Mapping the Milky Way

Parallax measures (at present) only reach << 10% of the distance to the galactic center.

Q What are some other ways we measure distances on Milky-Way scales ?

Mapping the Milky Way

- Q: What is a good distance indicator? What criteria should we use to judge it, since we don't actually know distances *a priori*?

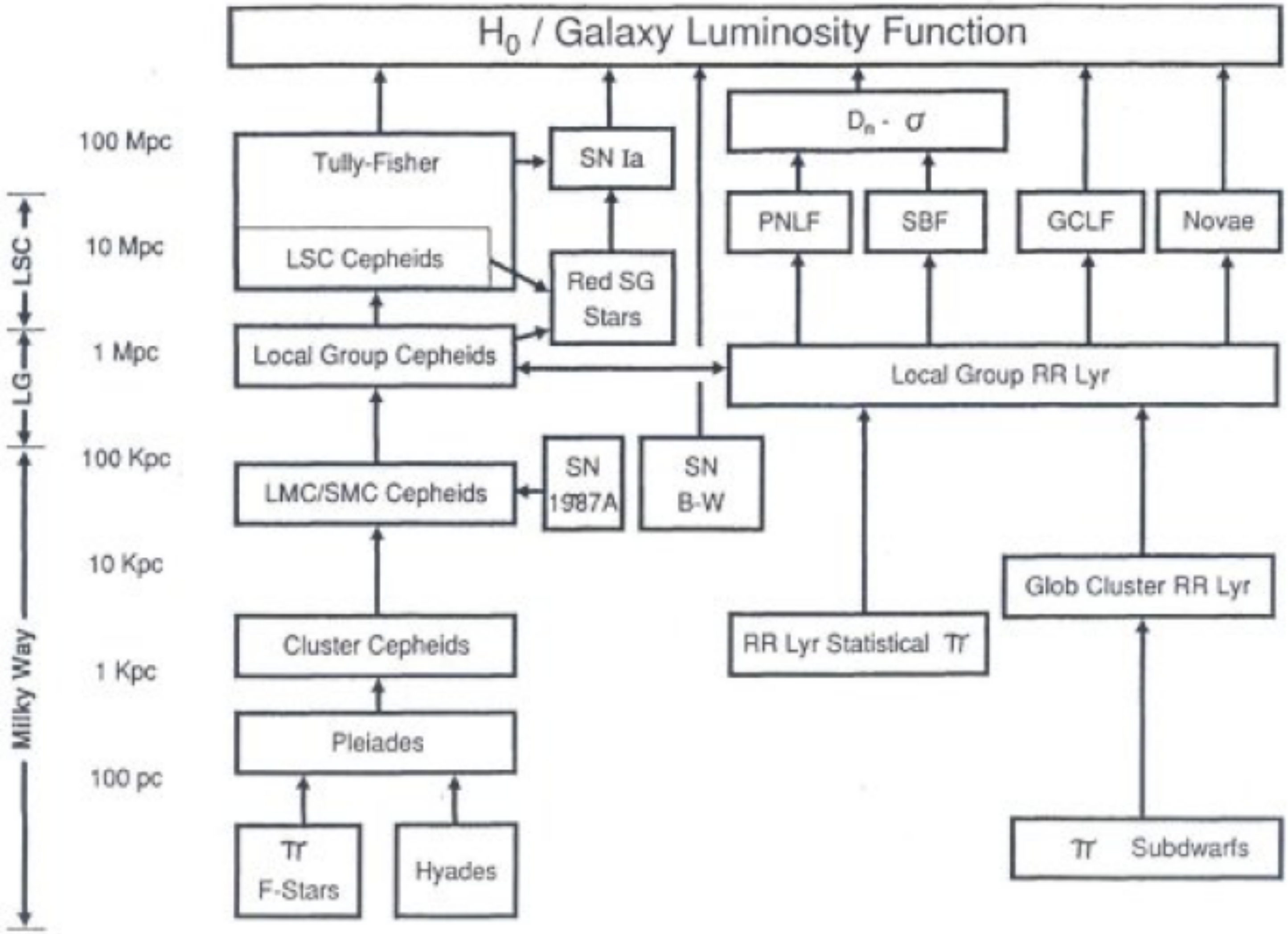
Possible deciding factors :

- we know how it works
  understand its physical basis

- we can tell it works, even though
  we dont understand why

Which is most important ?

The distance ladder (Jacoby et al 92)



Pathways to Extragalactic Distances

—In this diagram we illustrate the various modern routes which may be taken to arrive at H_0 and the genealogy and approxima

