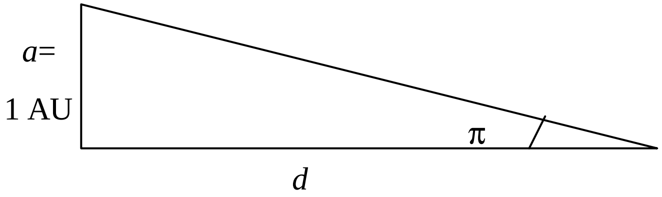
Stars: Observations

Trigonometric Parallax

The only direct distance measurement to a star.



$$p = a/d \quad \Rightarrow \quad p'' = 1/d.$$

π in arcsec and *d* in pc in latter equation.

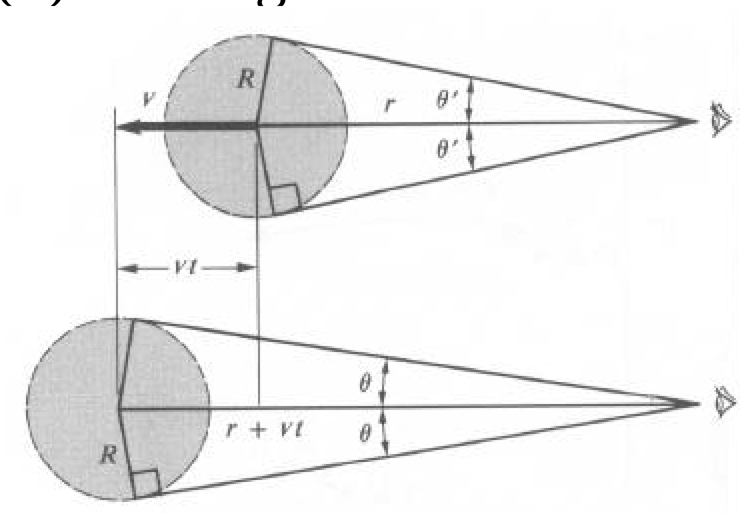
Nearest star, α Centauri π = 0.76” => *d* = 1.3 pc.

π can be measured down to values 0.01”, or *d* = 100 pc.

Fewer than 10,000 measured (500 known well), but > 10^{11} stars in Galaxy, on scales up to 30 kpc.

Other Geometric Methods

(1) Moving cluster method:



Measure change in apparent angular size of a cluster.

$$r = [vt \sin q]/[\sin q' - \sin q]$$

$$\Rightarrow r \cong vtq/\Delta q.$$

Works for Hyades cluster, d = 43 pc, and a few others.

(2) Mean motion of the Sun: Sun’s motion in the Galaxy (4.1 AU/yr) provides a parallax over time. Measure mean parallax of a group of stars.

Luminosity Distances

If we can estimate intrinsic luminosity *L* and measure flux *f*, use

$$f = \frac{L}{4p\, d^2}$$ to get distance *d*.

Magnitude Scale

Based on Hipparchus’ scale ~ 2000 yr ago.

Brightest - 1st mag, faintest - 6th mag.

5 mag difference = factor of 100 in brightness => 1 mag difference = factor $100^{1/5}$=2.51 in brightness.

A logarithmic scale, like human eye response.

$$f \to 10 f \to 100 f$$
$$m \to m + 2.5 \to m + 5$$

Equal ratios of actual intensity correspond to equal intervals in magnitude.

Magnitude Scale

Keep the historical scale but extend to brighter ($m < 1$) and fainter ($m > 6$) objects. Modern scale defined by

$$m_2 - m_1 = 2.5 \log_{10}\left(\frac{f_1}{f_2}\right),$$ where m_1 and m_2 are apparent magnitudes.

Key elements of magnitude scale:

(1) scale is logarithmic

(2) brighter objects have smaller magnitudes (even negative)

(3) an object has relatively low apparent magnitude if it has high luminosity and/or is close to us.

