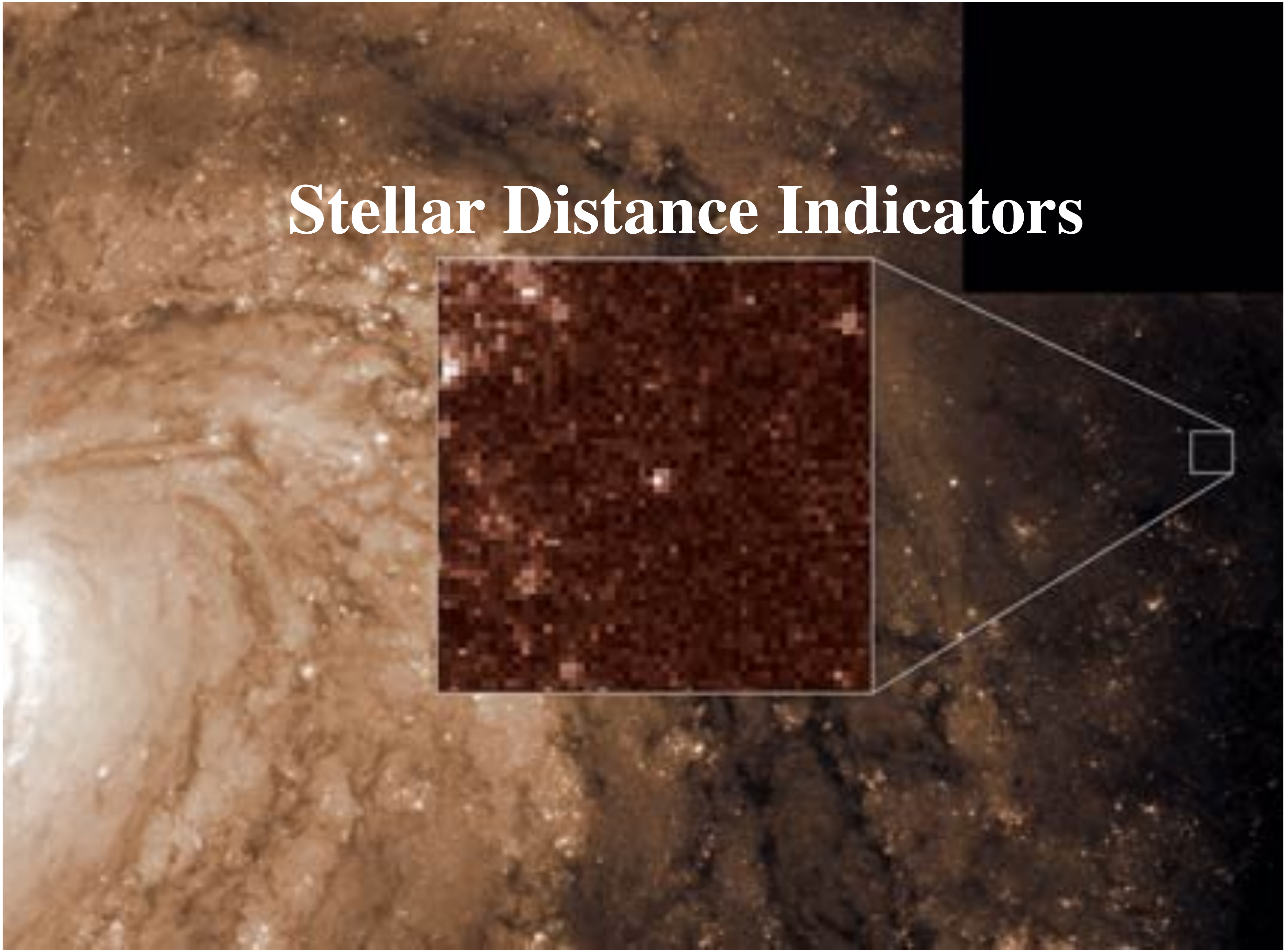
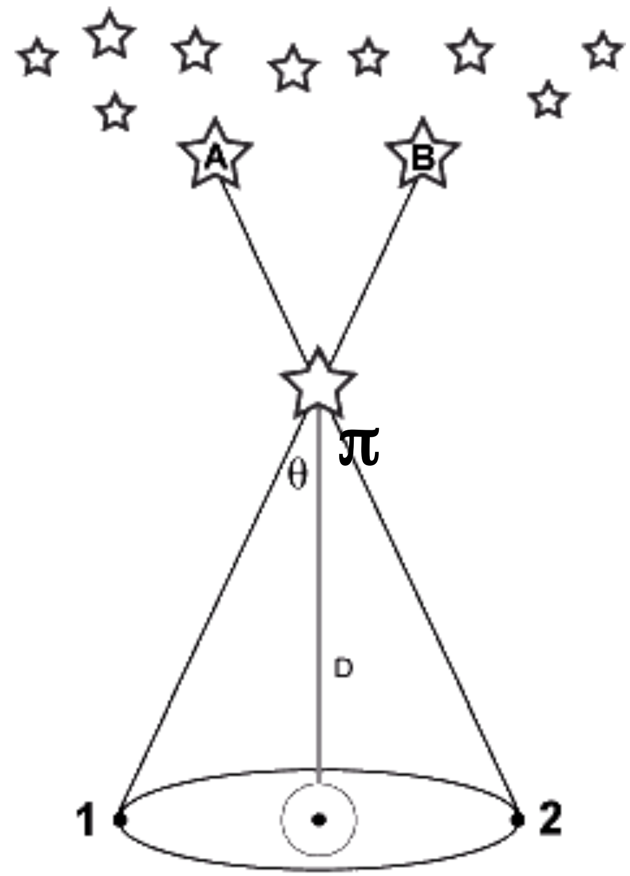
Stellar Distance Indicators



Trigonometric Parallax

- Straightforward, geometric, and the only "true" method - the fundament of the distance scale
- Measure the shift in observed position of nearby stars relative to background stars as earth moves in orbit around sun
- Can get distances of nearby stars, out to a few hundred pc with milliarcsec precision (achievable with the Hipparcos satellite) for ~ 10^5 stars
- Parallaxes provide absolute calibrations to the next rung of the distance ladder – subdwarfs, Cepheids, nearby star clusters



