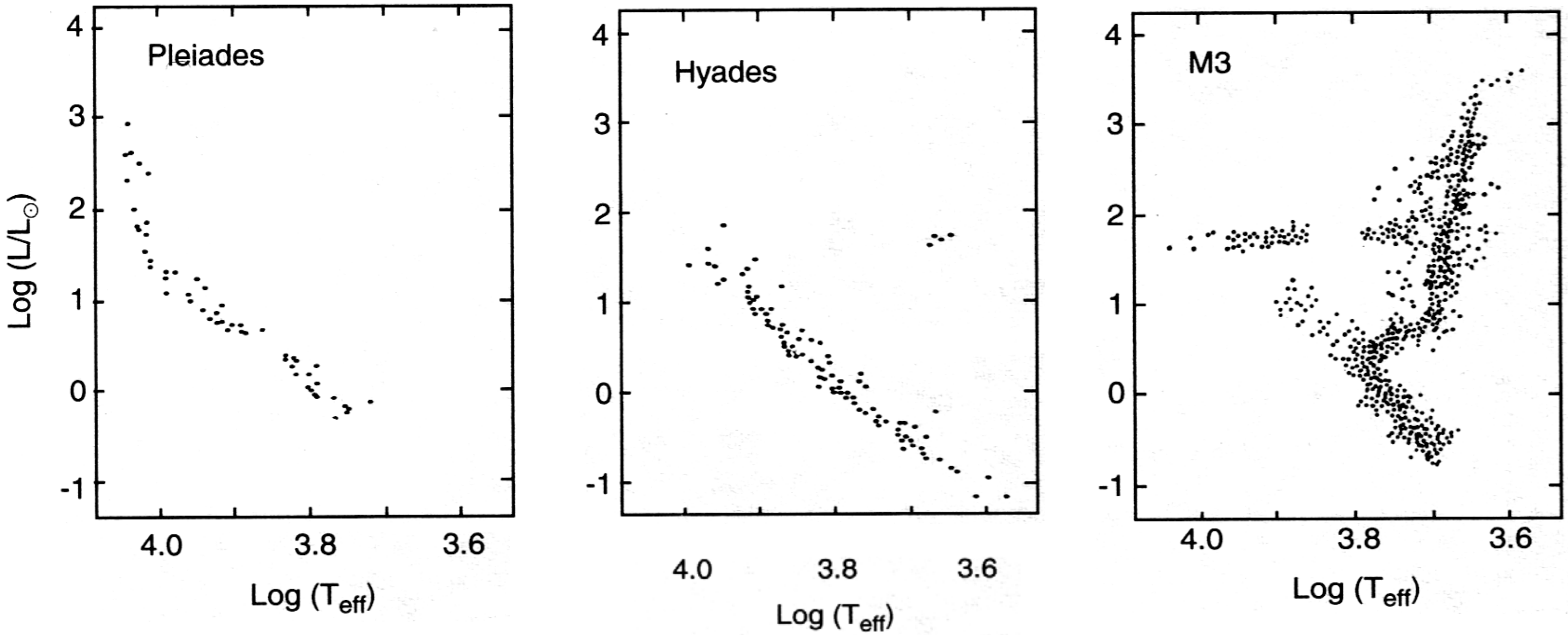
Constructing the HR-diagram for systems where the age and the composition of the stars are essentially identical allows some progress.

Historically, could be achieved without distance information to provide distribution of relative brightness for stars in a cluster.

M15 typical globular cluster with age >10^{10}yr



HR-diagrams for 3 stellar clusters of very different ages



Radically different morphology of HR-diagrams as a function of age. An "isochrone" describes location of stars of fixed age in HR-diagram. (M3 $\approx 11 \times 10^9$yr; Hyades $\approx 6 \times 10^8$yr)

