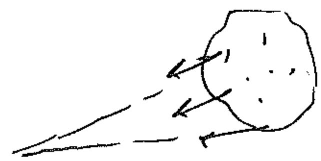
L19 – Cosmic Distance Ladder

Distances to Clusters: The Hyades

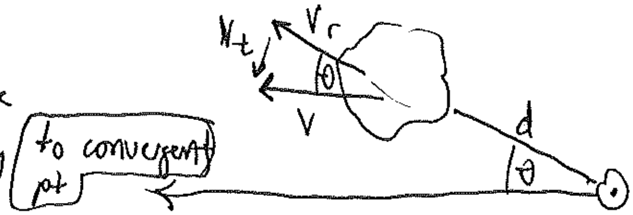
- We use (trigonometric) parallax on individual stars to get D out to ~ 1 kpc (for which the parallax is 10^{-3} arc sec).

- The next step is taken by "spectroscopic parallax" on clusters of stars. But first, the main sequence of a cluster with known distance must be established. The benchmark is the Hyades, for which we use the

moving cluster method



Proper motion of stars appears to approach a "convergent point."



Explanation: The cluster as a whole is moving away from us. We detect, via proper motion, the tangential component of the recession velocity $\vec{V}$.

$$\left.\begin{aligned} V_r &= V\cos\theta \\ V_t &= V\sin\theta \end{aligned}\right\} \qquad V_t = V_r \tan\theta$$

$$\text{But } V_t = d\dot{\theta}$$

Here $\dot{\theta}$ [usually denoted μ] is the proper motion in arc sec/yr

$$d\dot{\theta} = V_r \tan\theta \rightarrow \boxed{d = \frac{V_r \tan\theta}{\dot{\theta}}}$$

For each star, observe θ = angular separation to tangent point. Also measure $\dot{\theta}$ [proper motion]. Finally, measure V_r via Doppler shift of spectral lines.

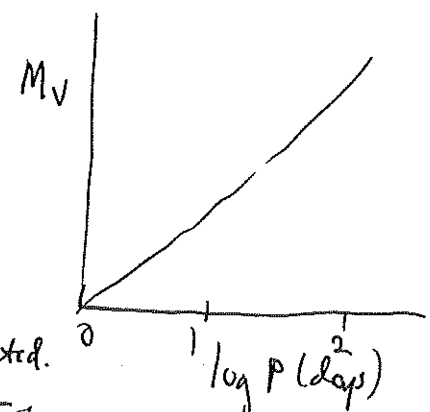
Should, of course, get the same D. Find $D = 46$ pc ± 2 pc.

Knowing D, we can construct the $(M_V, B-V)$ main-sequence.

Cepheid Variables as Distance Indicators (used from 10 kpc – 30 Mpc)

- John Goodricke (1784) found that the star δ Cephei varies w/ P ≈ 5 days. It is a pulsating, post-MS star → Classical Cepheid.

- Henrietta Leavitt (~1910) observed variable stars, including Cepheids, in the SMC. She noticed that the brighter Cepheids took longer to complete one period.
  Since all the Cepheids are at the same D (≈ 60 kpc), she had found, in effect, a relation between the period and the luminosity. PERIOD-LUMINOSITY RELATION



But what is M_V? She didn't know the distance to the SMC.

- Hertzsprung (1913) found D to a Cepheid using parallax. Thus, the P-L relation was calibrated.

$$\log \frac{\langle L \rangle}{L_\odot} = 1.15 \log P_d + 2.47$$

NB: Typically, $P_d = 10$ (days) $\rightarrow \log \frac{\langle L \rangle}{L_\odot} = 3.6 \rightarrow$ $L = 8000\,L_\odot$

So Cepheids can be seen over large distances

- Shapley (1917) found Cepheids in globular clusters of the MW, establishing the shape of our Galaxy.

- Hubble (1923) found them in Andromeda, establishing D (= 800 kpc today) and ending the Curtis-Shapley debate.

Complication – Two types of Cepheids were actually used, each w/ its own P-L relation.

