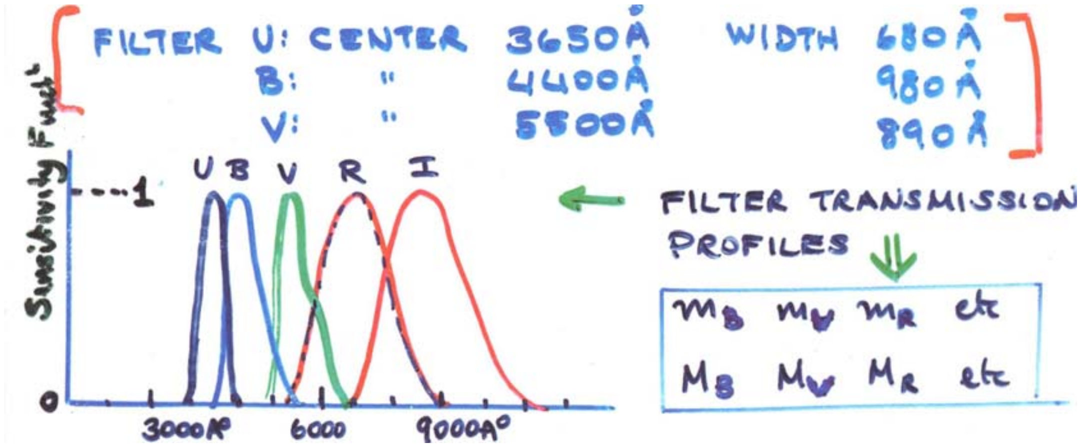
AY 20 Fall 2010

Electromagnetic Radiation: Stellar Spectra

Reading: Carroll & Ostlie, Chapters 5, 8

Color Index: differences between stellar radiation at different colors



U-B = $M_U - M_B$ or B-V = $M_B - M_V$ and so on
Note: *smaller* B-V = bluer = hotter

Recall distance modulus, m-M = 5logd – 5,

$m_B - m_V = M_B - M_V$

$\therefore$ Color index independent of distance
i.e. an intrinsic stellar property

Define Bolometric Correction = BC = $m_{bol} - V = M_{bol} - M_V$
(common usage: $V \equiv m_V$, $B \equiv m_B$ etc; BC is –ve)

Earlier: monochromatic flux $F_\lambda d\lambda = L_\lambda/4\pi r^2 \, d\lambda$

(Note typo on p17 last class)

and $F_\lambda d\lambda = B_\lambda R^2/r^2 \, d\lambda$, R = stellar radius

$\therefore \; F_\lambda d\lambda = B_\lambda (R^2/r^2) d\lambda$

$\therefore \; m_U - m_B = U - B = -2.5\log(B_U \Delta\lambda_U/(B_B \Delta\lambda_B) + C_{U-B}$

and $B_\lambda(T) \propto \lambda^{-5}$

$\therefore \; C_{U-B} = U\text{-}B + 2.5\log[(4400)^5/(3650)^5 \times 680/980]$

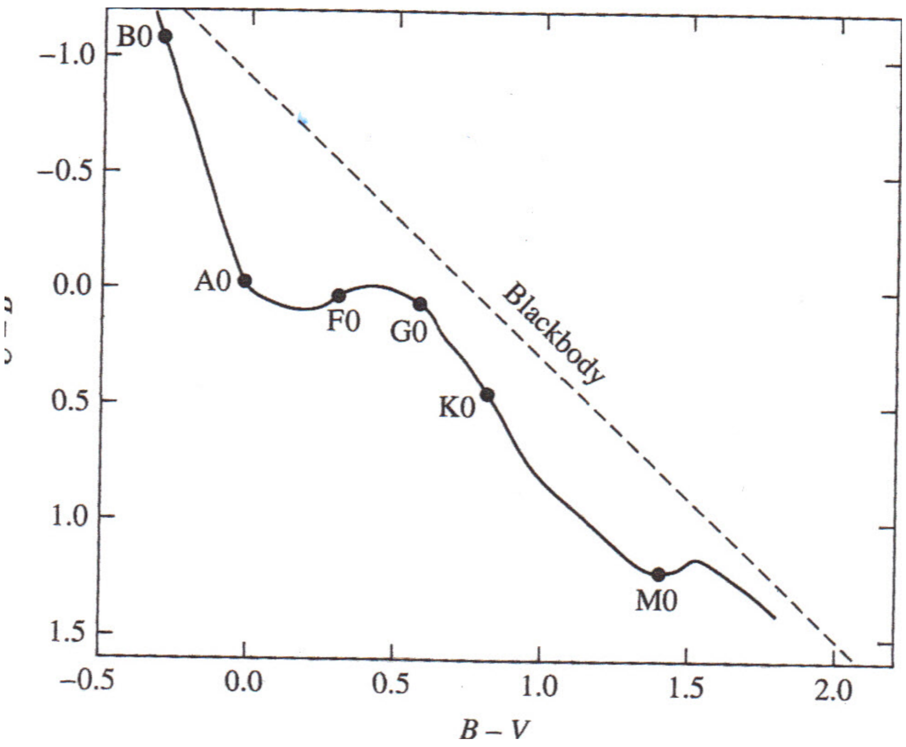
And similarly for C_{B-V}

For Vega, assume magnitude seen in each filter is zero (very approximate but works) → values for constants

Again color indices seen to be intrinsic to star (and a measure of temperature)