Absolute vs Relative Distance Indicators

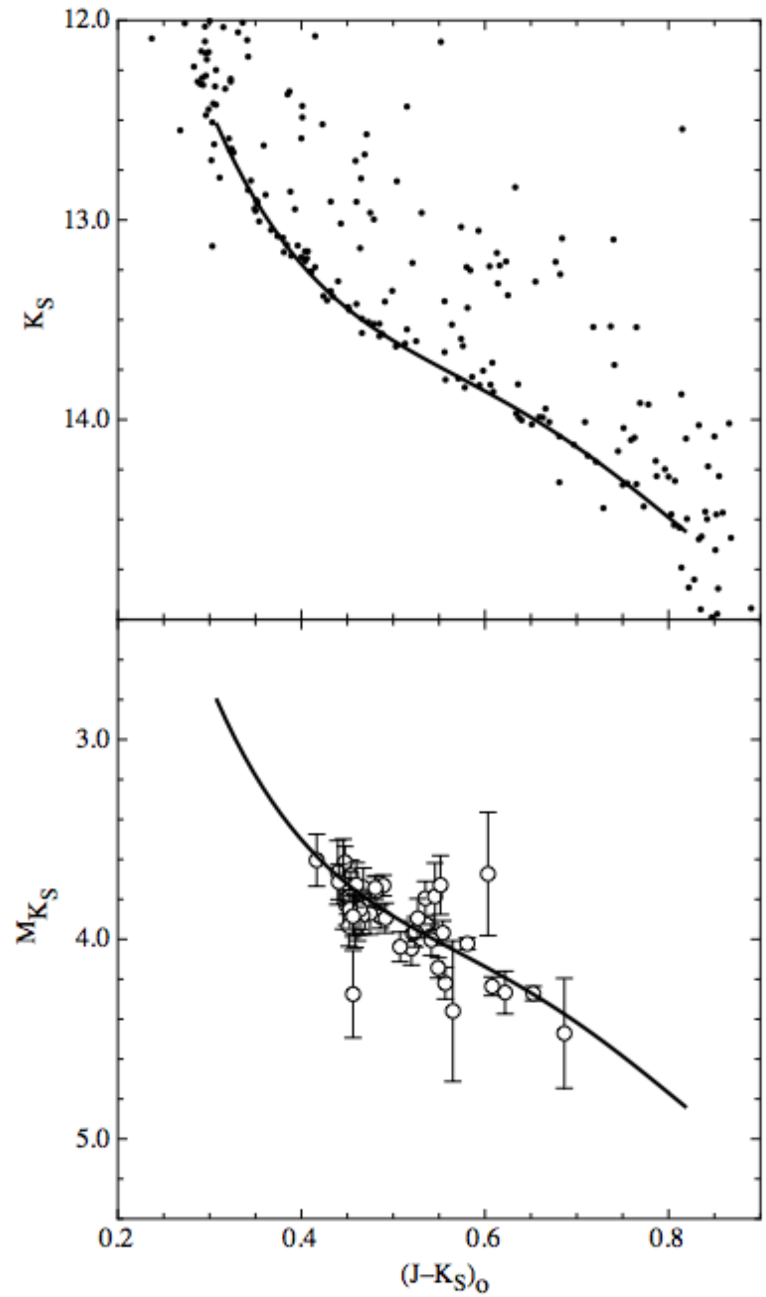
Absolute distance indicators dont require the 'distance ladder' – the shaky structure that is constructed to give distances via parallax, then other indicators

Q What are examples of each sort?

Main sequence fitting

If we have the color-magnitude diagram of a cluster (M67 is shown) and also have stars with known distances from parallax then we can deduce the distance of the cluster

Q: what is your estimate of M67's distance?



Sarajedini et al 09

Main sequence fitting: complications

Q What determines the position of a cluster main sequence in a CMD ?

→ [Fe/H]

→ reddening

→ sometimes age

Isochrones?

- Can also use isochrones directly, if you are confident that the stellar models are accurate and the transformation from L to Mv is accurate
- Q: How would one derive a transformation from a star's luminosity to its absolute magnitude in a given passband?

SDSS CMDs for old clusters in the Milky Way.

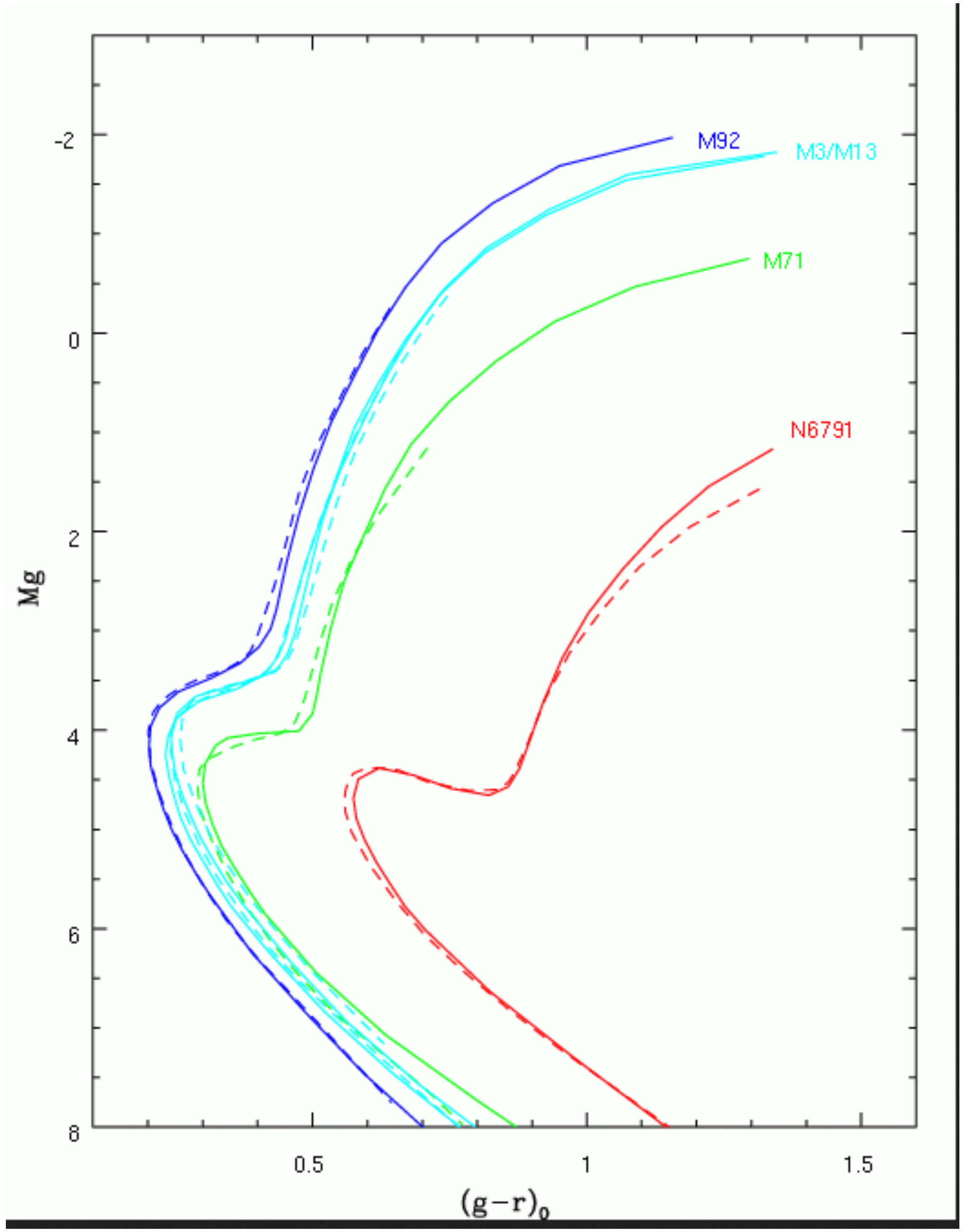
[Fe/H] values from top to bottom are

M92 -2.4

M13 -1.6

M71 -0.8

NGC 6791 +0.3



Problem : position of zero-age main sequence depends on stellar metallicity because of line-blanketing

(see Mihalas & Binney p 116)

Very metal-poor stars have spectra that are close to black bodies.

