AY 20 Fall 2010

Stellar Clusters, Pulsating Stars

↓

Milky Way Structure & Morphology

Reading: Carroll & Ostlie, Chapter 13.3, 14.1, **24.1**, 24.2

Nearest Example of a Galaxy: our Milky Way

In our Galaxy, star clusters can probe age and distance

Other distance indicators: variable stars -

classical Cepheids, RR Lyrae stars

Last class: main sequence and post-main sequence evolution result of nuclear burning (i.e. change of μ)

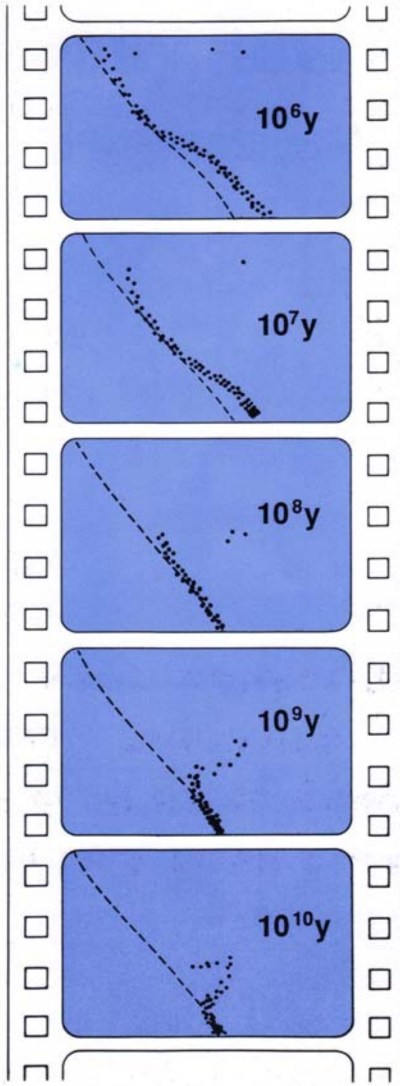
Recall Vogt-Russell: star's mass and composition structure uniquely determine L, r (T_{eff}) and subsequent evolution

e.g. convective/radiative core + convective envelope OR convective core radiative envelope

Mass and composition also influence end states

e.g. white dwarfs, supernovae, pulsars, neutron stars, black holes

- Star formation: collapse process leads to fragmentation
- Fragmentation → simultaneous formation of multiple stars
- Star cluster = group of stars with common properties
  - Same distance
  - Same age
  - Same composition
- ∴ different evolutionary states of cluster members due only to different masses
  - Ignoring binarity, rotation, magnetic fields
- Last class: time for newly-formed stars to reach main sequence is a function of mass (e.g. NGC 2264)
- Lifetime of stars on main-sequence also a function of mass
- Over time, turn-off point from main-sequence occurs at lower T_{eff} (redder color) and lower L
  - → estimate of cluster age from turn-off point



Theoretical H-R diagrams—evolution of a star cluster

Seeds: Horizons, 1995 ed., Fig. 10–19; Foundations of Astronomy, 1994 ed., Fig. 12–17

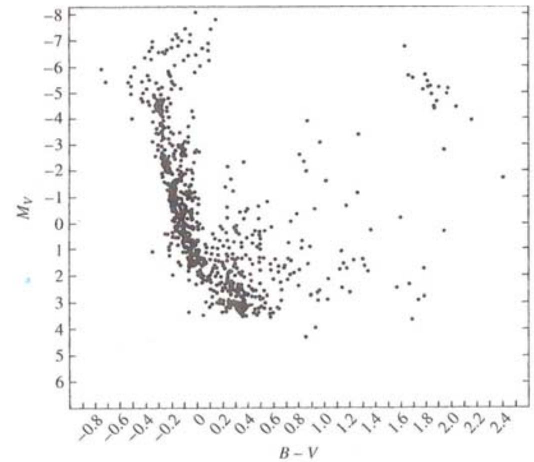


FIGURE 13.18 A color–magnitude diagram for the young double galactic cluster, h and χ Persei. Note that the most massive stars are pulling away from the main sequence while the low-mass stars in the middle of the diagram are still contracting onto the main sequence. Red giants are present in the upper right-hand corner of the diagram. (Figure adapted from Wildey, *Ap. J. Suppl.*, *8*, 439, 1964.)