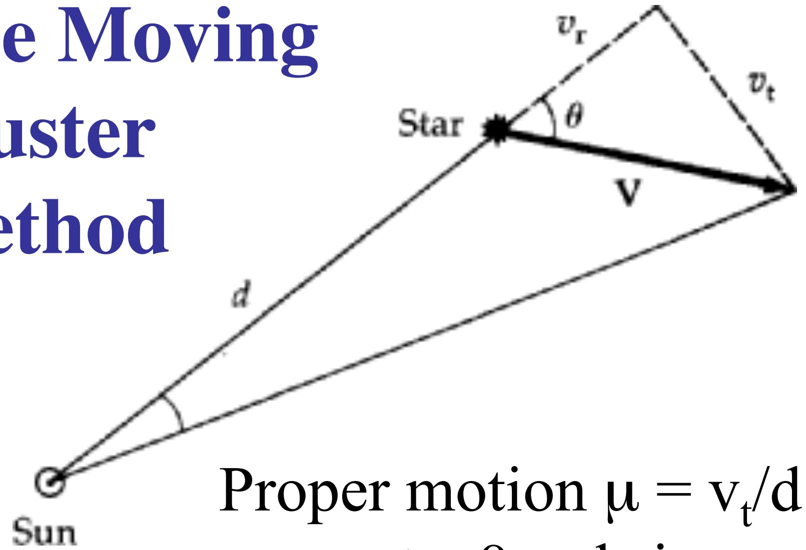
Parallax

D [pc] **= 1 / π** [arcsec]

Moving Cluster Method

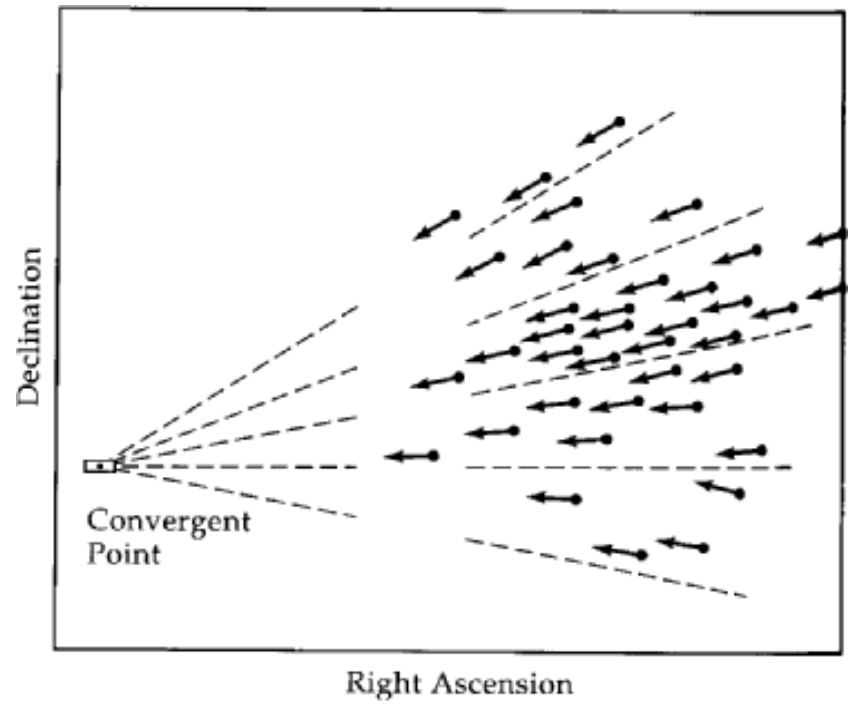
- A geometrical method, with some assumptions
- Nearby clusters of appreciable angular extent (e.g., Hyades) have stellar proper motions which converge to a point in the sky parallel to cluster's mean motion relative to the sun
- This gives the angle between our line of sight and the cluster's motion – what fraction of the motion is tangential (proper motion) and what fraction is radial
- Allows us to calibrate the magnitudes of the stars in the cluster; this calibrates the H-R diagram main sequence
- Can get distances out to the Hyades & Pleiades, young open star clusters, nearly Solar metallicity
- D(Hyades) = 46 ± 2 pc, and from Hipparcos parallaxes D = 46.3 ± 0.3 pc

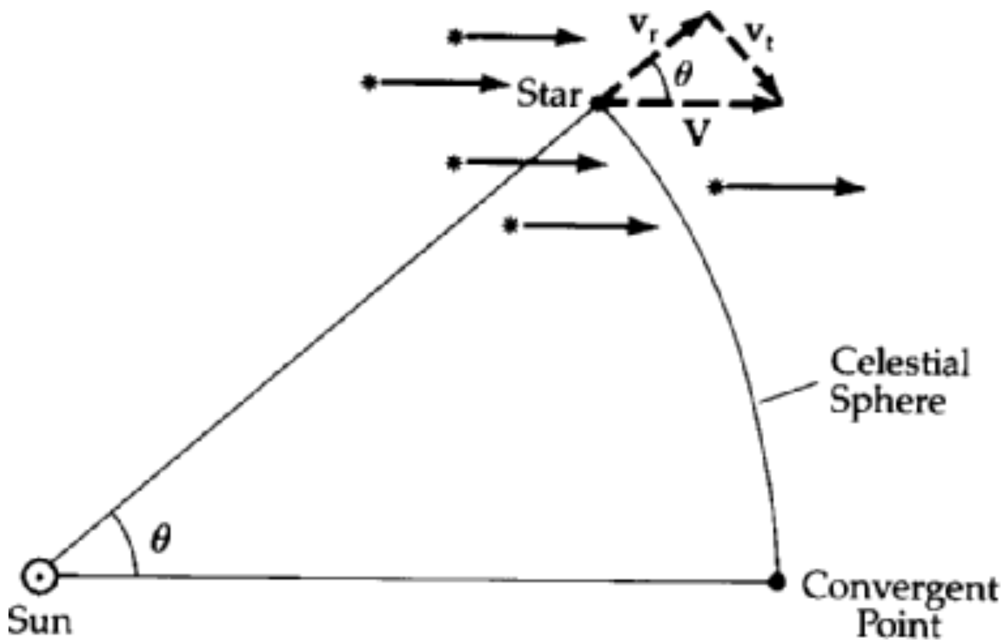
The Moving Cluster Method



Proper motion $\mu = v_t/d$

$v_t = v_r \tan\theta = d \sin\mu \sim d\mu$





$v_t = 4.74\ \mu\ d = (4.74\ \mu) / p$ (km/s)
where p is parallax in arcsec
and μ is proper motion in arcsec/yr

