SO FAR:

- Galaxy types
- Ancient history
  - Properties of Interstellar Dust
- Milky Way and spiral galaxy morphology
  - Nuclear bulge
  - Disk
  - Stellar halo
  - Dark matter halo
- Chemical enrichment
  - Measuring chemical abundances
    - – Absorption lines (stars)
    - – Continuum energy distributions (stars)
    - – Emission lines (H II regions)
  - Star-forming regions

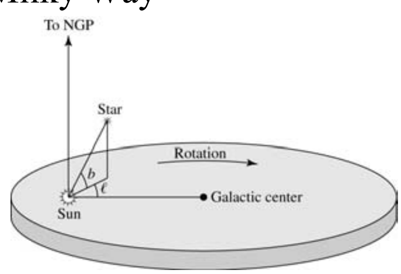
NOW… Kinematics of spiral galaxies

- Rotation curves ➔ mass distribution (includes sidetrack about measuring distances)
- Spiral structure

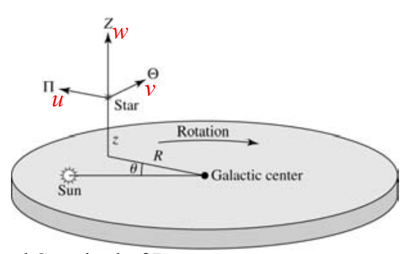
- General properties of S, E, Irr galaxies
- Midterm

Kinematics of the Milky Way

- From [CO] 24.3, especially pp 901-14.
- Coordinate systems
  - Spherical coordinates centered on Sun: Galactic latitude (l_{II}) , longitude (b_{II})



  - Π, Θ, Z
    - Velocity components in cylindrical coordinate system centered on Galactic Center



  - Peculiar velocities *u, v, w*
    - Π, Θ, Z velocities but relative to Local Standard of Rest
    - LSR is point instantaneously centered on Sun, but moving in a perfectly circular orbit.
    - Solar motion: motion of sun relative to LSR

- Star density is higher towards GC.
  - Those stars are on orbits that Sun overtakes.
- Velocity ellipsoids and asymmetrical drift.
- Sun's orbital velocity
  $V \sim 220$ km s^{-1}
- Sun's orbital period
  $$P = \frac{R_0}{V} \sim 230 \text{ million yrs.}$$
- Approx. mass interior to Sun's orbit
  $$F_{centrifugal} = F_{grav}$$
  $$\frac{mV^2}{R_0} = \frac{GmM}{R_0^{\ 2}}$$
  $$M = \frac{V^2 R_0}{G} \sim 9\text{x}10^{10}\ M_\odot$$

LSR's orbit

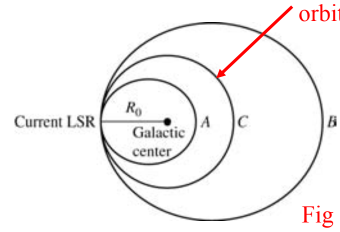


Fig 24.20

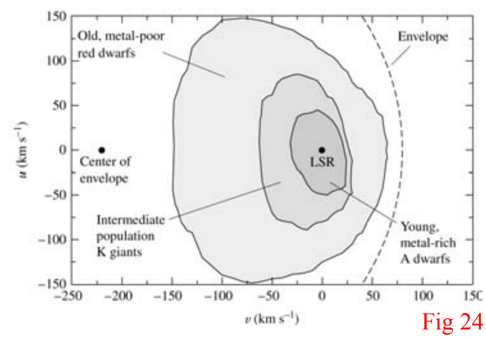


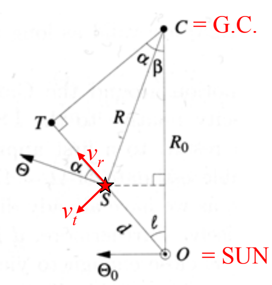
Fig 24.21

Differential Rotation (see [CO pp. 909-911)

- From the figure:
  $$v_r = \Theta \cos\alpha - \Theta_0 \sin\ell,$$
  $$v_t = \Theta \sin\alpha - \Theta_0 \cos\ell,$$
- Angular rotation velocity:
  $$\Omega(R) \equiv \frac{\Theta(R)}{R}$$
- + some geometry ➔
  $$v_r = (\Omega - \Omega_0)\, R_0 \sin\ell,$$
  $$v_t = (\Omega - \Omega_0)\, R_0 \cos\ell - \Omega d.$$
- Taylor expansion:

$$\Omega(R) = \Omega_0\,(R_0) + \left.\frac{d\Omega}{dR}\right|_{R_0} (R - R_0) + \cdots$$

$$v_r \simeq Ad \sin 2\ell,$$
$$v_t \simeq Ad \cos 2\ell + Bd$$



[Fig 24.22]