Apparent Magnitudes

Object	magnitude
Sun	-26.5
Full moon	-12.5
Venus	-4
Jupiter	-2
Mars	-2
Sirius	-1.5
Aldebaran	1
Altair	1
Naked-eye limit	6.5
Binocular limit	10
15 cm telescope	13
5 m telescope (visual)	20
5 m photographic limit	24

Δm	f_1/f_2
0.5	1.6
1	2.5
1.5	4
2	6.3
4	40
5	100
6	251
10	10,000
20	100,000,000
25	10,000,000,000

$$\frac{f_1}{f_2} = 10^{2/5(m_2 - m_1)}$$

Absolute Magnitude

Since apparent magnitude depends on distance, need a true measure of a star's luminosity.

Absolute magnitude *M* = apparent magnitude if star is at distance *D* = 10 pc from the Sun; a measure of true luminosity. If *d* = actual distance, then

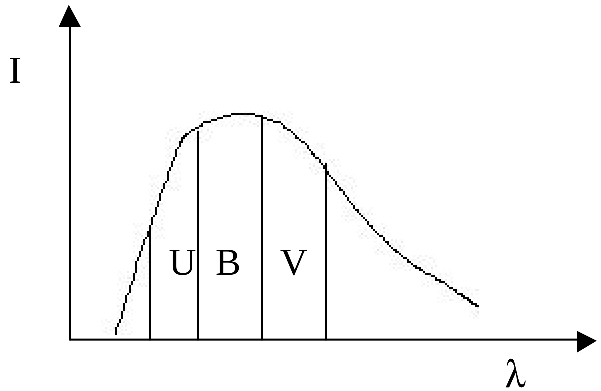
$$f = \frac{L}{4p\, d^2} \Rightarrow \frac{f_M}{f_m} = \left(\frac{d}{10}\right)^2, \quad \text{where } d \text{ is in pc.}$$

$$\therefore m - M = 2.5\log\left(\frac{d}{10}\right)^2 = 5\log\left(\frac{d}{10}\right),$$ often called the "distance modulus".

Can get *M* (i.e., *L*) if we measure *m* (i.e., *f*) and know *d*.

Magnitudes at Different Wavelengths

Detectors usually sensitive to particular wavelength bands.



A star's blackbody (BB) spectrum.

Take $\Delta\lambda$=100 nm, and center bands at 365 nm, 440 nm, and 550 nm => UBV photometry.

If spectrum approx. BB, ratio of fluxes at different λ's => temperature.

Measure apparent magnitudes U, B, V. If know d, get absolute magnitudes M_U, M_B, M_V.

Color index (CI): $U - B\ (= M_U - M_B) = \text{constant} + 2.5\log(f_B / f_U)$,

$$B - V\ (= M_B - M_V) = \text{constant} + 2.5\log(f_V / f_B).$$

Pick constant so that U - B = B - V = 0 for $T=10^4$ K.

So, "hot" stars ($T > 10^4$ K) have CI < 0, and "cool" stars ($T < 10^4$ K) have CI > 0.

Bolometric Magnitude

Total (bolometric) flux $f_{bol} = \int f(l)\, dl$.

Use to get an apparent bolometric magnitude

$$m_{bol} = m_V + 2.5\log\left(\frac{f_V}{f_{bol}}\right),$$

Can also get M_{bol} if know d. In practice:

(1) Measure m_V or M_V for a star.