Thus,

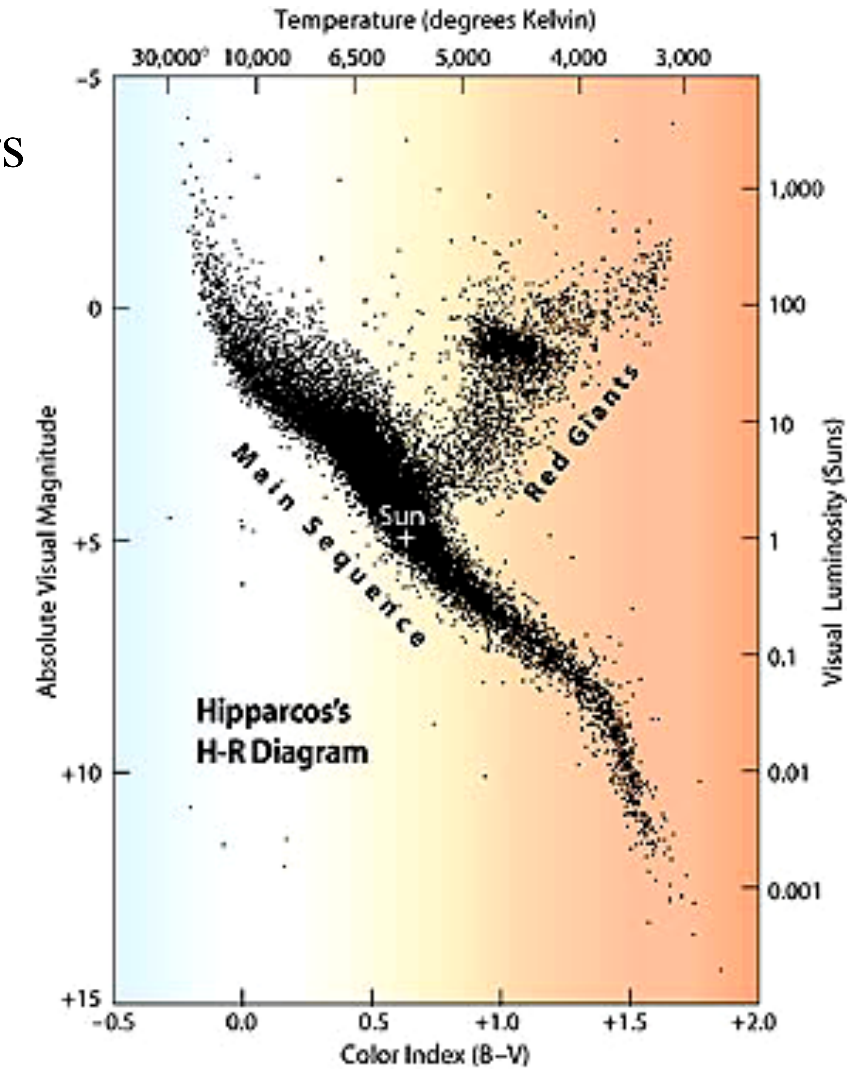
$$d = (\langle v_r \rangle \tan\theta) / (4.74 \langle \mu \rangle)$$

$$p = (4.74 \langle \mu \rangle) / (\langle v_r \rangle \tan\theta)$$

Main Sequence Fitting for Star Clusters

Luminosity (distance dependent) vs. temperature or color (distance independent)

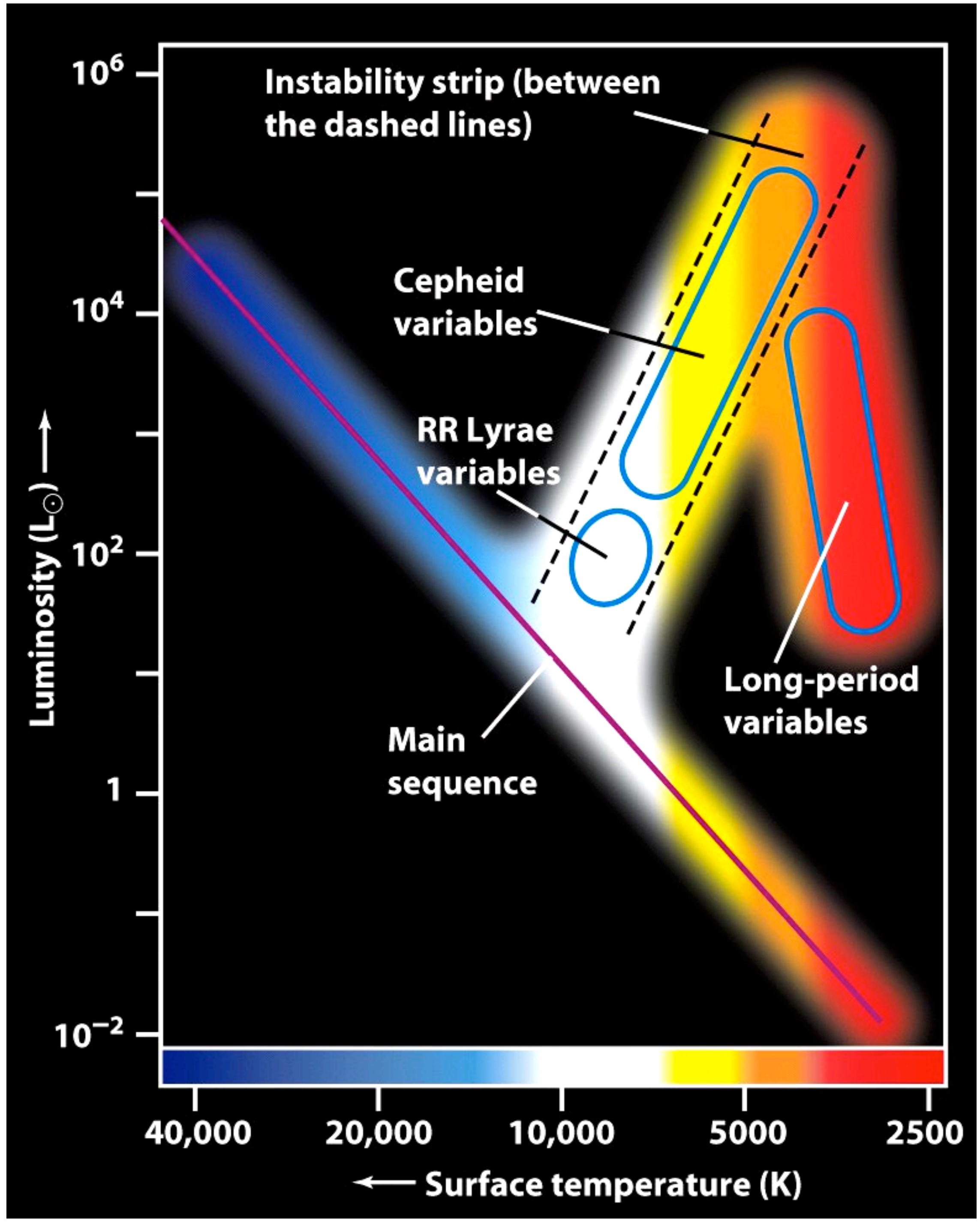
- Can measure distance to star clusters (open or globular) by fitting their main sequence of a cluster with a known distance (e.g., Hyades)
- The apparent magnitude difference gives the ratio of distances, as long as we know reddening!
- There are no parallaxes to GCs (no nearby globulars) so we use parallaxes to nearby subdwarfs (metal-poor main sequence stars)