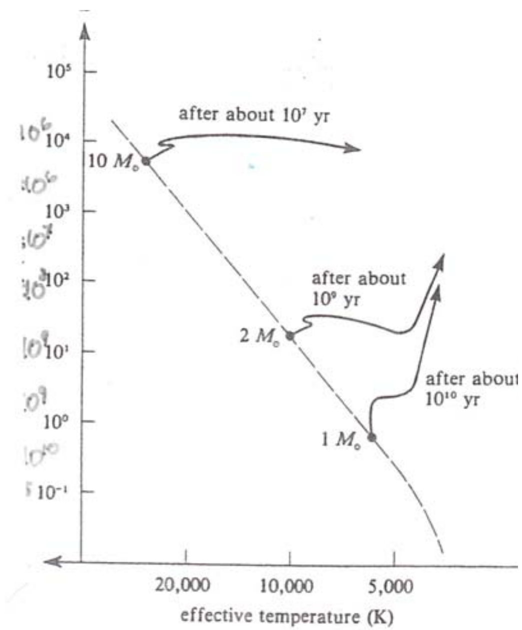


Figure 9.9. The evolution of stars of different masses away from the main sequence. (Adapted from Icko Iben, *Ann. Rev. Astr. Ap.*, 5, 1967, 571.)

Ages of clusters

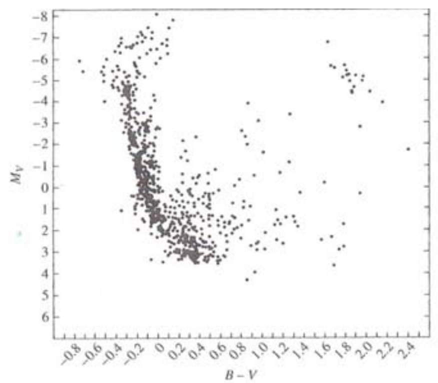
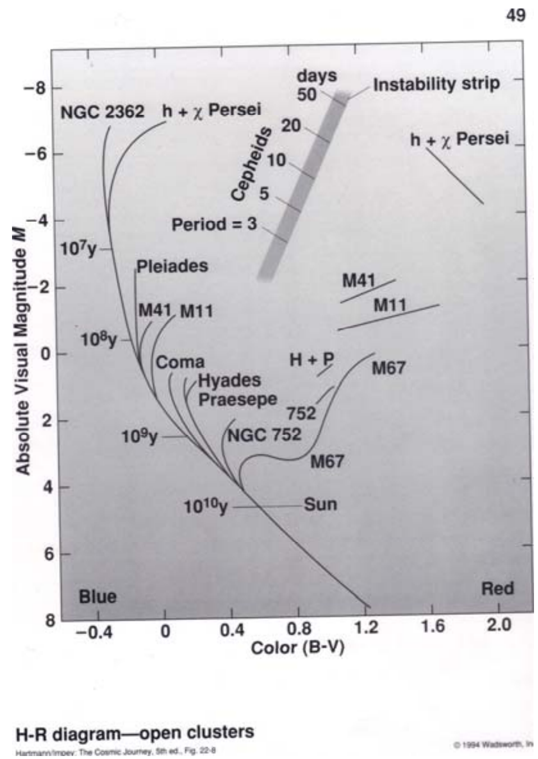


FIGURE 13.18 A color–magnitude diagram for the young double galactic cluster, h and χ Persei. Note that the most massive stars are pulling away from the main sequence while the low-mass stars in the middle of the diagram are still contracting onto the main sequence. Red giants are present in the upper right-hand corner of the diagram. (Figure adapted from Wildey, *Ap. J. Suppl.*, *8*, 439, 1964.)



Adaptation of original figure by Alan Sandage

- Galactic clusters ("open" clusters) – 10's to 100's stars
- Nuclear time scales, t_N longer for decreasing M_*
- Older clusters have existed long enough for low mass stars to burn most H, leave main sequence
- ∴ turn-off point → age of cluster
- Here NGC 2362 youngest; M67 oldest
- Note y-axis: M_V – need cluster distances to compare ages

