Astro 5465 Wed. Jan. 30, 2020
Today's Topics

- **Review of Basic Stellar Properties**
  - **Distances, Magnitudes, and Luminosities**
  - **Spectral Energy Distributions**
  - **Colors and Temperatures**
  - **Elemental Composition**
  - **Extinction and Reddening of Starlight**
  - **Bolometric Magnitudes & Luminosities**

Basic Stellar Properties: Distances via Parallax

The angular diameter here is "π" – the "parallax" in arcsec. Star traces ellipse depending on ecliptic latitude. The linear diameter is 1 AU.

π(radians) = 1AU/d

Since 1 rad = 206265 arcsec, and d = 206265/π in AUs then:

d = 1/π in units of "parsecs" and so:

1 parsec or 1pc = 206265 AU, and:

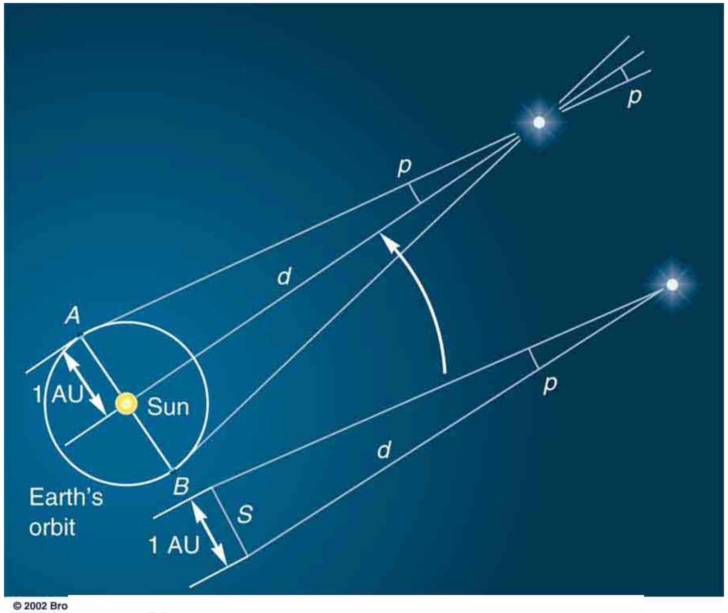
1 pc = 3.086 x 10^{16} m = 3.26 light years

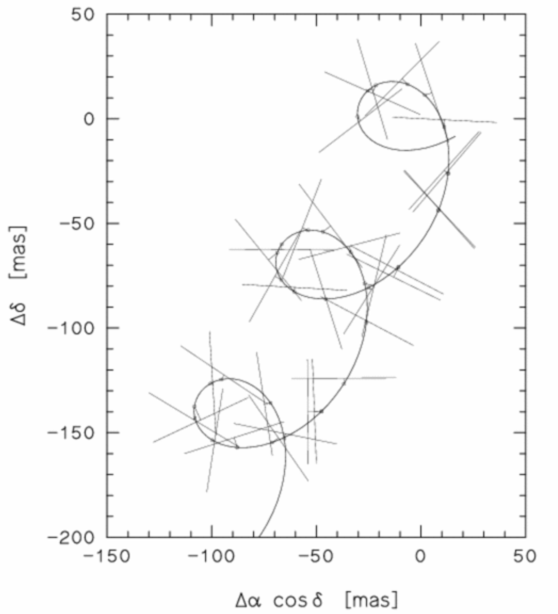
History(Perryman):
https://arxiv.org/pdf/1209.3563.pdf

GAIA astrometric satellite has been revolutionary!

www.cosmos.esa.int/web/gaia/dr1

Proper motion: Radial velocity measured via Doppler but velocity vector requires space motion: μ = arcsec/yr and so: $V_t = 4.74\mu r$ if r is in parsecs. Thus: $\mu = 0.211 V_t p$ (with p in arcsec)





Other Methods for Estimating Distance

- **Accurate parallaxes are currently (Hipparcos) limited to distances of about 100 pc.**
  - **GAIA (2018 -) will extend this to 10 kpc, a revolution in astrometry! (http://sci.esa.int/science-e/www/area/index.cfm?fareaid=26)**
  - **Secular Parallax:**
    - **Motion of the Sun through space (20 km/sec, 4.1 AU/year) creates an apparent drift in the positions of stars over time (secular).**
    - **This is a statistical measure since the stars have random motions as well and so we must average to remove them.**
    - **Example: the average parallax of a large set of stars of a given spectral class can be used to infer an average distance and hence an average luminosity.**
- **Moving Clusters:**
  - **Since stars of a nearby star cluster are all at the same distance the Sun's motion through space creates an apparent "convergence point" for the cluster stars. Solving the geometry results in an average distance for the cluster. The method is taught in introductory astronomy classes but is obsolete given GAIA.**

Astronomy's Magnitude Scale - I

- Recall that the original magnitude scale was developed by Hipparcos.
  - The brightest stars are class 1, the faintest visible stars are class 6; the eye is logarithmic.
  - Modern quantitative measurements indicate this is roughly a factor of 100 in brightness (flux).
  - Response of the eye is known to be logarithmic
  - Thus we define a logarithmic intensity scale:

    $F_n/F_m = 100^{(m-n)/5}$ thus:

    $\log(F_n/F_m) = [(m-n)/5] \times 2$ so:

    $m_m - m_n = -2.5 \log(F_m/F_n)$ note that larger mags. are fainter

  - Since magnitudes are a relative scale we define a zero point:
    - m_λ(Vega) = 0.03 (Vega mags: originally 0.0 but a small error!)
    - m_λ(ST): $m_\lambda(\lambda) = -2.5 \log F_\lambda(\lambda) - 21.19$ (F_λ in erg s^{-1} cm^{-2} A^{-1})
    - m_λ(AB): $m_\nu(\lambda) = -2.5 \log F_\nu(\lambda) - 48.6$ (F_ν in erg s^{-1} cm^{-2} Hz^{-1})

Absolute Magnitudes: Correcting for Distance

- **To correct intensity or flux for distance, use Inverse Square Law**

$$\frac{F_{\text{distance A}}}{F_{\text{distance B}}} = \frac{L/(4\pi r_A^{\,2})}{L/(4\pi r_B^{\,2})} = \left(\frac{r_B}{r_A}\right)^2$$

- **Up to now we have used "apparent magnitudes" m_v**
- **Define absolute magnitude M_v as magnitude star would have if it were at a distance of 10 pc.**

$$m_A - m_B = 2.5\log(I_B / I_A) \qquad \text{A} = \text{true distance d}, \ \text{B} = 10\ \text{pc}$$

$$m - M = m_d - m_{10\,\text{pc}} = 2.5\log\left(\frac{I_{10\,\text{pc}}}{I_{\text{distance d}}}\right) = 2.5\log\left(\frac{d}{10\ \text{pc}}\right)^2 = -5 + 5\log\left(\frac{d}{1\ \text{pc}}\right)$$

$$m - M = -5 + 5\log\left(\frac{d}{1\ \text{pc}}\right) \qquad d = 10^{(m-M+5)/5}$$

- **This gives us a way to correct Magnitude for distance, or find distance if we know absolute magnitude. Note: the book writes m_V and M_V: The "V" stands for "Visual" -- Later we'll consider magnitudes in other colors like "B=Blue" "U=Ultraviolet"**

Example: What is the Absolute Magnitude of the Sun?

- We can determine the absolute magnitude of any star given its apparent magnitude and its distance (parallax). For historical reasons we adopt 10 pc as a fiducial distance:

  $m - M = 2.5 \log[(d/10)^2]$ or:

  $m - M = 5.0 \log(d) - 5.0$ where d is in parsecs

- What about the Sun?
  - Since 1pc = 206265 AU:

    $m_V - M_V = 5.0 \log(1/206265) - 5$ thus:

    $-26.75 - M_V = 5.0 \times (-5.314) - 5$ or:

    $M_V(\text{Sun}) = 4.82$ barely visible to the eye at 10 pc.

