PHY 521: Stars

Course Overview

- We want to understand the physics of stars

class meeting	topic	HKT Ch.
1	general overview	A
2–3	preliminaries	1
4–5	stellar evolution overview	2.1–2.7, 2.9, 2.10
6–7	equation of state	3
8–9	radiative & conductive transfer	4.1–4.6
10–11	convection	5
12–13	stellar energy sources	6
14–18	stellar models	7 + MESA
19–20	structure and evolution of Sun	9
21	structure and evolution of WDs	10
22–24	things that go BOOM	2.8, 2.9, 2.13 + other
25–6	stellar atmospheres	other
27–28	class discussion	

Course Overview

- Course texts:
  - *Stellar Interiors: Physical Principles, Structure, and Evolution*, 2nd Edition, by Hansen, Kawaler, & Trimble
  - *Stellar Physics*, by Brown (http://open-astrophysics-bookshelf.github.io/)

Course Overview

- Lectures will be a mix of chalkboard writing and slides
  - Slides will be posted online on the course webpage
- There will be ~8 homework assignments
- Some assignments will require programming / plotting
- No exams
- Final project:
  - I will provide some suggestions of interesting problems to explore
  - You can alternately do a ½ class lecture

Course Overview

- Homeworks will be mix of analytic and short programming problems
  - ODE integration, root finding, basic linear algebra will be needed
  - I'll provide a review of basic numerical methods
  - I'll do my examples / solutions in Jupyter + python

#	topic	assigned	due	PDF
1	basics of stars	08-30-21	09-13-21	
2	evolution & equation of state	09-13-21	09-22-21	
3	radiation	09-22-21	09-29-21	
4	convection	09-29-21	10-06-21	
5	reactions	10-13-21	10-20-21	
6	stellar models	10-27-21	11-08-21	
7	the Sun and white dwarfs	11-08-21	11-15-21	
8	explosions & remaining topics	11-15-21	11-22-21	

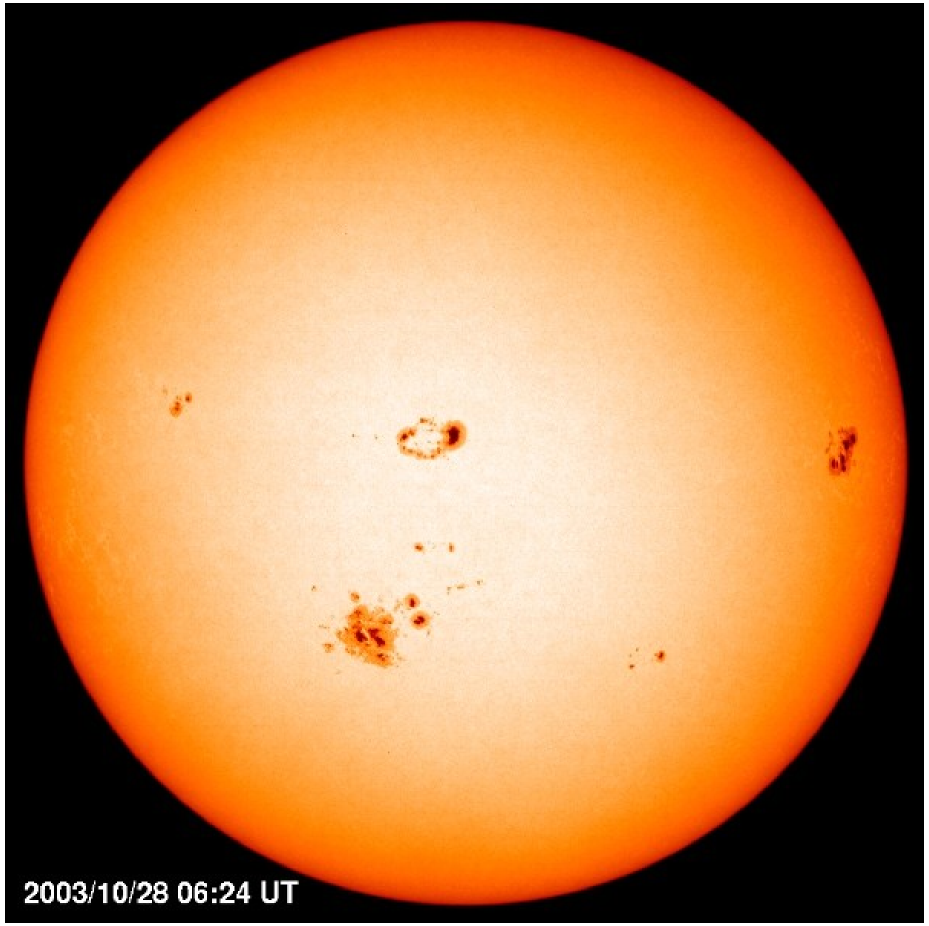
Class Business

- Main website: http://bender.astro.sunysb.edu/classes/stars
- Blackboard will be used only for the gradebook

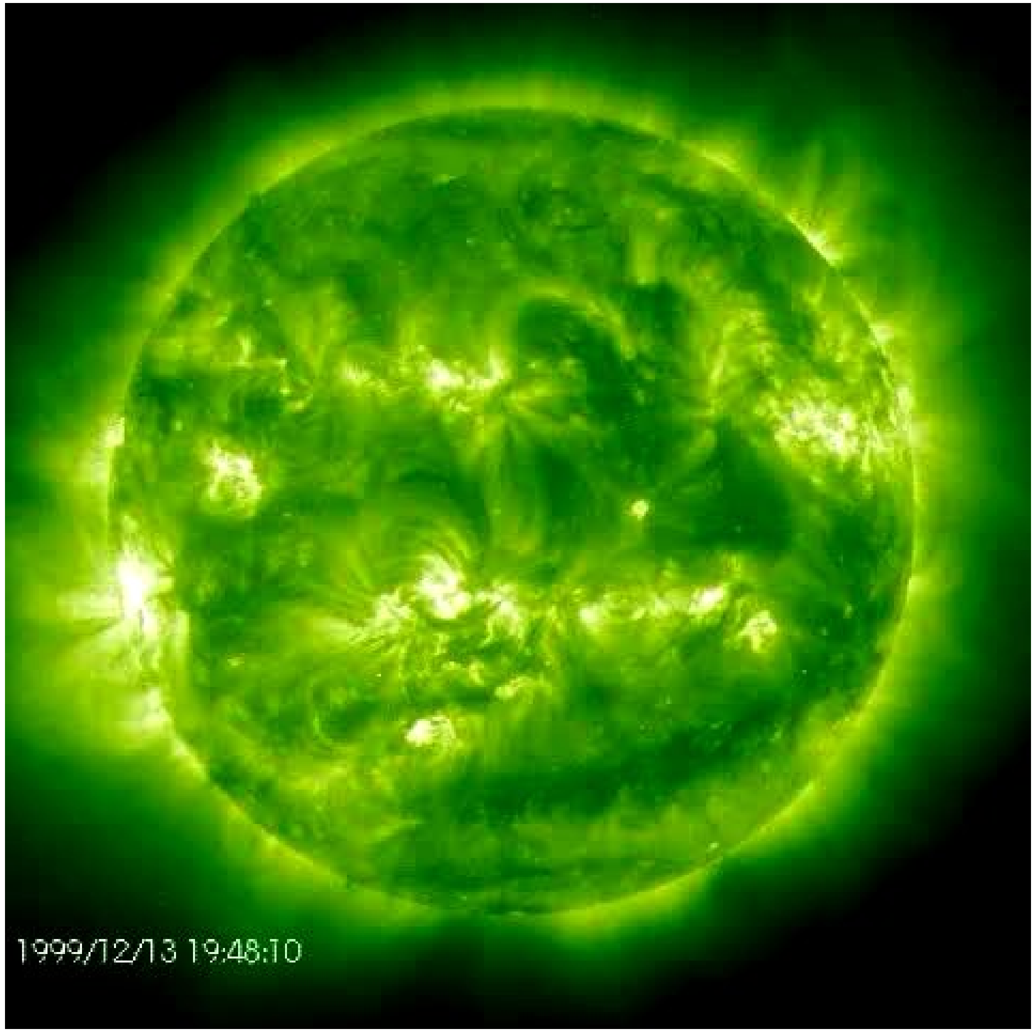
Overview of Stellar Properties

- Read HKT Appendix A
- What properties do you think that we can measure?
  - Mass
  - Surface temperature
  - Composition
  - Radius
  - Energy output
  - Distance from us

The Sun



(SOHO/NASA)



(Fe XII at 195 angstroms imaged by the EIT instrument on SOHO)

Properties of the Sun

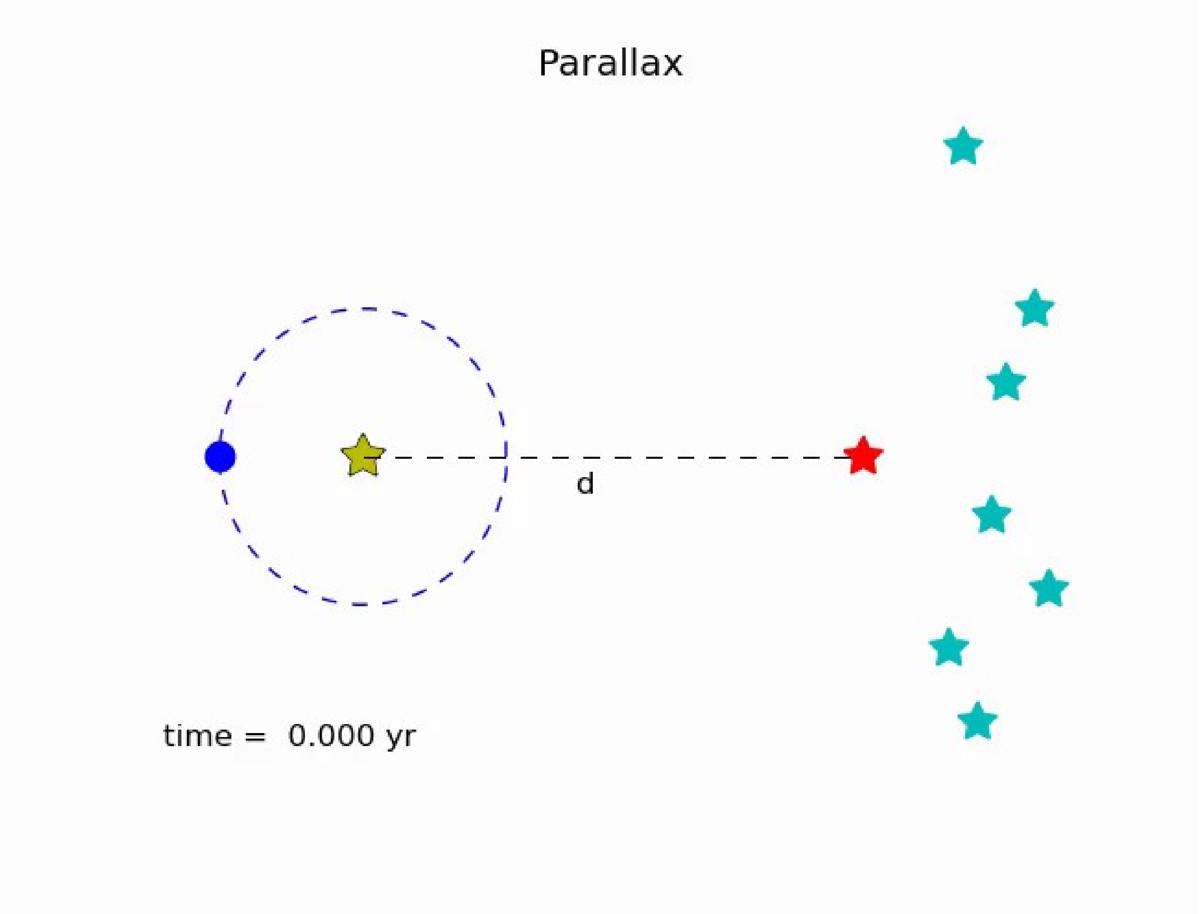
- Mass = 2.0×10^{33} g (333,000 Earth masses)
- Diameter = 1.4×10^{11} cm (109 Earth Diameters)
- Average Density = (Mass/Volume) = 1.4 g / cm^3
- Luminosity (i.e., total power output) = 4×10^{33} erg/s
- Surface Temperature = 5800 K
- Rotation Period (at equator) = 25 days
- Distance from Earth = 1 AU = 1.5×10^{13} cm