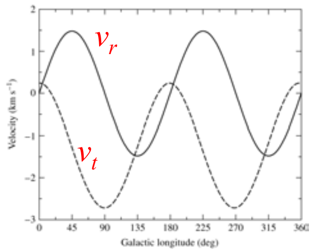
Oort's Constants:

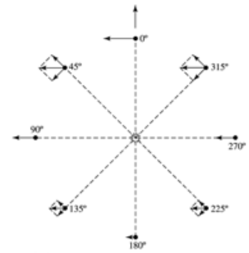
$$A \equiv -\frac{1}{2}\left[\left.\frac{d\Theta}{dR}\right|_{R_0} - \frac{\Theta_0}{R_0}\right]$$
$$B \equiv -\frac{1}{2}\left[\left.\frac{d\Theta}{dR}\right|_{R_0} + \frac{\Theta_0}{R_0}\right]$$

Oort's Constants

$$A \equiv -\frac{1}{2}\left[\frac{d\Theta}{dR}\bigg|_{R_0} - \frac{\Theta_0}{R_0}\right]$$

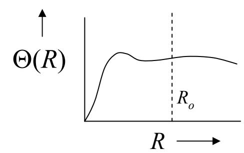
$$B \equiv -\frac{1}{2}\left[\frac{d\Theta}{dR}\bigg|_{R_0} + \frac{\Theta_0}{R_0}\right]$$





- Easily (?) evaluated from the observations: $v_r \simeq Ad \sin 2\ell,$ $v_t \simeq Ad \cos 2\ell + Bd$
- contain important information about Galactic rotation curve.
  - Angular velocity for circular motion at R_o:

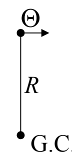
$$\Omega_o = A - B$$



  - Gradient of rotation curve at R_o:

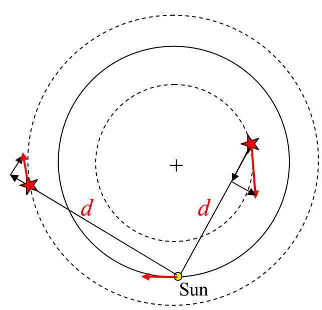
$$\frac{d\Theta}{dR}\bigg|_{R_o} = -(A+B)$$

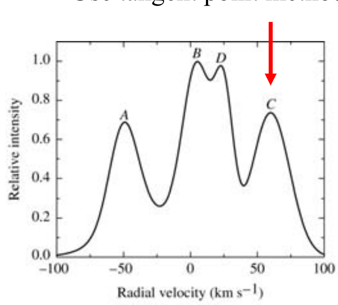
$$\Omega(R) = \frac{\Theta(R)}{R}$$



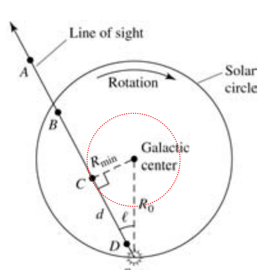
Observed MW rotation curve

- In principle, for stars, clusters, etc:
  - measure distance d and v_r
  - assume circular orbit
- For H I 21cm, CO, etc. radio emission:
  - Only can measure v_r
  - Use tangent point method





(a)

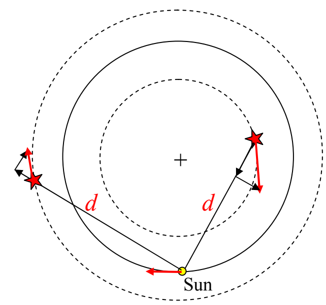


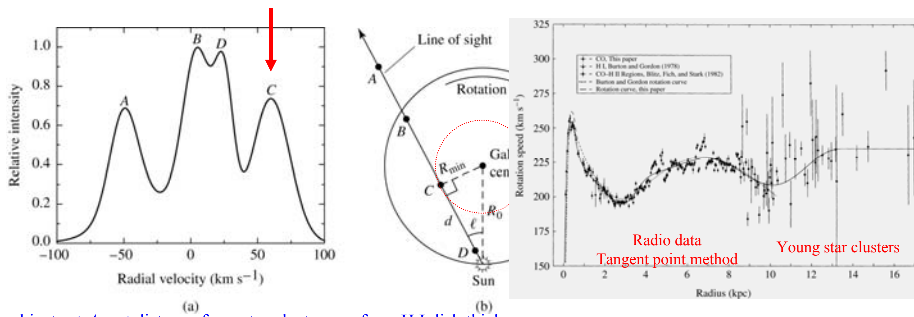
(b)

For objects at A: get distance from star clusters, or from H I disk thickness.