Magnitudes at Other Wavelengths

- Early photography allowed astronomers to measure the apparent brightness of stars at only blue and visual wavebands.
- With an electronic detector we can define magnitudes at several wavelengths using filters. The standard set is known as the Johnson/Kron-Cousins system.
- Quantitatively this corresponds to integrating the spectral energy distribution (S_λ) of an astronomical object multiplied by a filter band-pass (F_λ):

$$m_\lambda = -2.5 \log \left\{ \int_0^\infty F_\lambda S_\lambda d\lambda \Big/ \int_0^\infty F_\lambda d\lambda \right\} + C_\lambda$$

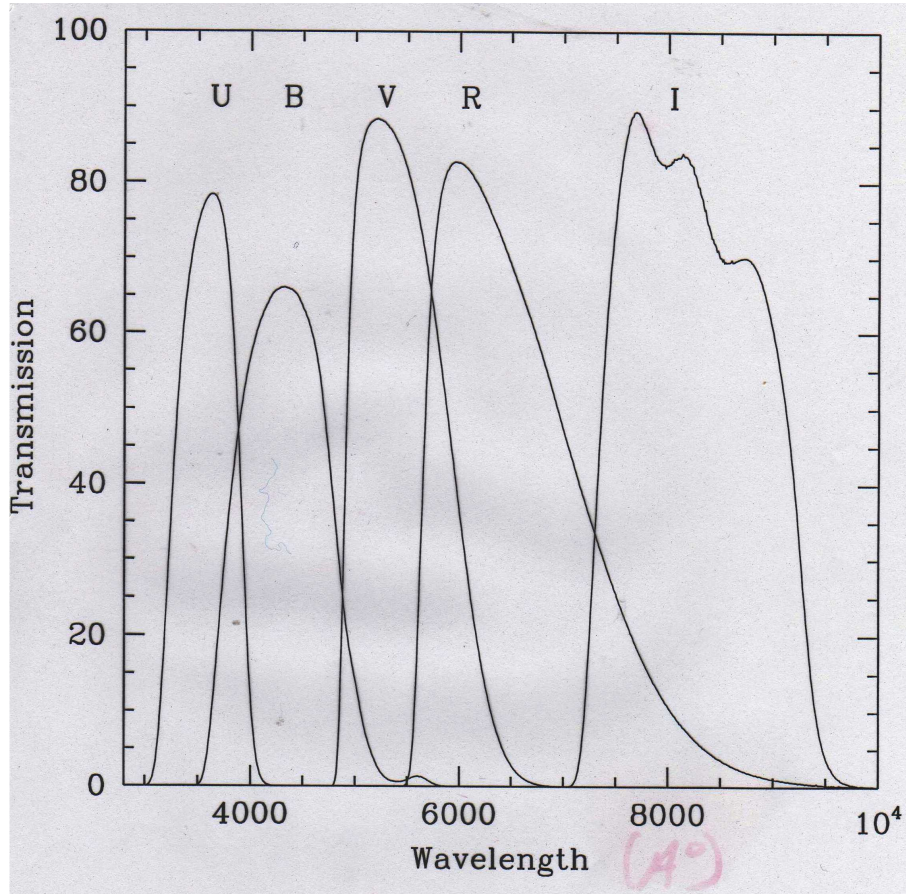
Johnson/Kron-Cousins Filters

Sets of colored filters are used to span the optical and near-infrared wavelengths.

Trade-off between resolution and small number of filters.

Several filter systems exists. Some, like Johnson, are designed to be broadly applicable and others, like Stromgren, are designed to measure specific stellar spectral features. See. Following slides and:

http://voservices.net/filter/



Other Photometric Systems

- **The most common sets of filters are the Johnson/Cousins and the Sloan sets.**
- **Space missions often adopt their own.**

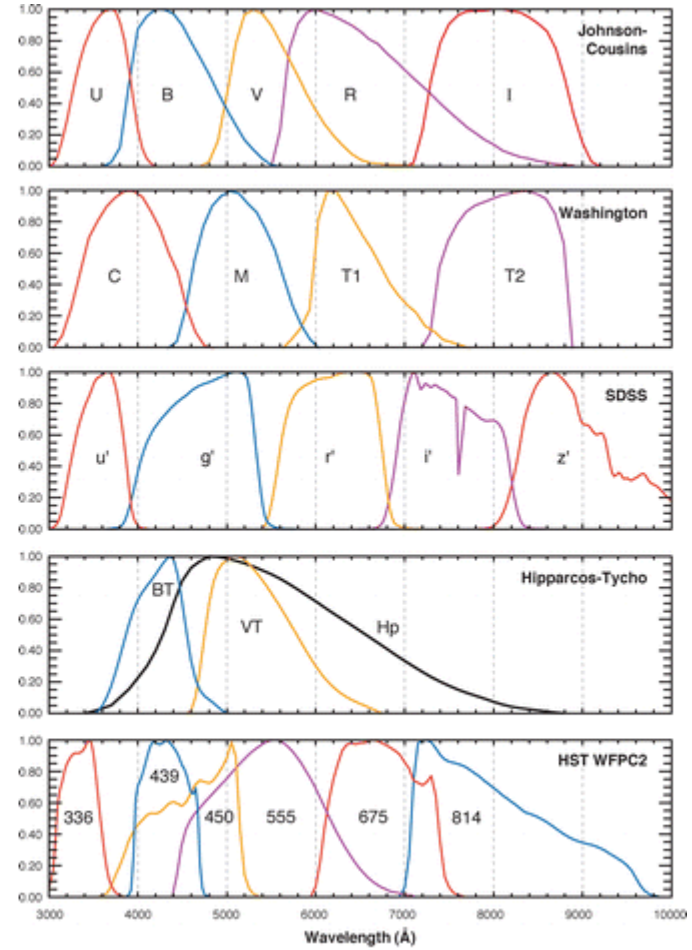
U,B,V,R,I Standards:
Landolt, A. U. 1992, AJ, 104, 340
Landolt, A. U. 1983, AJ, 88, 439
Landolt, A. U. 2007, AJ, 133, 2502

Gunn U, G, R, I, Z System:
(Oke, J. B., & Gunn, J. E. 1983, ApJ, 266, 713)

AB Magnitudes:

$m_{AB} = -2.5 \log(f_\nu) - 48.60$
(f_ν: ergs/cm^2/s/Hz)
(Oke, J.B. 1974, ApJS, 27, 21)

Given the spectral energy distribution of a standard star the zero points can be calculated via numerical integration over any bandpass.



Bessell, MS. 2005
Annu. Rev. Astron. Astrophys. 43: 293–336

Filter Bandpasses and Zero Points

- **The most common sets of filters are the Johnson/Cousins and the Sloan sets.**
- **Fluxes and Zero points below correspond to a zero mag. Source (**Bessel, M. S. 2005, ARA&A, 43, 293)

Band	λ (μm)	Flux ($W/m^{-2}/\mu m^{-1}$	Isophotal ν (Hz)	S (Jy)	AB mag.
U	0.366	4.175e-08	8.197e+14	1790	0.770
B	0.438	6.32e-08	6.849e+14	4063	-0.120
V	0.545	3.631e-08	5.490e+14	3636	0.000
R	0.641	2.177e-08	4.680e+14	3064	0.186
I	0.798	1.126e-08	3.759e+14	2416	0.444
Z	0.9206	8.74e-09	3.071e+14	2270	0.535
Y	1.036	5.810e-09	2.870e+14	2060	0.640
J	1.22	3.147e-09	2.394e+14	1589	0.899
H	1.63	1.138e-09	1.802e+14	1021	1.379
K	2.19	3.961e-10	1.364e+14	640	1.886
K’	2.121	4.479e-10	1.413e+14	676	1.826
L	3.45	7.08e-11	8.696e+13	285	2.765
L’	3.754	5.31e-11	7.982e+13	238	2.961

Astronomical Colors

- **Astronomers define color as the difference in magnitudes measured in two different band-passes.**

- **For example the B-V color:**

  $$B - V = m_B - m_V$$

Note that blue objects have negative colors and red objects have positive colors.

We can compute colors for Blackbodies:

$$B - V = -0.71 + 7090/T$$

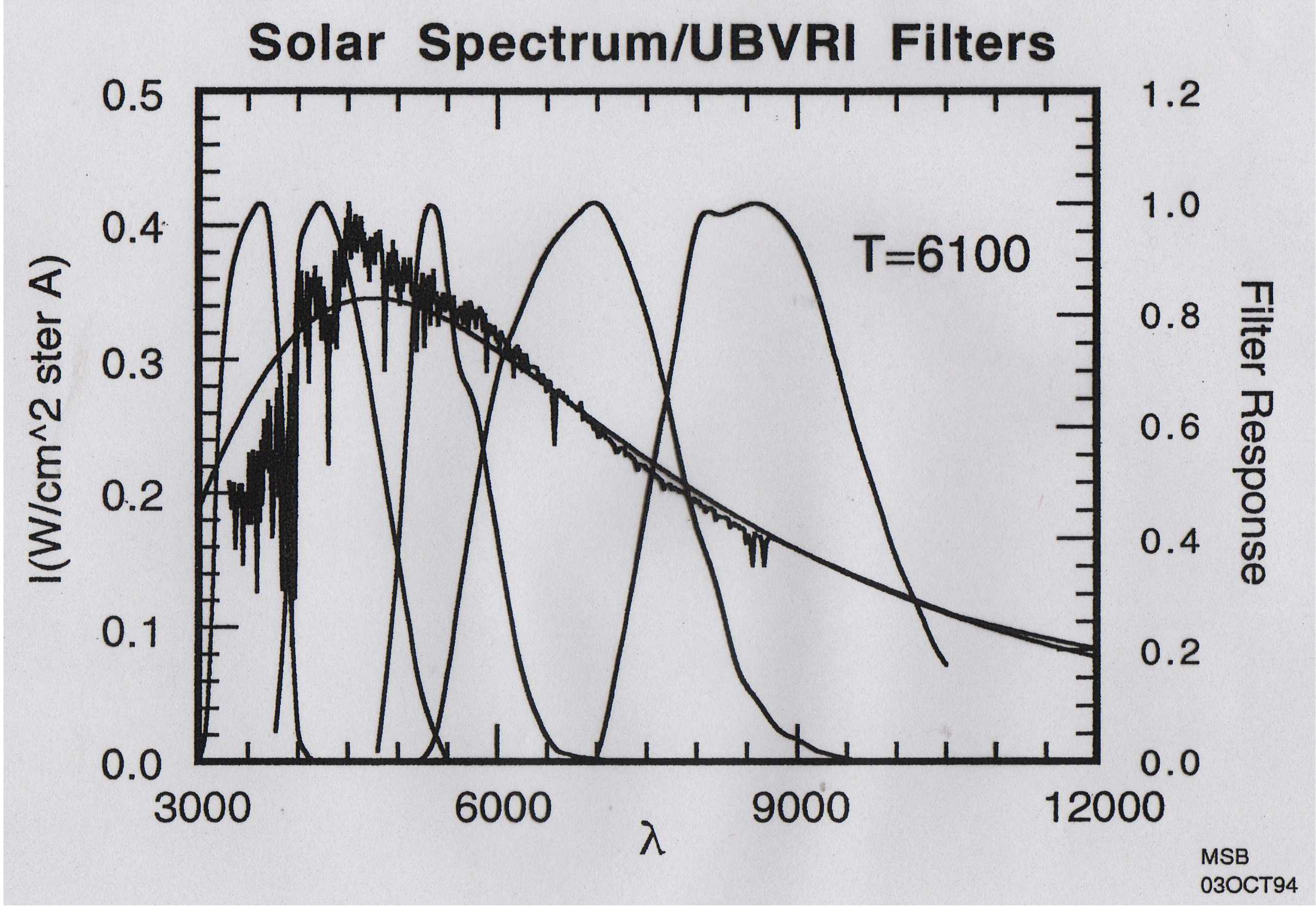
But stars are not really blackbodies so for stars similar to the Sun:

$$B - V = -0.86 + 8540/T$$

So we can use astronomical colors as a substitute for temperature.

But stars aren't black bodies so we need to either measure them or integrate under their SEDs.

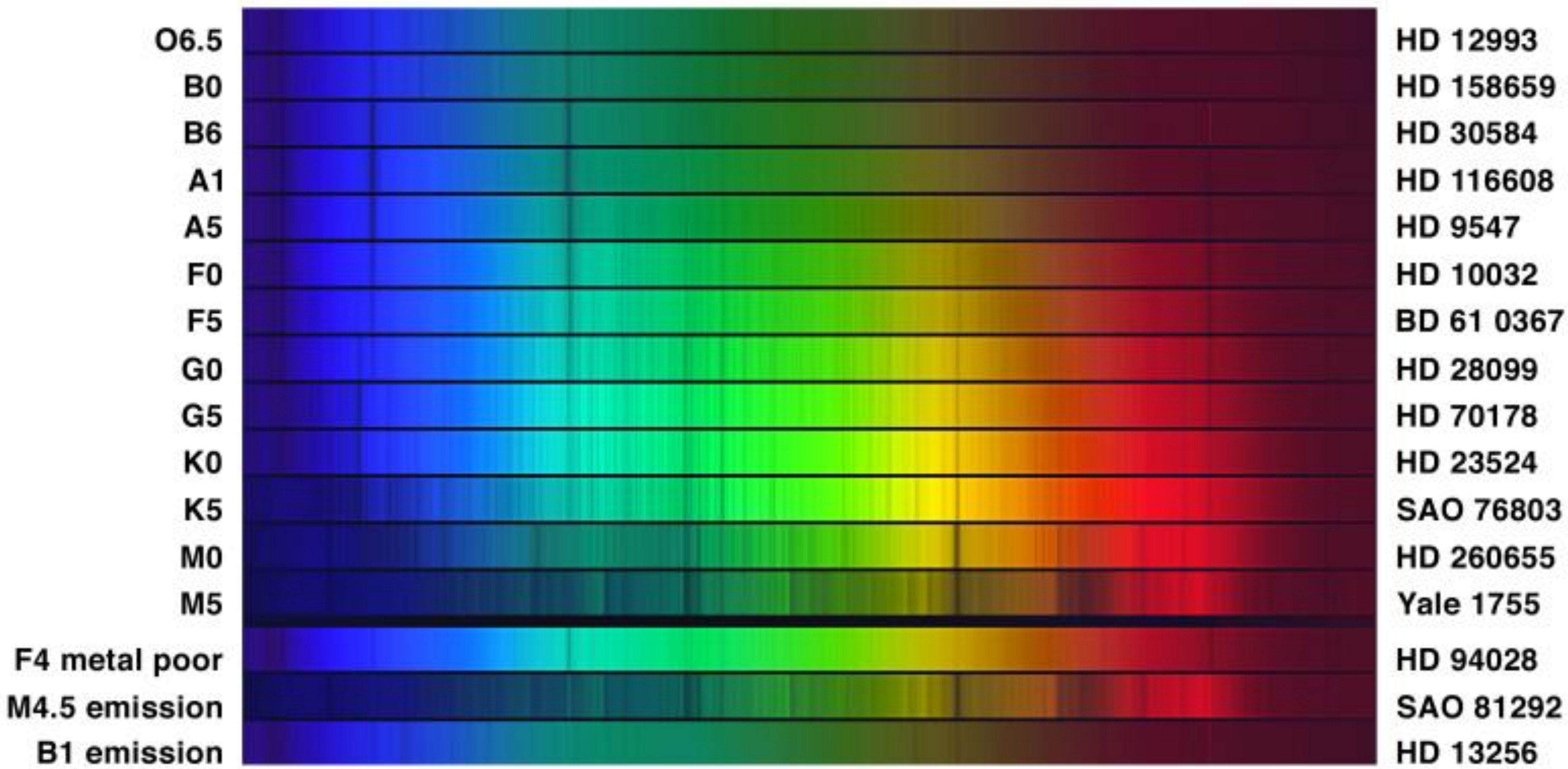
Example using Solar Spectrum



Knowing Filter Bandpasses, the SED for the Sun and Vega we numerically integrate and compare to place Sun on the Vega magnitude system.

Classification of Stellar Spectra

- A graphical representation of Harvard (A. Cannon) system is shown below.
  - Note the smooth progression in line strengths as spectra progress from hottest (top) to coolest (bottom).

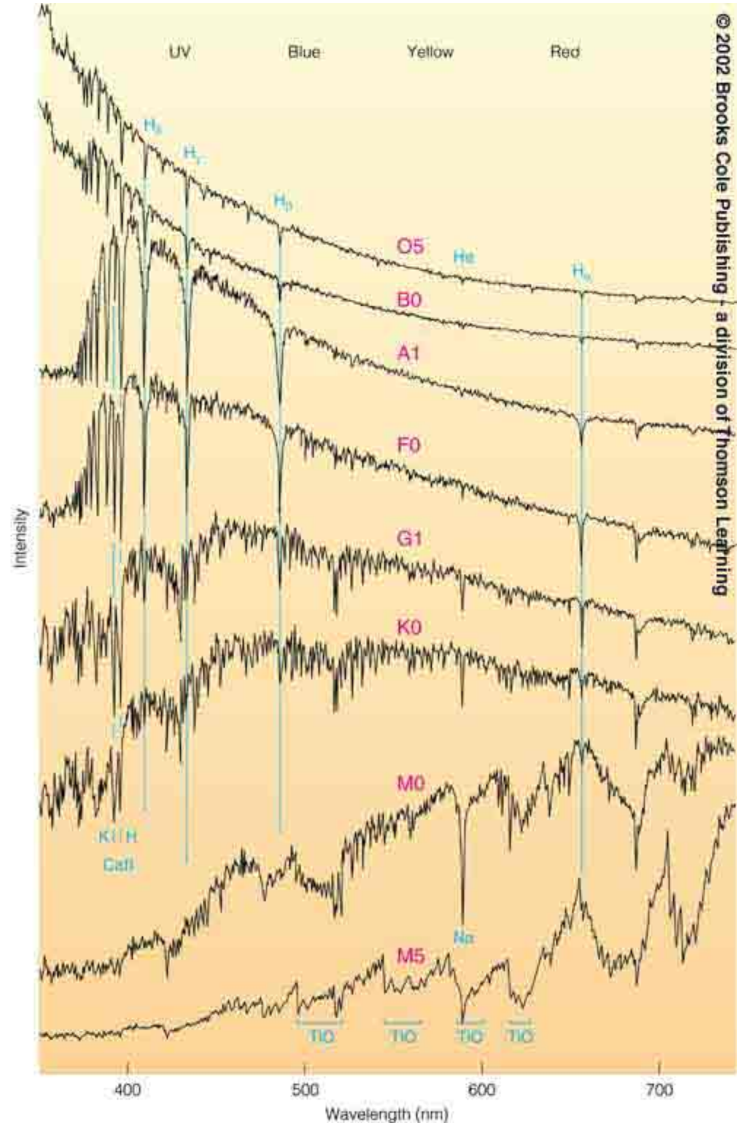


Classification of Stellar Spectra cont.