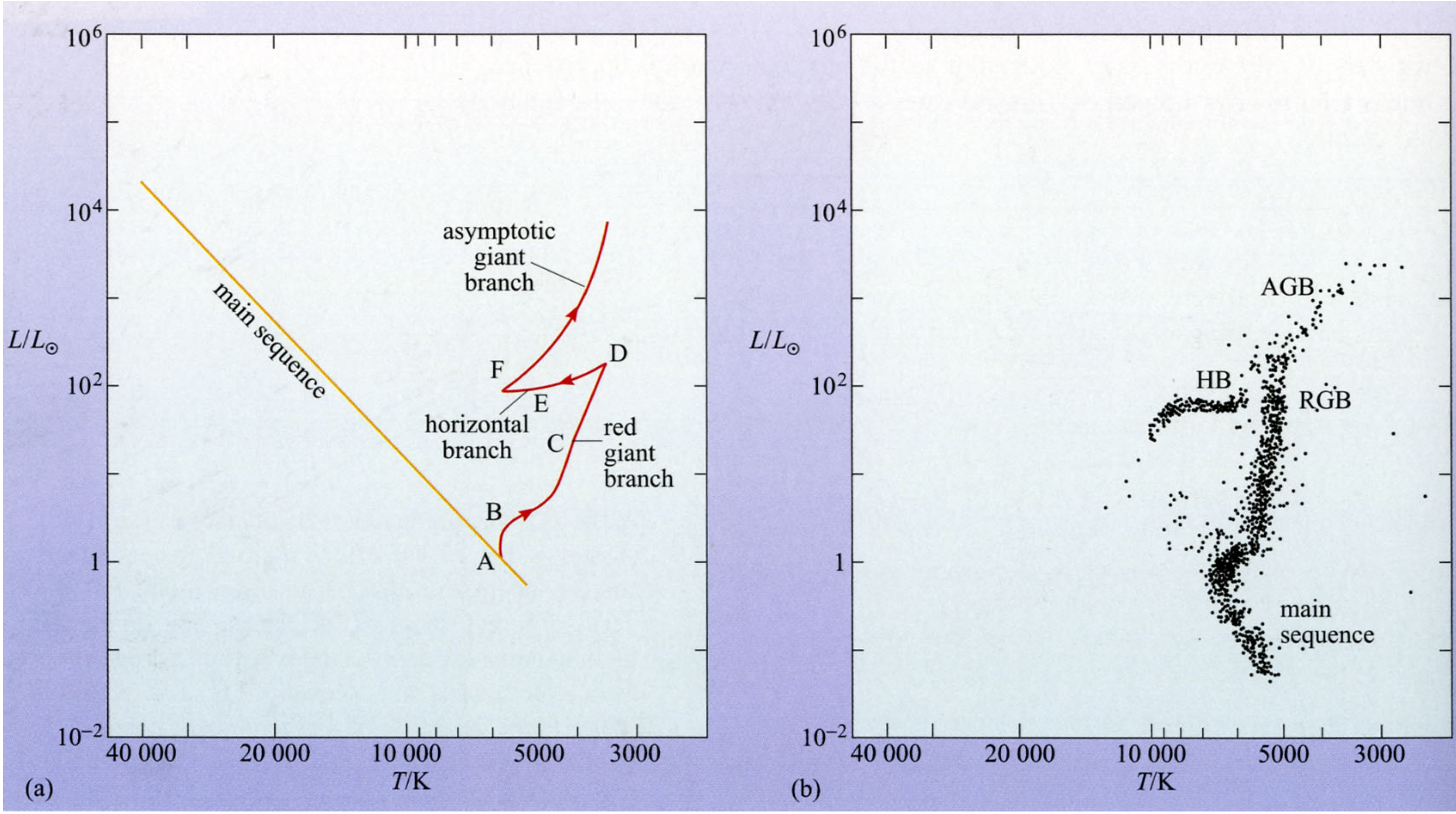


Figure 7.3 (a) The predicted path of a $1 M_\odot$ star, plotted on the same scale with the same labels as Figure 7.2, (A) hydrogen core fusion; (B) onset of hydrogen shell fusion; (C) hydrogen shell fusion continues; (D) helium core fusion starts; (E) helium core fusion continues; (F) helium shell fusion starts. (b) The H–R diagram of a globular cluster which illustrates how stars tend to concentrate in these regions.

Lecture 3: Summary

You should understand:

The basis of the MK spectral classification scheme – primary dimension, photospheric temperature – including the O,B,A,F,G,K,M sequence

The origin of absorption line widths and the secondary dimension of the MK spectral classification – luminosity class – and relationship to stellar radii

The form of the observational and theoretical HR-diagrams including quantitative axes

The morphology of the HR-diagram for stellar clusters and the importance of isochrones

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