Pleiades

h & χ Persei

Cluster distance measurement

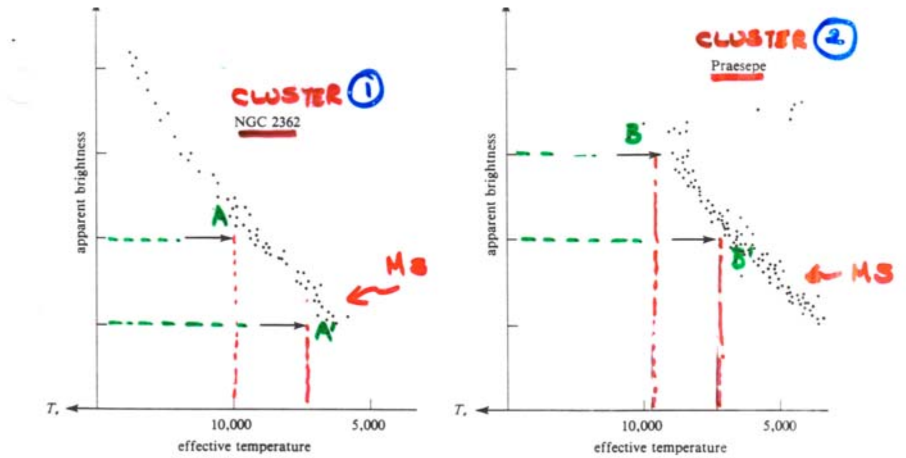


Figure 9.7. The H-R diagrams of the NGC 2362 and the Praesepe open clusters. The segments of main-sequence stars between the two arrows in each diagram refer to intrinsically similar stars; the segment in Praesepe appears displaced upward from the segment in NGC 2362 only because the former cluster is closer than the latter. (Adapted from H. L. Johnson and W. W. Morgan, *Ap. J.*, **117**, 1953, 313, and H. L. Johnson, *Ap. J.*, **116**, 1952, 640.)

SINCE ALL STARS IN CLUSTER AT SAME DISTANCE USE "MAIN-SEQUENCE FITTING"

Here stars in NGC 2362 on main sequence between A and A′
have same T_{eff} as
stars in Praesepe between B and B′

∴ A-A′ stars and B-B′ stars are of similar spectral type i.e. similar stars

∴ differences in m_v must be due to distance differences

Magnitude of vertical shift to "match" A-A′ and B-B′ main sequences
≡ distance measurement

e.g. FIRST TAKE ACCOUNT OF REDDENING

OBSERVED $m_V = m_{V,0} + a_V$

$\therefore m_{V,0} = m_V - a_V$

SINCE $m_{V,0} - M_V = 5 \log d - 5$

$m_{V,0} = (M_V + \text{distance modulus})$

$\therefore$ PLOT OF $m_{V,0}$ v. B−V

$\equiv$ DISTANCE MODULUS DIFFERENCE

(STARS HAVE SIMILAR M_V, B−V)

$\therefore$ VERTICAL DIFFERENCE

$$\equiv 5 \log d_1 - 5 \log d_2$$

IF d_1 KNOWN $\rightarrow d_2$

'STANDARD' USUALLY HYADES

$d \sim 40\,pc$

FROM HIPPARCOS satellite

Recall other distance measures:

trigonometric parallax – accurate up to ~ 1 kpc

e.g. Hyades from Hipparcos = 47 pc

Main sequence fitting based on Hyades → distances accurate to ~ 7 kpc (but Galactic Center at 8 kpc)

Method also used for greater distances (Magellanic Clouds at 50 pc) but less accurate

More accurate distance measurements use pulsating variable stars – Cepheids (extragalactic distance scale)

Cepheids – supergiants; cyclic variations in magnitude as star expands and contracts