- O B A F G K M scheme
  - Originally in order of H strength – A,B, etc
    Above order is for decreasing temperature
  - Standard mnemonic: Oh, Be A Fine Girl (Guy), Kiss Me
  - Use numbers for finer divisions: A0, A1, ... A9, F0, F1, ... F9, G0, G1, ...

Table 6-1 Spectral Classes

Spectral Class	Approximate Temperature (K)	Hydrogen Balmer Lines	Other Spectral Features
O	40,000	Weak	Ionized helium
B	20,000	Medium	Neutral helium
A	10,000	Strong	Ionized calcium weak
F	7500	Medium	Ionized calcium weak
G	5500	Weak	Ionized calcium medium
K	4500	Very weak	Ionized calcium strong
M	3000	Very weak	Titanium oxide strong



From our text: Horizons, by Seeds

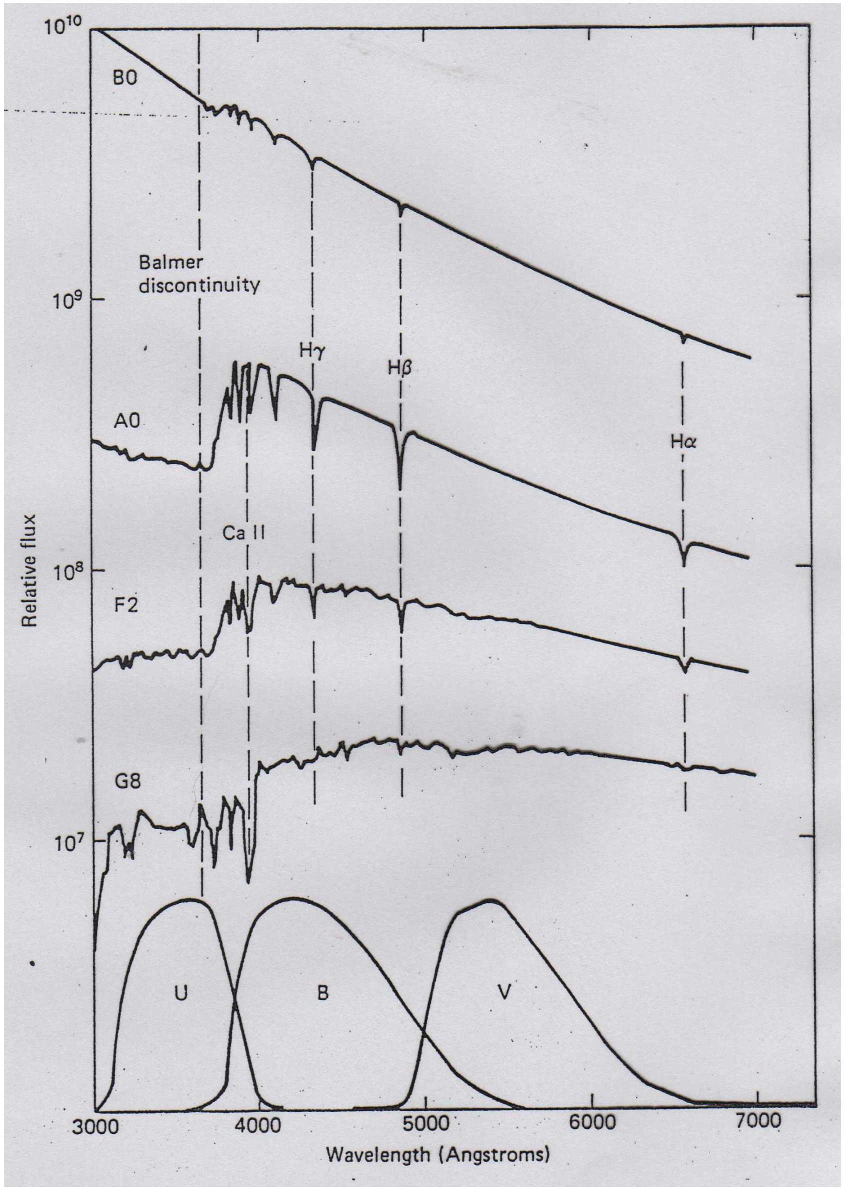
Stars of Different Temperature

Hotter stars are bluer, cooler stars are redder but none are blackbodies.

T_{eff} is the temperature of an equivalent blackbody with the same luminosity. Can be measured using empirical correlations with colors from broadband filters.

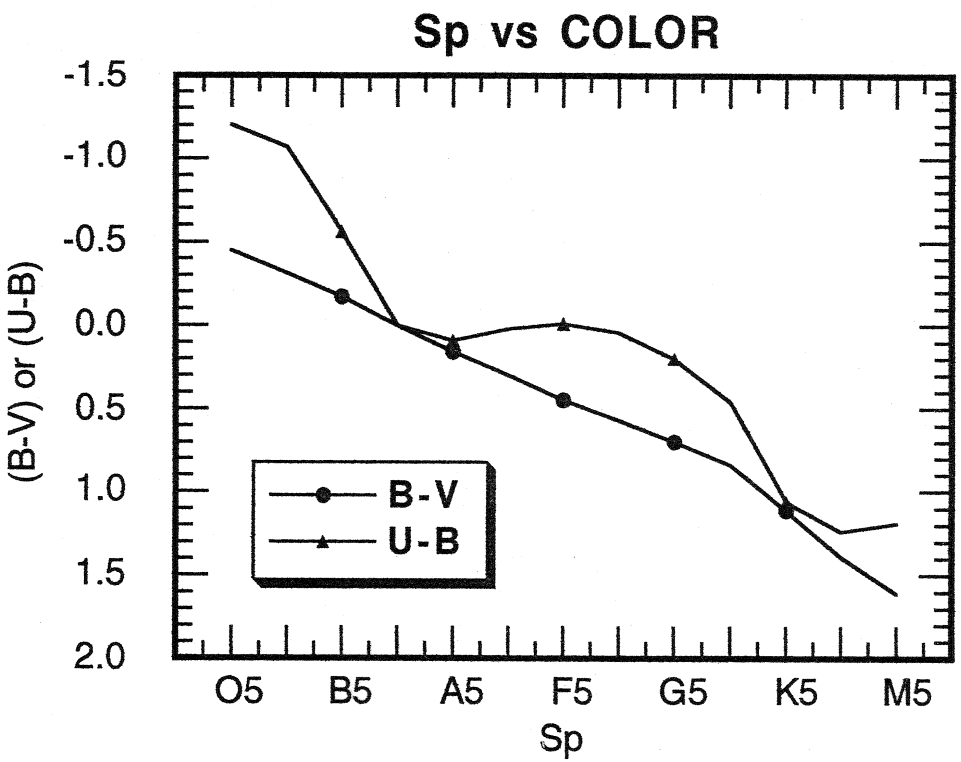
The original Johnson system included the U, B, and V filters. Kron and Cousins extended these to redder colors detectable with CCDs.