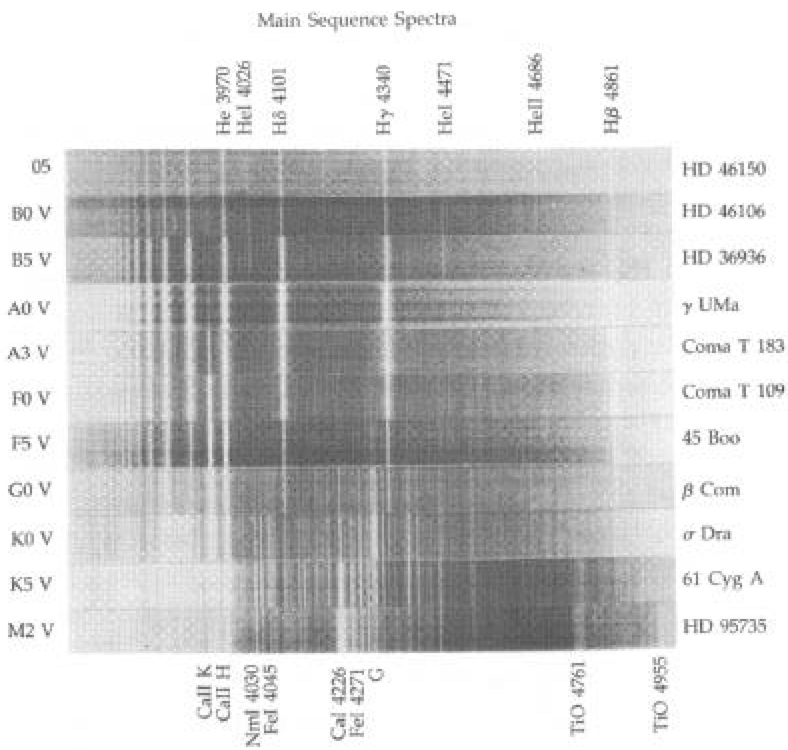
(2) use theoretical models for the inferred type of star to estimate total luminosity L_{bol} or flux f_{bol}.

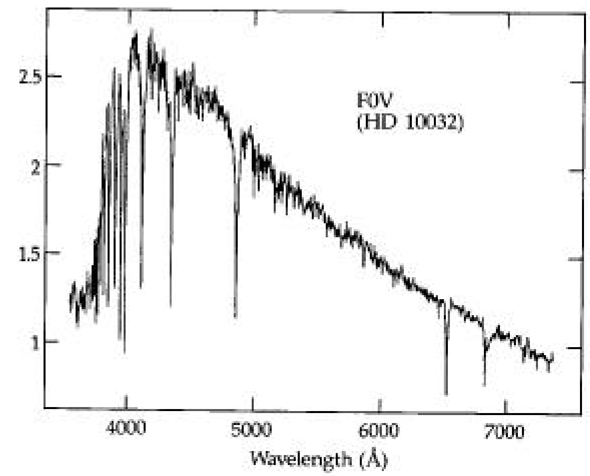
(3) estimate bolometric correction (BC) and get M_{bol};

$M_{bol} = M_V + BC$, where $BC = m_{bol} - m_V = M_{bol} - M_V = -2.5\log\left(f_{bol} / f_V\right)$.

Note: BC hard to estimate when only a small fraction of star's energy radiated in V band. BB curve peaks in V when T= 6700 K.

Classifying Stellar Spectra





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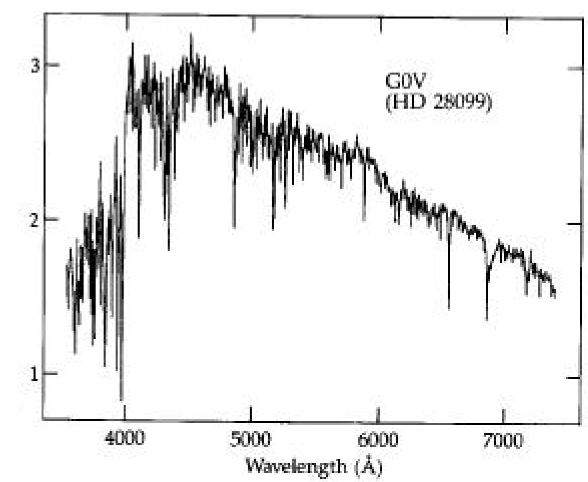


(C)

Can classify stars into several broad categories based on their spectral line patterns.