Line blanketing

Metal lines are more common in the UV and blue of stellar spectra than in the red, so a metal-richer star has less UV light than a metal poor one

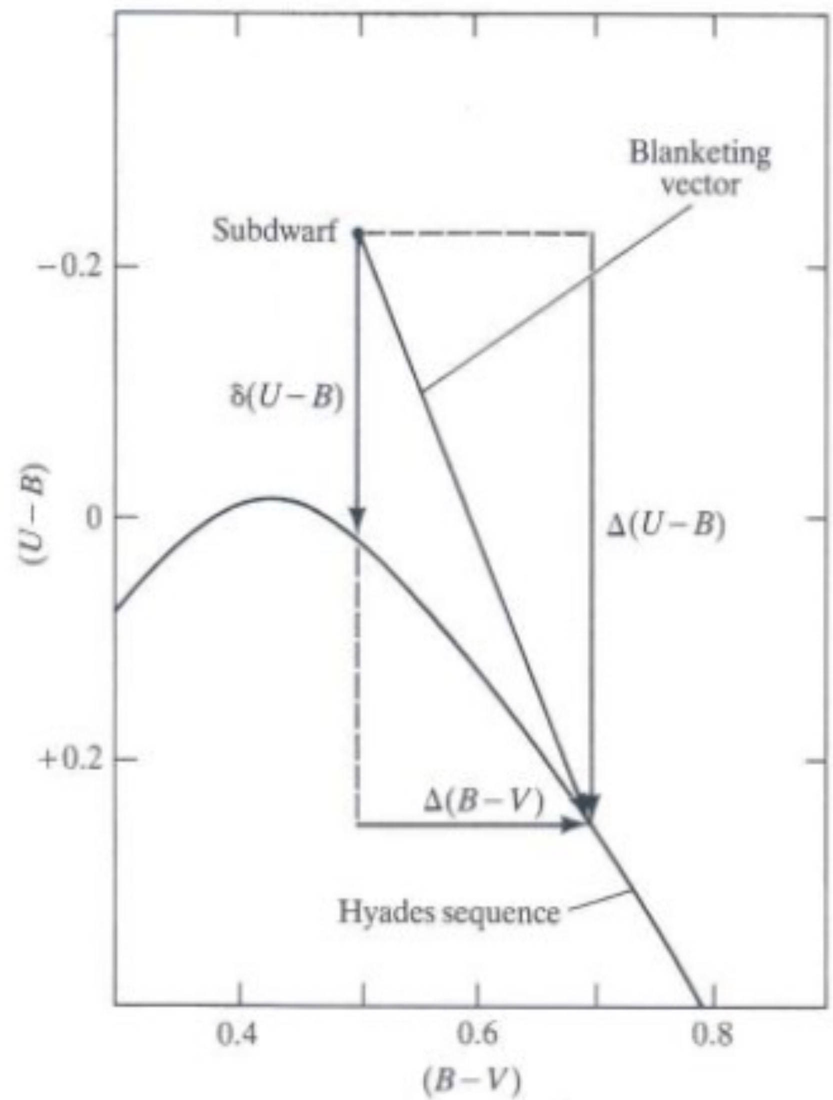
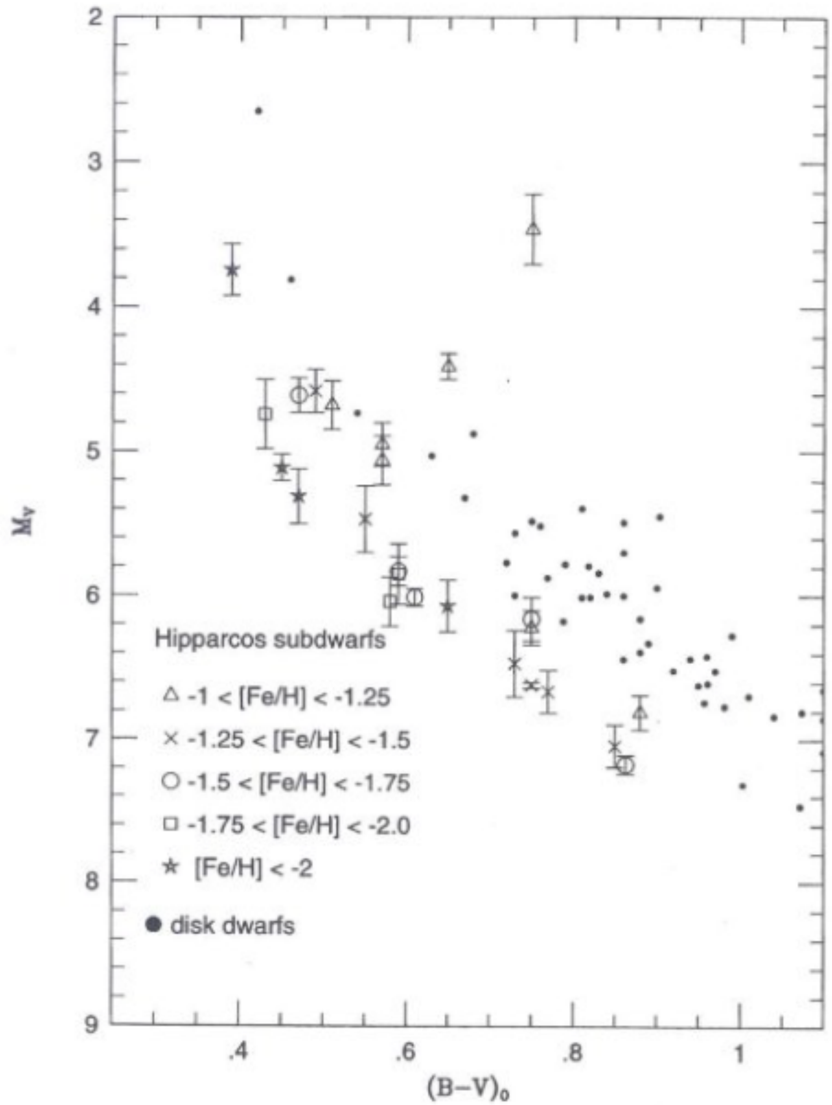