Useful examples 3.6.1, 3.6.2 *C & O*

Color-Color Diagram indicates physical properties



Real stars don't behave like B-Bs

Hottest stars behave most like black bodies

e.g. O5 star at 44,500K

U-B = -1.19, B-V = -0.33, – very blue

λmax = 0.29/44500 ~650Å

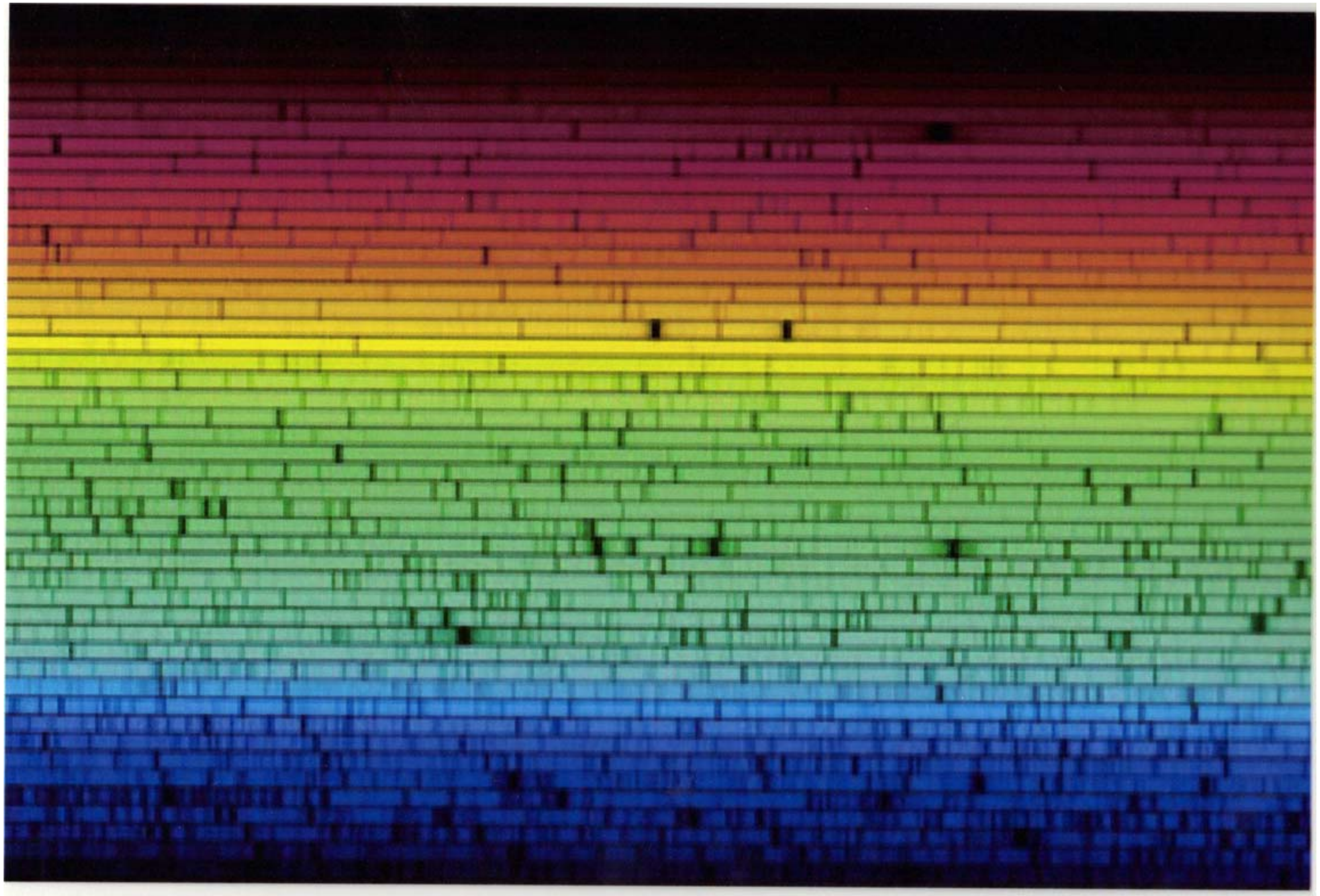
i.e. peaks outside range of U filter

(680Å wide centered at 3650Å

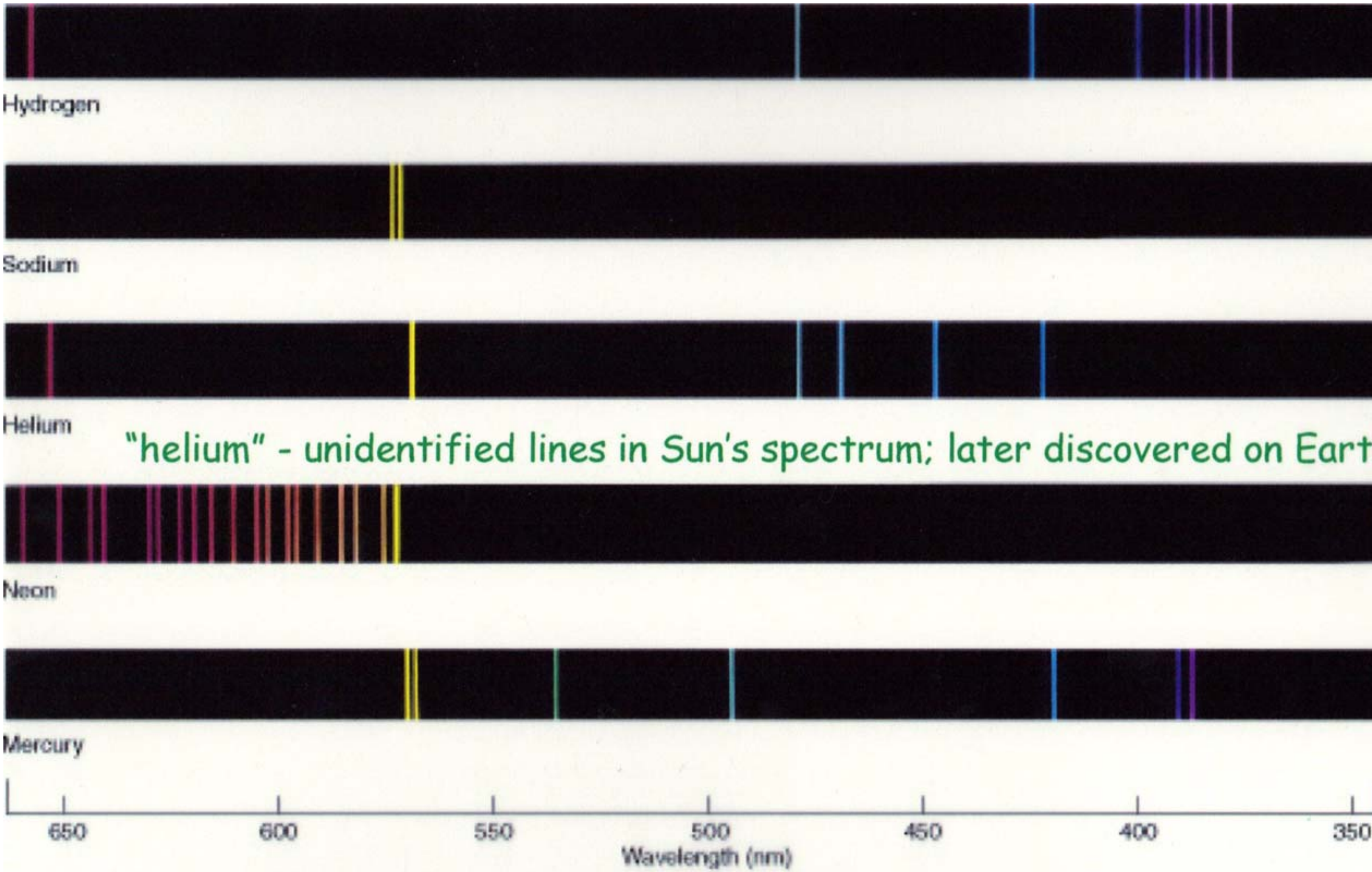
Absorption of light in transit displaces from B-B line

Other factors also modify radiation (see later)

Spectral Lines: Fraunhofer spectrum



Solar spectrum -absorption lines on continuum



Spectral lines due to presence of different elements
Detection in stars → chemical composition

Kirchhoff's Laws empirical again!