Stellar Spectra

Classification yields information about

(1) temperature (to 1st approximation, Sp type <=> temperature)

and also

(2) luminosity

(3) chemical abundances

(4) velocity, rotation, mass inflow/outflow, magnetic fields

Spectral classification system (early 1900’s at Harvard, Annie J. Cannon) based on spectra of ~ 400,000 brightest stars.

1st try: order according to Balmer line strengths, A to P, with A strongest and P weakest. Later, some letters dropped and reordered to correspond to decreasing temperature sequence.

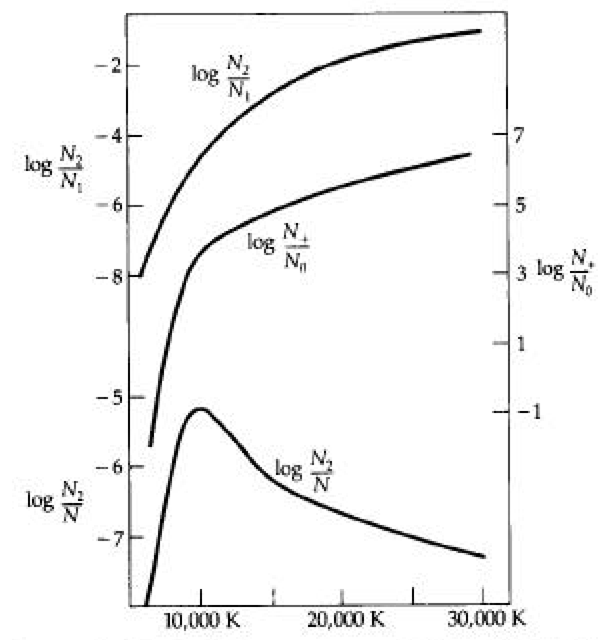
Spectral Types

O B A F G K M

hottest (O) Balmer lines peak (A) coolest (M)

"early type" ⟶ "late type"

Recall Boltzmann and Saha eqn.'s =>
n=2 state most populated at T = 10^4 K.



Each spectral type has 10 subclasses, 0 - 9,

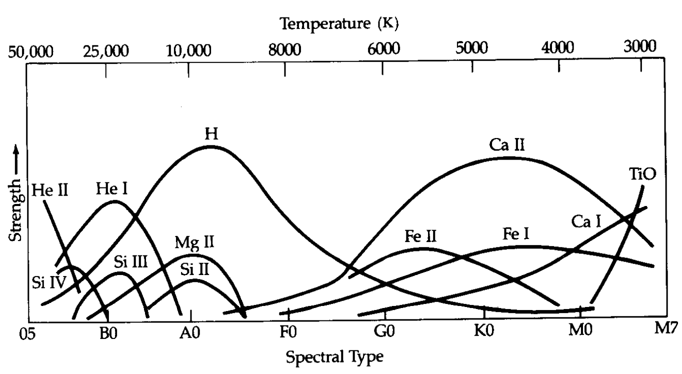
e.g., O0…O9, B0…B9, A0,…A9, etc.

Sun is type G2.

Spectral Types

The Harvard Spectral Sequence:

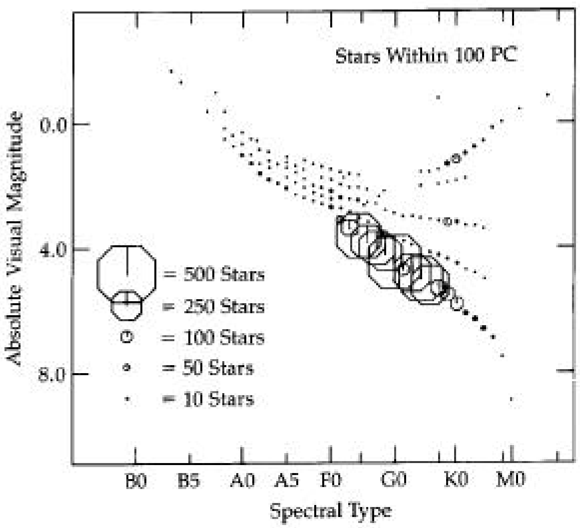
Spectral Type	Principal Characteristics
O	Hottest bluish-white stars; relatively few lines; He II dominates
B	Hot bluish-white stars; more lines; He I dominates
A	White stars; ionized metal lines; hydrogen Balmer lines dominate
F	White stars; hydrogen lines declining; neutral metal lines increasing
G	Yellowish stars; many metal lines; Ca II lines dominate
K	Reddish stars; molecular bands appear; neutral metal lines dominate
M	Coolest reddish stars; neutral metal lines strong; molecular bands dominate