Figure 3-10. Blanketing vector in two-color diagram for a metal-deficient subdwarf. The subdwarf has an ultraviolet excess $\delta(U - B)$ compared to a Hyades star (which has near-solar metal abundance) of the same $(B - V)$. A Hyades star *of the same effective temperature* has colors that differ by amounts $\Delta(B - V)$

Main sequence fitting for subdwarfs

- Halo stars are rare.
  - So metal-poor subdwarfs are rare
- They are all shown
  - on the plot to the right (Reid 1997)
  - (note errorbars)



Reid 1997

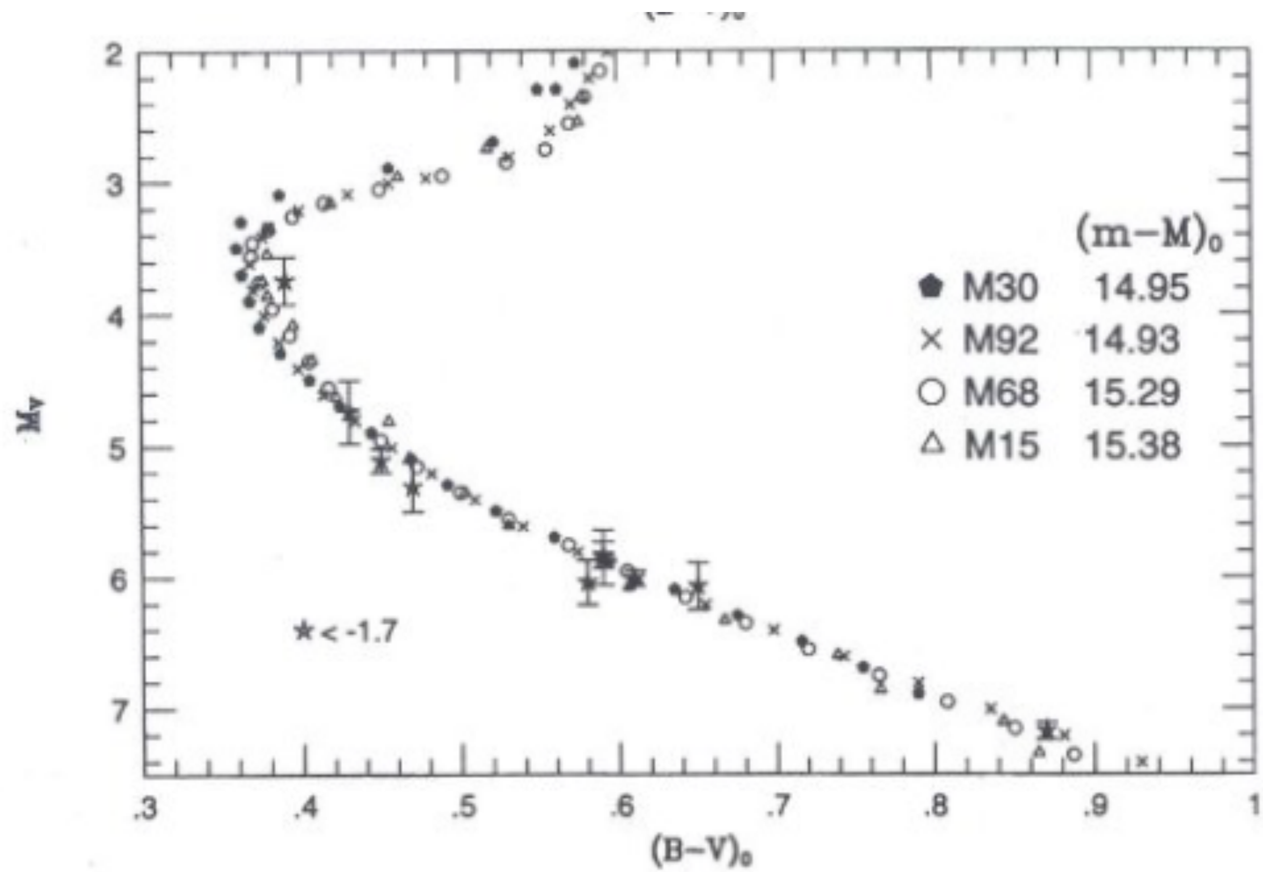


FIG. 5. Main-sequence fitting for the four metal-poor globular clusters.

Q: How well defined is a relation based on 8 stars?

Cepheids as distance indicators

Cepheids are particularly useful as distance indicators because they show a period/ luminosity relation