1. Hot opaque solid (dense gas) emits light of all wavelengths → continuous spectrum of radiation
2. Low density (transparent) hot gas emits spectrum of bright emission lines
3. Low density (transparent) cool gas in front of a blackbody absorbs wavelengths from the continuous spectrum → dark absorption line spectrum on continuous spectrum (wavelengths same as emission lines from hot gas)

Spectra produced by a diffraction grating

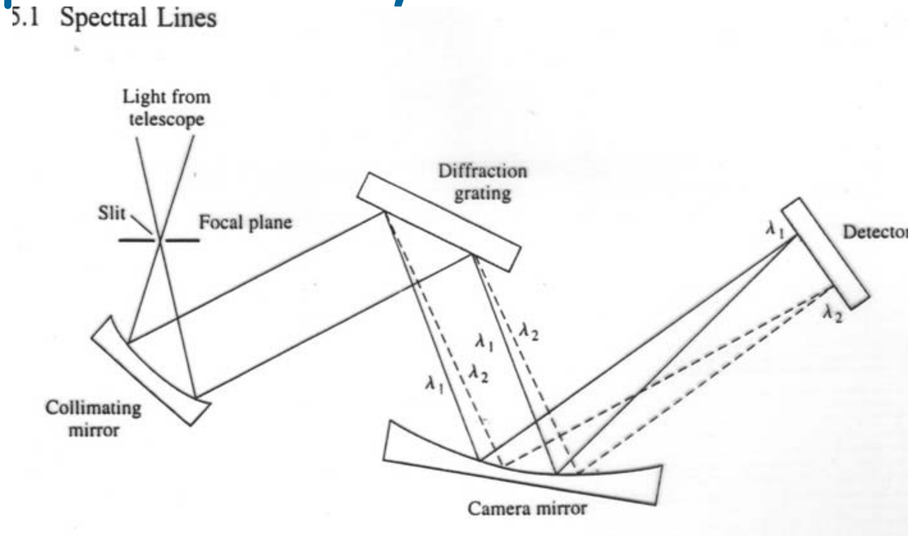


Figure 5.2 Spectrograph.

Diffraction grating ≡ ruled lines ≡ series of double slits
typically few x 1000 lines/mm → many pairs

$d\sin\theta = n\lambda$, where d = separation of ruled lines

$\therefore \lambda = d\sin\theta/n \propto \sin\theta/nN$

where N = number of grating lines illuminated; θ varies with λ

Smallest separation measurable $\Delta\lambda \sim \lambda/nN$

Resolving power of spectrograph = $\lambda/\Delta\lambda$

= 50,000 at Keck

Spectral lines → Doppler shifts → radial velocities

radial velocity, v_r = velocity of source in line of sight

Doppler: change in wavelength of a moving source of sound:

source moving away from observer: $\lambda_{obs} > \lambda_{rest}$ redshift

source moving towards observer: $\lambda_{obs} < \lambda_{rest}$ blueshift

$$(\lambda_{obs} - \lambda_{rest})/\lambda_{rest} = \Delta\lambda/\lambda_{rest} = v_r/v_s,$$

(v_s speed of sound in medium)

not precisely applicable to light; medium not relevant

Define redshift parameter $z \equiv (\lambda_{obs} - \lambda_{rest})/\lambda_{rest} = \Delta\lambda/\lambda_{rest}$

Non-relativistic case: speed of source << c, velocity of light

$$z = \Delta\lambda/\lambda_{rest} \approx v_r / c$$

for receding source $v_r > 0$ ($\Delta\lambda > 0$)

for approaching source $v_r < 0$

e-m radiation: formation of spectral lines

- Quantum transitions
  - energy levels within atomic and molecular systems quantized
  - only discrete orbits/energies permitted

- when atom makes a transition between 2 states, gives up energy corresponding to the difference
  - discrete amounts of energy only (photons)

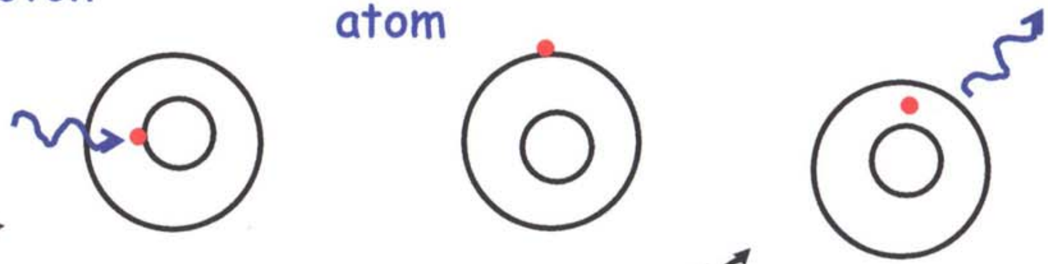
    $\Delta E = E_{final} - E_{initial} = h\nu$ (h = Planck's constant, 6.6×10^{-27} erg sec)

- types of transition
  - collisional excitation/de-excitation $\Delta E = \frac{1}{2}mv^2$
  - radiative absorption + spontaneous emission; stimulated emission

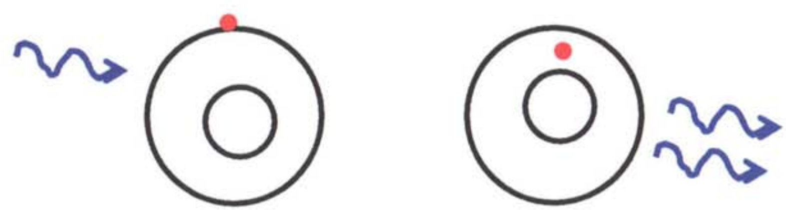
    photon energy $\propto$ radiation frequency (color)

    $\Delta E = h\nu = hc/\lambda$

e.g. for $\lambda = 7000Å$, $E_{photon} \sim 2$ eV ($1eV = 1.6 \times 10^{-12}$ ergs)
- very low energy



$h\nu = E_{upper} - E_{lower}$



3 radiative processes

- photon absorption
- spontaneous decay w/ emission of photon
- stimulated emission

2 collisional processes

- collisional excitation
- collisional de-excitation

$\Delta E = E_{final} - E_{initial} = h\nu$ (radiation) OR $= 1/2\, mv^2$ (collisional)

Hydrogen Atom

Adopt Bohr atom assuming quantization of angular momentum (only integral multiples of $h/2\pi \rightarrow L=nh/2\pi$)

Energy levels are $E_n = -(\mu e^4/32\pi 2\varepsilon_o h/2\pi)1/n^2 = -c/n^2$

c= constant

Principal quantum number n: in ground state n=1

$E_1 = -2.18 \times 10^{18}$ J = -13.6 eV = constant

$\therefore E_n = -13.6 \text{ eV}/n^2$

For electron in ground state 13.6 eV needed to ionize atom

In first excited state E = -13.6/4 = -3.4 eV (more energy)

Balmer Lines and Rydberg constant

Spectral lines of hydrogen at 6563Å ($H\alpha$), 4861Å ($H\beta$), 4340Å ($H\gamma$), 4102Å ($H\delta$) ≡ Balmer series

Experiment: wavelengths given by $1/\lambda = R_H(1/4 - 1/n^2)$

R_H = Rydberg constant = 1.097 x 10^{-5} cms; n = 3, 4,…

Bohr semi-classical approach: photon of energy ΔE is emitted (or absorbed) when electron makes transition from orbit n to m

$$\Delta E = E_n - E_m$$

$$\therefore hc/\lambda = -13.6 \text{ eV } (1/m^2 - 1/n^2) \text{ with } m < n$$