- The Sun is an average star in almost every way

Distances

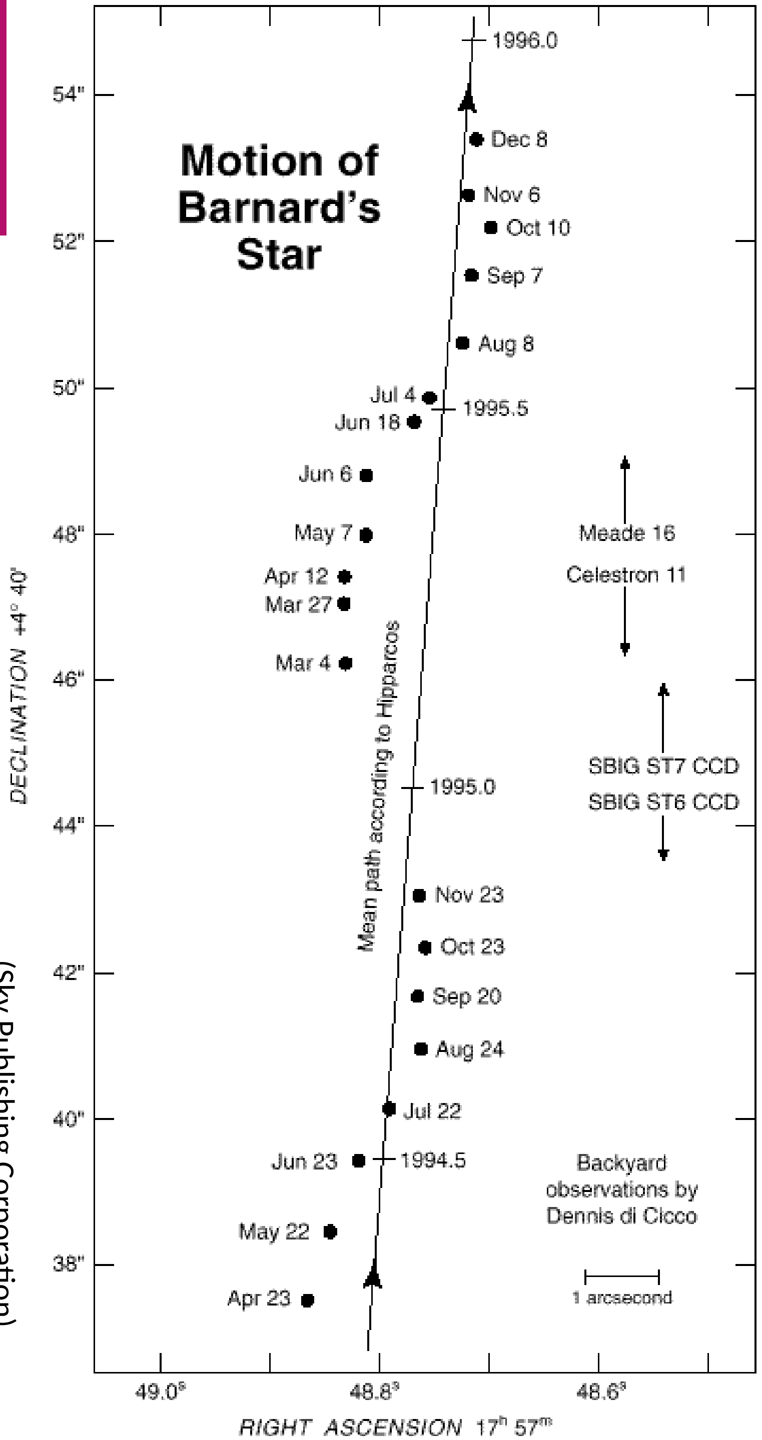
- Direct measurement: parallax
  - Look at apparent shift in foreground star as Earth orbits the Sun
  - Parsec: distance at which Earth-Sun separation subtends 1”

$$\frac{d}{1\ pc} = \frac{1"}{p}$$



Stellar Motions

- Stars have relative motions wrt one another
- Proper motion is the speed across the sky (typically < arcseconds / year)
  - Barnard's star was a proper motion of 10.3" / year



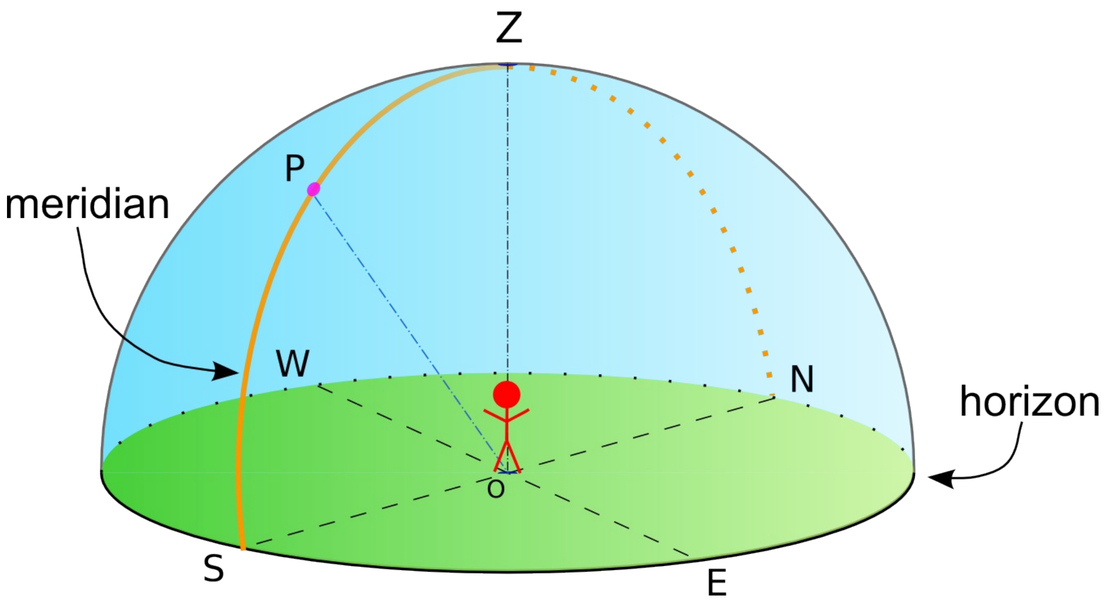
(Sky Publishing Corporation)

Other Distance Measures

- More indirect—rely on calibration with parallax
- Many based on the idea of a standard candle:
  - Measure apparent brightness of an object with known luminosity
  - Spectroscopic parallax: use known brightnesses of different types of stars
  - Cephids: variable stars with known period-luminosity relation
  - Type Ia supernovae: brightness correlates with the time it takes to fade

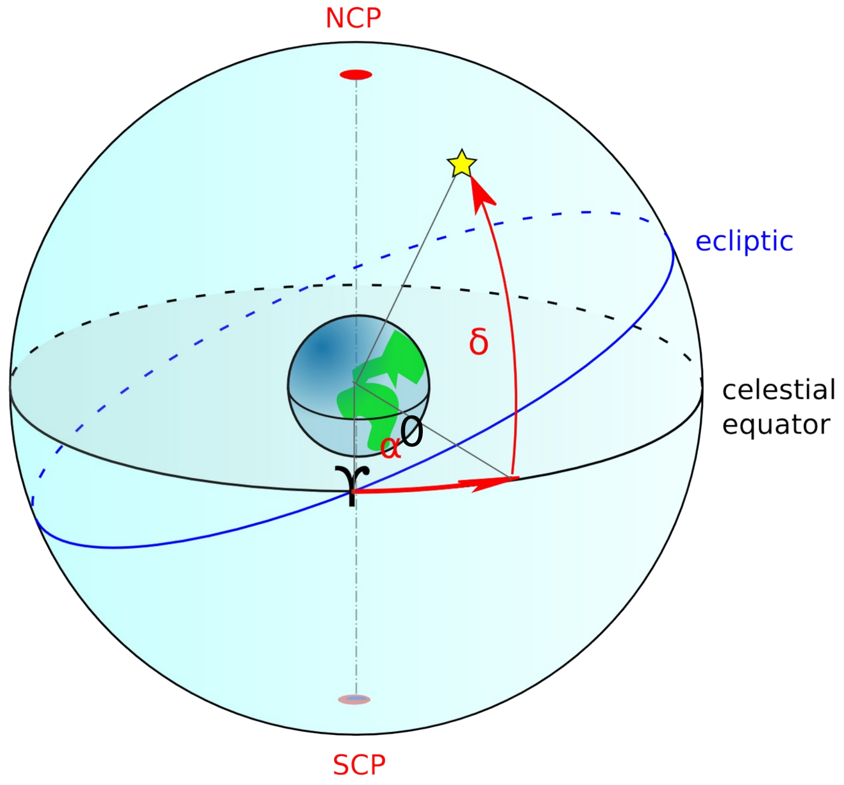
Coordinate Systems

- Altitude-azimuth
  - Your "backyard" reference



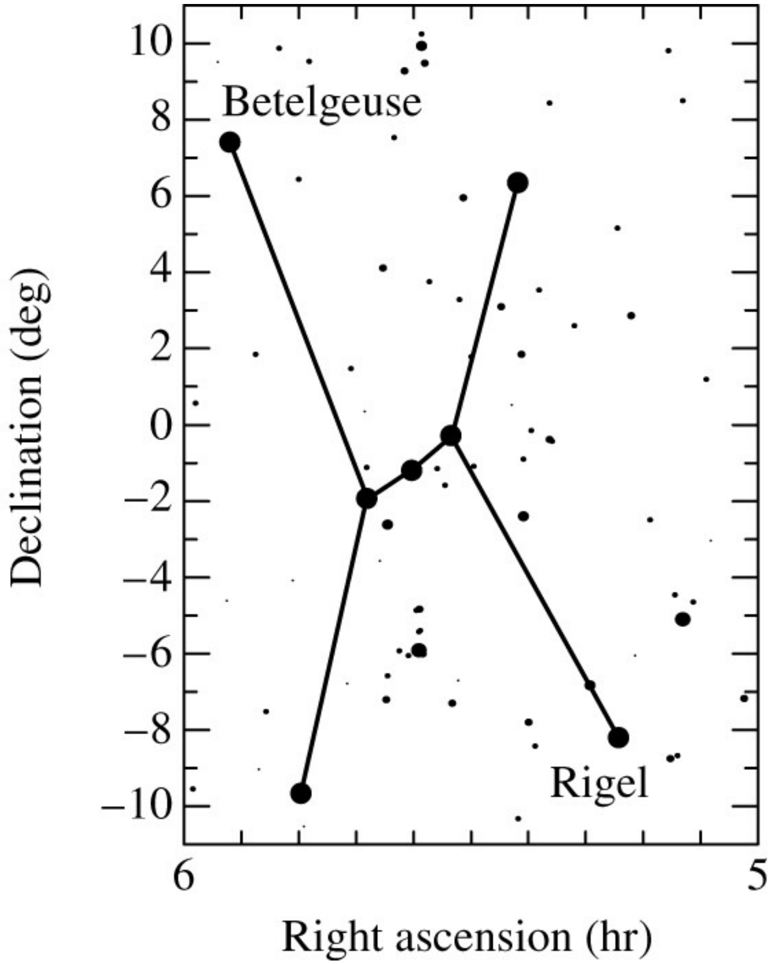
Any point in the sky can be specified by its altitude (degrees above the horizon) and azimuth (degrees from North along the horizon)

