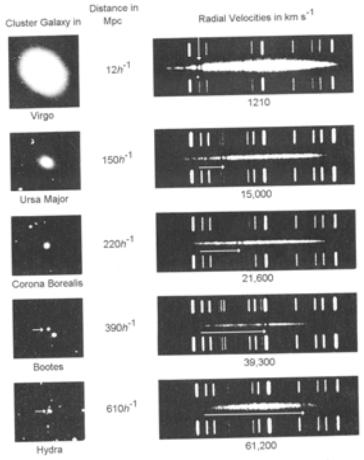
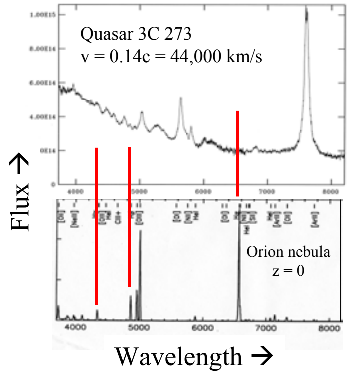
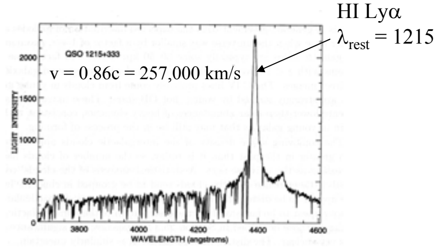
Redshifts







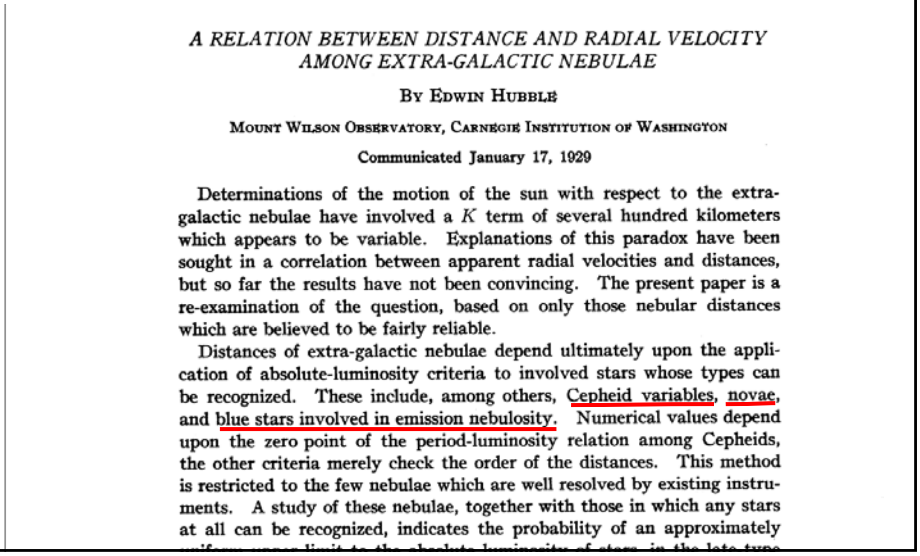
$$\text{Redshift} = z = \frac{\lambda_{obs}-\lambda_{rest}}{\lambda_{rest}} = \frac{\Delta\lambda}{\lambda} \approx \frac{v}{c}$$

$$\frac{v}{c} = \frac{(z+1)^2-1}{(z+1)^2+1}$$

Special relativistic result [CO eqn. 4.38]

Distance Measurements

From *The Astrophysical Journal*, 1929:



A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

By Edwin Hubble

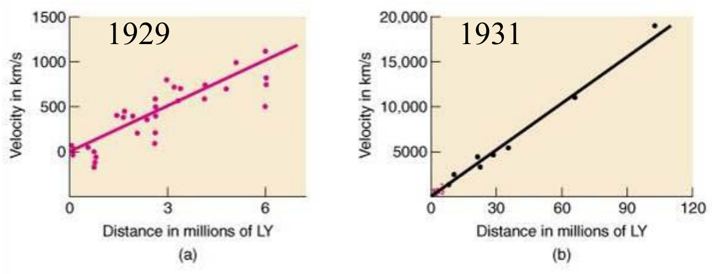
Mount Wilson Observatory, Carnegie Institution of Washington

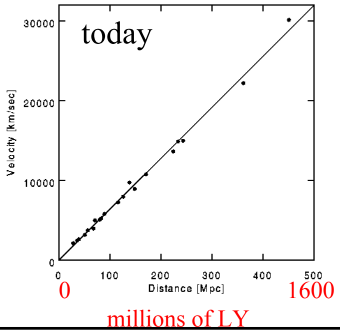
Communicated January 17, 1929

Determinations of the motion of the sun with respect to the extra-galactic nebulae have involved a *K* term of several hundred kilometers which appears to be variable. Explanations of this paradox have been sought in a correlation between apparent radial velocities and distances, but so far the results have not been convincing. The present paper is a re-examination of the question, based on only those nebular distances which are believed to be fairly reliable.

Distances of extra-galactic nebulae depend ultimately upon the application of absolute-luminosity criteria to involved stars whose types can be recognized. These include, among others, Cepheid variables, novae, and blue stars involved in emission nebulosity. Numerical values depend upon the zero point of the period-luminosity relation among Cepheids, the other criteria merely check the order of the distances. This method is restricted to the few nebulae which are well resolved by existing instruments. A study of these nebulae, together with those in which any stars at all can be recognized, indicates the probability of an approximately

Hubble’s Law (1929)

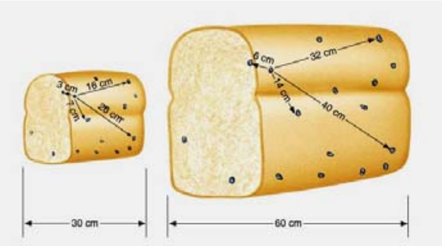




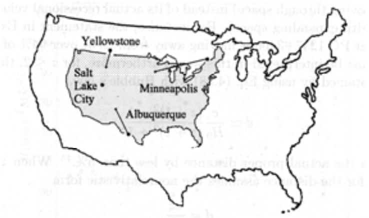
- Measure radial velocity v from Doppler shift.
- Hubble’s Law:

  $v = H_o d$
- H_o is called “Hubble constant”

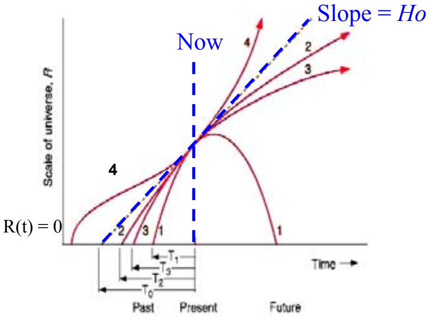
The Expanding Universe
Homogeneous * Isotropic



As seen from a Wonder Bread raisen



As seen from Utah



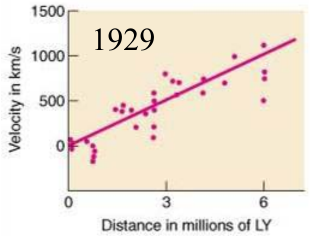
$$H_o = \frac{1}{R}\frac{dR}{dt}$$

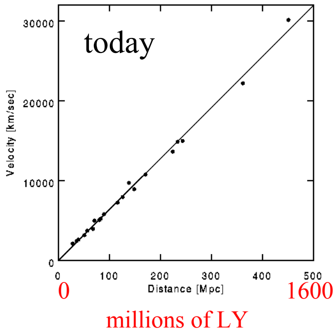
H_o = velocity/time

= km s^{-1} $\mathrm{Mpc}^{=1}$

$$\frac{1}{H_o} = \text{age of universe}$$

The Expanding Universe
Homogeneous * Isotropic



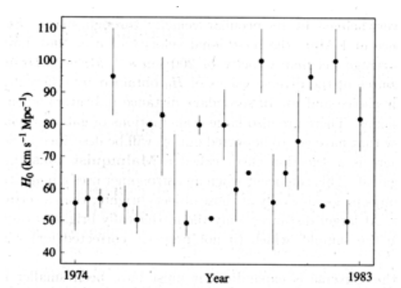


- The Hubble Un-constant (blush)