Period between 1 and 50 days, variations of several magnitudes in brightness

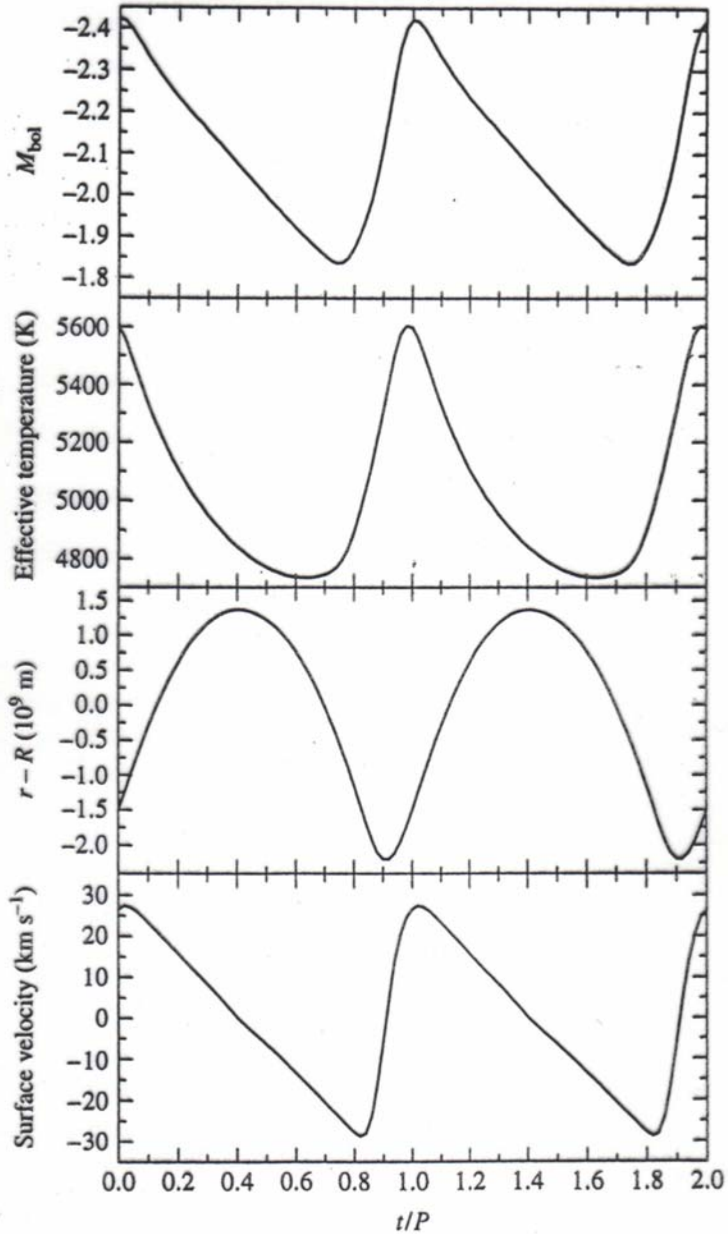


FIGURE 14.7 Observed pulsation properties of δ Cephei, a typical classical Cepheid. (Data from Schwarzschild, *Harvard College Observatory Circular*, *431*, 1938.)

Recall other distance measures:

trigonometric parallax – accurate up to ~ 1 kpc

e.g. Hyades from Hipparcos = 47 pc

Main sequence fitting based on Hyades known distance
$\rightarrow$ distances accurate to ~ 7 kpc (but Galactic Center at 8 kpc)

Method also used for greater distances (Magellanic Clouds at ~ 50 kpc)

More accurate distance measurements use pulsating variable stars – particularly Cepheids (extragalactic distance scale)

Cepheids – supergiants;
cyclic variations in magnitude as star expands and contracts

Period between 1 and 50 days; brightness variations ~ several magnitudes

Henrietta Leavitt: $L_* \sim P_* \sim m_v$; $m_v \sim M_V$ (since all in Small Magellanic Cloud i.e. at same distance)

i.e. for Cepheids, periods $\rightarrow$ absolute magnitude $\rightarrow$ distance

BUT need calibration = independent distance measurement to ONE Cepheid variable

Period-Luminosity Relation for Classical Cepheids

Nearest Cepheid is Polaris @ ~ 200 pc – simple parallax methods inaccurate until Hipparcos space mission

However, Hertzsprung (1913) used secular parallax method for distances to Cepehids with same period →

$$M_{\langle V \rangle} = -2.81 \log P_d - 1.43$$

$$\text{or } \log \langle L \rangle / L_\odot = 1.15 \log P_d + 2.47$$

Now Cepheids = “standard candles” for extragalactic distance measures too

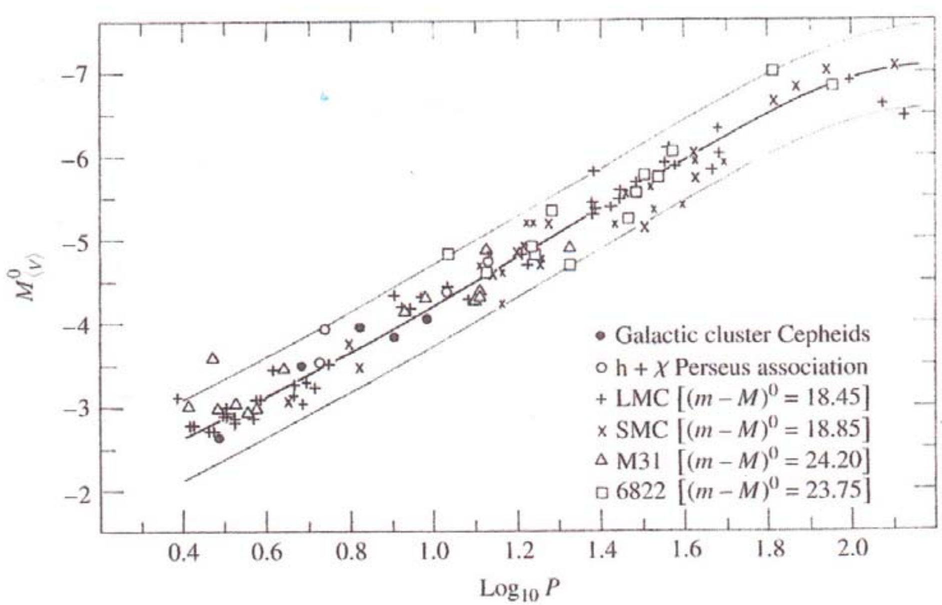


FIGURE 14.5 The period–luminosity relation for classical Cepheids. (Figure adapted from Sandage and Tammann, *Ap. J.*, *151*, 531, 1968.)