- Equatorial system ("earth-centered" celestial sphere)
  - Right ascension (analogous to longitude)
  - Declination (analogous to latitude)



Coordinate Systems

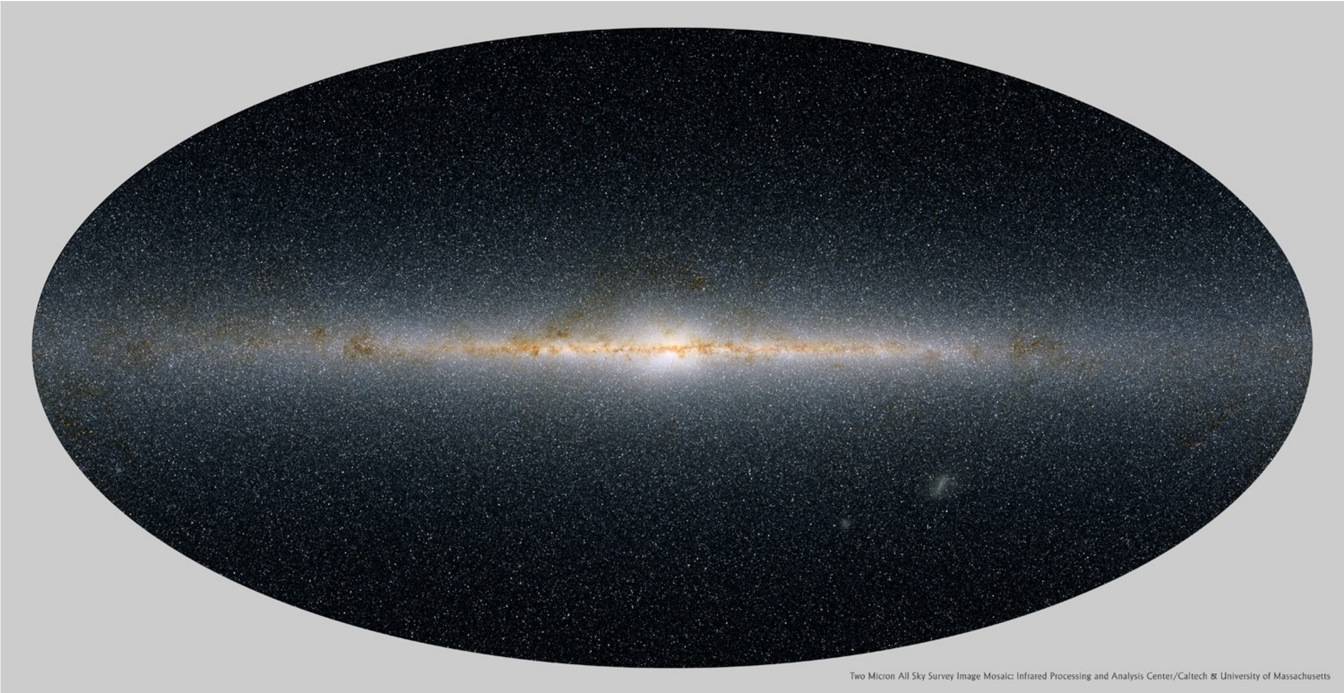
- Equitorial coordinates do not change with rotation of earth or time of year
  - Slow precession of earth's axis

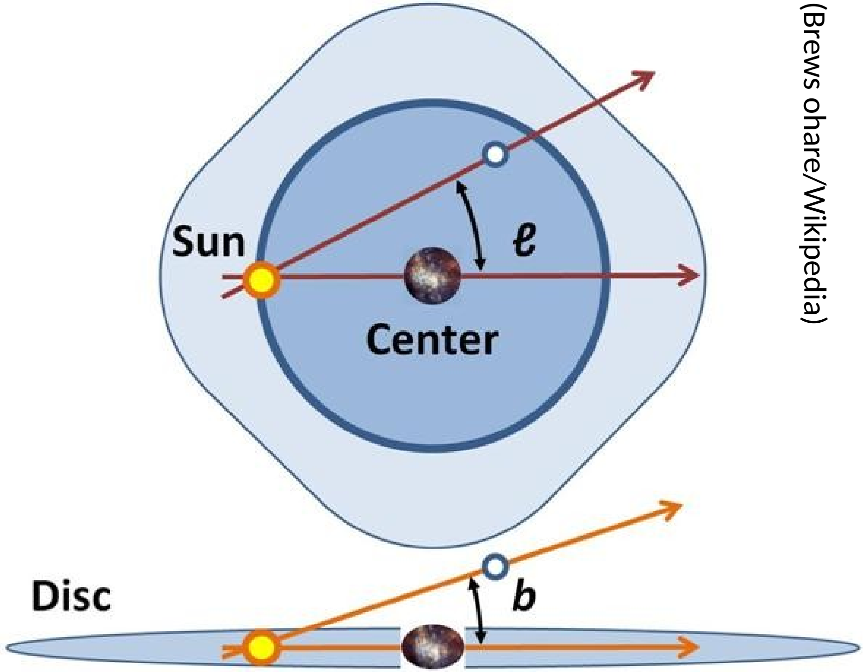


(Carroll and Ostlie)

Coordinate Systems

- Galactic coordinates reference the center of the galaxy (from our vantage point)





(Brews ohare/Wikipedia)

Magnitudes

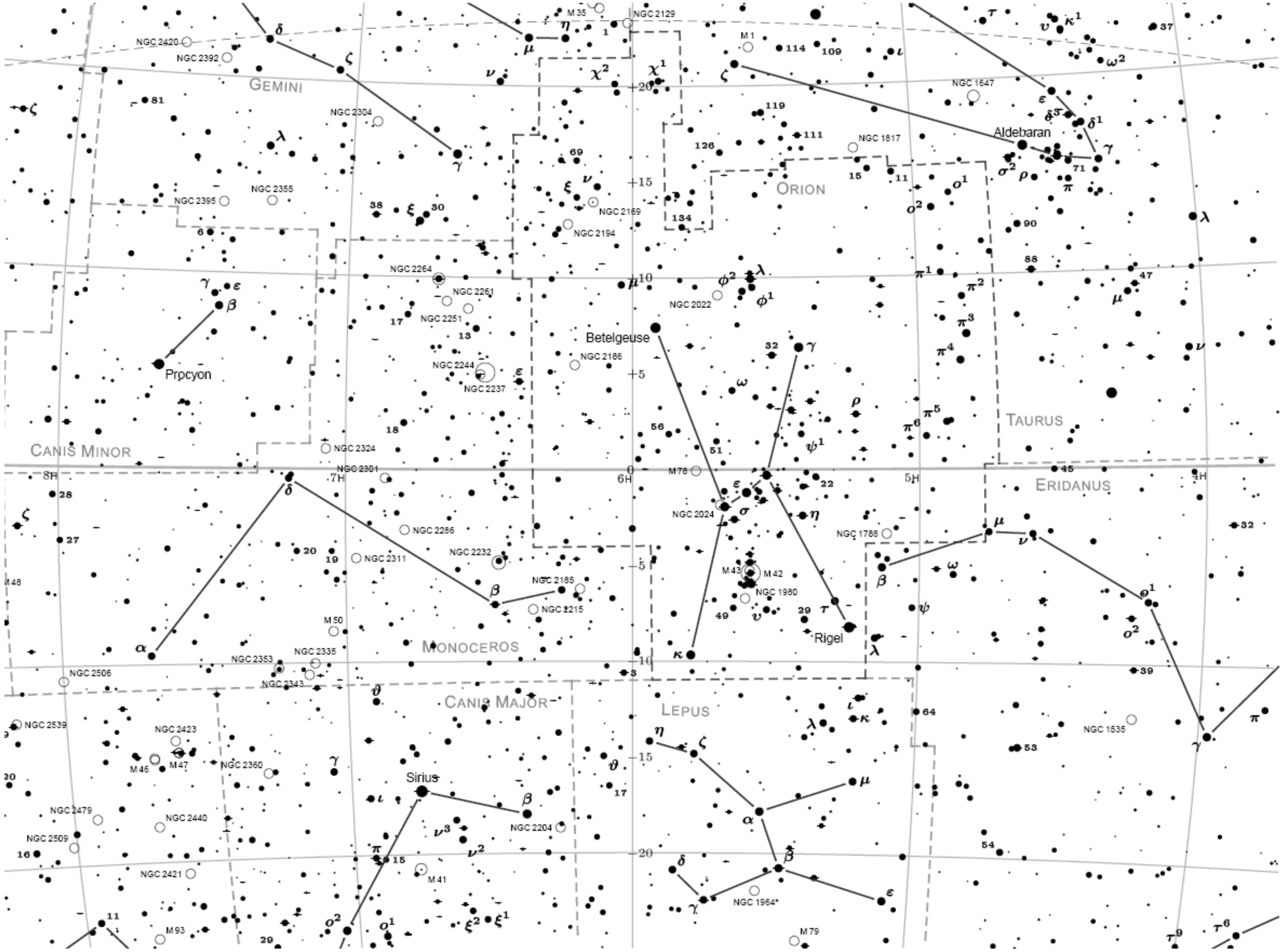


Chart 9: *RA* 4^h *to* 8^h, *Declination* $+20^o$ *to* -20^o

Magnitude: 0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0

Magnitudes

- Look at the night sky: some stars are brighter than others
- Greek astronomers created the magnitude system.
  - Stars assigned brightness on a scale of 1 to 6
    - 1 = brightest, 6 = faintest.
  - Standardized: 5 magnitude difference = factor of 100 in brightness
    - Logarithmic scale—our eye's response to light is also logarithmic

$$\frac{f_1}{f_2} = 100^{(m_2 - m_1)/5}$$

- By brightness, we really mean flux—energy/area/second
- Remember: the brighter the object, the smaller the magnitude