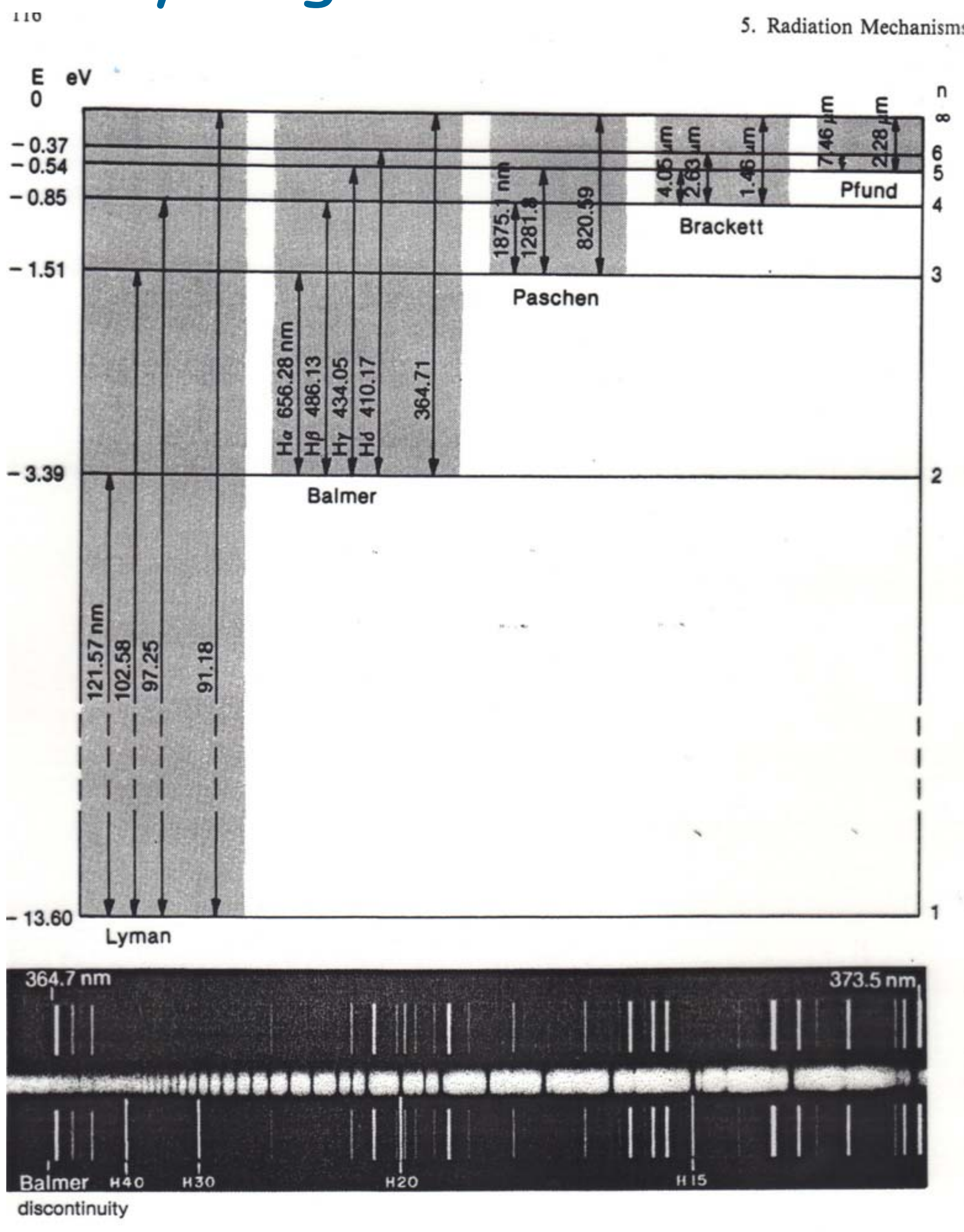
$$\therefore 1/\lambda = R_H(1/m^2 - 1/n^2)$$

Balmer series, m = 2, n=3 → $H\alpha$, n=4 → $H\beta$ …

Lyman series m=1, n=2 → $Ly\alpha$, n=3 → $Ly\beta$ …

Paschen series m=3, n=4 → $Pa\alpha$…

Transitions of Hydrogen Atom



Kirchhoff's laws revisited

Hot dense gas (or opaque solid) emits continuous spectrum of radiation described by Planck function, $B_\lambda(T)$ or $B_\nu(T)$

Hot diffuse (low density) gas produces bright emission lines when an electron makes a downward transition from higher to lower orbit. Energy lost = $h\nu$ or hc/λ.

Cool diffuse gas in front of a source of continuous radiation produces dark absorption lines in the continuous spectrum when an electron makes an upward transition to a higher orbit. The incident photon from continuous spectrum must have exactly the right energy (equal to the difference in energy between the lower and upper orbit), to be absorbed by an atom.

Spectra of 7 stars w/ different surface temperatures

tightly bound atoms

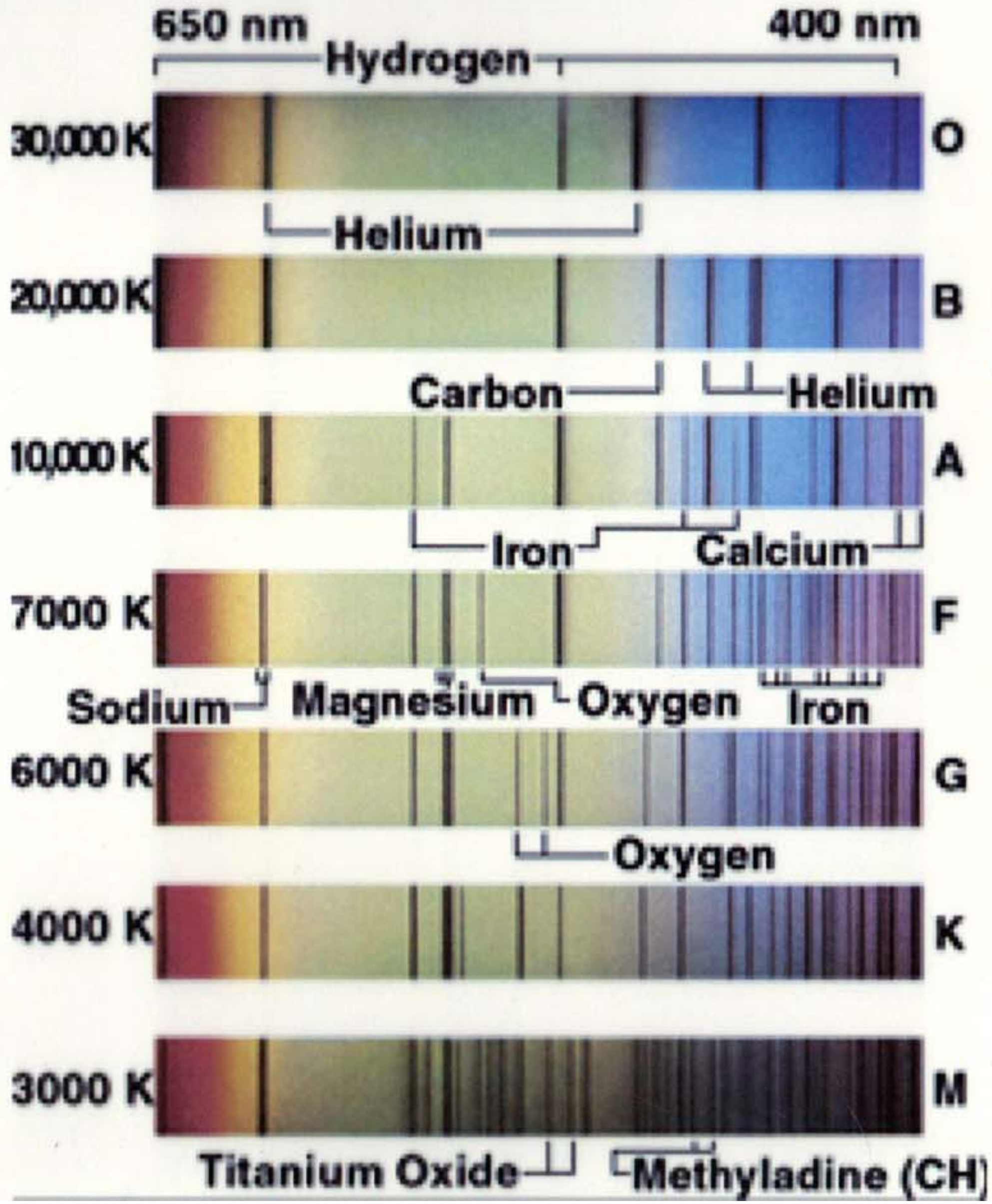
(e.g. H, He survive)
up to few x 10,000K