Observed MW rotation curve

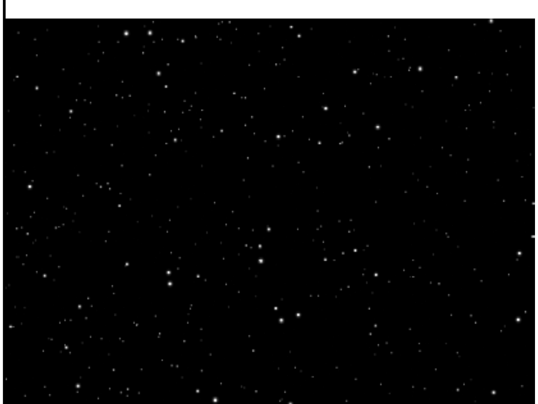
- In principle, for stars, clusters, etc:
  - measure distance *d* and v_r
  - assume circular orbit
- For H I 21cm, CO, etc. radio emission:
  - Only can measure v_r
  - Use tangent point method

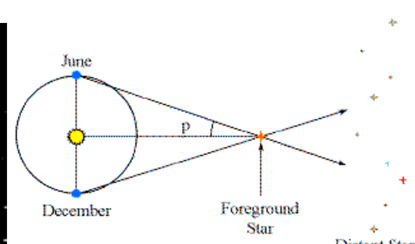




For objects at *A*: get distance from star clusters, or from H I disk thickness.

Measuring the Distances to the Stars: Parallax



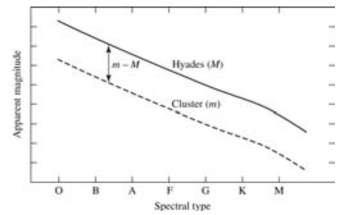


Parsec (pc)
= distance to star for which angle p = 1 arcsec
= 3.26 LY

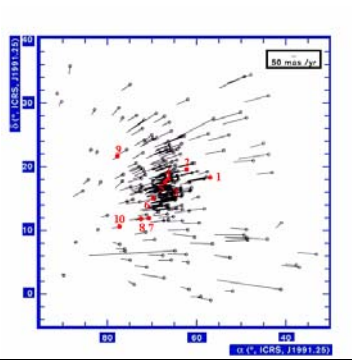
http://sci2.esa.int/interactive/media/html/sec23p1.htm

Measuring Distances inside the MW

- Parallax
- Pulsating variables
- Main sequence fitting for clusters



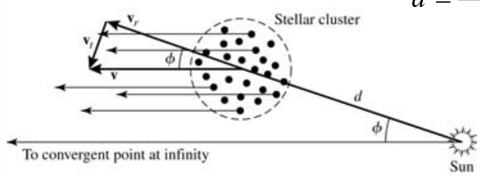
  - Calibrate with Hyades (moving cluster method = pp. 919-922)



$$v_t = v_r \tan\phi$$

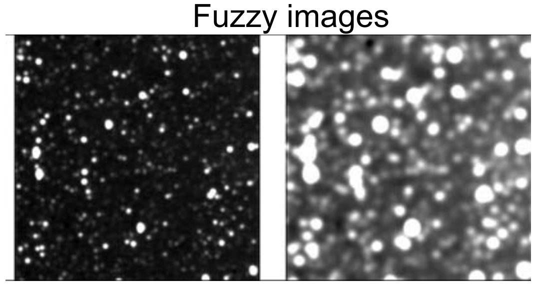
$$\mu = \frac{v_t}{d}$$

$$d = \frac{\langle v_r \rangle \tan\phi}{\langle \mu \rangle}$$



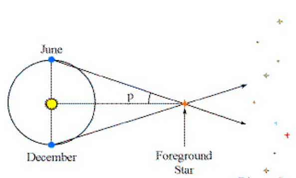
What sets the parallax limit?