Magnitudes

- Today:
  - Large telescopes see down to magnitude 30 and below
  - Brightest stars have negative magnitudes
- Apparent magnitude: measure of how bright something appears when viewed from earth
- Absolute magnitude: measure of how bright something would appear if it were 10 pc from earth

$$m - M = 5\log\left(\frac{d}{10\ \mathrm{pc}}\right)$$

Magnitudes

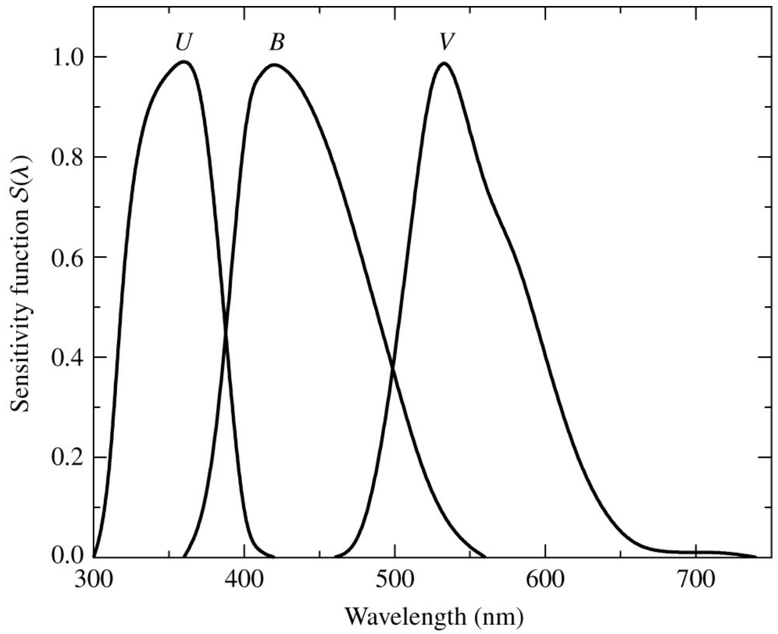
(from Wikipedia)

Apparent Magnitudes of Known Celestial Objects

App. Mag.	Celestial Object
−26.73	Sun
−12.6	full Moon
−9.5	Maximum brightness of an Iridium Flare
−4.7	Maximum brightness of Venus
−3.9	Faintest objects observable during the day with naked eye
−2.9	Maximum brightness of Mars
−2.8	Maximum brightness of Jupiter
−1.9	Maximum brightness of Mercury
−1.5	Brightest star (except for the sun) at visible wavelengths: Sirius
−0.7	Second brightest star: Canopus
0	The zero point by definition: This used to be Vega (see references for modern zero point)
0.7	Maximum brightness of Saturn
3	Faintest stars visible in an urban neighborhood with naked eye
4.6	Maximum brightness of Ganymede
5.5	Maximum brightness of Uranus
6	Faintest stars observable with naked eye
7.7	Maximum brightness of Neptune
12.6	Brightest quasar
13	Maximum brightness of Pluto
27	Faintest objects observable in visible light with 8m ground-based telescopes
30	Faintest objects observable in visible light with Hubble Space Telescope
38	Faintest objects observable in visible light with planned OWL (2020)
(see also List of brightest stars)	

Colors

- We only see the outer part of the star (the atmosphere)
- Color tells us about the temperature
- So far our magnitudes have been bolometric (the entire EM spectrum)
- We observe through filters



(Carroll and Ostlie)

(Mouser Williams)

Colors

- Flux through B filter: f_B
- Flux through V filter: f_V
- Magnitude difference:

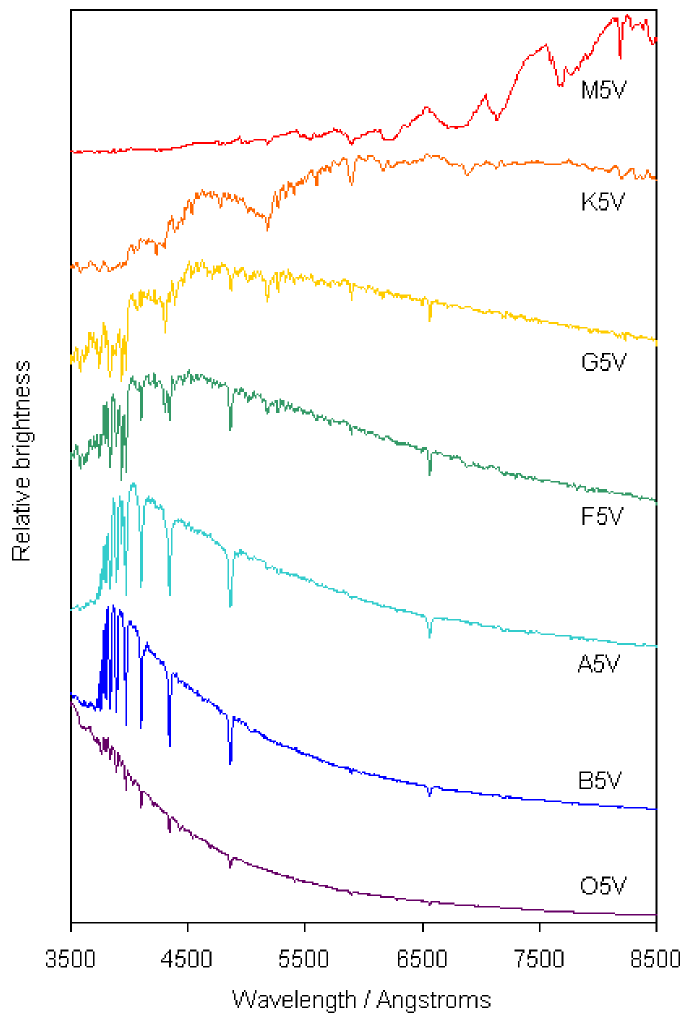
$$m_B - m_V = 2.5 \log \left(\frac{f_V}{f_B} \right)$$

  – Usually just written as B - V

- B – V: measure of the color of a star—also directly related to temperature
- As T increases, f_B/f_V increases, so B - V decreases

Colors

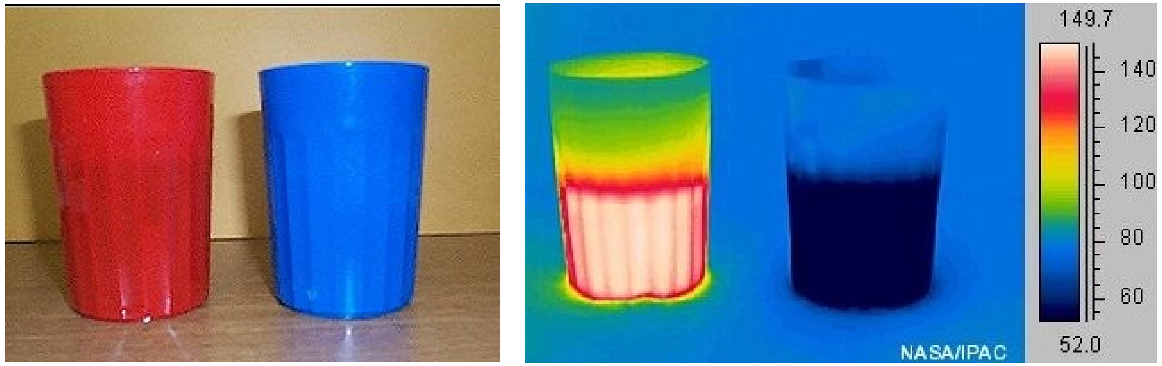
- Spectra consist of a smooth continuum + absorption lines)
- Tells us composition, temperature, ionization state information



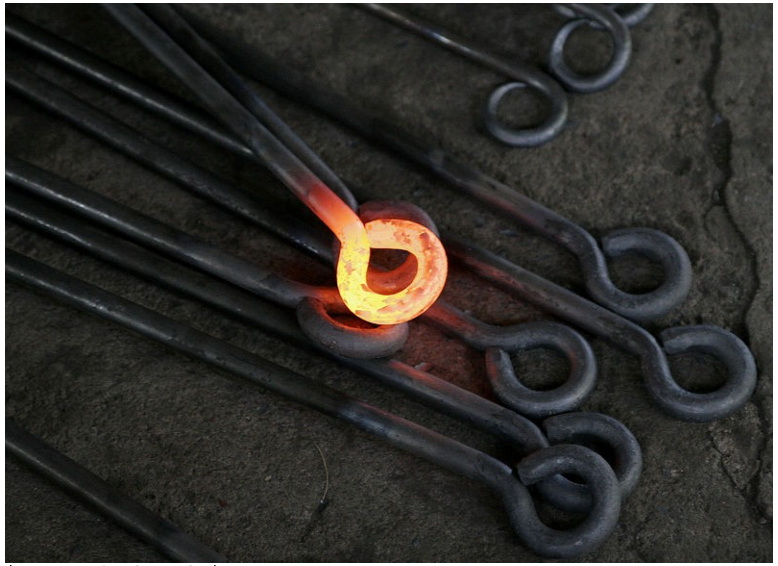
(Jodrell Bank Observatory; based on Pickles 1988)

Blackbody Radiation

- Stars are very good blackbodies
  - Thermal equilibrium: emission = absorption
  - Emission spectrum is well known
    - Function of T only (unpolarized and isotropic)
    - Emission spectrum can be different that absorption spectrum—only need net energy gain to be 0



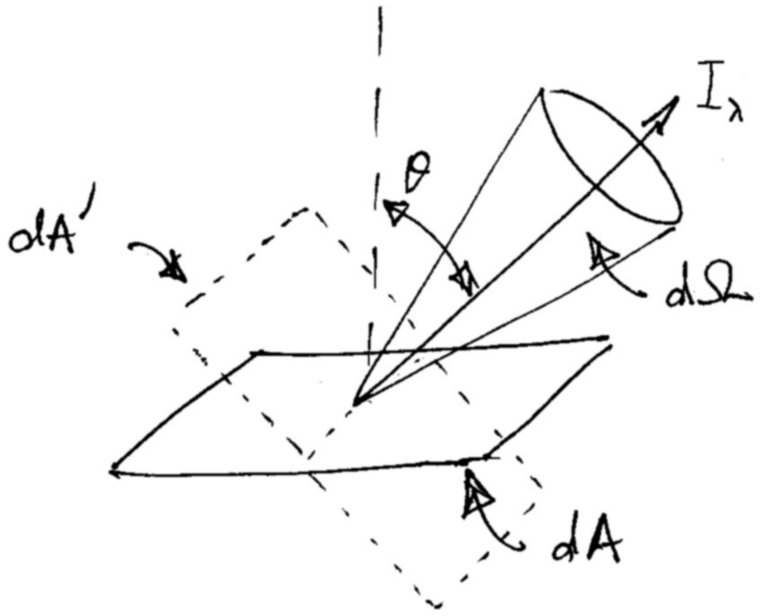
http://coolcosmos.ipac.caltech.edu/cosmic_kids/learn_ir/index.html



(Fir0002/Wikipedia)

Blackbody Radiation

- Intensity: I(ν)dν = energy/unit time/unit surface area in the frequency range ν to ν + dν emitted into a cone of solid angle dΩ