- Leavitt relation empirical. Eddington theory: $P \propto \langle\rho\rangle^{-1/2}$
  - $M_V \sim L^* \sim R^*$ and $\langle\rho\rangle^{-1/2} \sim P$

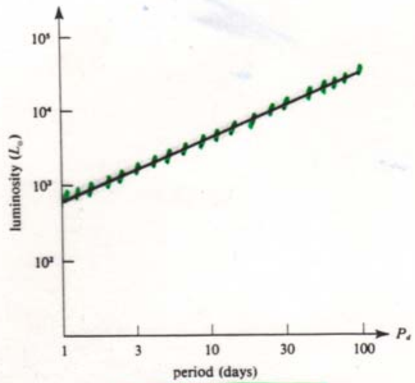
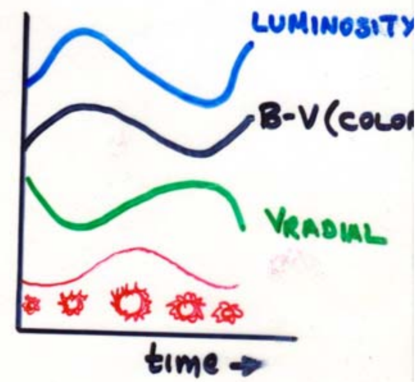


Figure 9.12. The period-luminosity relationship for classical Cepheids. The shaded strip centered on the mean line indicates schematically that there are slight deviations from a one-to-one relation, because of both theoretical reasons and observational uncertainties.



AMPLITUDE OF PULSATION GREATEST IN OUTER LAYERS (VERY SMALL AT CENTER)

THE CYCLE:
- INCREASE R_* → DECREASE ρ, T
- → DECREASE P
- → GRAVITY DECREASES R_*

FOR H, He PARTIALLY IONIZED, COMPRESSION → INCREASED OPACITY

THEN COMPRESSION → MORE IONIZ^N, LOWER TEMP INCREASE $\therefore \kappa \propto \rho / T^{3.5}$ → HIGHER OPACITY (NOT LESS)

FOR EXPANSION, ρ ALSO DOMINATES → LOWER OPACITY

$\therefore$ THIS LAYER 'STOPS' TRANSPORT OF ENERGY WHEN COMPRESSED, ENHANCES WHEN EXPANDS

(THEN LAYER COLLAPSES DOWN AGAIN)