weakly bound atoms

(ionized above ~8000K)

molecules

survive only up to
3000K



"METALS" ↓

TABLE 8.1 Harvard Spectral Classification.

Spectral Type	Characteristics
O	Hottest blue-white stars with few lines Strong He II absorption (sometimes emission) lines. He I absorption lines becoming stronger.
B	Hot blue-white He I absorption lines strongest at B2. H I (Balmer) absorption lines becoming stronger.
A	White Balmer absorption lines strongest at A0, becoming weaker later. Ca II absorption lines becoming stronger.
F	Yellow-white Ca II lines continue to strengthen as Balmer lines continue to weaken. Neutral metal absorption lines (Fe I, Cr I).
G	Yellow Solar-type spectra. Ca II lines continue becoming stronger. Fe I, other neutral metal lines becoming stronger.
K	Cool orange Ca II H and K lines strongest at K0, becoming weaker later. Spectra dominated by metal absorption lines.
M	Cool red Spectra dominated by molecular absorption bands, especially titanium oxide (TiO) and vanadium oxide (VO). Neutral metal absorption lines remain strong.
L	Very cool, dark red Stronger in infrared than visible. Strong molecular absorption bands of metal hydrides (CrH, FeH), water (H_2O), carbon monoxide (CO), and alkali metals (Na, K, Rb, Cs). TiO and VO are weakening.
T	Coolest, Infrared Strong methane (CH_4) bands but weakening CO bands.

S and C spectral types for evolved giant stars are discussed on page 466.

The Harvard Lady Computers

Fig. 51. Miss Antonia Caetano Maury, research associate, 1888–1933.

Antonia Maury

Williamina Fleming

Annie Jump Cannon

EARLY(O) → LATE (M →)
" Ø → 9

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- O: 20,000 – 35,000 K; MULTIPLY IONIZED ATOMS, C III, N III, Si V
- B: 15,000 K; 4030 Å; Ca II weakening; B9 – no He I
- A: 9,000 K
- F: 7,000 K; some Ti II
- G: 5,500 K; stongest at G0
- K: 4,000 K; K5 - TiO bands
- M: 3,000 K
- ↓ cooler

Critical lines: Balmer series, He I, Fe I lines
Ca II H & K lines, TiO

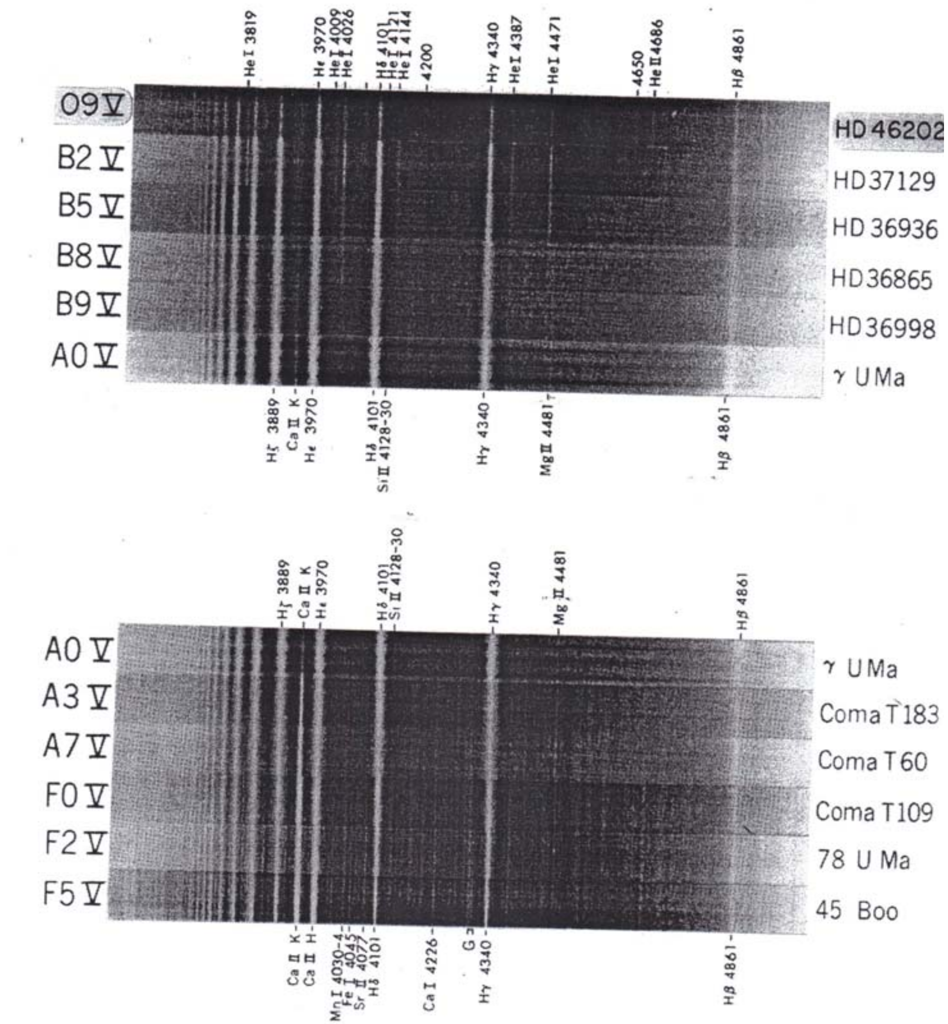


FIGURE 8.2 Stellar spectra for main-sequence classes O9–F5. Note that these spectra are displa as negatives; absorption lines appear bright. Wavelengths are given in angstroms. (Figure from A et al., *An Atlas of Low-Dispersion Grating Stellar Spectra*, Kitt Peak National Observatory, Tucs AZ, 1968.)