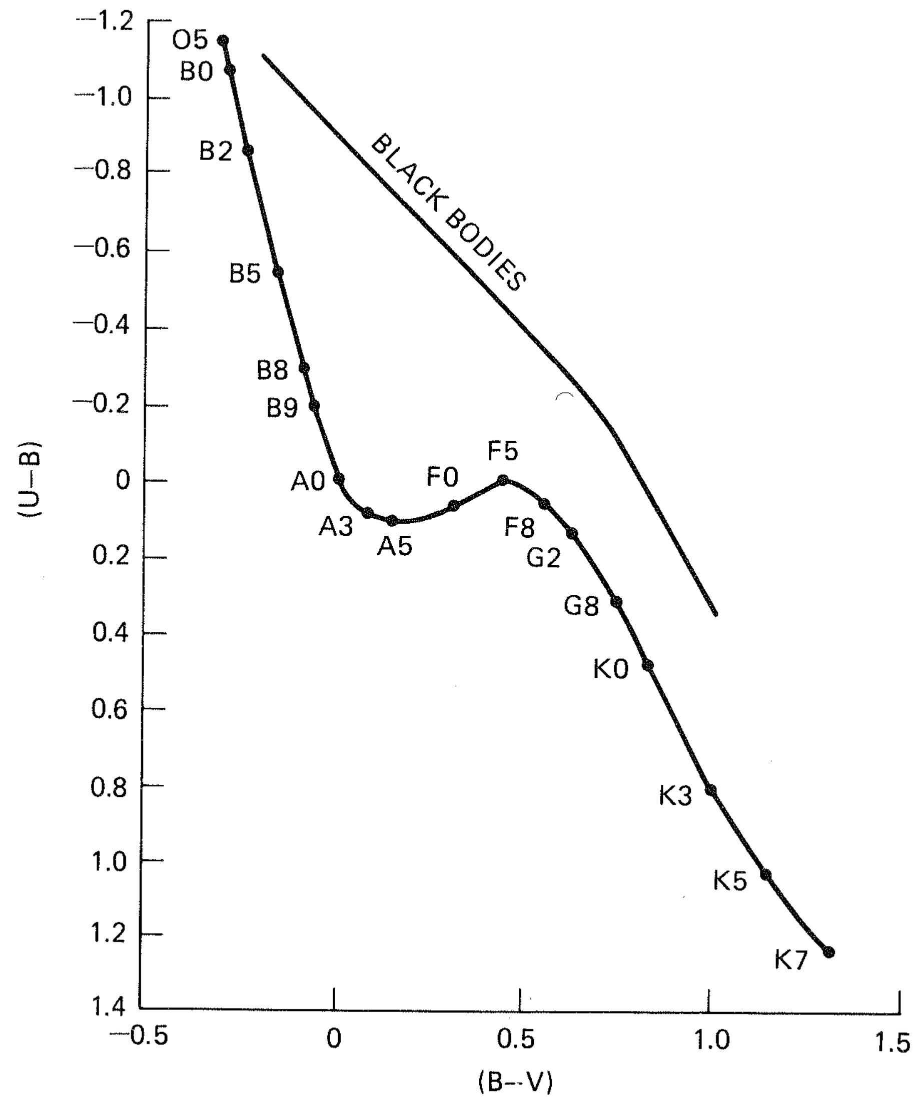
Note that the B-V color is a good tracer whereas U-B is not. Why?



Colors vs. Spectral Type - I

- **UBV colors vs. spectral types**
  - **Non-linear in U-B, linear in B-V**
  - **B-V used as substitute for temperature**
  - **Note that stars are not black bodies.**



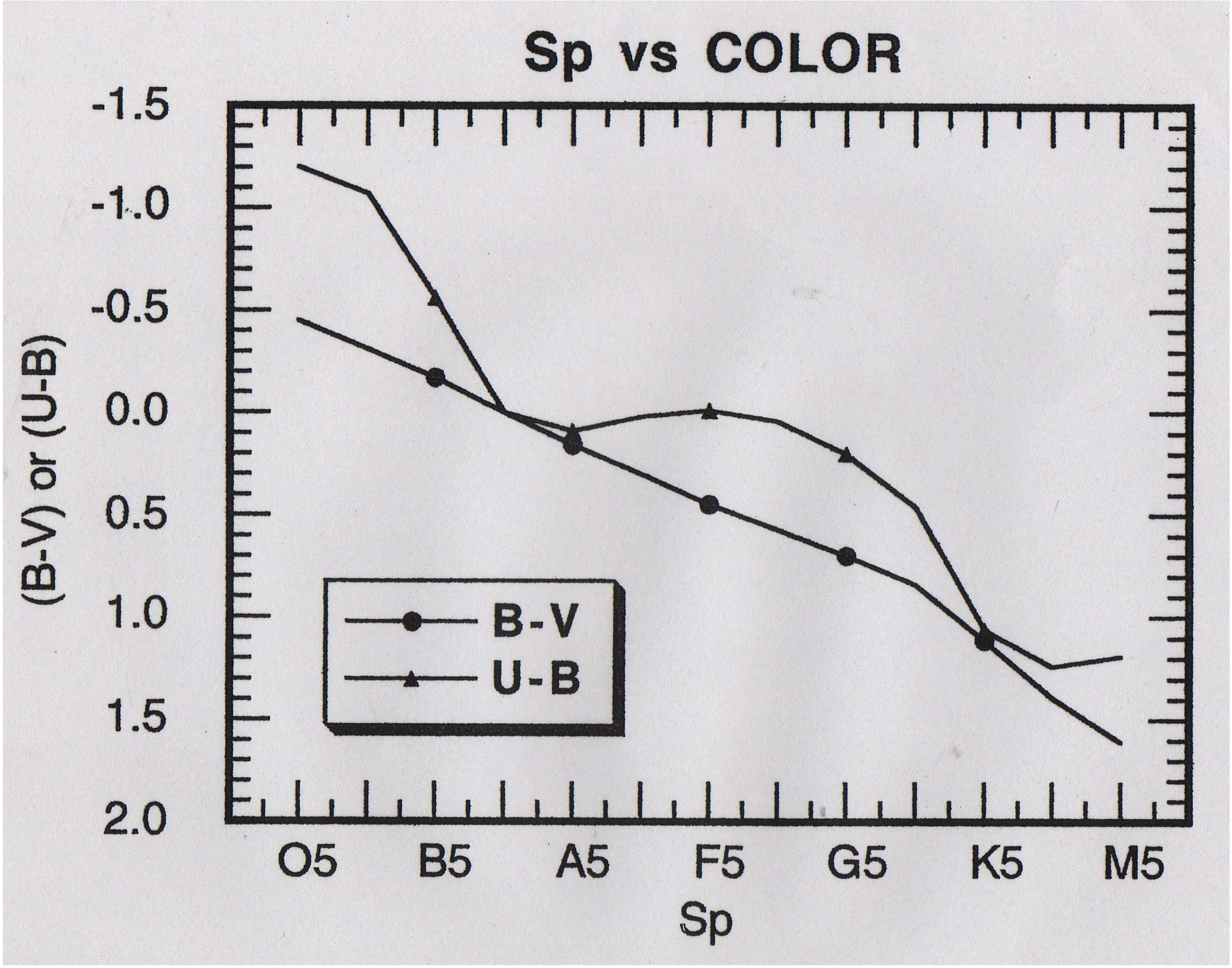


Color vs. Spectral Type - II

The colors and spectral types have been measured for hundreds of nearby stars.

The B-V color correlates strongly with the spectral type and is thus an accurate, continuous measure of a star's temperature.

Colors can be measured for many more and for fainter stars than spectroscopy.

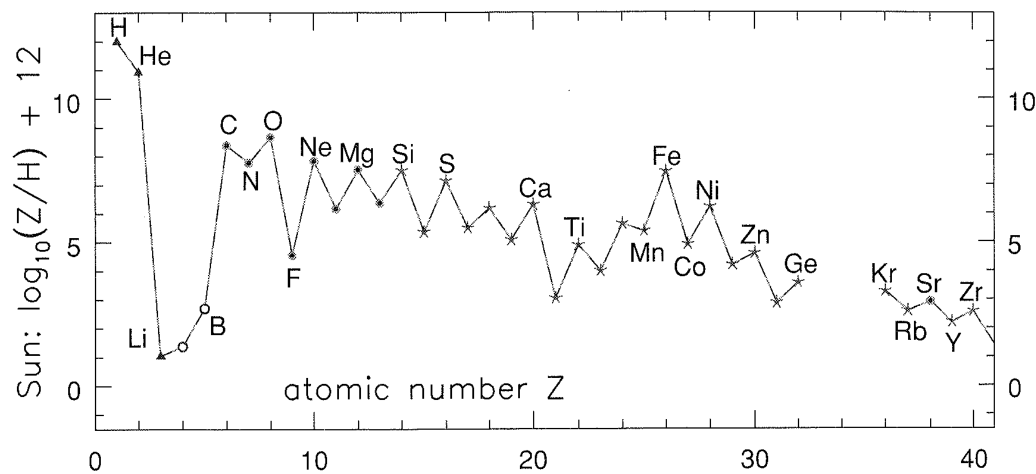


Elemental Composition of Stars

- Atomic Physics (Quantum mechanics + Boltzman Equation)
  - Line strengths vs. temperature (use HeI, II for hot, FeI, II for cool)
- Stellar Atmosphere allows line strengths -> elemental abundances
  - H, He most abundant, huge depletion of Li, Be, B with C, N, O, etc. elevated
  - Subtle patterns – related to nuclear fusion in stars