Hipparcos H-R diagram

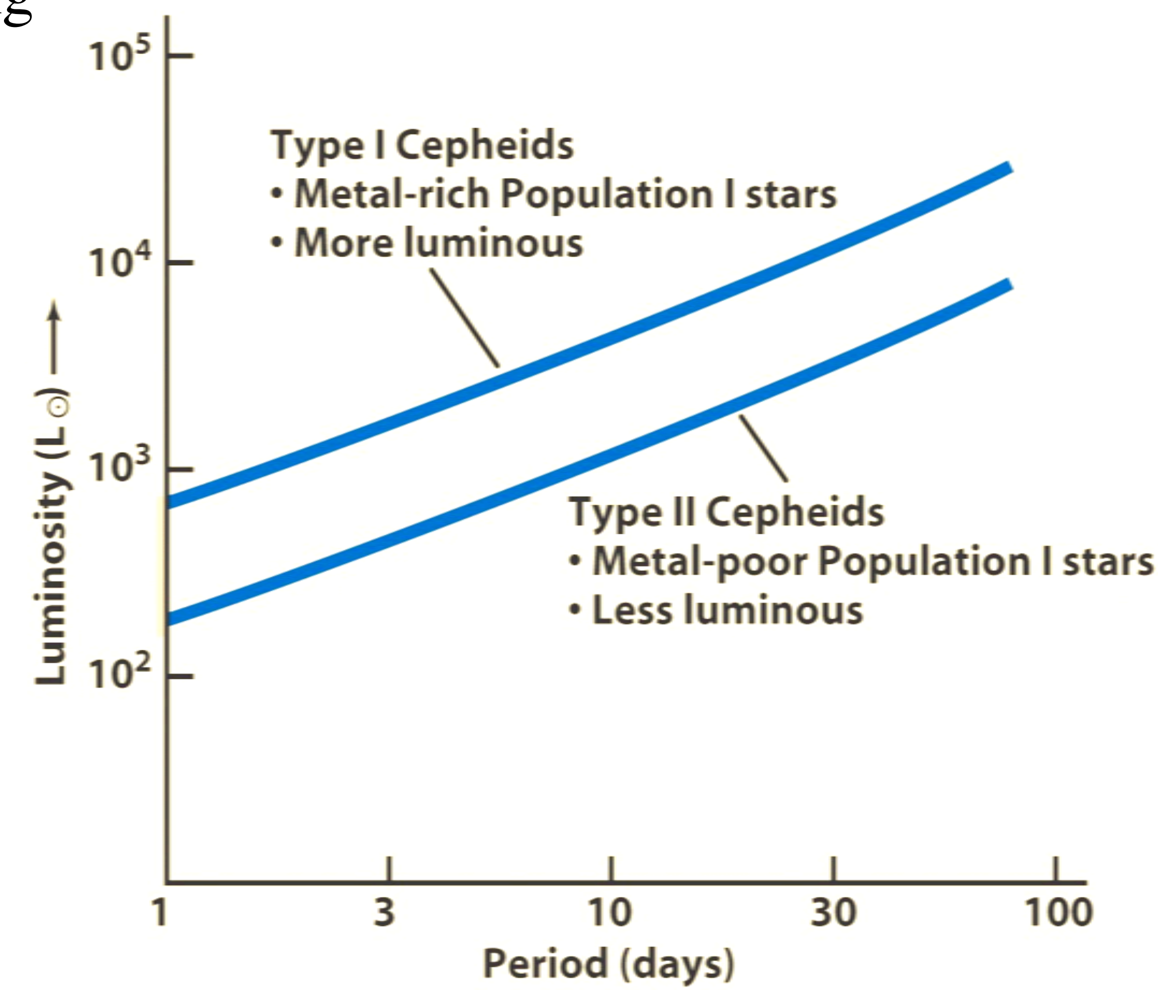
Pulsating Variables

- Cepheids are high-mass, Pop. I stars
- RR Lyrae are low-mass, metal-poor stars, often found in globulars
- Long-period variables (e.g., Miras) pulsate in a fashion that is less well understood
- All obey empirical period-luminosity rel’s which can be calibrated to yield distances



Population I *vs*. Population II

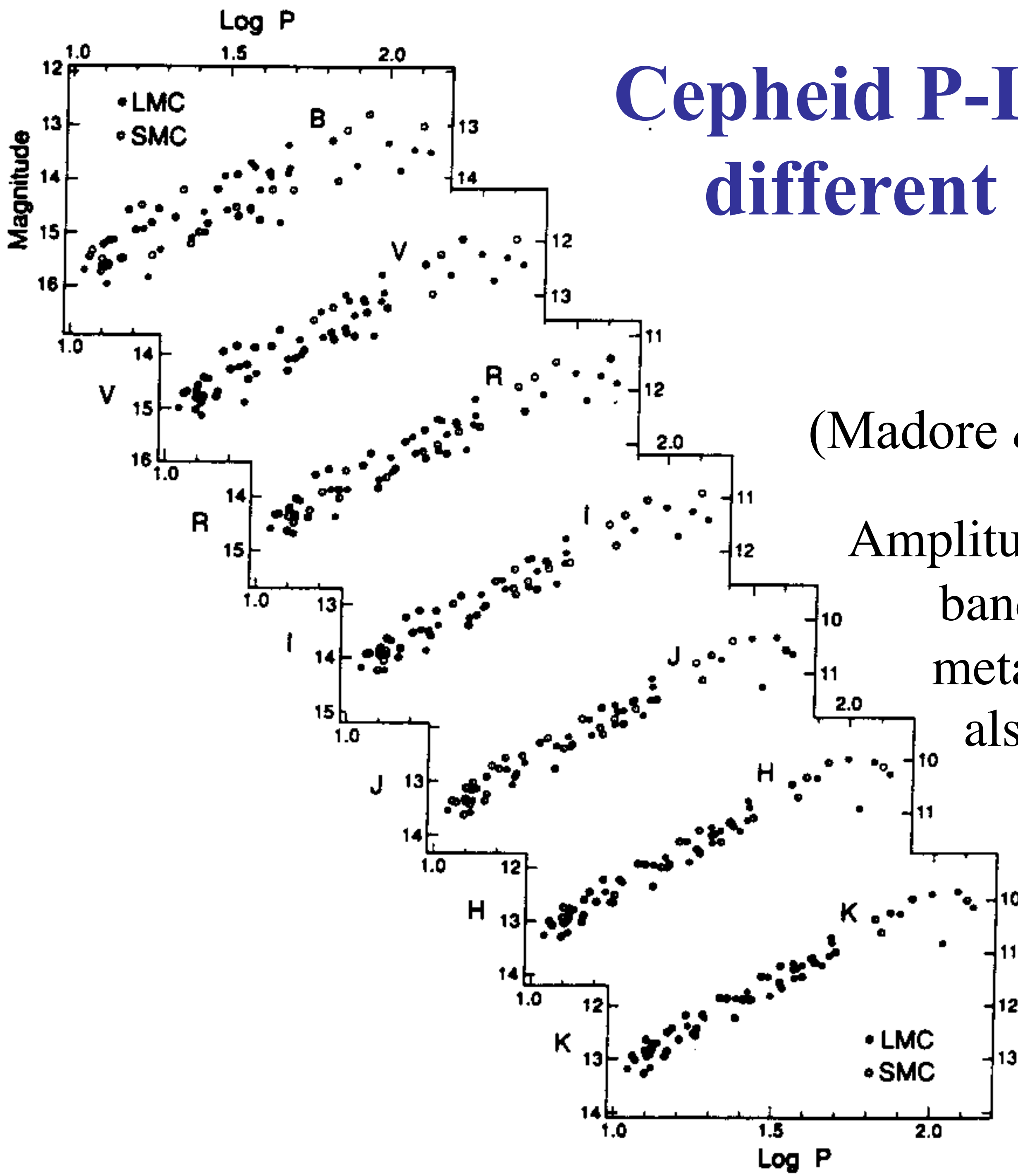
The first major revision in the distance scale was Walter Baade's realization that there are different stellar population - and their most common pulsating variables (classical Cepheids vs. RR Lyrae stars) have vastly different luminosities at the same pulsation periods