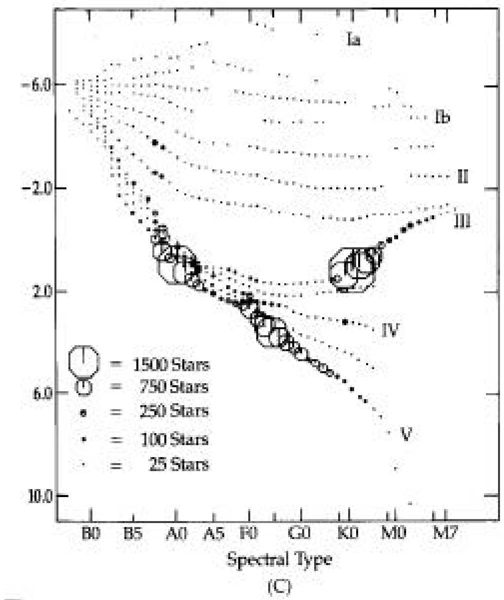


Strength of various spectral lines at different temperatures (Sp type).

Hertzsprung-Russell (H-R) diagram

For nearby stars, know absolute magnitude (due to parallax) as well as Sp type. Plot M_V vs. Sp type => H-R diagram ~1911-1913.



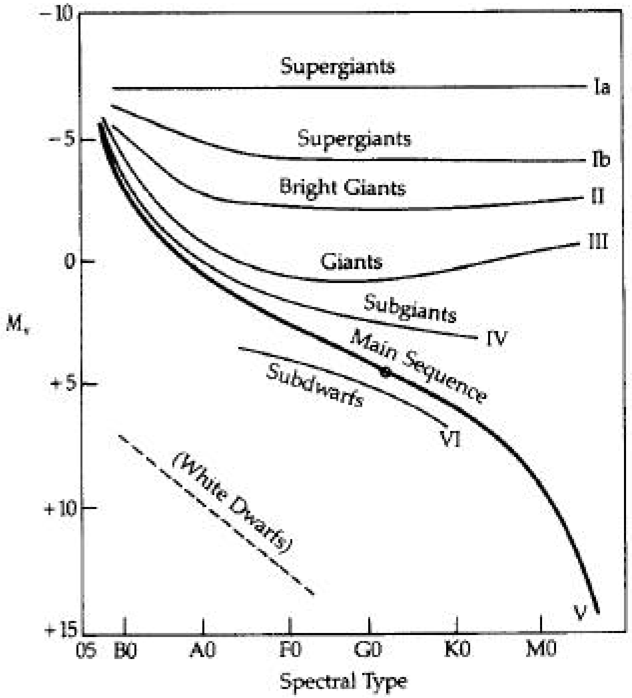


36,000 stars

~ 90% of nearby stars fall on main sequence. But notable exceptions exist. For some Sp types, a few stars have very different luminosities.

Luminosity Classes

Morgan-Keenan (M-K) classification scheme - purely empirical; subclasses also exist.



Sun is a G2V (or G2 dwarf) star.

For a given Sp type, higher *L* stars have (1) much narrower spectral lines, and (2) stronger ionized species lines.

Note that higher *L* with the same *T* implies larger radius *R*, since

$L = 4\pi R^2 \sigma T^4$. Hence "giants."