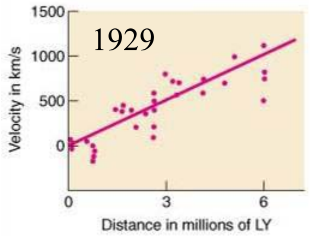
  $H_o = 100h$ km s^{-1} Mpc^{-1}

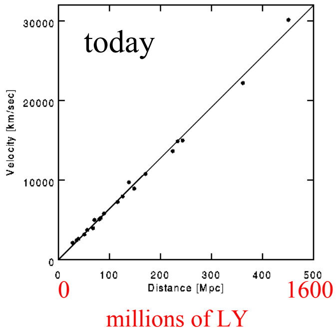
- Hubble time

  $t_H = 1/H_o = 9.78 \times 10^9\ h^{-1}$ yr.



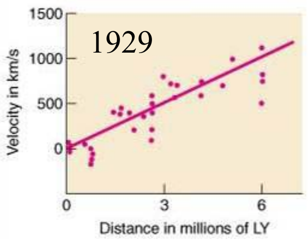
Large Distances Needed

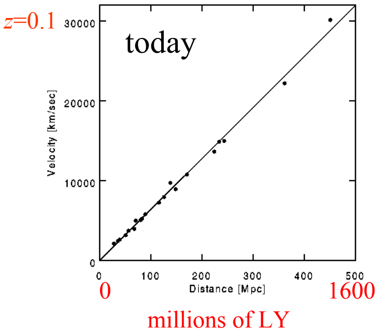




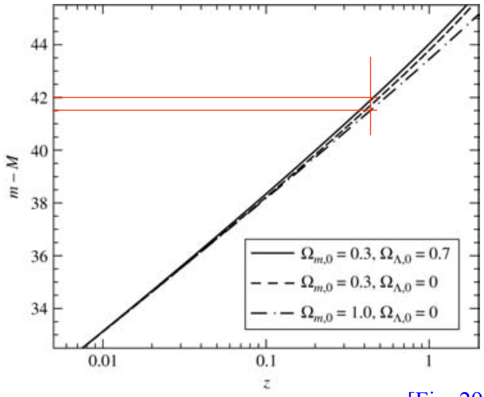
- Hubble flow: $v = Ho\ d$
  - Peculiar velocities are superimposed on this.

Large Distances Needed





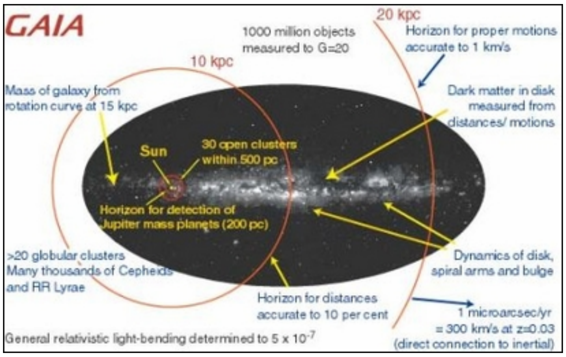
- To distinguish between cosmological models
  - In the example, 0.5 mag accuracy ~ 50% accuracy.