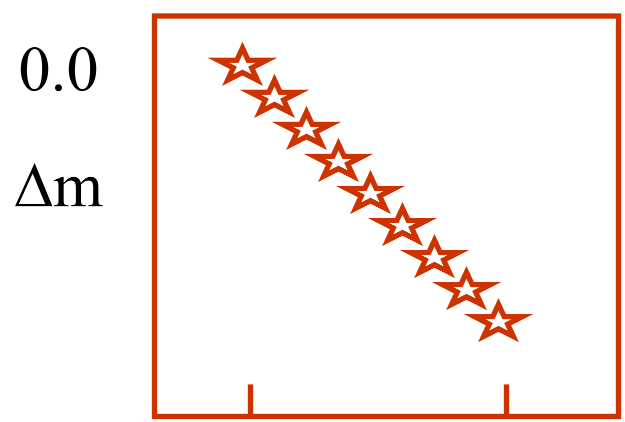
Table 6-2 The Most Abundant Elements in the Sun

Element	Percentage by Number of Atoms	Percentage by Mass
Hydrogen	91.0	70.9
Helium	8.9	27.4
Carbon	0.03	0.3
Nitrogen	0.008	0.1
Oxygen	0.07	0.8
Neon	0.01	0.2
Magnesium	0.003	0.06
Silicon	0.003	0.07
Sulfur	0.002	0.04
Iron	0.003	0.1



Extinction of Starlight - I

- **Scattering and dust in the Earth's atmosphere cause an extinction of starlight.**
  - **Light gets fainter as it is scattered or absorbed by more atmos.**
  - **Atmosphere scatters more in the blue so the star is also reddened as is it observed further from Zenith [Airmass = sec(Z)]**
  - **By measuring stars of known magnitude (standards) as a function of zenith angle the extinction slope can be measured via least-squares fit to the standards.**
  - **Reddening can also be measured and correlated with extinction.**
- **Astronomers use this technique to calibrate the effects of the Earth's atmosphere on their measurements and correct for it.**



Air Mass = 1/cos (Z) = sec (Z)

Extinction of Starlight - II

- **As light passes through the atmosphere a small amount is scattered. The longer the path length the more the extinction. Recall the corresponding solution to the transfer equation:**

$dF(\lambda) = F(\lambda)k(\lambda)dl$ and integrating gives $F(\lambda) = F_0(\lambda)\, e^{-\tau(\lambda)}$

The optical depth (τ) depends upon the properties of the atmosphere (k) and how much we look through (path length or air mass):

$\tau(\lambda) = \tau_0(\lambda) \sec(Z)$

- **In terms of magnitudes we then have:**

$$
\begin{aligned}
m(\lambda) - m_0(\lambda) &= -2.5 \log[F(\lambda)/F_0(\lambda)] \\
&= -2.5 \log\{\exp[-\tau(\lambda)]\} \\
&= 2.5 \log(e)\, \tau(\lambda) \\
&= 1.086\, \tau_0(\lambda) \sec(Z)
\end{aligned}
$$

or:

$$m_0(\lambda) = m(\lambda) - k_0(\lambda) \sec(Z)$$

Extinction is linear effect in mags.

Can either measure several stars at different airmass or follow them across the sky. Using a range of colors you can transform onto the standard system.

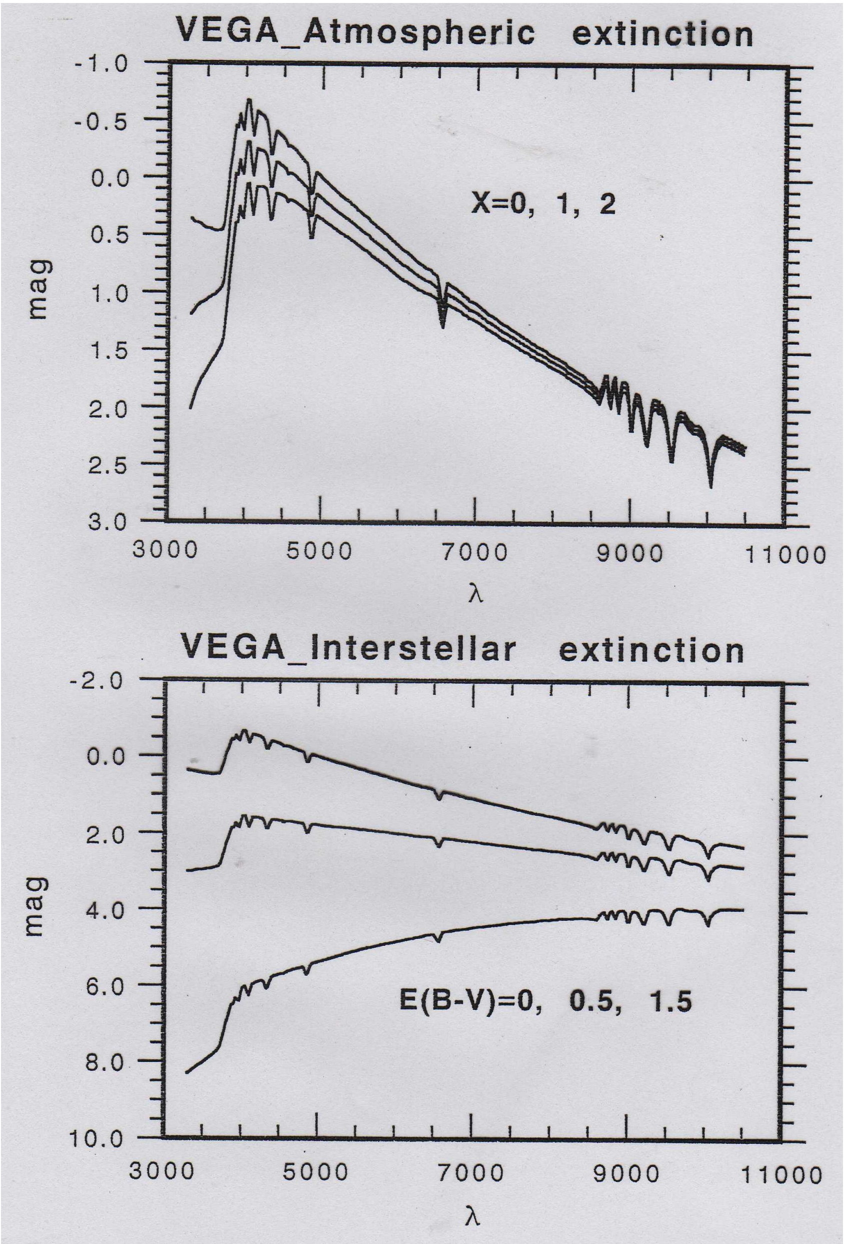
Reddening and Extinction Go Together

As star viewed through increasing amounts of atmosphere, i.e., closer to setting, the star gets redder.

A similar effect occurs as we look at distant stars due to the dust in interstellar space.

Note that the relative strength of adjacent spectral features is unchanged by extinction (~ same λ) but the broader λ colors will be affected.

So, if the intrinsic colors of a given stellar spectral type are known then the measured colors can give the "color excess" (see below).