- Radiation moves through a small area dA into the cone described by dΩ
- Energy moving through this area into dΩ is

$$dE = I_\nu \cos\theta dA\, d\nu\, d\Omega\, dt$$

- Intensity is measured in units of erg s^{-1} cm^{-2} Hz^{-1} $ster^{-1}$

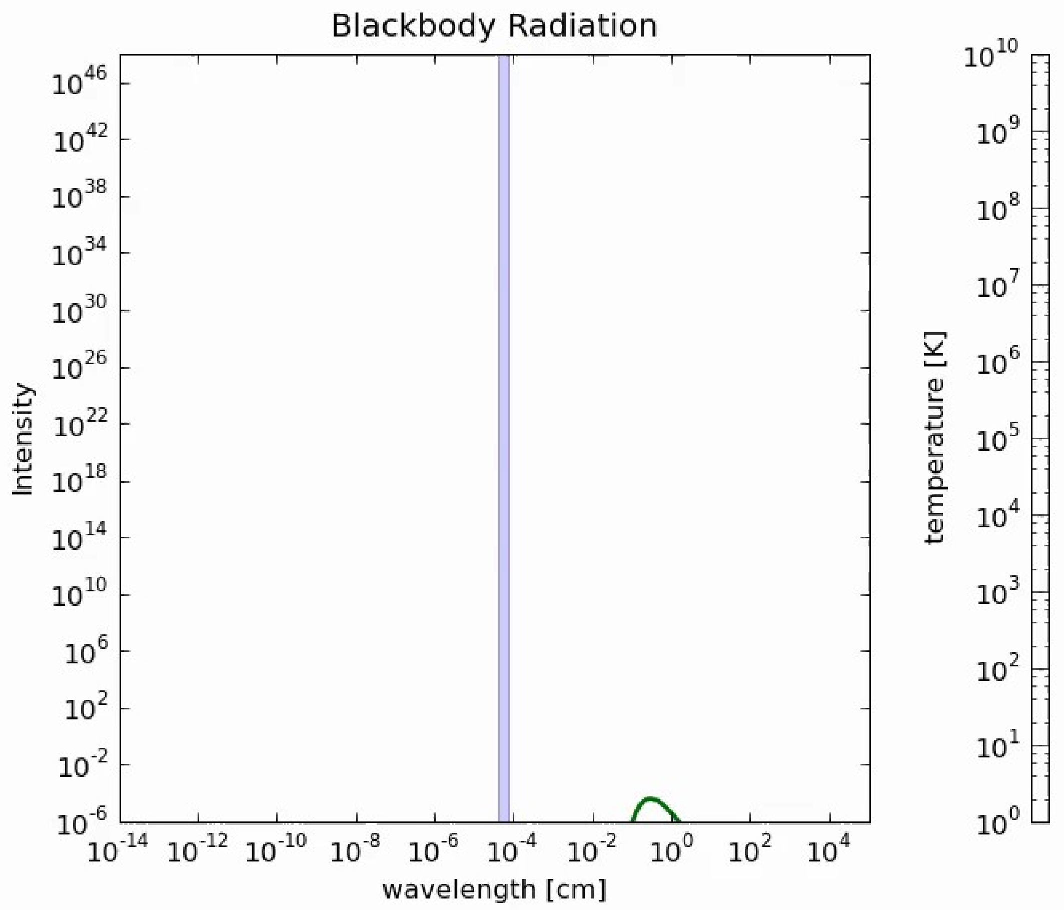
Blackbody Radiation

- Blackbody intensity:

$$I(\nu, T) = \frac{2h\nu^3/c^2}{e^{h\nu/kT} - 1}$$

$$I(\lambda, T) = \frac{2hc^2/\lambda^5}{e^{hc/\lambda kT} - 1}$$

$$\begin{aligned} dE &= I_\nu \, \cos\theta dA \, d\Omega \, dt \, d\nu \\ &= I_\lambda \, \cos\theta dA \, d\Omega \, dt \, d\lambda \end{aligned}$$



Blackbody Radiation

- Flux at the surface of a star

integrate over outward pointing
hemisphere

$$f = \int \frac{dE}{dA\,dt} = \int I_\nu \cos\theta \, d\Omega \, d\nu = \sigma T^4$$

$$\sigma = 5.67 \times 10^{-5} \text{ erg cm}^{-2} \text{ K}^{-4} \text{ s}^{-1}$$

Stefan-Boltzmann constant

- Luminosity of a star:

$$L = 4\pi R^2 \sigma T^4$$

- Wien's law:

$$\lambda_{\max} T = 0.29 \text{ cm K} = 2.9 \times 10^6 \text{ nm K}$$

Hotter stars have spectra that peak at shorter wavelengths

Flux vs Luminosity

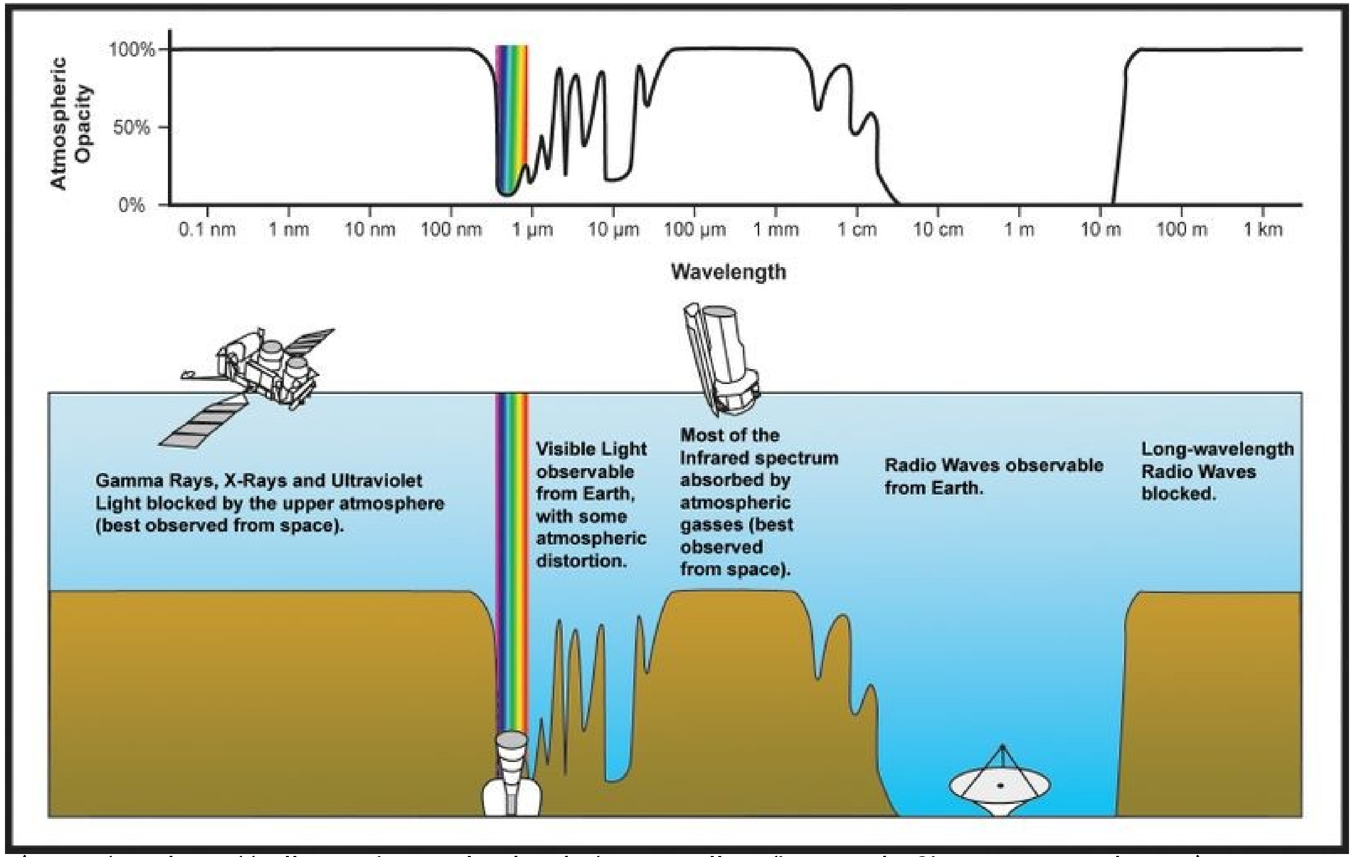
- Intensity has a direction, i.e. it is the energy/time/area/frequency emitted per unit solid angle in a specific direction.
- Detectors measure the energy flux (erg s^{-1} cm^{-2} Hz^{-1}) hitting the detector.
  - Records energy hitting the detector area from all directions.
  - Frequency dependent—monochromatic flux.
- Integrate over all frequencies → total flux (erg s^{-1} cm^{-2})
- We've now talked about flux in 2 different contexts
- Flux at the surface of a star: $f = \sigma T^4$
  - Blackbody
- Flux received from some distant star:
  - $F = L / (4\pi r^2)$, where r is the distance to the star
  - This is the flux that enters into the magnitude equation.

Ex: Surface Temperature of Earth

- What would you expect the surface temperature of the Earth to be, based on its distance from the Sun?

Astronomy and the EM Spectrum

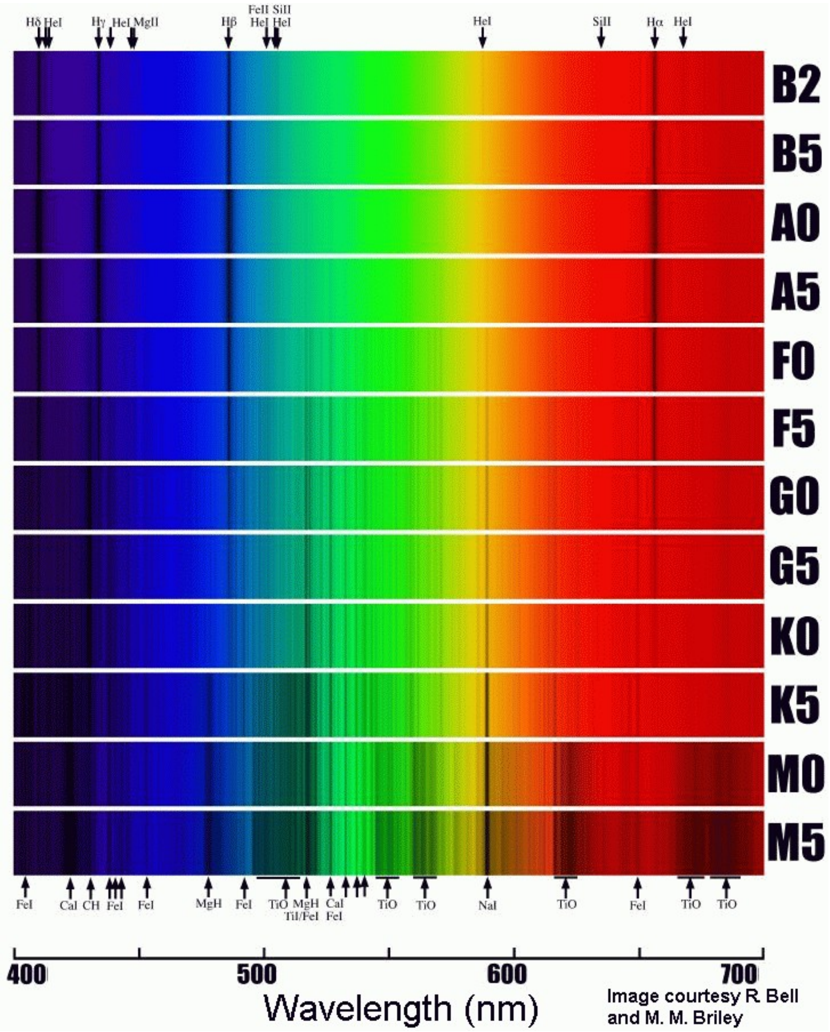
- Our atmosphere is not transparent to all wavelengths