Cepheids

- Luminous ($M \sim$ -4 to -7 mag), pulsating variables, evolved high-mass stars on the instability strip in the H-R diagram
- Shown by Henrietta Leavitt in 1912 to obey a period-luminosity relation (P-L) from her sample of Cepheids in the SMC: brighter Cepheids have longer periods than fainter ones
- **Advantages:** Cepheids are bright, so are easily seen in other galaxies, the physics of stellar pulsation is well understood
- **Disadvantages:** They are relatively rare, their period depends (how much is still controversial) on their metallicity or color (P-L-Z or P-L-C) relation; multiple epoch observations are required; found in spirals (Pop I), so extinction corrections are necessary
- P-L relation usually calibrated using the distance to the LMC and now using Hipparcos parallaxes. *This is the biggest uncertainty now remaining in deriving the H_0!*
- With HST we can observe to distances out to ~25 Mpc

Cepheid P-L Relation in different photometric bandpasses



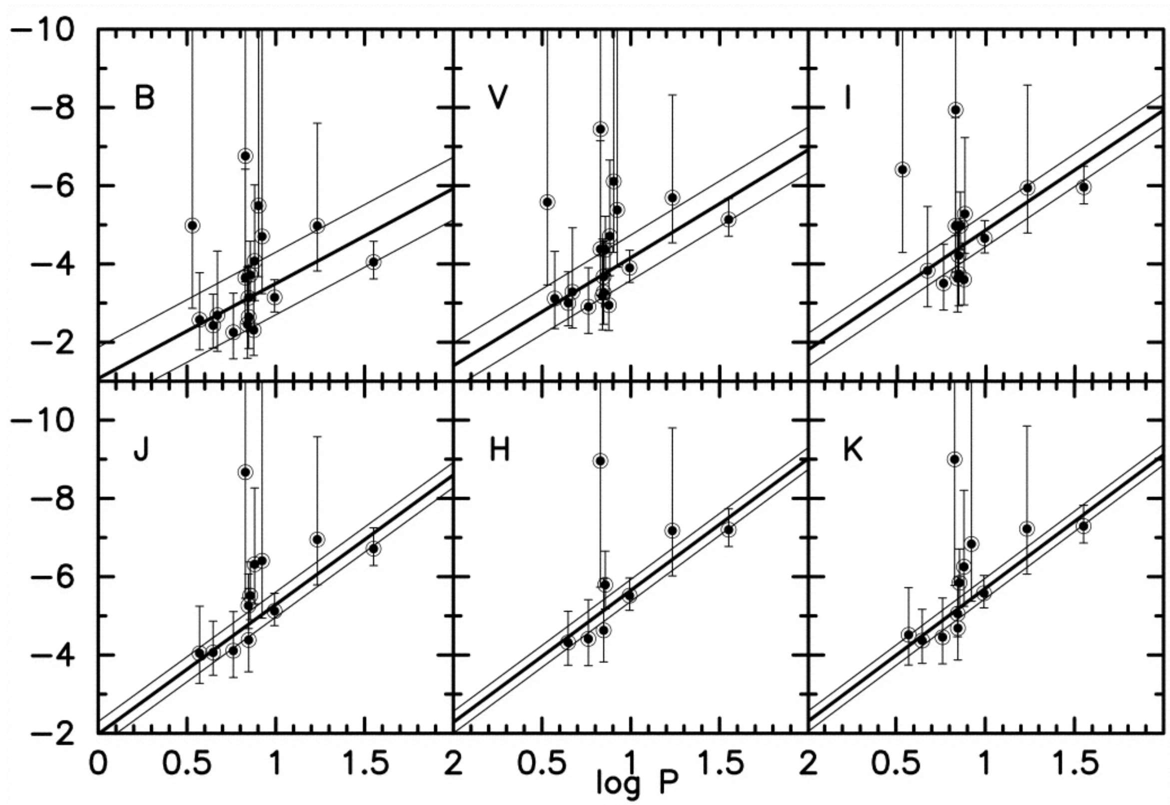
(Madore & Freedman 1998)

Amplitudes are larger in bluer bands, but extinction and metallicity corrections are also larger; redder bands may be better overall

Hipparcos Calibration of the Cepheid Period-Luminosity Relation

P-L relations for Cepheids with measured parallaxes, in different photometric bands

(from Freedman & Madore)



Typical fits give:

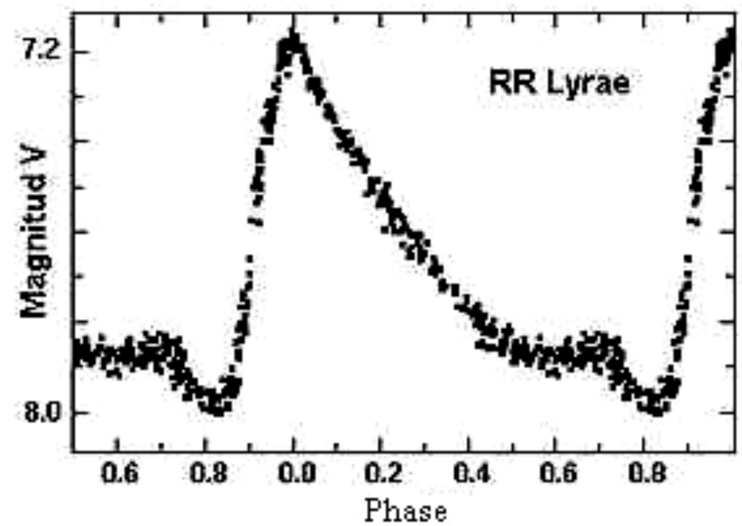
$$\langle M_V \rangle = -2.76 \log P - 1.45$$

$$\langle M_I \rangle = -2.96 \log P - 1.88$$

… with the estimated errors in the range of **~5% - 20%**

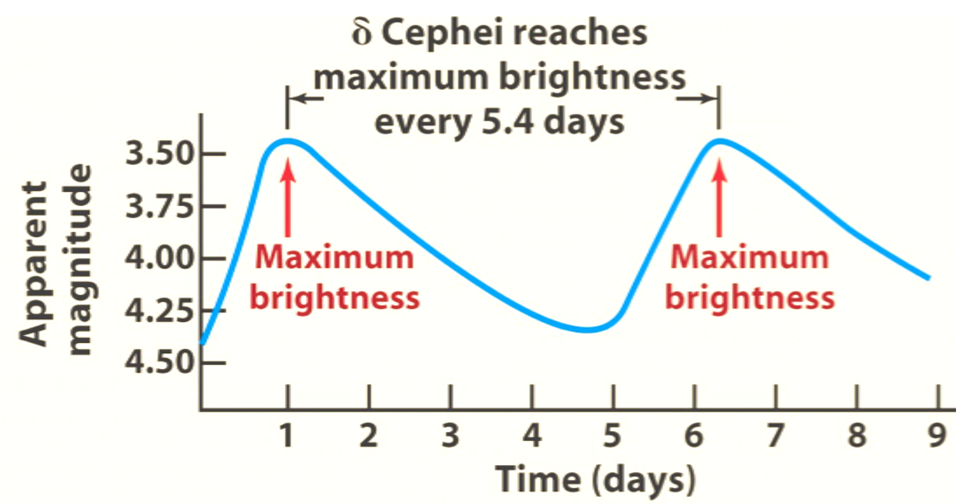
RR Lyrae Stars

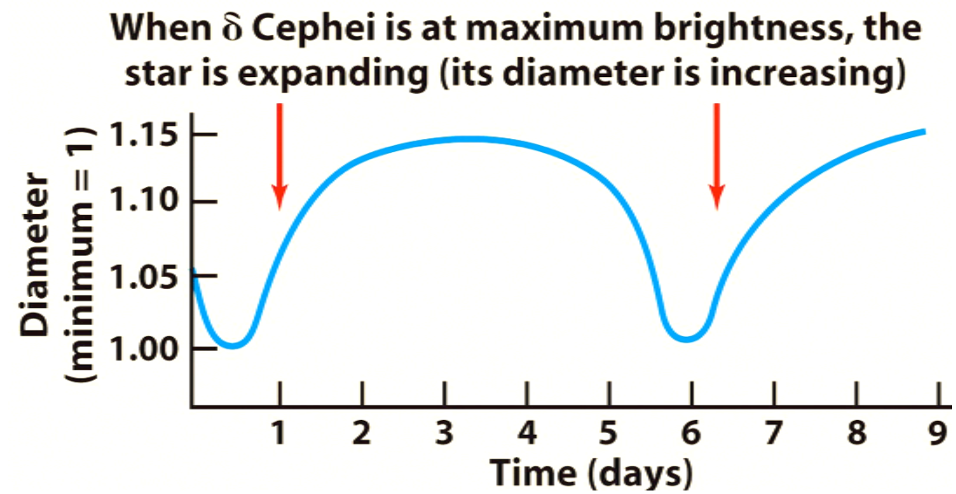
- Pulsating variables, evolved old, low mass, low metallicity stars
  - Pop II indicator, found in globular clusters, galactic halos
- Lower luminosity than Cepheids, $M_V \sim 0.75 +/- 0.1$
  - There may be a metallicity dependence
- Have periods of 0.4 – 0.6 days, so don't require as much observing to find or monitor
- **Advantages:** less dust, easy to find
- **Disadvantages:** fainter (2 mag fainter than Cepheids). Used for Local Group galaxies only. The calibration is still uncertain (uses globular cluster distances from their main sequence fitting; or from Magellanic Clouds clusters, assuming that we know their distances)

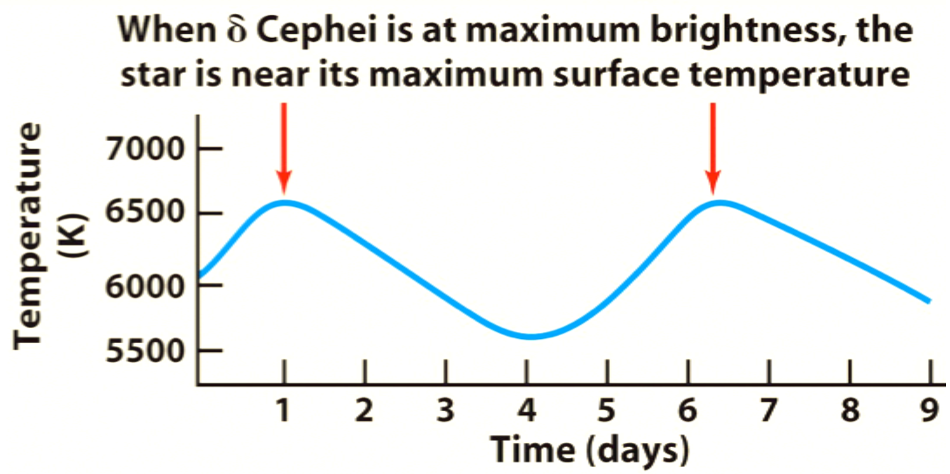


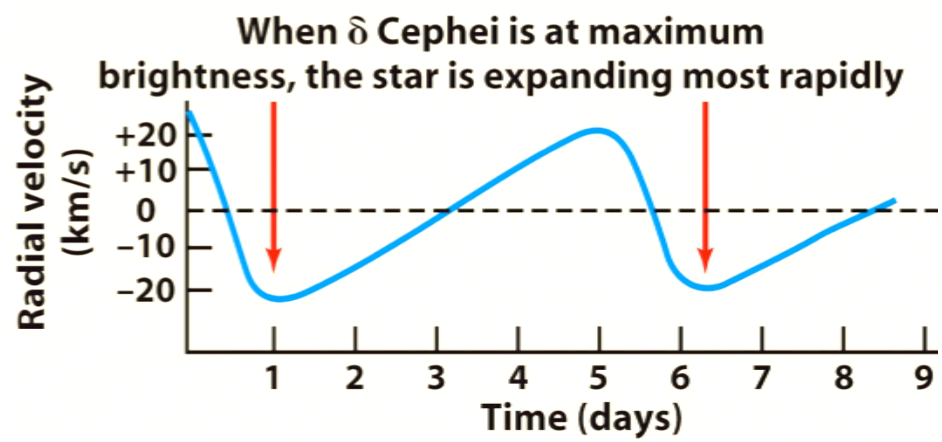
Physical Parameters of Pulsating Variables