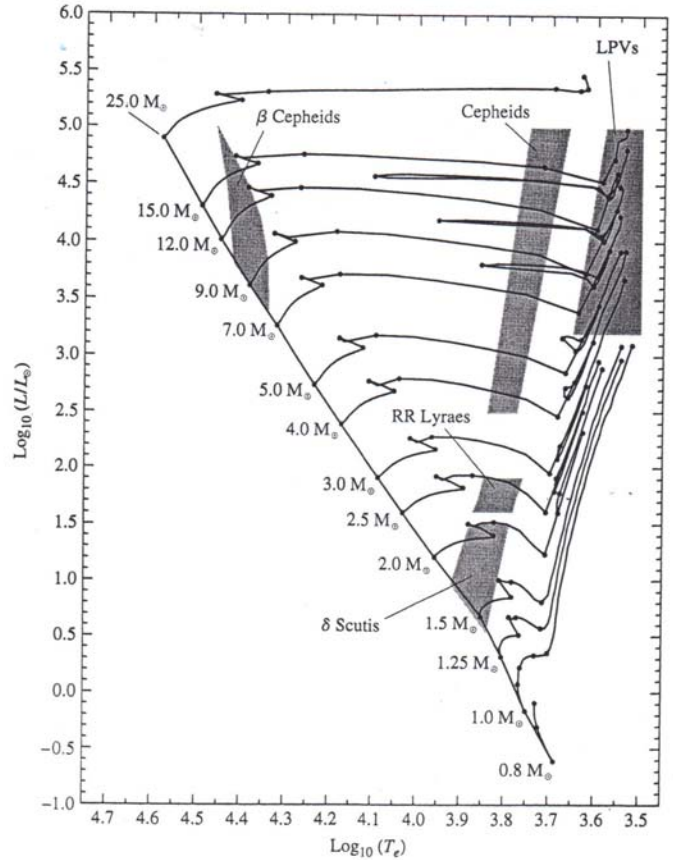
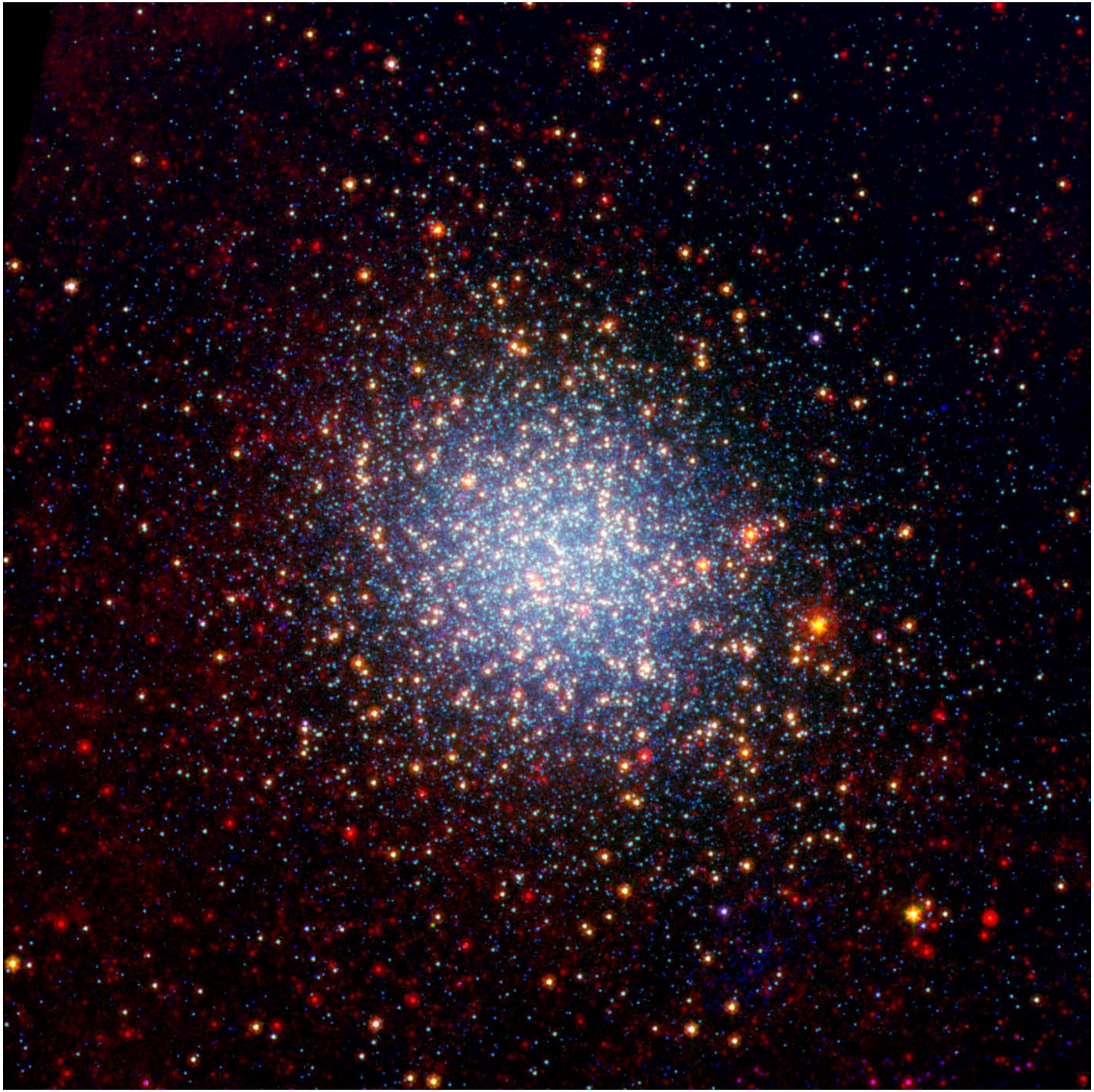


FIGURE 14.8 Pulsating stars on the H–R diagram. (Data for the evolutionary tracks from Scha et al., *Astron. Astrophys. Suppl.*, *96*, 269, 1992.)

TABLE 14.1 Pulsating Stars. (Adopted from Cox, *The Theory of Stellar Pulsation*, Princeton University Press, Princeton, NJ, 1980.)

Type	Range of Periods	Population Type	Radial or Nonradial
Long-Period Variables	100–700 days	I,II	R
Classical Cepheids	1–50 days	I	R
W Virginis stars	2–45 days	II	R
RR Lyrae stars	1.5–24 hours	II	R
δ Scuti stars	1–3 hours	I	R,NR
β Cephei stars	3–7 hours	I	R,NR
ZZ Ceti stars	100–1000 seconds	I	NR



Distances from variable stars in globular clusters

Omega Centauri
Spitzer image
(infrared)