[Fig. 29.26]

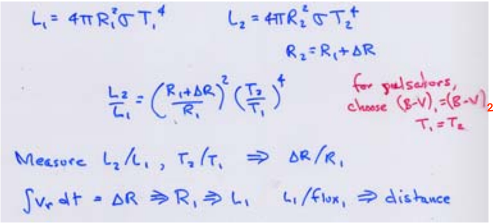
Parallaxes

- GAIA will be great within Milky Way
  - but not to cosmological distances



Some other absolute distance measurements
(and why they are not accurate enough)

- The problem: always need something measured in absolute units at the object.
- Baade-Wesselink method for expanding or pulsating ~BB sources (Cepheids, SNe)



$$L_1 = 4\pi R_1^2 \sigma T_1^4 \qquad L_2 = 4\pi R_2^2 \sigma T_2^4$$

$$R_2 = R_1 + \Delta R$$

$$\frac{L_2}{L_1} = \left(\frac{R_1+\Delta R}{R_1}\right)^2 \left(\frac{T_2}{T_1}\right)^4$$

for pulsators, choose $(B-V)_1 = (B-V)_2$

$T_1 = T_2$

Measure L_2/L_1, T_2/T_1 $\Rightarrow$ $\Delta R/R_1$

$\int v_r\, dt = \Delta R \Rightarrow R_1 \Rightarrow L_1$ $\quad L_1/\text{flux}_1 \Rightarrow$ distance

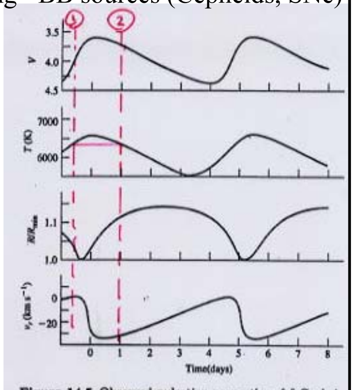
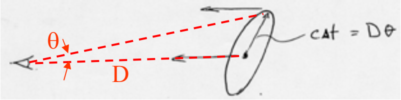


Figure 14.5 Observed pulsation properties of δ Cephei.

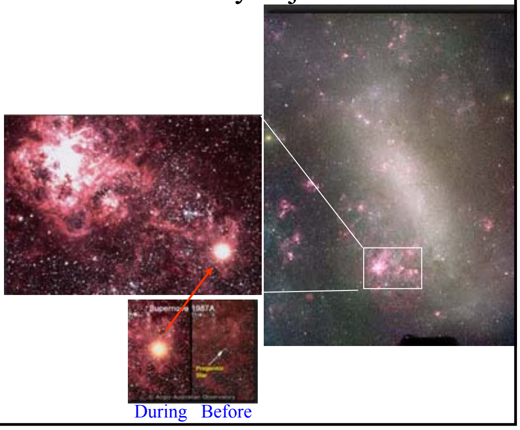
- integrate radial velocity curve to find ΔR
- measure L_2/L_1, T_2/T_1, solve for R, then for L
- problems:
  - stars, SNe not really BB radiators
  - absorption lines formed at different depths in atmosphere
  - SN 1987a gives up to factor 2 error.

Time delays: the ring around SN 1987A

- emission lines from ring respond to variations in ionizing continuum from SN remnant
  - measure Δt = light travel time from center to ring
  - measure angular diameter of ring
- works fine, but only tried for this one nearby object

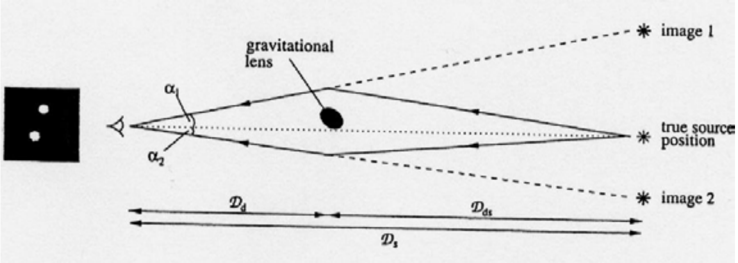


After



During Before

Gravitational lens time delays



- Separations, relative brightnesses of images
  ==> model of geometry
  ==> relative values of D_d, D_s, D_{ds}
- Absolute measurement is Δt_{lens}
- Problems:
  - Need accurate measurements of time lags (many years)
  - Need accurate model of Φ and of lens geometry.
    - Models not unique ==> factor 10 uncertainty in H_0 (!)