Luminosity Classes

Explanation of features (1) and (2) of giants:

$$g_{surface} = \frac{GM}{R^2}$$ much smaller than for dwarfs, e.g., G2 supergiant is 12.5 mag brighter than the Sun.

Why? $$\frac{L_{SG}}{L_{Sun}} = 10^5 \Rightarrow \frac{R_{SG}}{R_{Sun}} = \left(10^5\right)^{1/2} = 10^{2.5}.$$

For a reasonable M_{SG}/M_{Sun} ratio (<100), find $$\frac{g_{SG}}{g_{Sun}} \approx 10^{-4}.$$

Therefore, photospheric gas pressure and density also much lower.

Less collisional (pressure) broadening of spectral lines explains feature (1), and lower electron density N_e means greater N_+/N_0 ratio in Saha equation for a given T, explaining feature (2).

Luminosity Classes

What about the subdwarfs?

Empirically, if know T and g in atmosphere, can predict line strengths. Then, if line strengths don't match, change abundance until match. Abundance = relative mass fractions of H (called X), of He (called Y) and of metals (called Z). This lead to discovery of two populations of stars.

Pop I: $Z \sim 0.02$, metal rich, younger, and located nearby and in Galactic disk.

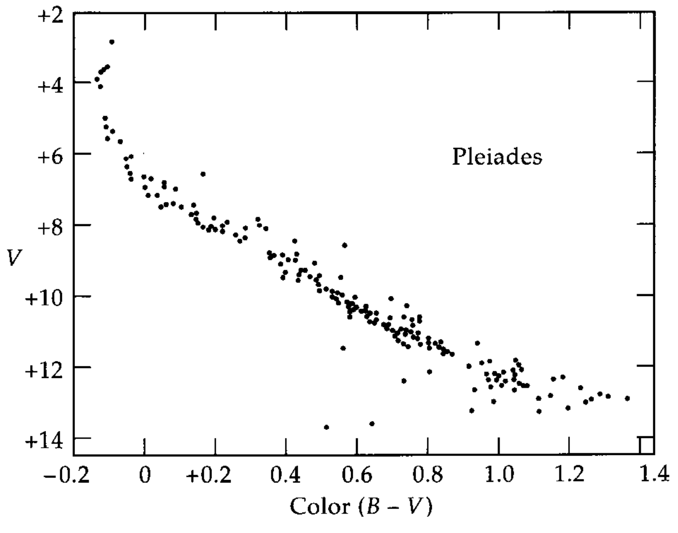
Pop II: $Z \sim 0.001$, metal poor, older, located mainly in Galactic halo.

Subdwarfs are Pop II stars; fewer heavy elements make them appear slightly hotter and bluer due to less line blanketing.

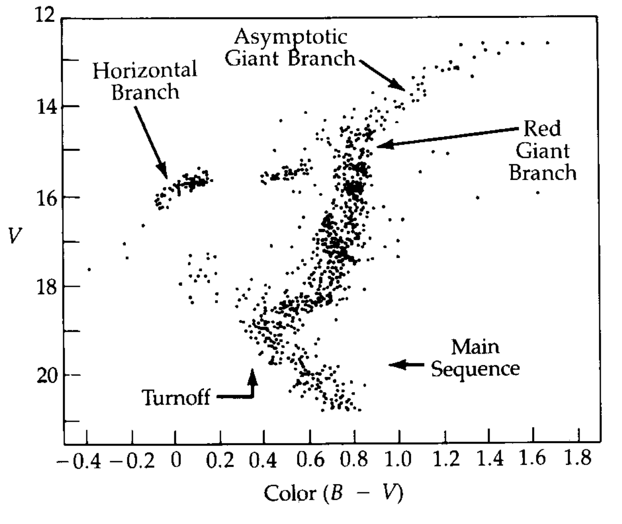
Color-magnitude diagrams

A quicker route to H-R diagram: use color indices (e.g., *B*-*V*), which correlate roughly with Sp type or temperature. Plot color index vs. absolute magnitude.