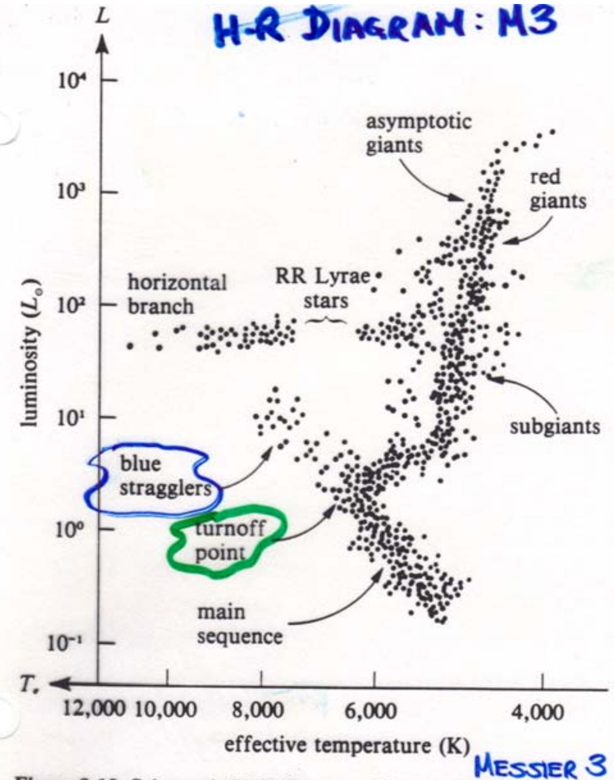


Figure 9.13. Schematic H-R diagram of the globular cluster M3. The distance to the cluster has been derived on the assumption that the luminosity of the RR Lyrae stars is $50L_{\odot}$. The diagram is somewhat schematic, because the conversion from the $B - V$ and V measurements of Johnson and Sandage to T_e and L is somewhat uncertain for Population II stars. (Adapted from H. L. Johnson and A. R. Sandage, *Ap. J.*, **124**, 1956, 379.)

GLOBULAR CLUSTERS

- POP II STARS
- OLD – TURN-OFF PT.
  → 1.2×10^{10} YEARS

~ AGE OF MILKY WAY GALAXY

RR Lyrae stars (cluster variables) lie on horizontal branch

USED FOR MODERN DETERMINATIONS OF DISTANCE TO GALACTIC CENTER (GC)

Note: $P_{RRLyrae} \leq 1$ day << $P_{Cepheid}$

ON HORIZONTAL BRANCH ∴ $L, M_V \sim$ CONST $\sim 0.6 \pm 0.3$

$\therefore 5 \log d = m_V - M_V + 5$

Again need to be aware of extinction (especially in plane of Galaxy)