As discovered by Baade (1952), Leavitt's SMC Cepheids (classical) were Pop I
Shapley's MW Cepheids (W Virginis) were Pop II

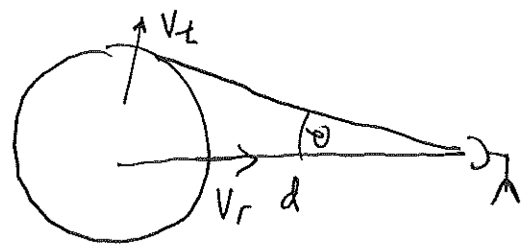
Tully-Fisher Relation ($D \lesssim 100$ Mpc)

Recall that this is a relation between the luminosity of a spiral galaxy and the maximum velocity in its rotation curve

The method was used, eg, to establish the 3D shape of the Virgo Cluster ($D \simeq 16$ Mpc).

Supernovae as Distance Indicators

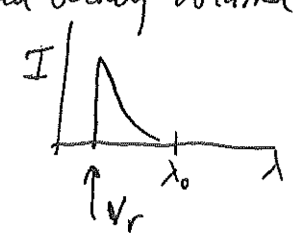
For relatively nearby SN's
expanding shell method



We observe $\theta(t)$

Differencing over time, we find $\dot{\theta}(t)$
The transverse velocity is $V_t = D\dot{\theta}$

This transverse velocity should equal V_r, the radial velocity obtained by Doppler. [actually, get V_r from maximum blueshift] →



So $D = \frac{V_r}{\dot{\theta}}$

For distant SN's Most useful are Type Ia

M_V (at peak) $= -19.3 \pm 0.03$

Most have close to this peak magnitude. They decline in brightness the fastest. Others, less bright at peak, decline more slowly.

So, if you measure rate of decline, deduce L_{max}.

<u>What are Type Ia SN's?</u> They are collapsing WDs that have surpassed the Chandrasekhar mass.

Could be <u>either</u> 2 WD's orbiting in a binary (that coalesce due to the emission of gravitational radiation) (but "coalescence" never completed).
<u>or</u> a giant spilling its mass over to a WD companion.

In any case, the WD that collapses was originally in a binary. No one has yet been able to model in detail the light curves.

<u>Application</u> — A SN has V = 14.0 at peak. Suppose $A_V = 0$.

$$m_V = M_V + 5\log\left(\frac{D}{10\text{ pc}}\right)$$

$$14 = -19 + 5\log\left(\frac{D}{10\text{ pc}}\right) \rightarrow D = 40\text{ Mpc}$$

In practice, one <u>does</u> need to account for extinction by dust

Q: How much farther can we see w/ a Type Ia SN than a Cepheid?

A: The brightest Cepheid is $M_V = -6.0$
The " SN is $M_V = -19.3$ } $\Delta M_V = 13.3$

$$\Delta M = 5\log\left(\frac{D_1}{D_2}\right) \rightarrow \frac{D_1}{D_2} = 460$$

So we can see out to ~1000 Mpc

<u>Galaxy Groups and Clusters</u>

Almost all galaxies are found in <u>groups</u> and <u>clusters</u> [Thus, the situation is unlike that for stars, most of which are in the field.] Both are <u>gravitationally bound</u>.

<u>GROUPS</u> — $N \lesssim 50$ diameter 1 Mpc $\sigma \sim 150$ km/s $\rightarrow M \sim 10^{13} M_\odot$

$\langle M/L \rangle \sim 300 \langle M_\odot/L_\odot \rangle$ lots of dark matter

CLUSTERS $N \gtrsim 50$ "poor" $N \lesssim 10^3$ "rich"

$\sigma \sim 1000$ km/s

$M \sim 10^{15} M_\odot$

$\langle M/L \rangle \sim 400 \frac{M_\odot}{L_\odot}$

The Local Group

We have two neighbors, the LMC & the SMC ($D \sim 50$ kpc)

Both are gas-rich and metal-poor

15% of mass ($\sim 10^9 M_\odot$) is in gas, mostly HI

$Z = \frac{1}{4} Z_\odot$

Both are blue, indicating vigorous star formation

In total, the group has a few dozen galaxies, with a radius of 2 Mpc.

M31 The most luminous galaxy is not us, but Andromeda (M31). It subtends 2.5° on the sky - 5 × the diameter of the Moon! Sb galaxy

The MW & M31 together comprise most of the mass.

There is a lower-mass spiral, M33 and a collection of irregulars and ellipticals. Most of these are dwarf spheroidals (no density cusp)

The smaller galaxies are clustered around M31 & us.

We can construct color-magnitude diagrams for all local group galaxies. In this way, can establish the SF history of each one. Find that the small galaxies undergo bursts of SF.