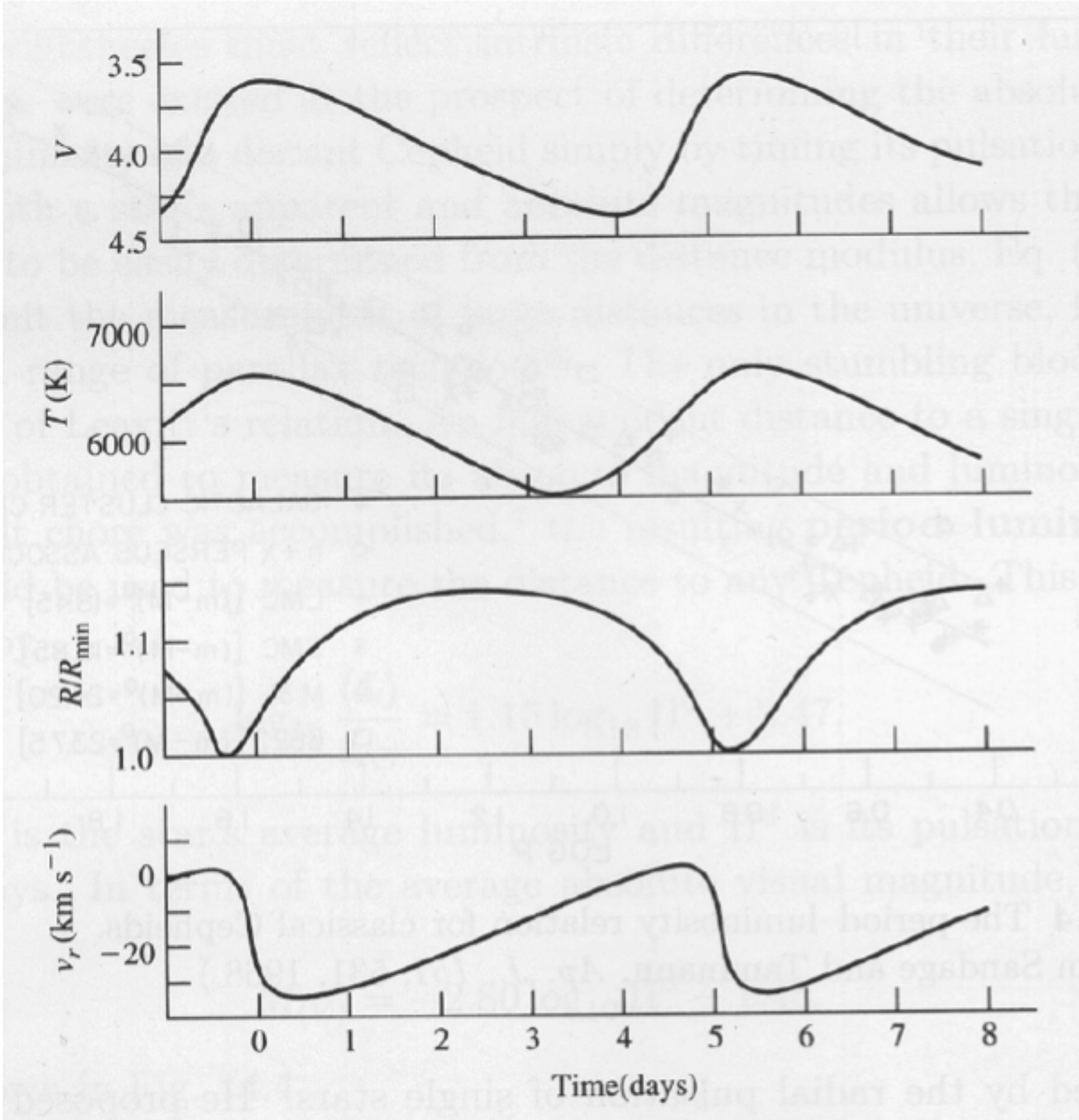
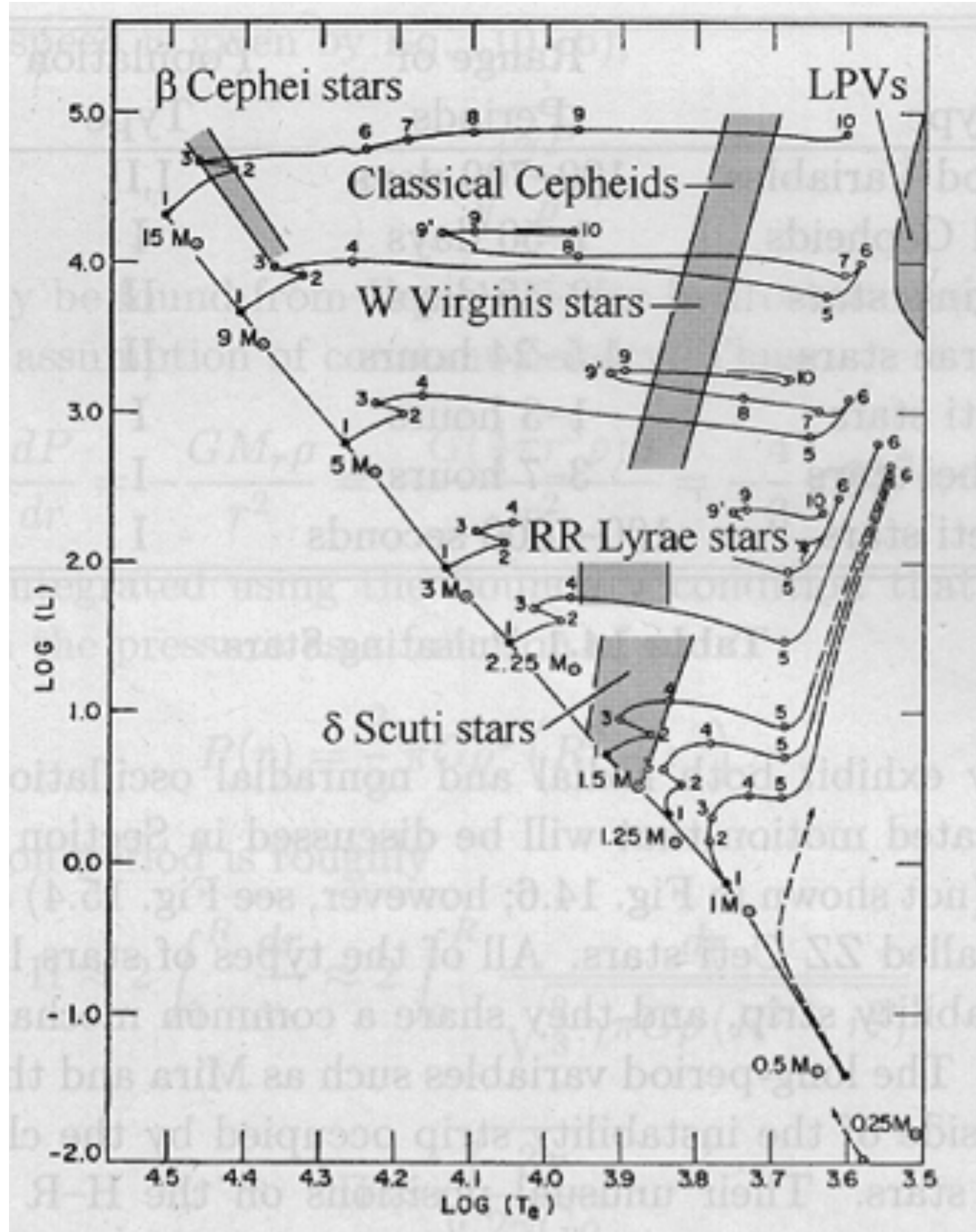


Figure 14.5 Observed pulsation properties of δ Cephei.