(NASA/JPL; http://gallery.spitzer.caltech.edu/Imagegallery/image.php?image_name=bg005)

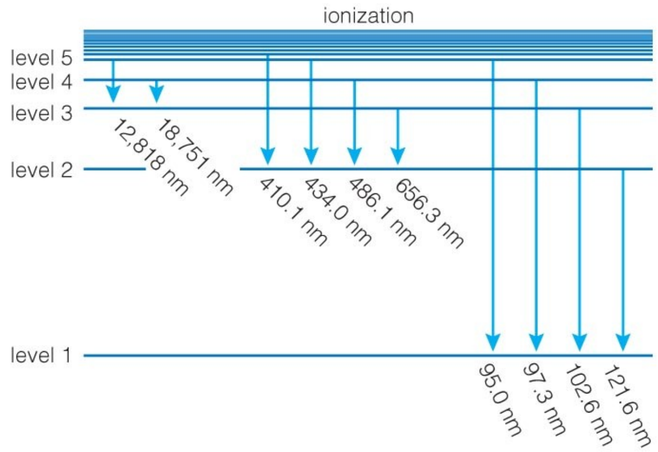
Spectral Types

- Stars are grouped into spectral types, depending on the appearance of their spectral lines
  - Originally ordered by strength of H lines (A stars had strongest, then B, …)
  - Now we order based on surface temperature (hottest to coolest)
  - O B A F G K M



Balmer Lines

- H and He are the most abundant elements in the Universe
  - Everything else is called a metal (< 2% by mass)
- The H Balmer lines are the transitions that end at n = 2—these are the only visible lines in H spectrum
  - Strength of lines depends on balance of excitation and ionization



a Energy level transitions in hydrogen correspond to photons with specific wavelengths. Only a few of the many possible transitions are labeled.

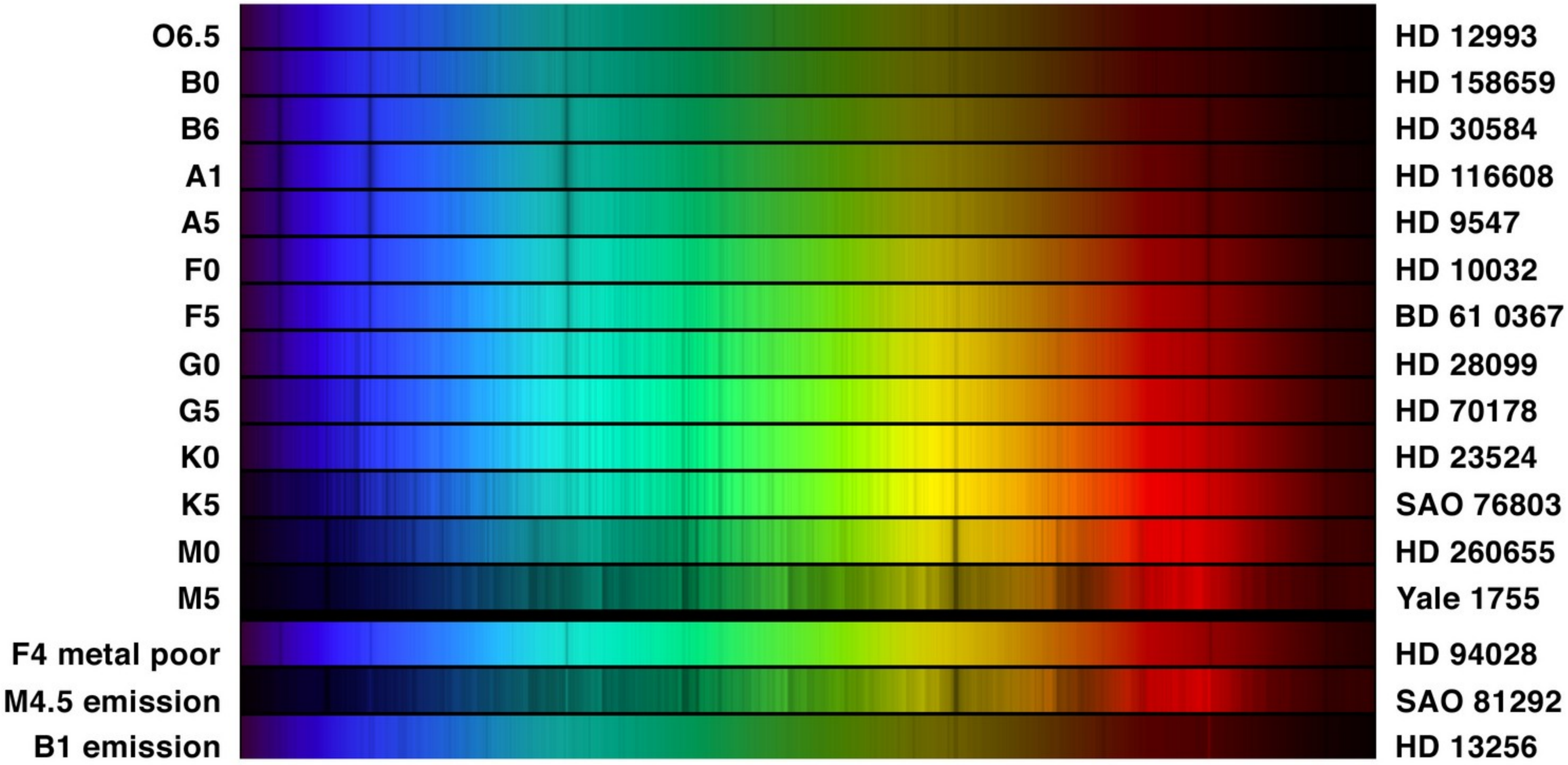
b This spectrum shows emission lines produced by downward transitions between higher levels and level 2 in hydrogen.

c This spectrum shows absorption lines produced by upward transitions between level 2 and higher levels in hydrogen.

(from Bennett et al.)

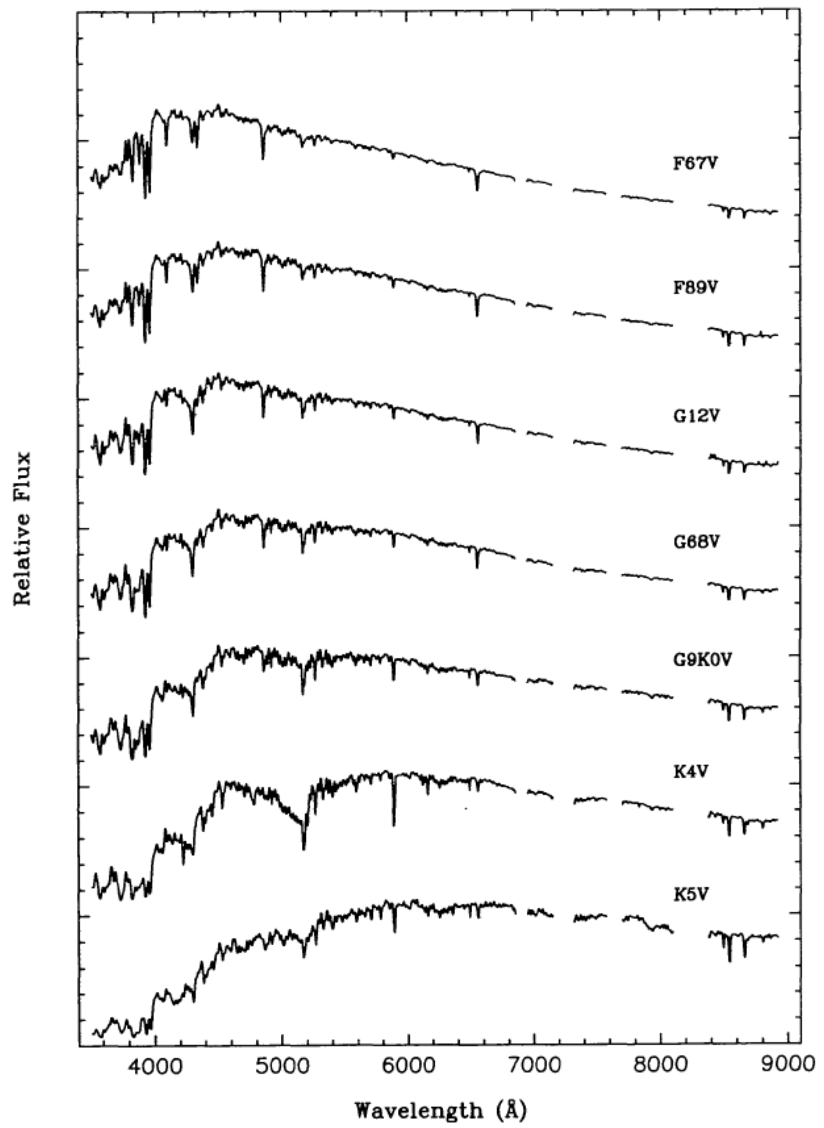
Spectral Types

- Originally thought that stars cool with age, so O stars are called “early” and M stars are “late”
  - Numbers further subdivide



(NOAO)

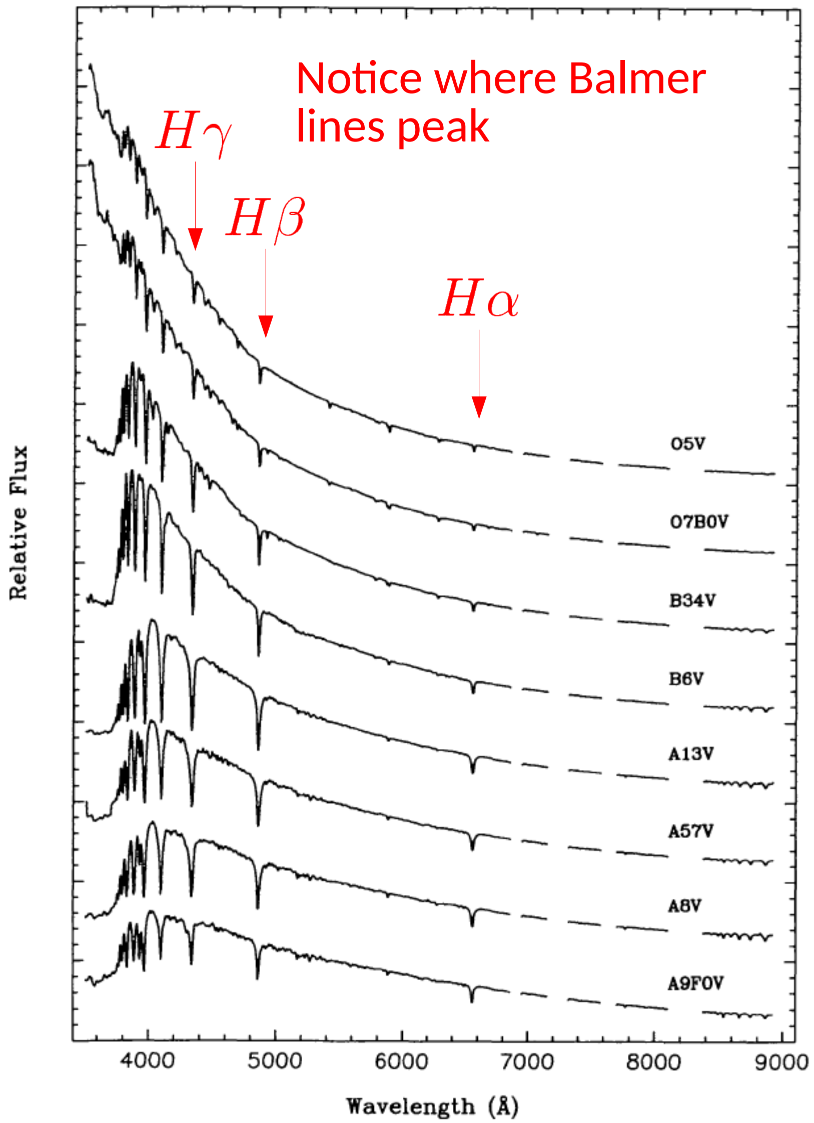
- M stars:
  - Coolest end of spectrum, T < 3500 K
  - No Hα absorption, some neutral metals
  - Molecules can form (CN, TiO, …)
- K stars:
  - T between 3500 and 5000 K
  - Neutral lines dominate
- G stars (sun is G2):
  - T between 5000 and 6000 K
  - H lines are stronger than in K stars.
  - Ionized metal lines appear (e.g. Ca II)
- F stars:
  - T between 6000 and 7500 K.
  - ionized metal lines stronger.