This method has pitfalls, since e.g., *B*-*V* not a good indicator for very hot or very cool stars. But colors are much easier to measure!



An <u>open</u> (or <u>galactic</u>) <u>cluster</u>. Younger stars with more heavy elements.



A <u>globular cluster</u>. Older stars with fewer heavy elements.

Star Clusters

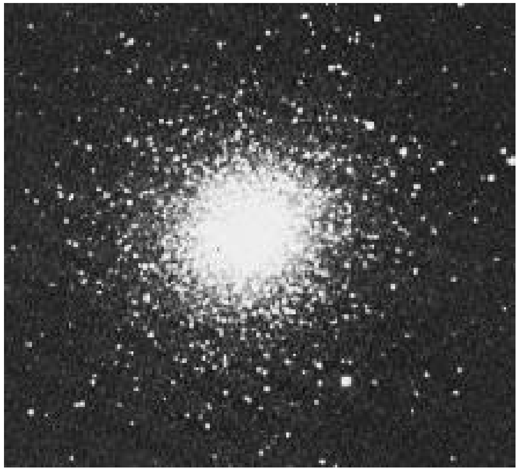
Groups of stars, held together by self-gravity. Two types:

(1) Open (galactic) clusters - ~10^2-10^4 stars, found close to Galactic plane, pop I

(2) Globular clusters - ~10^5-10^6 stars, large heights above Galactic plane, pop II, oldest observed objects in the universe.

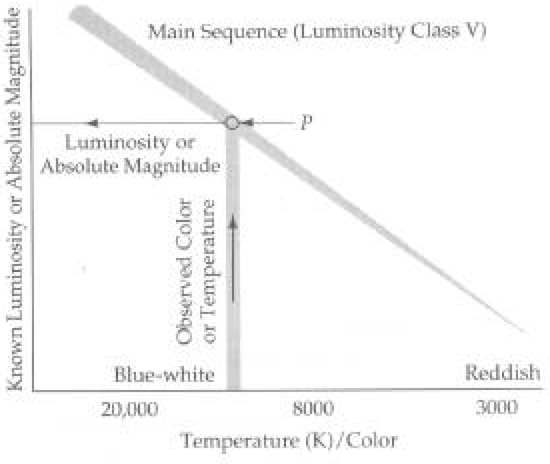
Both (1) and (2) are easily recognized, allow distance determinations and testing of stellar evolution theories.

Open cluster M6

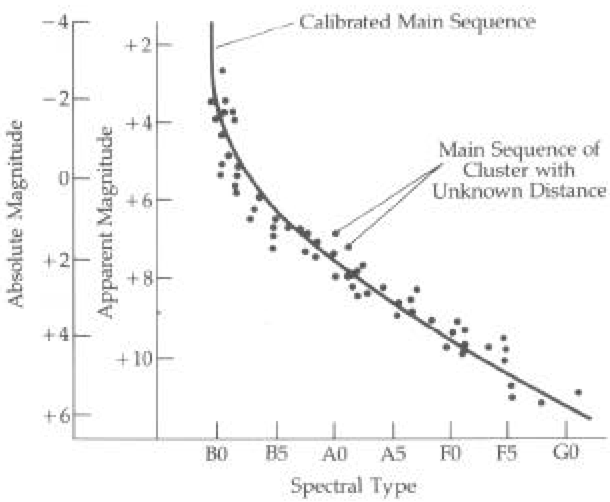


Globular cluster M2

Distance determinations to Clusters



(A)



(B)

Sp type can be used to estimate absolute mag *M* of a star. Compare to apparent mag *m* to determine distance *d* for a main sequence star (<u>spectroscopic parallax</u>).

Better yet, find the offset between *m* and *M* for an entire cluster main sequence (<u>main-sequence fitting</u>). Use to get *d* for the cluster. This minimizes errors.

Note that both rely on a well-calibrated H-R diagram (e.g., from parallax or moving cluster method).