Cepheids are evolved massive stars; RR Lyraes are equivalent for lower mass



Cepheids as standard candles

- bright (M_V = −2 to −7, young, massive stars passing thru instability strip)

  (visible to ~15 Mpc with HST)

- easily detected via variability, esp. in optical

- we understand physics of pulsation

But

- Young disk stars ~~have~~ can have dusty surroundings

Basis of P-L relation:

- more luminous stars have longer period

$$P^2 \propto \frac{R^3}{m} \quad \text{(Newton) (Kepler)}$$

$$L \propto m^k$$ (more massive stars have denser, hotter cores & are much more luminous)

$$L \propto R^2 T^4$$

P-L relation continued

Eliminating mass gives a relation between period, luminosity & temp. (color)

ie P-L-C relation

P-L relation has more scatter but easier to measure

Example of a P-L relation

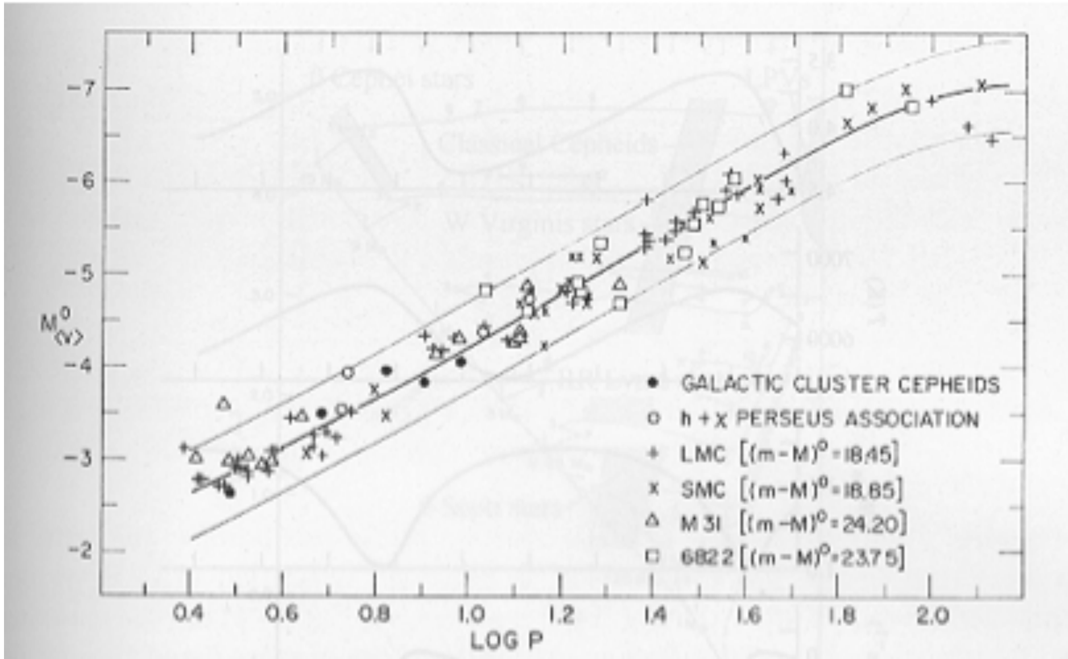


Figure 14.4 The period–luminosity relation for classical Cepheids. (Figure from Sandage and Tammann, *Ap. J.*, *151*, 531, 1968.)

$$M_{<V>} = -2.80 \log P - 1.43$$

Observational nitty-gritty details

- finding Cepheids straightforward at optical wavelengths
- period determination – need to avoid aliasing (HST Key project: 12+1 observations)
- absolute calibration of photometry difficult in crowded fields (5-10% error per galaxy)

More observational details

- reddening estimates important

  H-K color or H magnitudes good

  (H: 1.6μ)

  (H^- opacity causes deviation from blackbody & insensitivity to temp. around cycle)

Calibration of P-L or P-L-C relation

- Cepheids in LMC useful

  Why ?

  However, is there a metallicity dependence ?

  (LMC has lower mean metallicity than Milky Way, M31, large spirals)

- Milky Way Cepheids:
  - few (~20 in open clusters)
  - cluster Cepheids calibrated via mainsequence fitting, ~10% distance error
  - field stars calibrated via Baade-Wesselink
  - metallicity!
  - most Milky-Way Cepheids have shorter periods, while most HST Cepheids have long periods

Q Why?

Baade-Wesselink method
an absolute distance indicator:

(See Binney and Merrifield)

$$L = \sigma T_{eff}^4 \cdot 4\pi R^2$$

- L — luminosity
- T_{eff} — effective temperature
- R — stellar radius

If we know its luminosity & can measure its ~~absolute~~ apparent magnitude, we can infer its distance

Now T_{eff} is relatively straightforward to measure

Q How ?

Radius is much harder ...... direct measurements of radius via interferometry or speckle are only available for a few nearby stars, of little interest for the distance scale of radius for pulsating variable stars

(RR Lyraes, Cepheids)

Can work out change in radius between

times t_0 and t_1 :

$$\Delta r_1 = -p \int_{t_0}^{t_1} v_{los}(t)\, dt$$

↖ measured line-of-sight velocity

Q

why can't we just integrate the velocity curve directly? what is this ρ?

velocity

Hint: what do we measure when we measure v_{los}? How ~~would~~ could a velocity study of the Sun be better than one of an unresolved star?