(Silva and Cornell)

Spectral Types

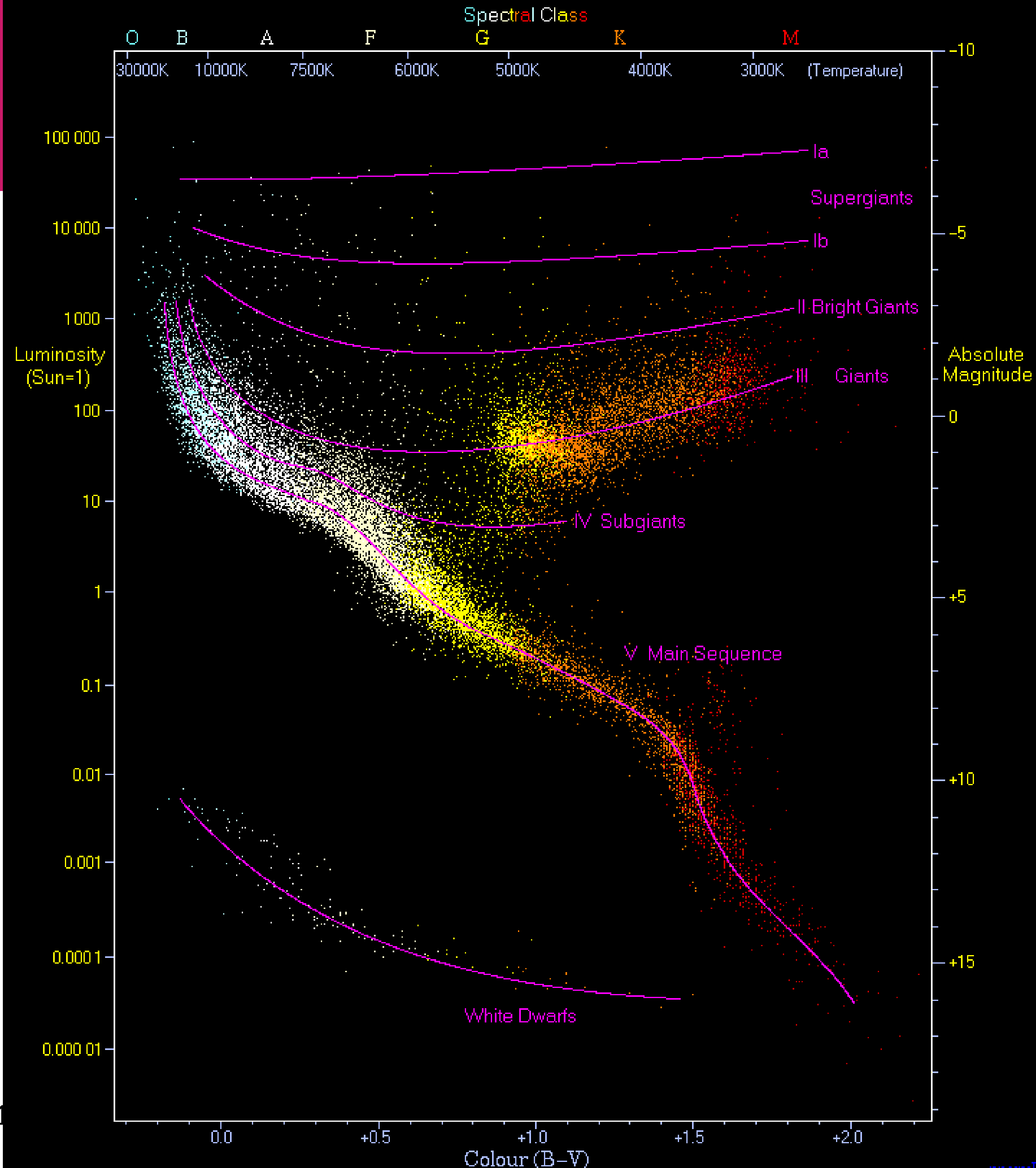
- A stars:
  - T ~ 7500 to 10000 K—white-blue.
  - H lines strongest in A stars.
  - Some ionized metal lines still present.
  - Vega = A0.
  - A0: $M_{bol} = 0$, $B - V = 0$
- B stars:
  - T between 10000 and 30000 K (blue)
  - H lines weaker (ionization)
  - He I and He II lines appear
- O stars:
  - Hottest, T > 30000 K
  - Very few observed
  - Very few lines in visible spectrum



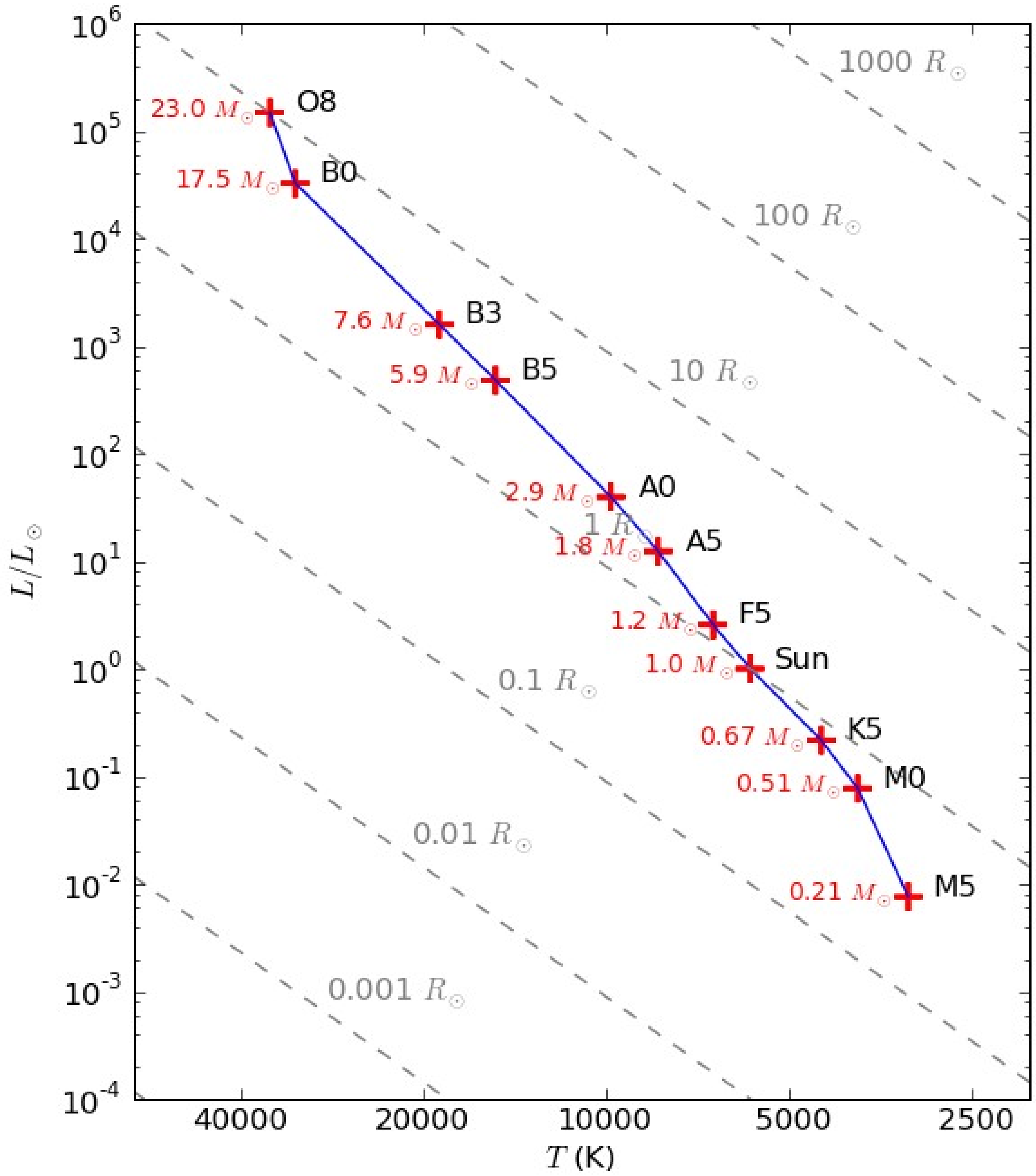
(Silva and Cornell)

HR Diagram

- Horizontal axis: spectral class, B – V, or T (increasing to left)
- Vertical axis: Luminosity or absolute magnitude
- main sequence: diagonal line running through all the spectral classes
- Some T-L combinations not realized in nature
- Wide range in L for stars of the same T
- Low L population: white dwarfs