Star's diameter, temperature (and thus luminosity) pulsate, and obviously the velocity of the photosphere must also change









Baade-Wesselink Method

Consider a pulsating star at minimum, with a measured temperature T_1 and observed flux f_1 with radius R_1, then:

$$f_1 = \frac{4\pi R_1^2 \sigma T_1^4}{4\pi D^2}$$

Similarly at maximum, with a measured temperature T_2 and observed flux f_2 with radius R_2:

$$f_2 = \frac{4\pi R_2^2 \sigma T_2^4}{4\pi D^2}$$

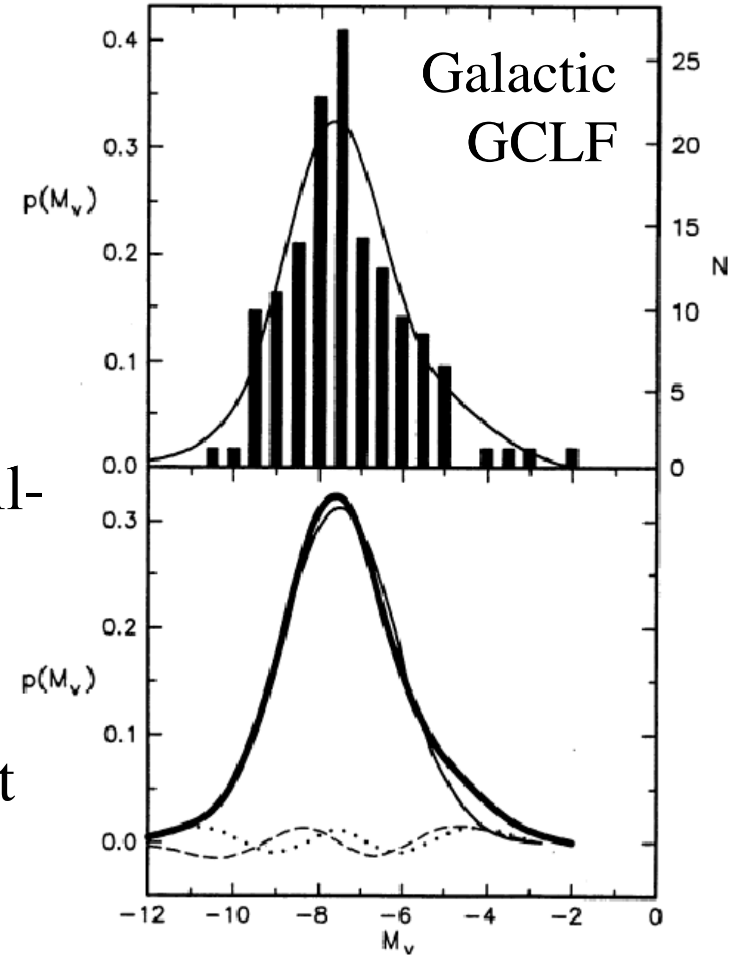
Note: T_1 , T_2 , f_1 , f_2 are directly observable! Just need the radius…
So, from spectroscopic observations we can get the photospheric velocity $v(t)$, from this we can determine the change in radius, ΔR:

$$R_2 = R_1 + \Delta R = R_1 + \int_{t_1}^{t_2} v(t)\, dt$$

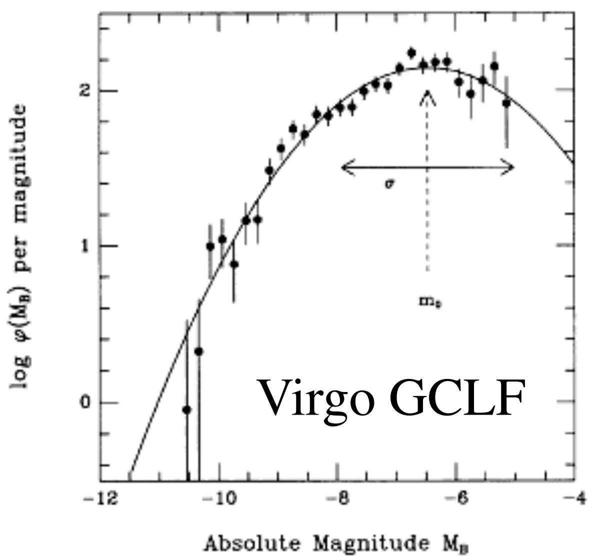
➞ **3 equations, 3 unknowns, solve for R_1, R_2, and D!**

Difficulties lie in modeling the effects of the stellar atmosphere, and deriving the true radial velocity from what we observe.

Globular Cluster Luminosity Function



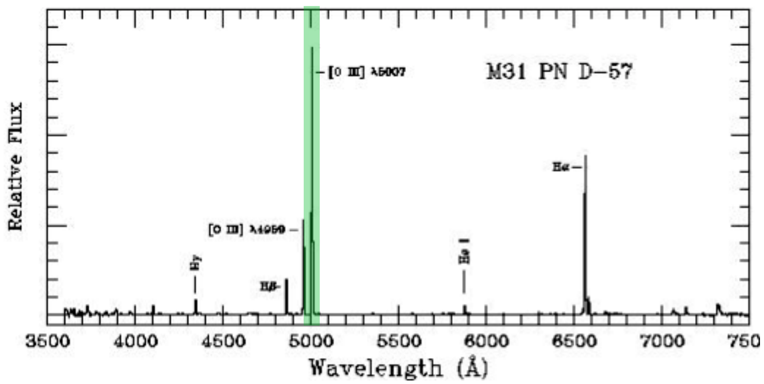
- GC's have a characteristic luminosity function, roughly log-normal, with a well defined peak ($M_B = -6.6 \pm 0.3$)
- GCLF is empirical, physical basis not well-understood
- **Advantages:** GCs are luminous, easy to find in elliptical galaxies, measuring the turnover possible out to 200 Mpc. No dust