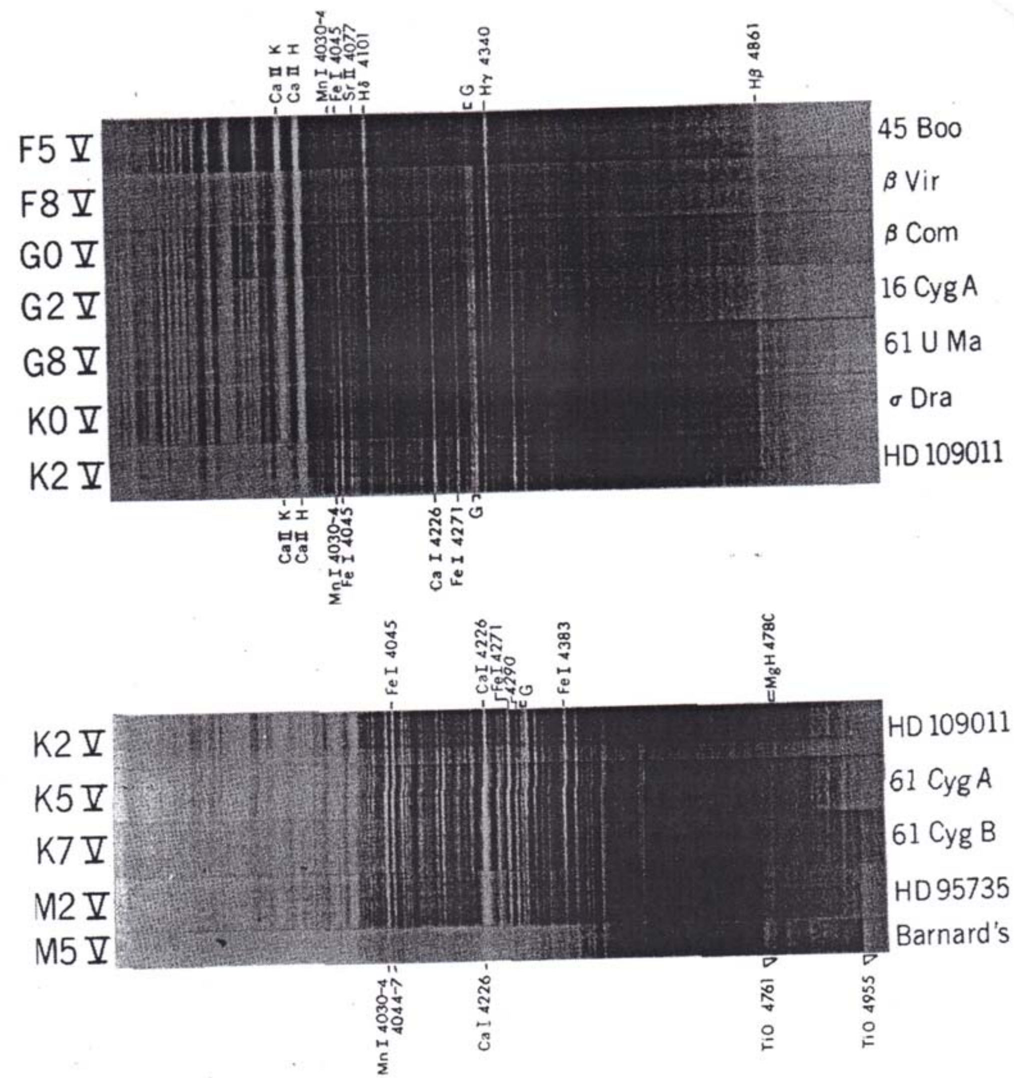
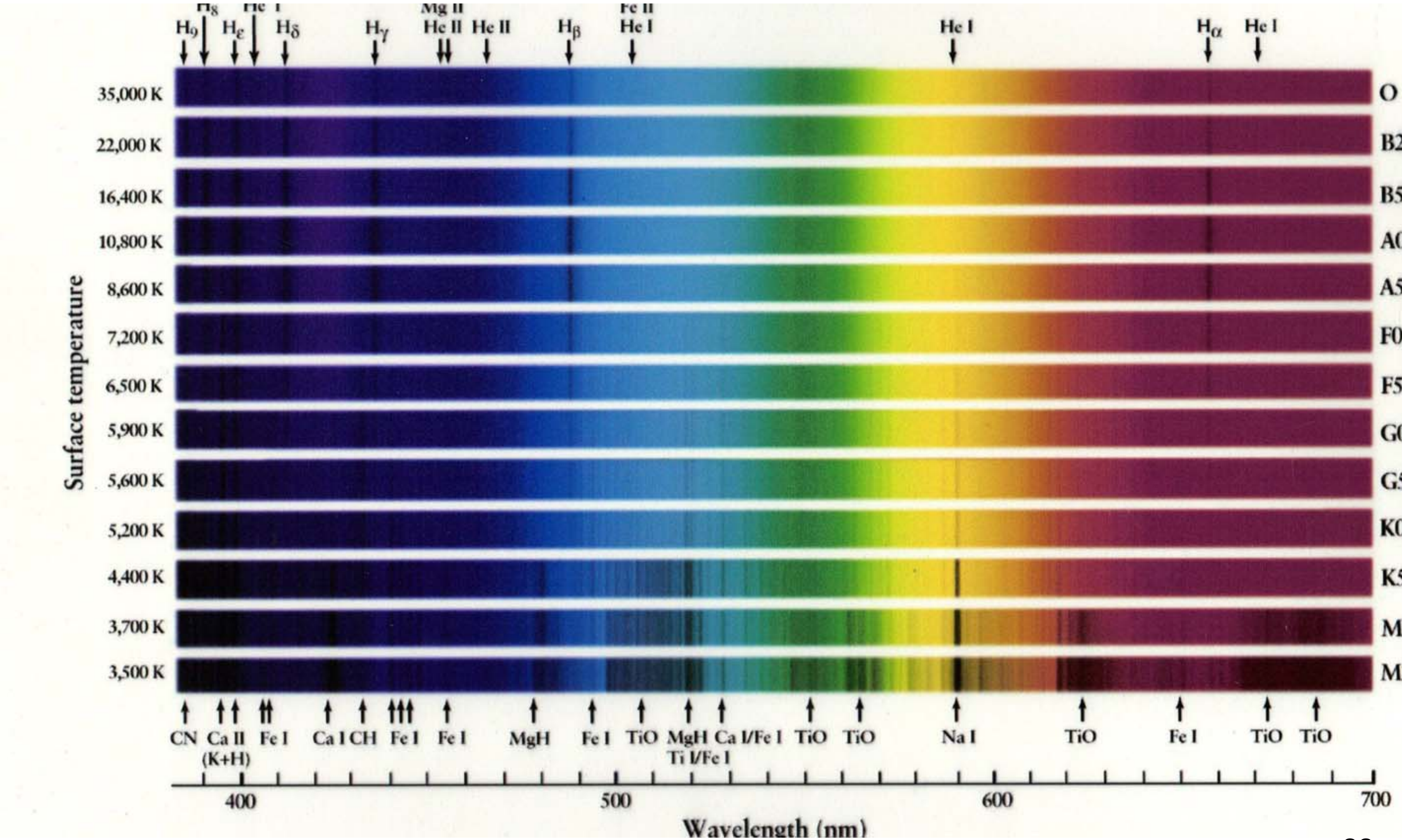


FIGURE 8.3 Stellar spectra for main-sequence classes F5–M5. Note that these spectra are displayed as negatives; absorption lines appear bright. Wavelengths are given in angstroms. (Figure from Abt, et al., *An Atlas of Low-Dispersion Grating Stellar Spectra*, Kitt Peak National Observatory, Tucson, AZ. 1968.)