Transparency 82

Figure 15-14

Chain of overlapping distance indicators

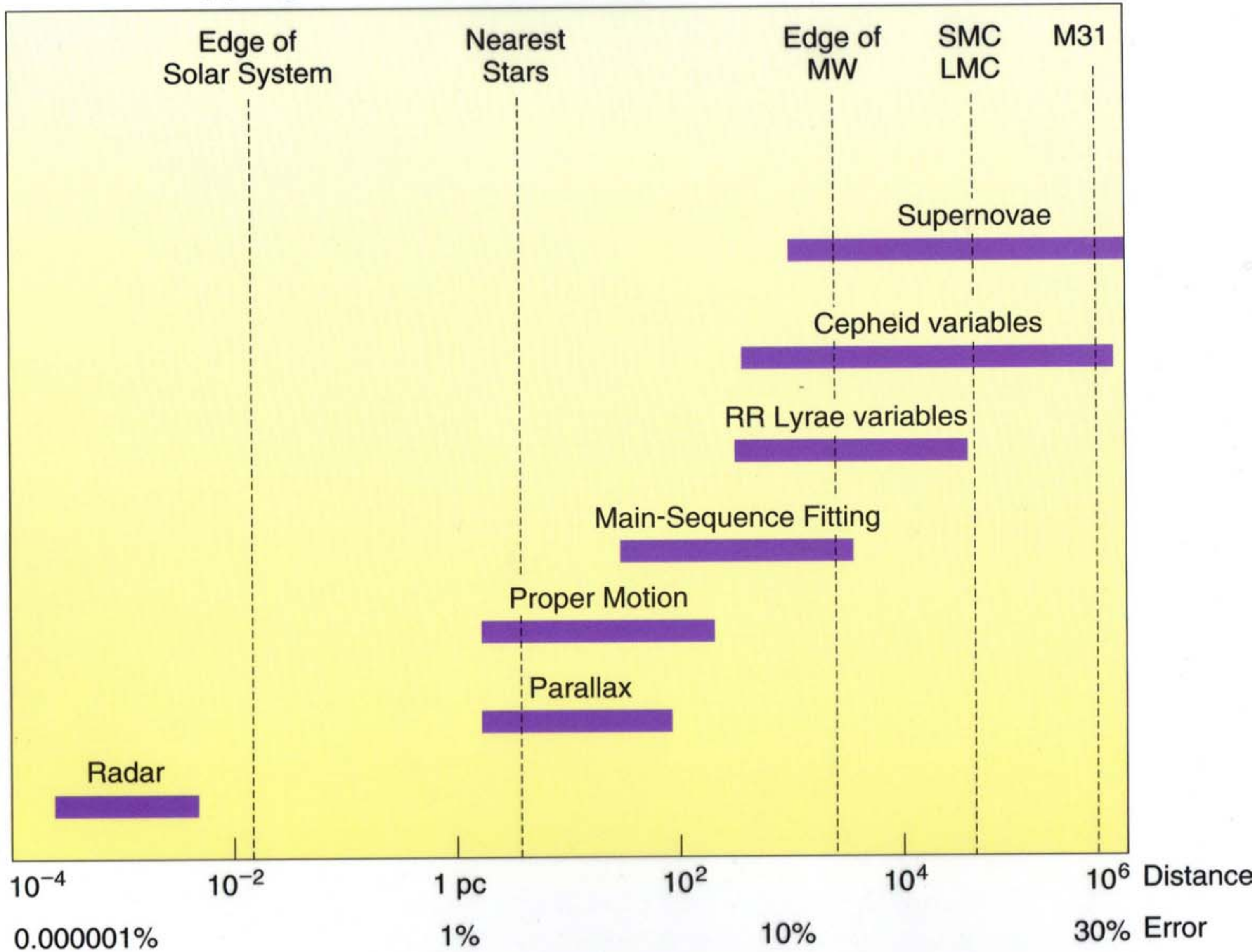


TABLE 27.1 Distance Indicators. (Adapted from Jacoby et al., *Publ. Astron. Soc. Pac.*, *104*, 599 1992.)

Method	Uncertainty for Single Galaxy (mag)	Distance to Virgo Cluster (Mpc)	Range (Mpc)
Cepheids	0.16	15 – 25	29
Novae	0.4	21.1 ± 3.9	20
Planetary nebula luminosity function	0.3	15.4 ± 1.1	50
Globular cluster luminosity function	0.4	18.8 ± 3.8	50
Surface brightness fluctuations	0.3	15.9 ± 0.9	50
Tully–Fisher relation	0.4	15.8 ± 1.5	> 100
D–σ relation	0.5	16.8 ± 2.4	> 100
Type Ia supernovae	0.10	19.4 ± 5.0	> 1000

CLUSTERS PROBE GALAXY STRUCTURE

CATEGORIES: POPULATION I & II
(DIFFERENT KINEMATICS
DIFFERENT CHEMICALY)

13.7×10^9 YRS AGO. BIG BANG
HYDROGEN, HELIUM ONLY, $Z = 0$

NEXT STARS (AFTER STELLAR NUCLEOSYNTHESIS)
METAL POOR, LOW Z

LATER GENERATIONS, METAL RICH $Z = 0.03$

	$Z = 0$	$Z \gtrsim 0$	$Z \sim 0.03$
POPULATION	III	II	I
		LOCATED OUT OF PLANE, HIGHER VELS	LOW VELOCITIES (RELATIVE TO SUN) LOCATED IN [redacted] DISK OF MILKY WAY

LED TO ORIGINAL DEFINITION OF POP I, POP II

GLOBULAR CLUSTERS - LARGE MEMBERSHIP
POPULATION II
∴ FORMED WHEN GALAXY YOUNG (∴ OLD)

GALACTIC CLUSTERS - OPEN CLUSTERS
POPULATION I (MORE RECENT
YOUNGER & SMALLER NUMBERS *S

GLOBULAR CLUSTERS ARE POPULOUS
- MANY OLDER STARS [POP II]

SUN AND MANY POP I STARS ARE:

NOT IN CLUSTERS
BUT FORM IN CLUSTERS
WHERE ESCAPE PROBABILITY
IS HIGH ∴ DISPERSE EASILY

STELLAR SEPARATION >> STELLAR DIAMETER
∴ FEW COLLISIONS

STARS 'ORBIT' CLUSTER CENTER

INWARD FORCE TO CENTER | INERTIA DUE TO RANDOM MOTION | GRAV'L EFFECT OTHER STARS

VIRIAL ⇒ $2K + U = 0$ IF STABLE

N STARS, AVE. SEP^{N} R, RANDOM VEL V
MASS m

$$N m V^2 = \frac{G(N-1)N m^2}{2R} \qquad \left(\frac{N(N-1)}{2} \text{ PAIRS}\right)$$

FOR 1 STAR, ESCAPE VELOCITY FROM

$$\frac{1}{2} m v_e^2 = \frac{G(N-1)m.m}{R}$$

$$= 2mV^2$$

$$\therefore v_e^2 = 4V^2$$

$$v_e = 2V$$

FOR GALACTIC CLUSTERS $t_{EVAP} \sim 3 \times 10^9$ YRS
GLOBULAR CLUSTERS $t_{EVAP} \sim 8 \times 10^{10}$ YRS
- LAST LONGER