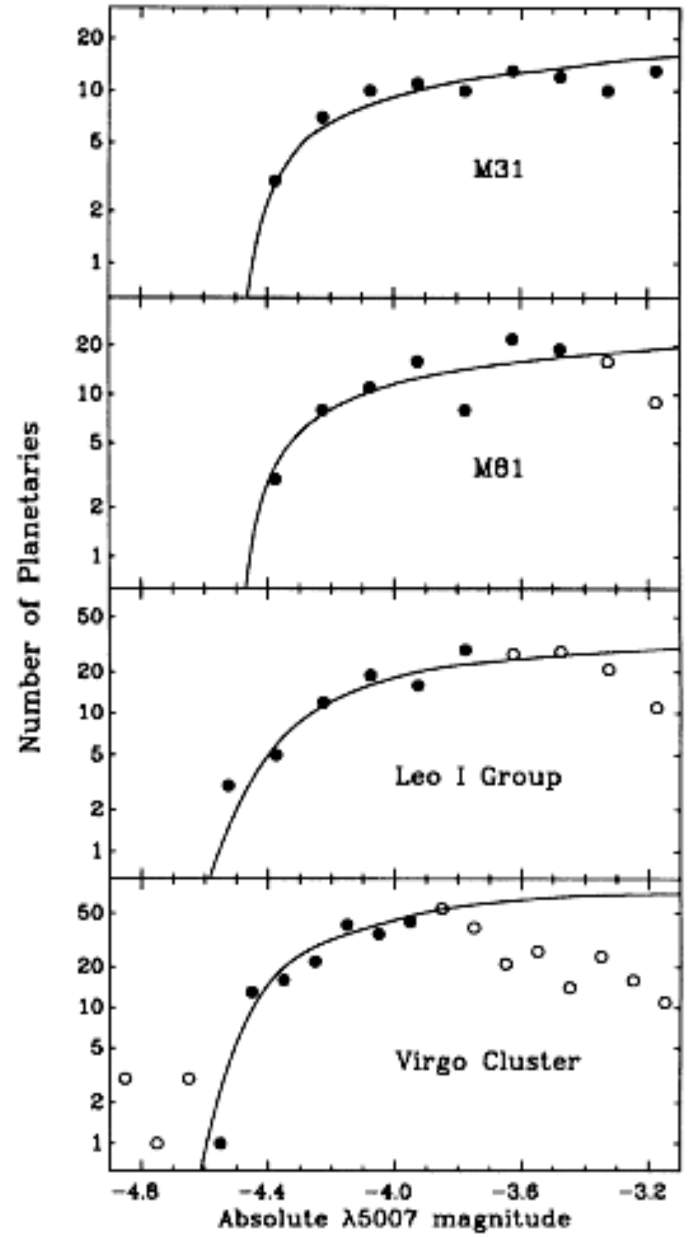
- **Disadvantages:** can't be used for late-type galaxies (Sc's and later). Need deep photometry to detect GCLF turnover. There is a slight metallicity dependence. Not as precise as other methods

Planetary Nebula Luminosity Function

- Planetary nebulae emit strongly in [OIII] λ5007 so are easy to find using narrowband filters

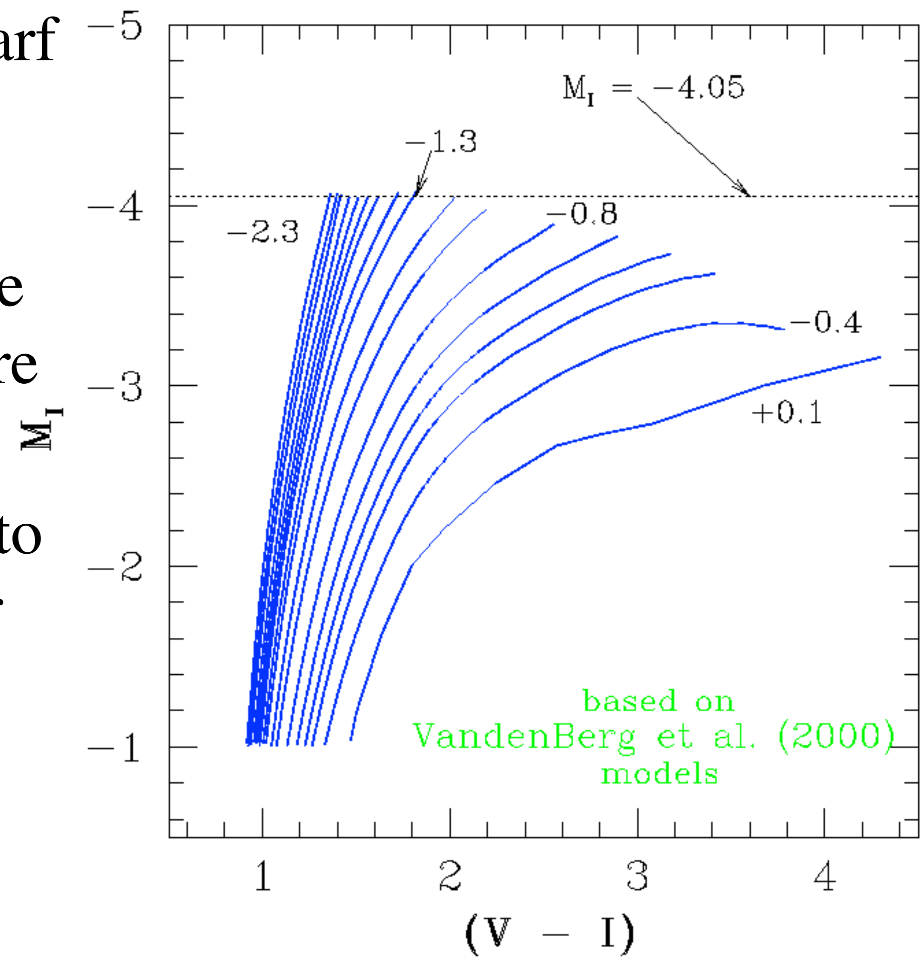


- Planetary Nebula Luminosity function (PNLF) has a characteristic sharp cutoff at the bright end which can be used as a standard candle, M_* (5007) = –4.48 ± 0.04, with a small metallicity correction
- Physical basis fairly well-understood from stellar evolution
- PNe are found in all Hubble Types (but requires a small metallicity correction)
- Only useful out to ~ 20 Mpc (Virgo)



Tip of the Red Giant Branch

- Brightest stars in old stellar populations are red giants
- In I-band, $M_I = -4.1 \pm 0.1 \approx$ constant for the tip of the red giant branch (TRGB) if stars are old and metal-poor ([Fe/H] < –0.7)
- These conditions are met for dwarf galaxies and galactic halos
- **Advantages:** Relatively bright, reasonably precise, RGB stars are plentiful. Extinction problems are reduced
- **Disadvantages:** Only good out to ~20 Mpc (Virgo), only works for old, metal poor populations
- Calibration from subdwarf parallaxes from Hipparcos and distances to galactic GCs



Next: Distance Indicator Relations