- A: Since the star is pulsating radially and since we measure only the line-of-sight velocity, we will get a strong contribution from the center of the stellar disk, and none at all from the edges.
- To derive p we need to integrate the component of velocity we see across the stellar disk. But effects like limb darkening make this non-trivial

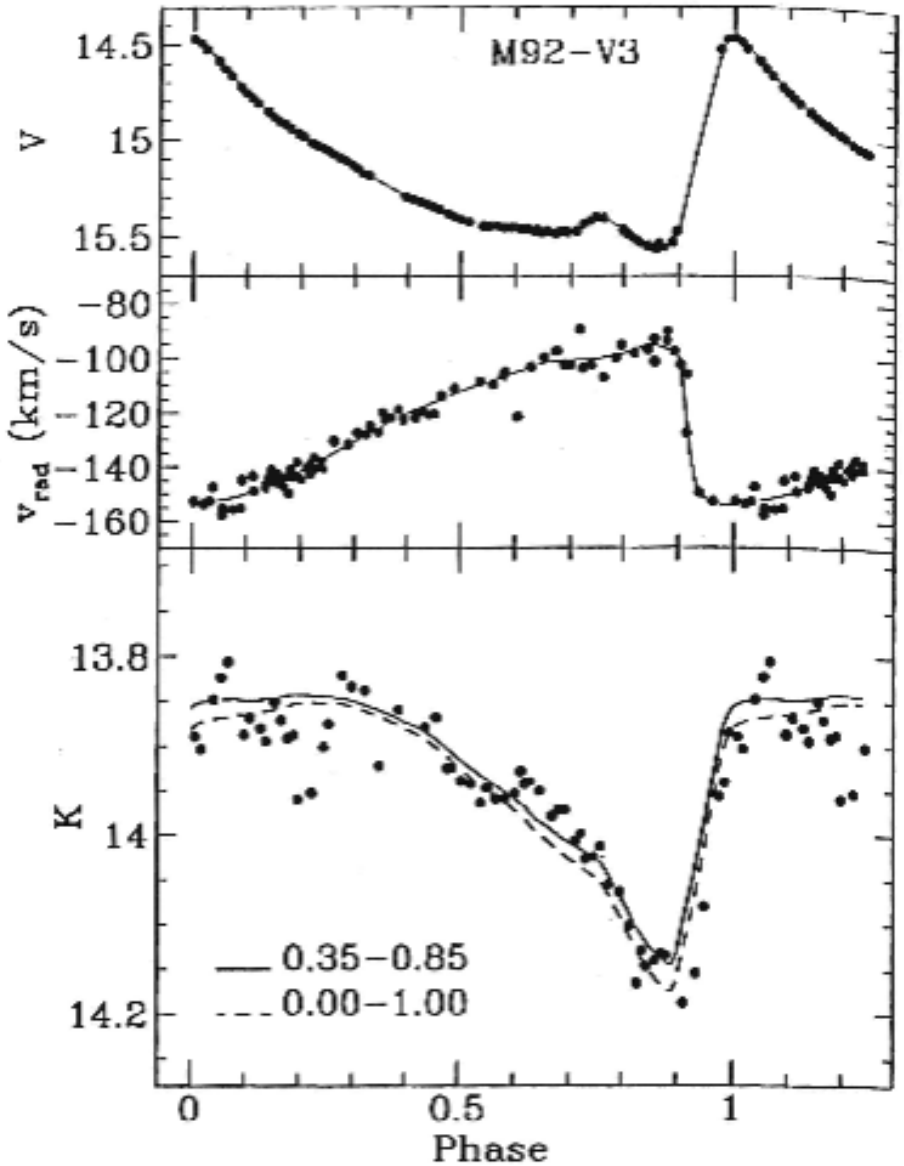


Fig. 4. V light curve, radial velocity curve and K band light curve for M 92-V 3. The individual points refer to the observed data except that

Now the measured brightness depends on total radius, not Δr.

By integrating velocity curve between different times we can estimate Δr and get a handle on radius and $\therefore$ luminosity :

$$m_{bol,1} - m_{bol,0} = M_{bol,1} - M_{bol,0}$$

$$= -5\left(\log(r_0 + \Delta r_1) - \log r_0\right) - 10\left(\log T_{eff,1} - \log T_{eff,0}\right)$$

r_0 is the only unknown here, so we can solve for it.

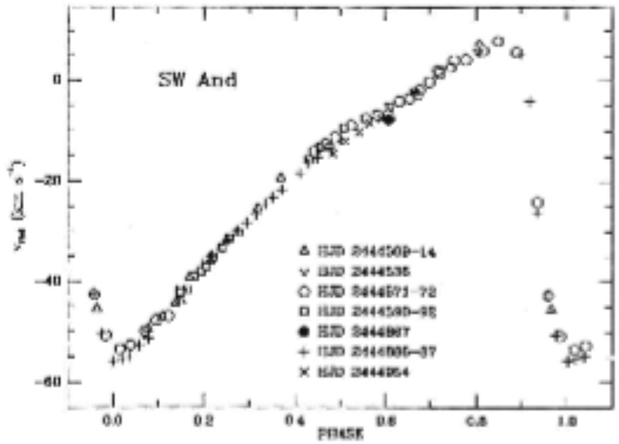


FIG. 2.—Radial velocities vs. phase for SW And

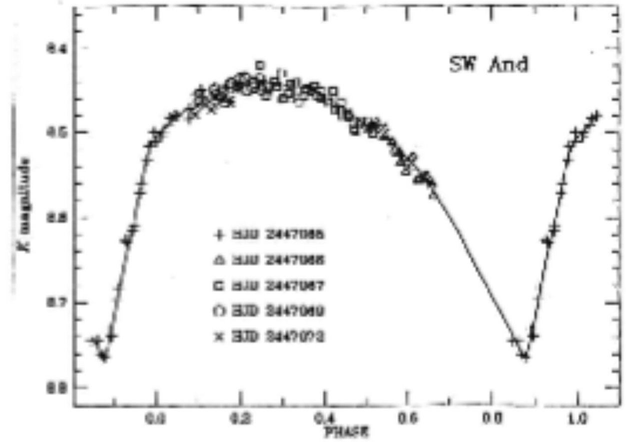


FIG. 1.—K magnitudes of SW And plotted vs. phase. The solid line represents the curve fitted to the data.