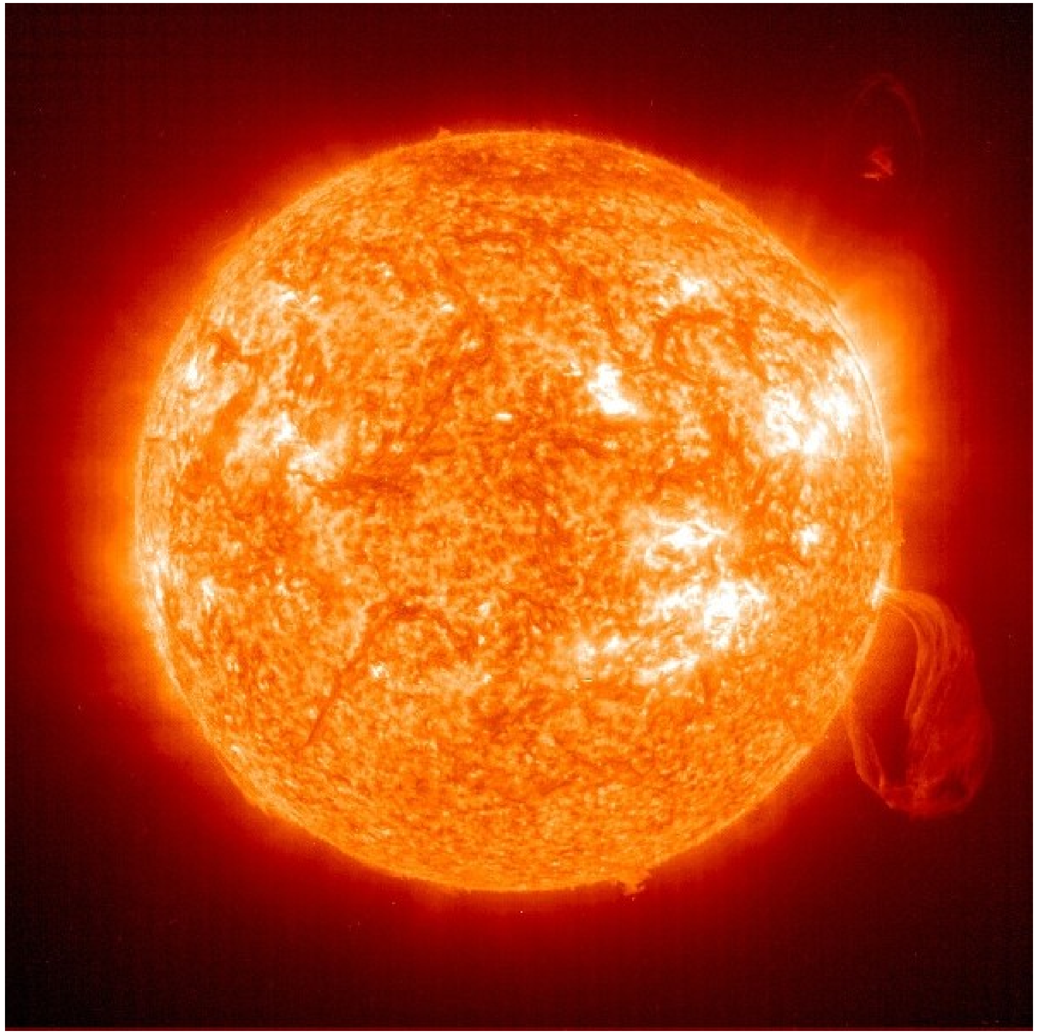
Main Sequence



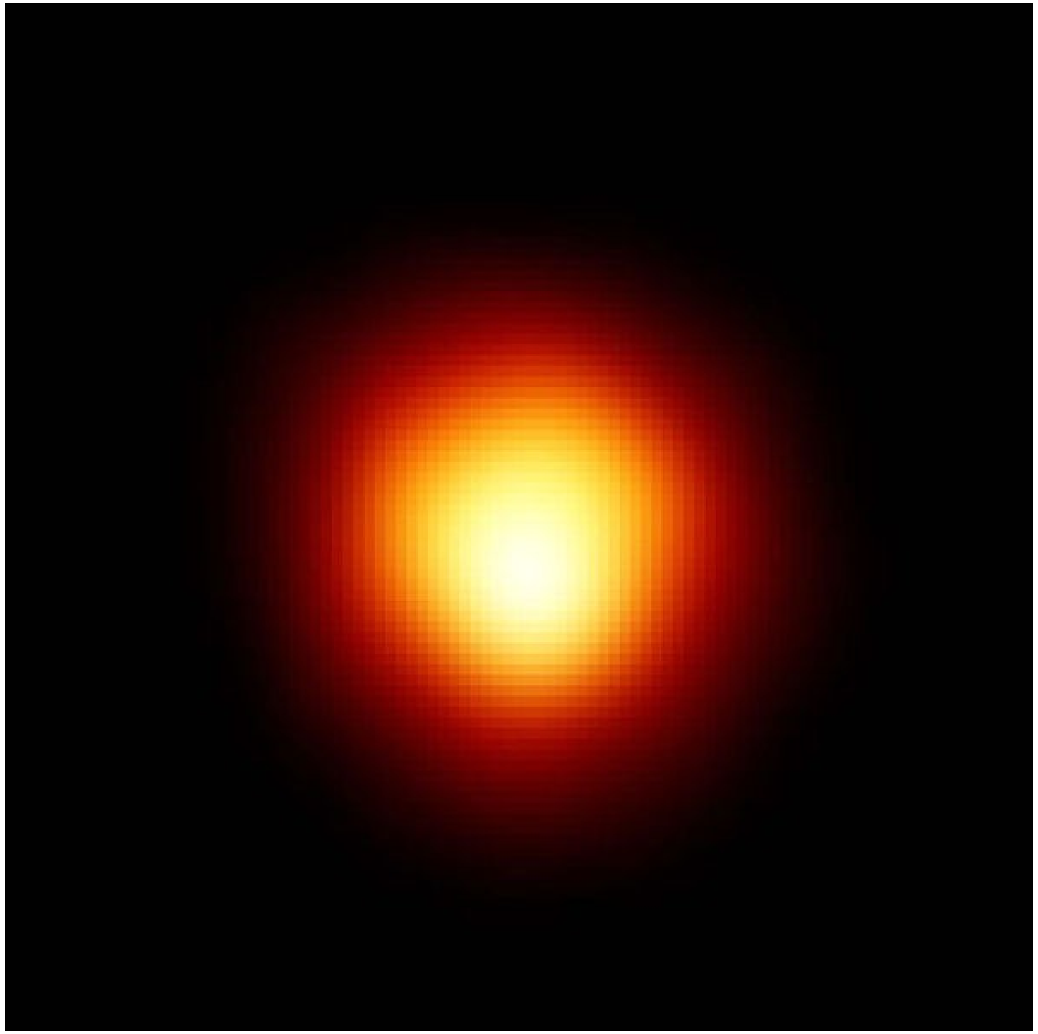
Luminosity Class

- Vertical position in the H-R diagram—the luminosity class
- Main sequence stars are luminosity class V (Sun = G2 V)
- Sub-giants denoted IV
- Giants denoted III
- Supergiants I (sometimes Ia and Ib)
- G star with luminosity $10^4\times$ higher than main sequence must be larger (why?)—giants and supergiants.

Luminosity Class



The Sun viewed in the extreme ultraviolet (SOHO/NASA)



Betelgeuse, a red supergiant star (NASA/STScI)

B - V

- Colors of the various spectral/luminosity types

Table 9.2. **Spectral type, color, and effective temperature.**[a]

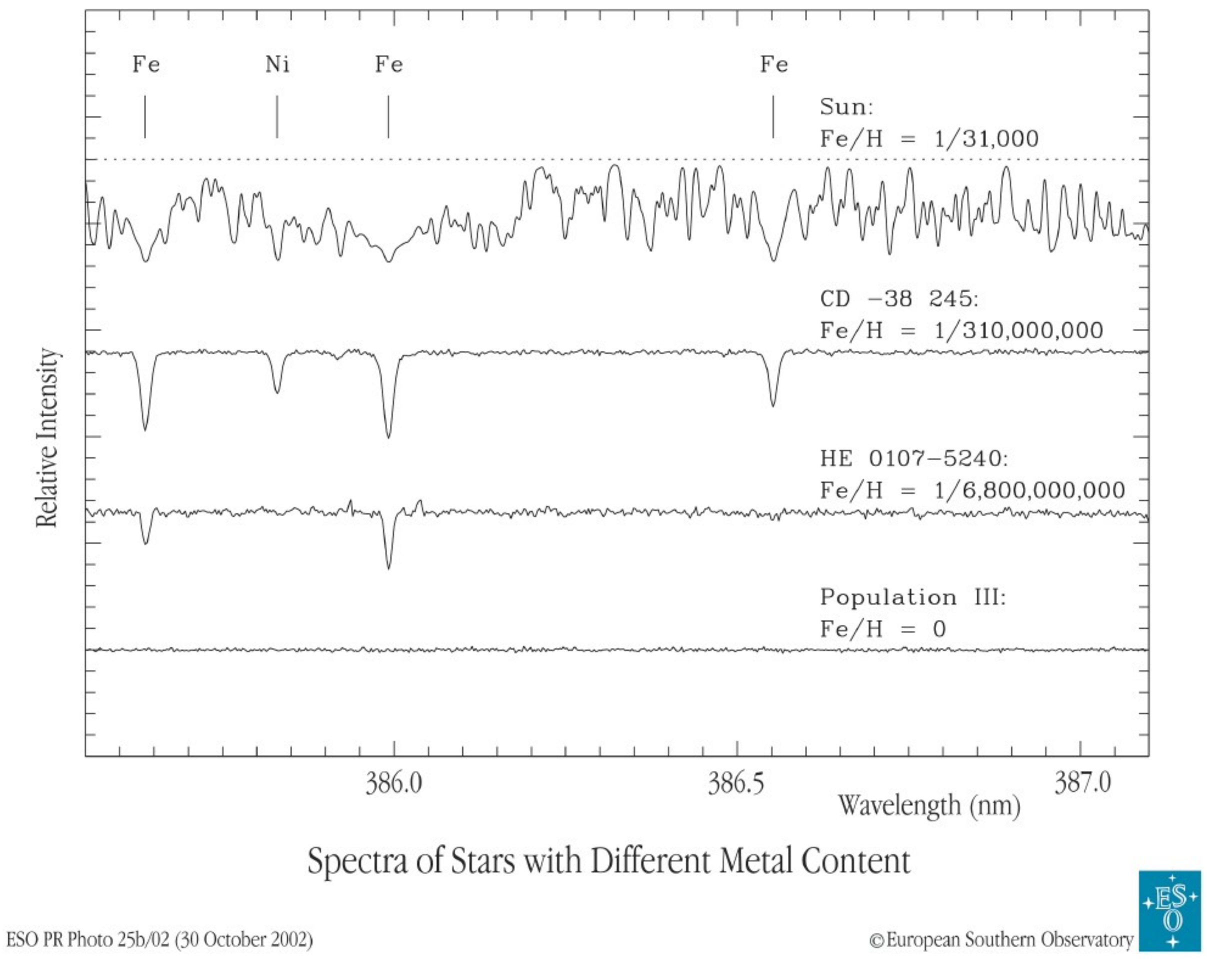
Spectral type	Main sequence $B-V$	Main sequence T_e (K)	Giants $B-V$	Giants T_e (K)
O5	−0.45	35,000	—	—
B0	−0.31	21,000	—	—
B5	−0.17	13,500	—	—
A0	0.00	9,700	—	—
A5	0.16	8,100	—	—
F0	0.30	7,200	—	—
F5	0.45	6,500	—	—
G0	0.57	6,000	0.65	5,400
G5	0.70	5,400	0.84	4,700
K0	0.84	4,700	1.06	4,100
K5	1.11	4,000	1.40	3,500
M0	1.24	3,300	1.65	2,900
M5	1.61	2,600	—	—

[a] Adapted from C. W., Allen, *Astrophysical Quantities*.

(Shu)

Stellar Populations

- Normal stars initially contain about 70% H, 28% He, and 2-3% metals by mass.
- Population I stars:
  - rich in metals (like the Sun)
  - later generation of stars (formed from the ashes of previous stars)
- Population II stars:
  - poor in metals (ex. stars in old globular clusters)
  - some stars with metalicity 1/100000th of the Sun are known
- Population III stars:
  - zero metalicity—very first stars to form
  - none known



Milky Way

- Halo:
  - Spherically symmetric distribution of older stars
  - Density falls off with distance from galactiy center
- Disk:
  - distribution of stars orbiting the galactic center in the thin plane
- Bulge:
  - Spherical distribution surrounding the galactic center