Fuzzy images



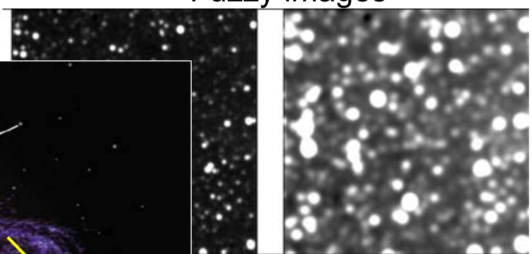
A field of stars …blurred by Earth's atmosphere.

Old limit for parallax distances:
20-50 parsecs

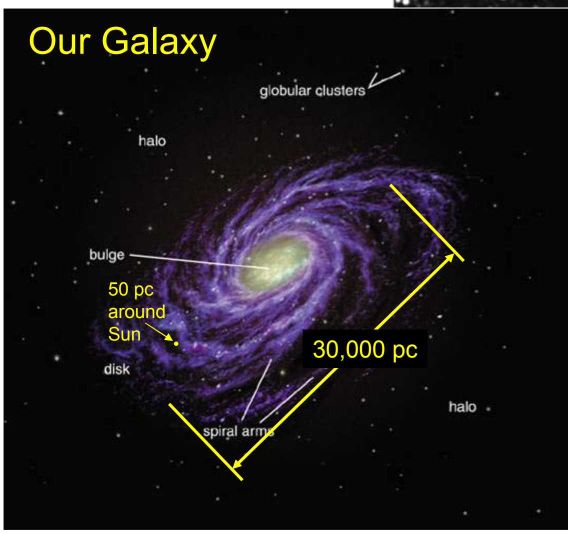


What sets the parallax limit?

Fuzzy images

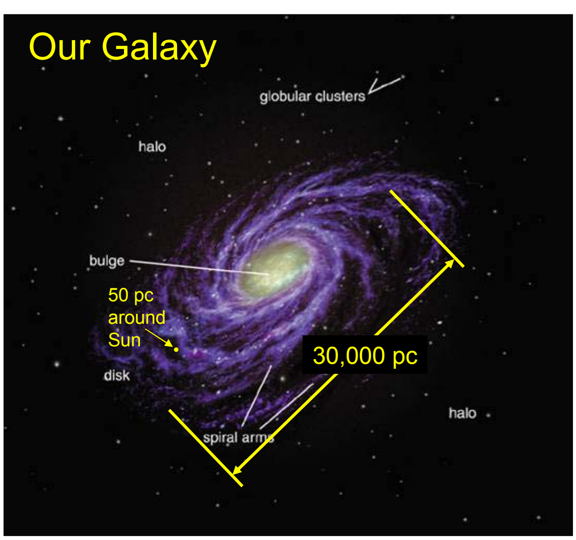


…blurred by Earth's atmosphere.



Old limit for parallax distances:
20-50 parsecs

Sharp Images from Space

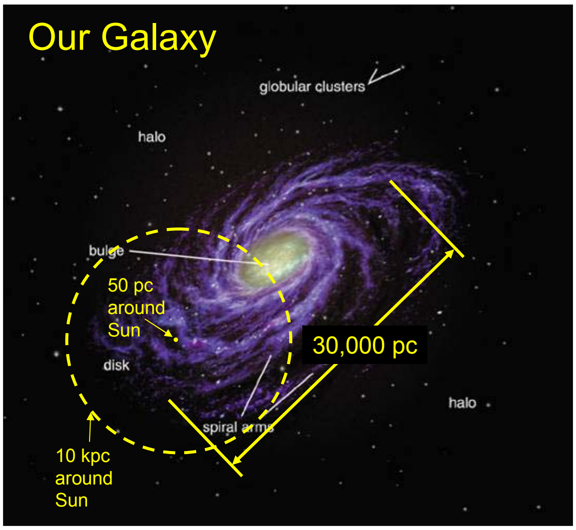


Hipparcos

Old limit for parallax distances:
20-50 parsecs

Hipparcos (1989-1993):
100-200 parsecs
(1σ =1 milliarcsec = 1kpc)

Coming Attraction



GAIA spacecraft: Dec 2011 launch

Old limit for parallax distances:
20-50 parsecs

Hipparcos (1989-1993):
100-200 parsecs
(1σ =1 milliarcsec = 1kpc)

GAIA: 10 kpc