Spectral Types of Stars → temperature sequence



Spectra of stars differ due to electrons in different atomic orbitals at different temperatures

Lines from ionized species, molecules also present

- HeI, HI, CaI etc ≡ neutral hydrogen, helium, calcium
- HII, HeII ≡ singly ionized hydrogen, helium: 1 electron "lost"
- SIII, SIV ≡ ionized silicon: 2 and 3 electrons "lost"

Balmer lines peak in strength at A0, T_e = 9250K

- at lower temperatures harder to excite hydrogen
- at higher temperatures ionization is beginning

HeI lines most intense in B2 stars T_e = 22,000K

CII lines most intense in K0 stars T_e = 5250K

Example spectra show peak of Planck function moving to shorter λ as T_e increases

Strong H absorption in A stars → "knee" in UBV diagram

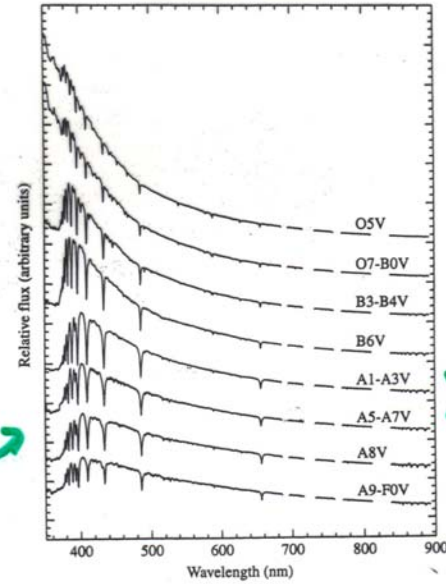


FIGURE 8.4 Digitized spectra of main sequence classes O5–F0 displayed in terms of relativ as a function of wavelength. Modern spectra obtained by digital detectors (as opposed to photog plates) are generally displayed graphically. (Data from Silva and Cornell, *Ap. J. Suppl.*, *81*, 865,

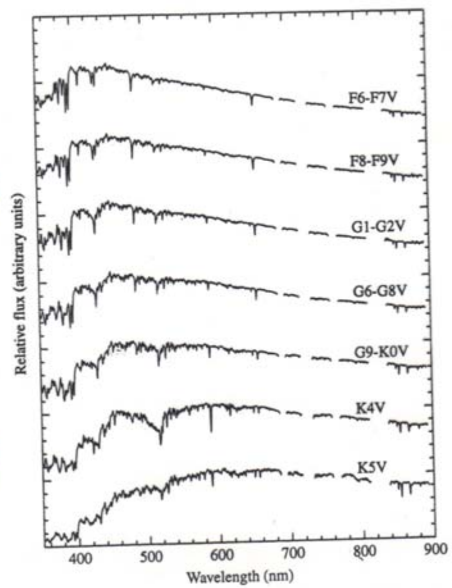
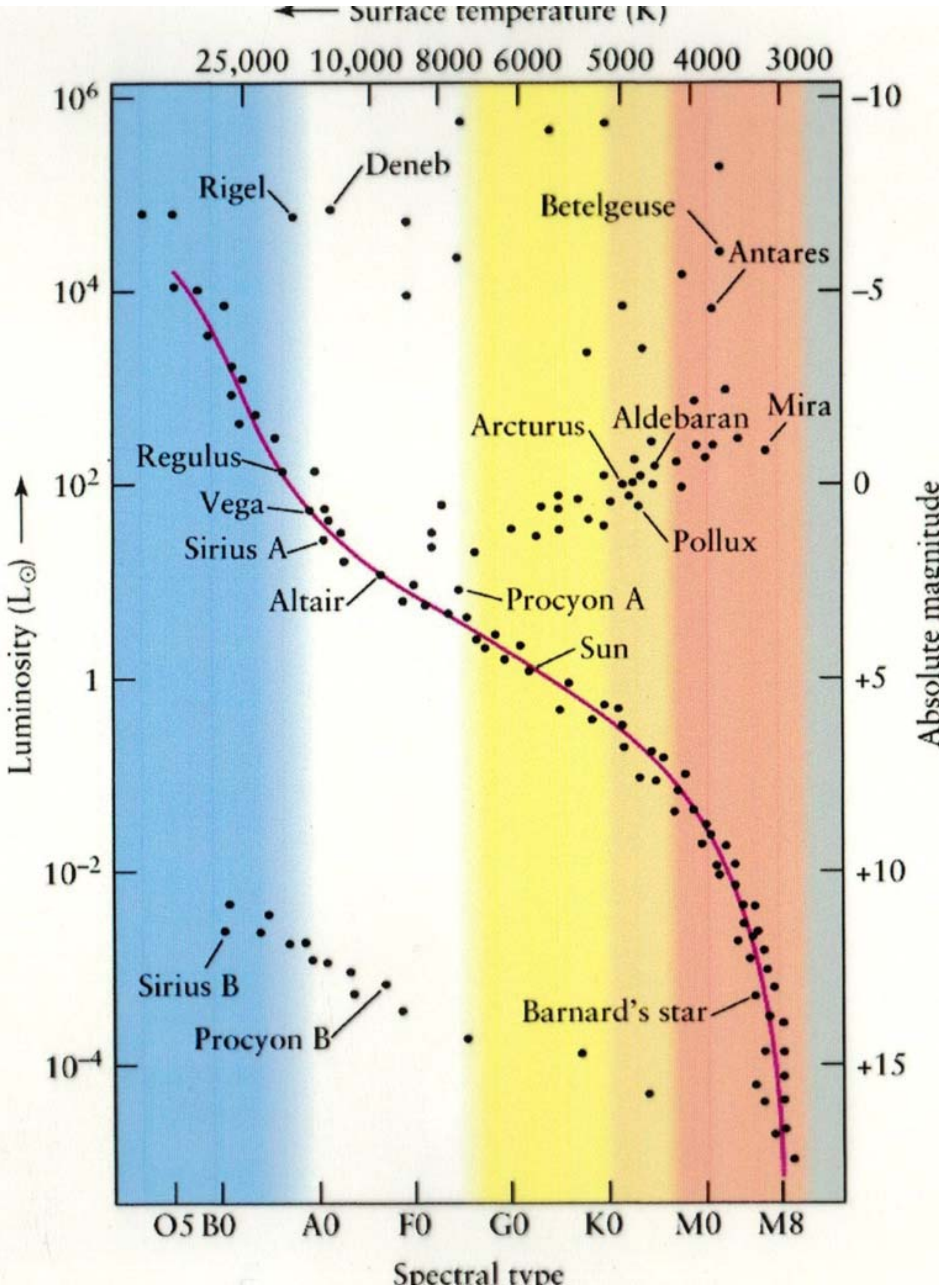