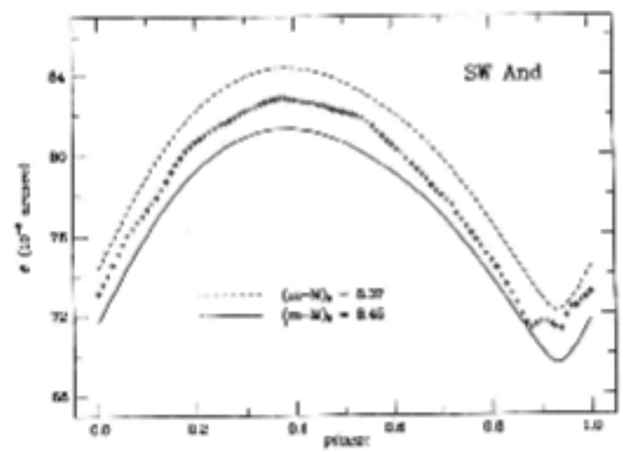


FIG. 4. Angular diameters vs. phase for SW And. Symbols depict photometric angular diameters obtained from K, $V-K$, while lines represent spectroscopic diameters derived from the radial velocity data at the listed distances.

TABLE 6

RESULTS FOR SW AND AND DX DEL

Star	Quantity	Expansion	Contraction	Combined
SW And	Phase interval	0.05–0.50	0.30–0.65	0.05–0.65
	$(m - M)_0$ (mag)	8.39	8.47	8.41
	$\langle R \rangle / R_\odot$	4.01	4.16	4.06
DX Del	Phase interval	0.00–0.45	0.30–0.75	0.00–0.75
	$(m - M)_0$ (mag)	9.00	9.07	9.03
	$\langle R \rangle / R_\odot$	4.97	5.16	5.07

- Q: Why might it be a good idea to divide light curves into different time intervals and solve for distance independently each time?

→ Recent direct measures of radii of Cepheid variables using VLT (8m!) interferometry has confirmed that Baade-Wesselink technique using V-K color works quite well.
(2002)

→ We also have interferometric measures of radius for 7 Cepheids which give quite accurate distances
(2009)

TABLE 1. Cepheids with interferometric pulsation parallaxes. Adapted from Fouqué *et al.* 2007.

Star	Log P (days)	π (mas)	$\sigma(\pi)$ (mas)	Distance (pc)	$\sigma(d)$ (%)	Source
δ Cep	0.72	3.52	0.10	284	2.8	Mérand *et al.* (2005)
Y Sgr	0.76	1.96	0.62	510	31.6	Mérand *et al.* (2009)
η Aql	0.85	3.31	0.05	302	1.5	Lane *et al.* (2002)
W Sgr	0.88	2.76	1.23	362	44.6	Kervella *et al.* (2004c)
β Dor	0.99	3.05	0.98	328	3.1	Kervella *et al.* (2004c), Davis *et al.* (2006)
ζ Gem	1.01	2.91	0.31	344	10.6	Lane *et al.* (2002)
Y Oph	1.23	2.16	0.08	463	3.7	Mérand *et al.* (2007)
l Car	1.55	1.90	0.07	526	3.7	Kervella *et al.* (2004b), Davis *et al.* (2009)

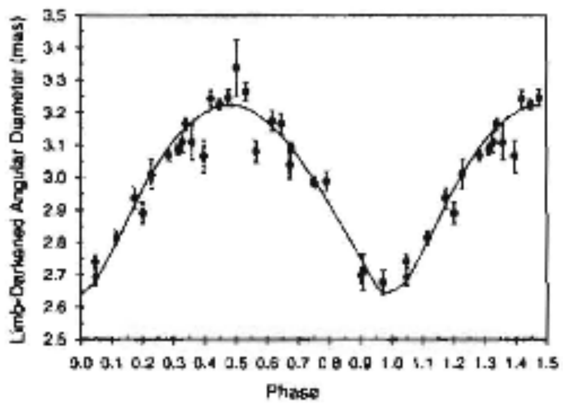


FIGURE 3. Observed angular diameters (points) of l Car compared to scaled linear displacements (smooth curve). Data from SUSI. Figure from Davis *et al.* (2009).

TABLE 2. Cepheids with trigonometric parallaxes from Benedict *et al.* 2007.

Star	Log P (days)	π (mas)	$\sigma(\pi)$ (mas)	Distance (pc)	$\sigma(d)$ (%)
RT Aur	0.57	2.40	0.19	417	7.9
T Vul	0.65	1.90	0.23	526	12.1
FF Aql	0.65	2.81	0.18	356	6.4
δ Cep	0.73	3.66	0.15	273	4.0
Y Sgr	0.76	2.13	0.29	469	13.6
X Sgr	0.85	3.00	0.18	333	6.0
W Sgr	0.88	2.28	0.20	438	8.8
β Dor	0.99	3.14	0.16	318	5.1
ζ Gem	1.01	2.78	0.18	360	6.5
l Car	1.55	2.01	0.20	497	9.9

→ AND we have parallax measurements of 10 Cepheids now with HST's fine guidance sensors

“workaday” distance estimates

- Photometric parallax: since any star spends most of its time on the main sequence, assume that the stars you are interested in are main sequence stars, measure a color, and derive absolute magnitude from an empirical or theoretical ZAMS
- Some more sophisticated versions of this estimate metallicity from stellar colors too
- Q: what bias might be problematical with the assumption about a star being on the main sequence?

Spectroscopic parallax

- Use spectrum to estimate [Fe/H] and luminosity class (luminosity can be tough)
- Use stellar color and fiducial or isochrone to read off absolute magnitude
- Then use m-M = 5 log d (in pc) - 5

(or estimate reddening and add that in; above |b|=5 one can use estimate from Schlegel et al 1998)