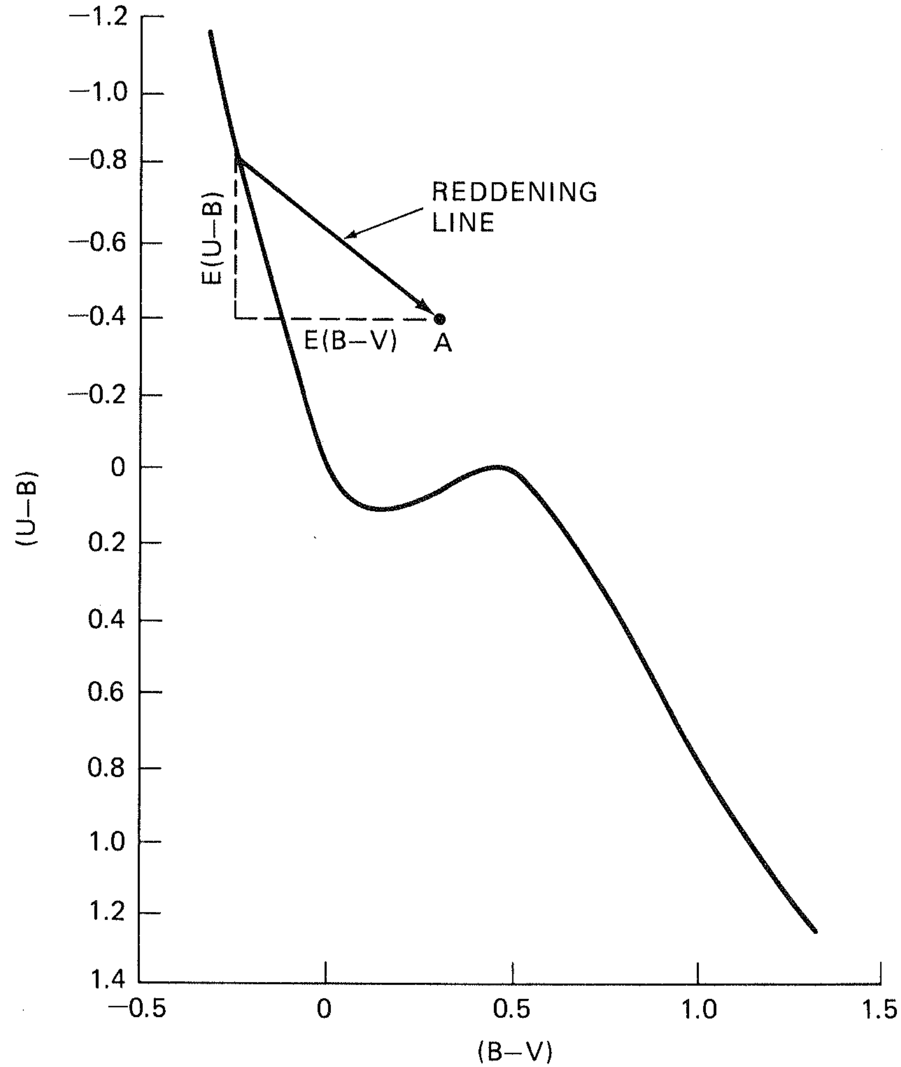
Color-Color Plots for Stars

Two color plots allow the temperature and spectral types of stars to be estimated. Detailed shape depends on filter systems.

The positions of the stars in a color-color plot are independent of distance.

However, the location of stars in the color-color plot do depend on extinction due to the reddening of starlight.

Bluer light suffers more extinction than redder so result is a reddening vector in color-color space.



Color-Color Plot of the Brightest Stars

The nearest stars are distributed along the locus of zero extinction.

More distant stars show increasing amounts of reddening as they are viewed through more and more dust.

Thus, the color excess or reddening of a star can be measured and can be used to estimate the amount of extinction (A):

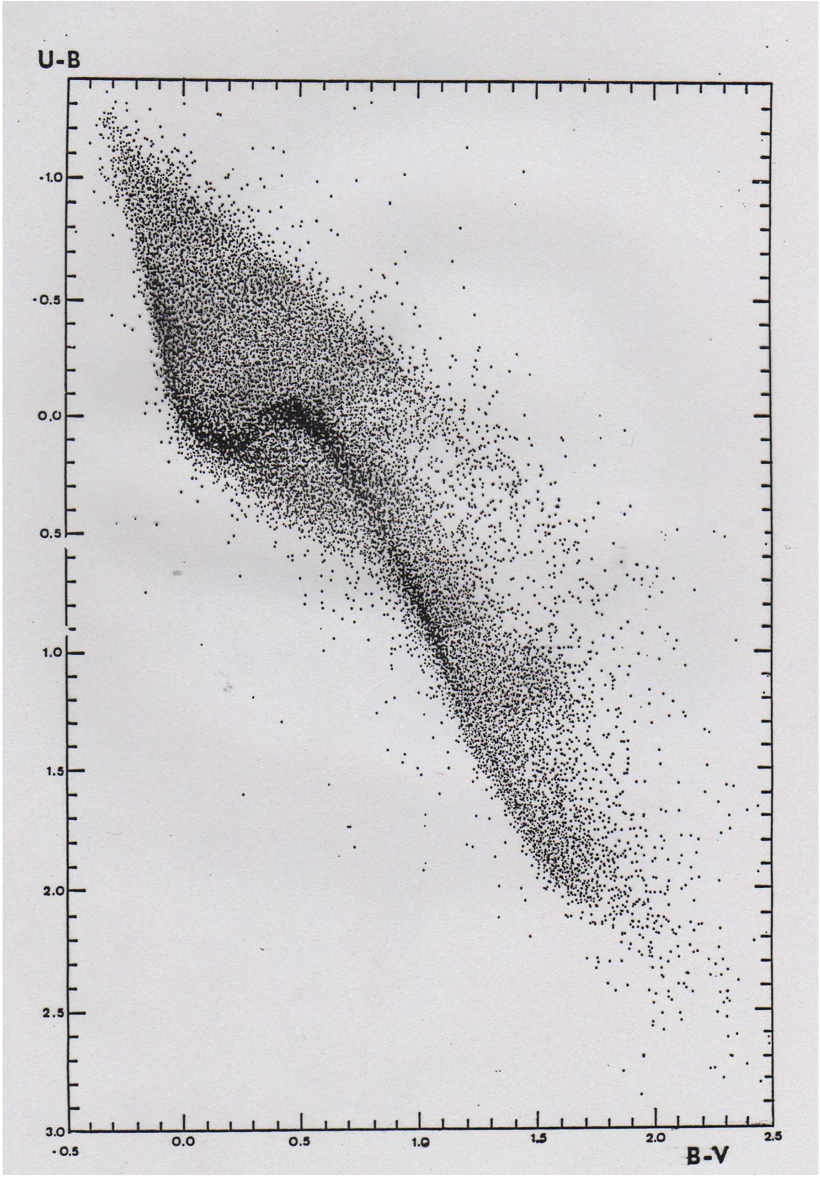
$m_B - M_B = 5 \log(d) - 5 + A_B$
$m_V - M_V = 5 \log(d) - 5 + A_V$

Subtracting:

$(B\text{-}V) = (B\text{-}V)_0 = A_B - A_V$

$E(B\text{-}V) = f(A_V)$ (color excess)

Determining $f(A_V)$ requires multi-wavelength photometry of stars of known intrinsic color.



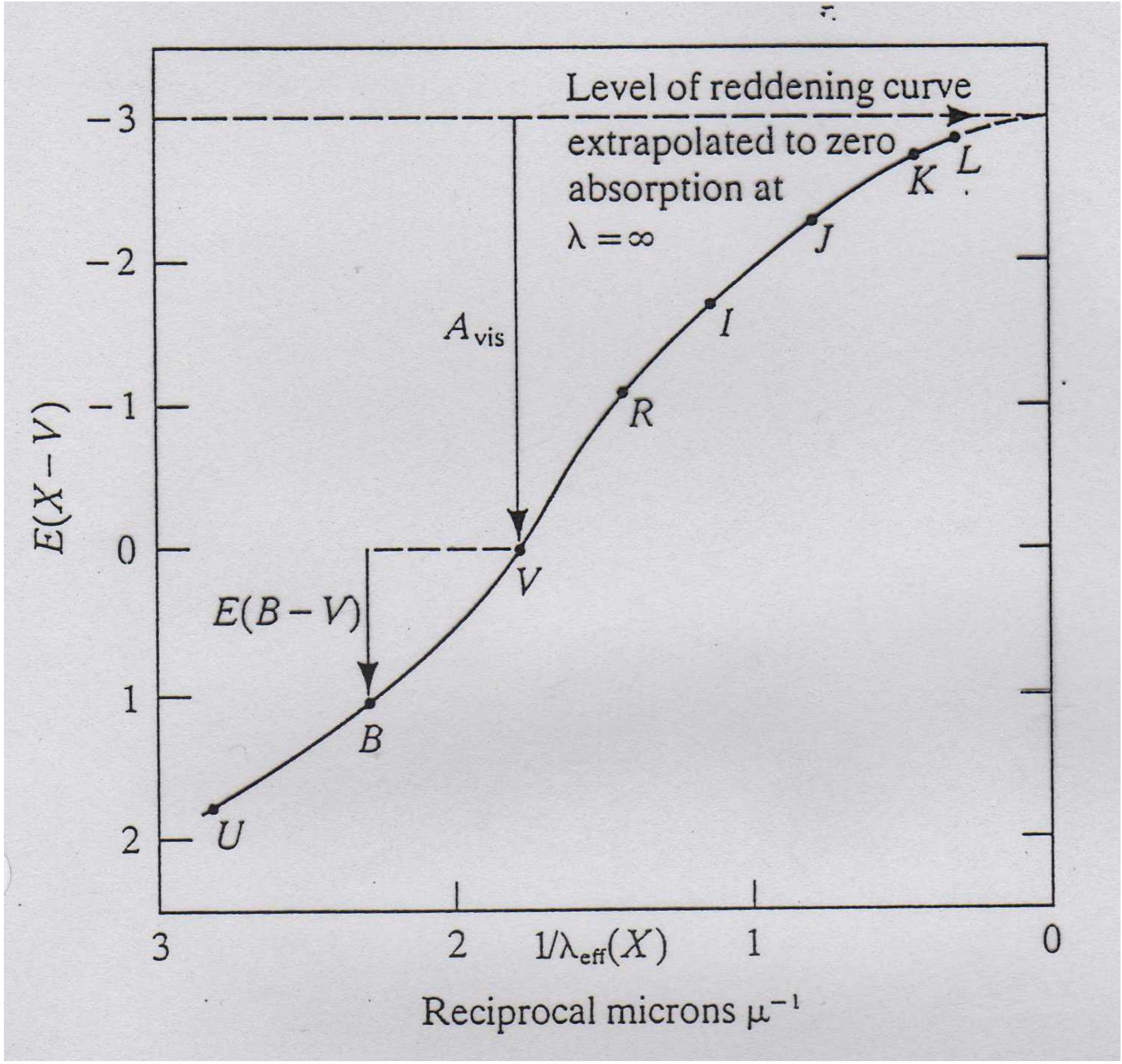
Interstellar Extinction Curve

The differential extinction can be fit with an extinction curve for stars of known color (Spectral Type).