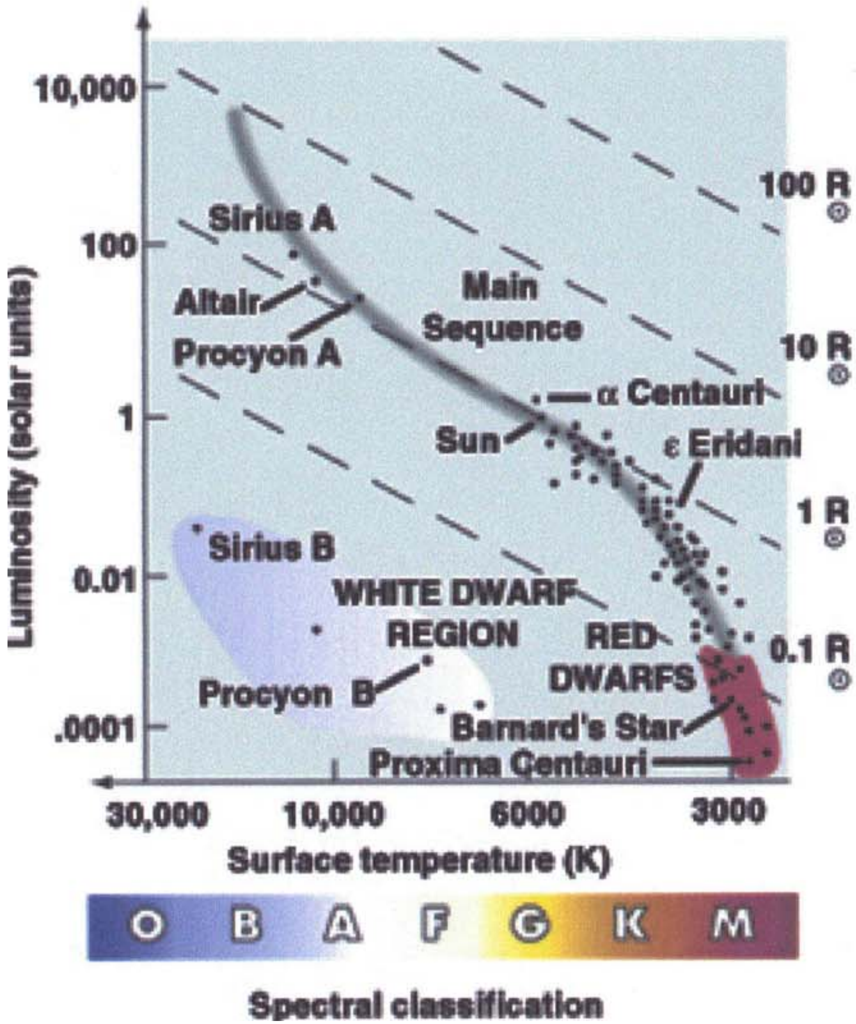
FIGURE 8.5 Digitized spectra of main sequence classes F6–K5 displayed in terms of relative as a function of wavelength. (Data from Silva and Cornell, *Ap. J. Suppl.*, *81*, 865, 1992.)

For original,
M_V v spectral type
main sequence
~80-90% all stars

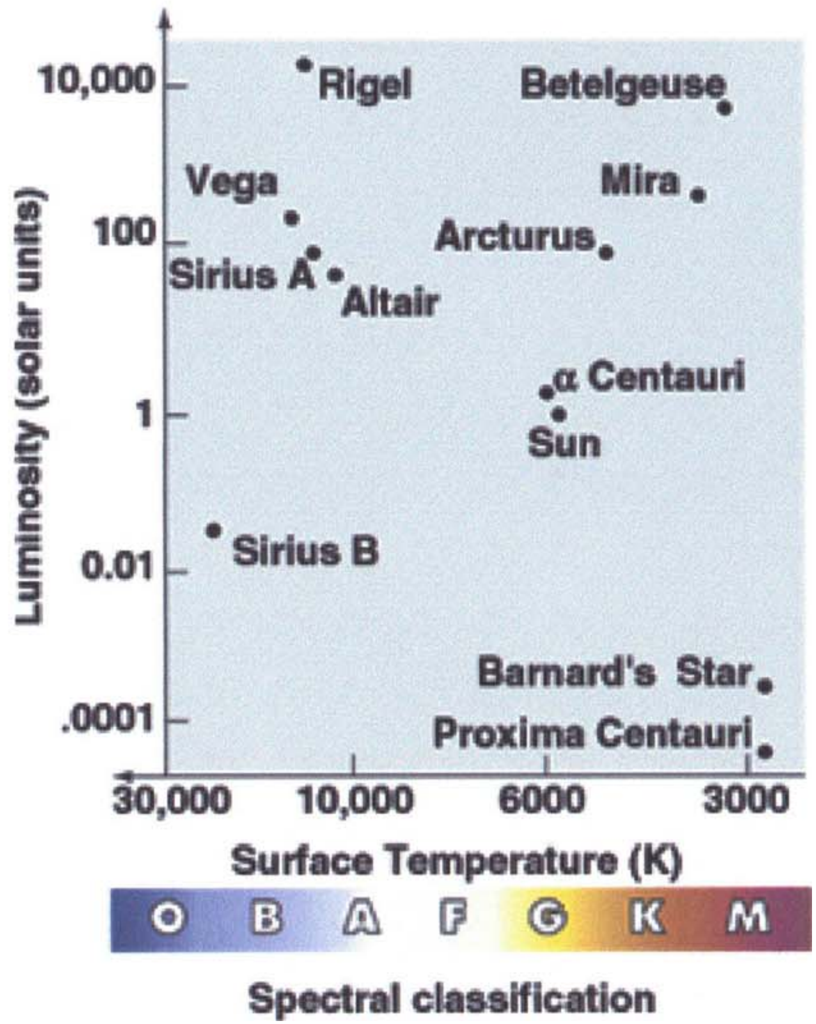
Hertzsprung-Russell Diagram
- explanation/physical basis
for main-sequence later



Nearest stars



Brightest stars



Refining spectral classification further

$$L = 4\pi R_*^2 T_e^4$$

$\therefore$ stars of same T_e have different L if R_* is different

gravitational acceleration $g \sim GM/R^2$

$\therefore$ stars of same mass may have different surface gravities

ρ and P in stellar atmosphere are different

$\rightarrow$ Yerkes or MKK (Morgan, Keenan, Kellman) system

Ia	most luminous supergiants
Ib	less Luminous supergiants
II	luminous giants
III	normal stars
IV	subgiants
V	mainsequence stars