A given amount of extinction, e.g. at V, results in reddening that can be quantified as a color excess E(B-V). In this example:

$A_V = R_V\ E(B\text{-}V)$

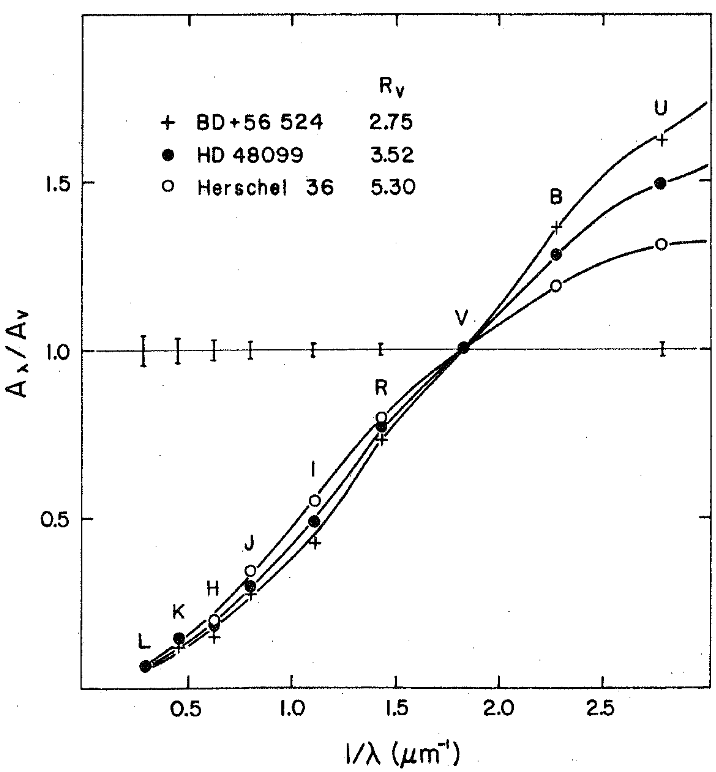
The value of R can be inferred by extrapolating the curve to infinite wavelength since at this point the extinction should go to zero. For the V-band $R_V \sim 3.1$, for the B-band $R_B \sim 4.1$, etc.

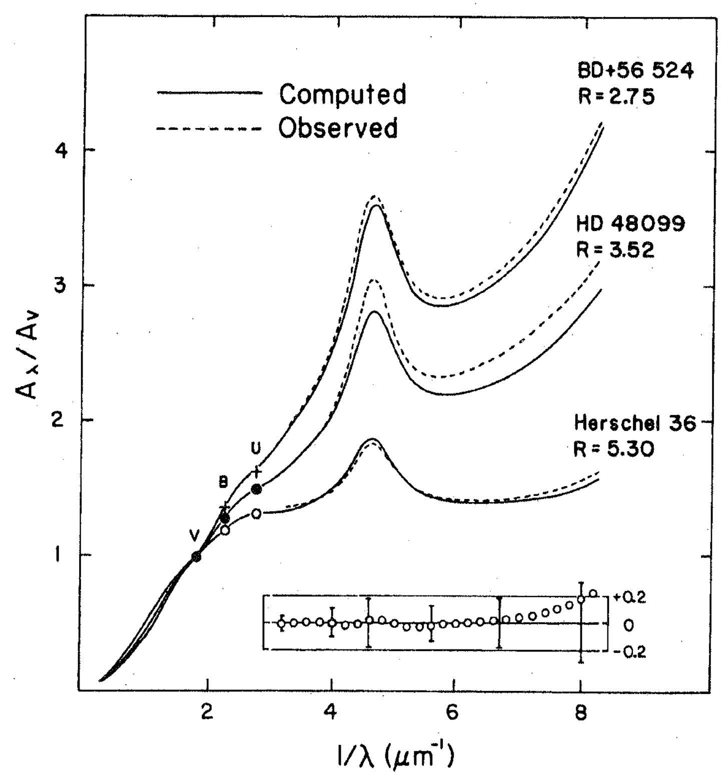


Interstellar Extinction Curve Cont.

One of the more extensive studies is that of Cardelli et al. 1989, ApJ, 345, 245

Unfortunately, they find that the interstellar extinction is <u>not universal</u> but varies for different sight lines! This phenomena is most pronounced in the UV. Thus, one must exercise caution when applying local results to the Galaxy as a whole or even another galaxy.





Bolometric Magnitudes

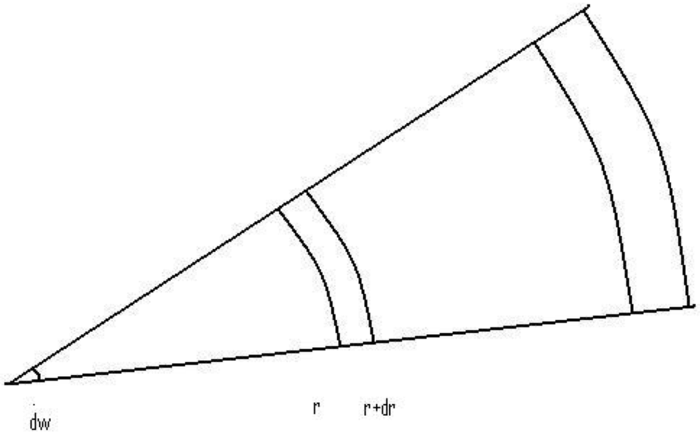
- **The large temperature range of stars means that no single filter band samples the total luminosity so that blue stars and red stars can be easily compared.**
  - **Solution is to measure brightness of the full range of spectral classes from the UV to IR in order to derive their total apparent magnitude. When compared with the V-band the difference is known as the bolometric correction and is a function of stellar spectral type (see Table A4-3).**
  - **Recall that the Sun's integrated flux and distance are known. The flux can be measured over the V-band so we can compute the absolute V magnitude ($M_V = 4.82$).**
  - **The bolometric correction (BC) is defined such that:**

$$M_V - M_{bol} = BC$$

  - **Thus the absolute bolometric magnitude of the Sun is 4.75**

Counting Stars vs. Magnitude

- **Stellar Number Counts vs. Mag. Reveal Distribution**
  - **Consider some solid angel ω.**
  - **For a <u>constant space density</u> lets derive expected N vs. mag. for a given star (M)**



$$\frac{dN}{dm} = \frac{dN}{dV}\frac{dV}{dm} \quad \text{but} \quad \frac{dV}{dm} = \frac{dV}{dr}\frac{dr}{dm} = 4\pi r^2 \frac{dr}{dm}$$

and since $m - M = 5\log(r) - 5$

$$r = 10^{0.2(m-M+5)} \quad \text{so} \quad \frac{dr}{dm} = 10^{0.2(m-M+5)} 0.2\ln 10$$

Combining we have:

$$\frac{dN}{dm} = \rho 4\pi 10^{0.4(m-M+5)} \cdot 10^{0.2(m-M+5)} \cdot 0.2\ln 10 \quad \text{so:}$$

$$\frac{dN}{dm} = \rho\frac{4\pi}{5}\ln 10 \cdot 10^{0.6(m-M+5)}$$

Thus a plot of logN vs. mag (logF) we expect a straight line with a slope of 0.6.

Kapteyn: model log N vs mag with $\rho(r)$ variable.

If logN falls below trend (0.6 slope) it must be due to drop in $\rho(r)$. (really?)

Reading this Week

By Monday:

Finish Reading Chapter 1 in text

Begin Chapter 2