Relative Distance Estimators:
The Cosmic Distance Ladder

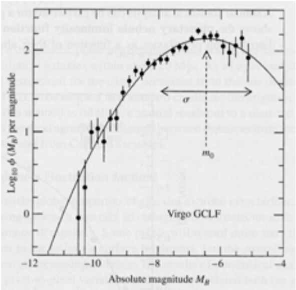
- The historical approach
- Still the most accurate (from HST key project)
- Starts with absolute measurements of distances to nearby stars
  - use those to calibrate distances out to nearest examples of more luminous objects
  - then those to calibrate distances to still more luminous objects, and so on…
- Empirically-based
  - doesn't depend on wrong physical models
  - but lack of physics ==> absolute calibrator needed somewhere.

The Local Baseline

- Parallaxes, moving cluster method ➔ distance to Hyades, etc.
- Cluster main sequence fitting
- Variable stars
  - Cepheids $M_V \sim -3$ ==> out to Virgo cluster with HST
  - RR Lyraes $M_V \sim 0.6$ ==> only in Local Group

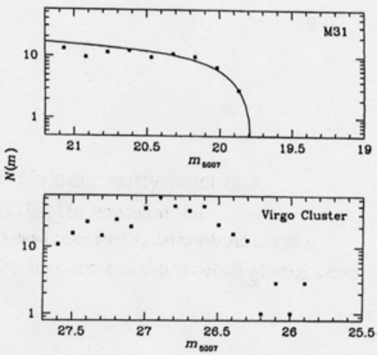
Globular cluster luminosity functions

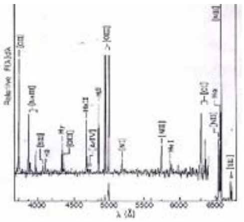
- Gaussian distribution of L, mean is same in M31, MW, LMC etc.
- at large distances, only practical to measure them in E's
- but calibration is from Milky Way, a spiral
  - ==> uncertain method



- Planetary nebula luminosity functions
  - strong [O III], Hα emission line
    - ==> easily detected by narrow-band imaging
  - luminosity function has sharp cutoff at bright end
  - can find brightest planetary out as far as Virgo cluster

    (17 Mpc, v = 1200 km/s, z = 0.004)





- Novae
  - Correlation between L and rate of decline
    - fainter ones decay more slowly

Also... brightest stars in galaxies, brightest H II regions, etc.

Results: Distances in the Local Group

Galactic center

- huge reddening problems

  ➔ poor test of distance indicators.

Table 7.1 Galactic center distance estimates

Method	Distance/kpc
H_2O masers	7.2 ± 0.7
RR Lyrae stars	7.8 ± 0.4
Globular clusters	8.0 ± 0.8
Cepheids	8.0 ± 0.5
Red clump stars	8.4 ± 0.4

LMC

- all stars at ~ same distance, yet close. enough to see stars far down the main sequence

  ➔ ideal lab for studying relative luminosities.
- RR Lyrae distance scale looks wrong.

Table 7.2 LMC distance estimates

Method	Distance/kpc
Main Sequence Fitting	50 ± 5
Cepheids	50 ± 2
RR Lyrae	44 ± 2
SN1987a time delay	52 ± 3
SN1987a Baade–Wesselink method	55 ± 5

M31

- another good lab for comparing, although farther away.
- M31 is same mass as distant spirals (unlike LMC).
- table appears to be based on *ratio* of distances M31/LMC.

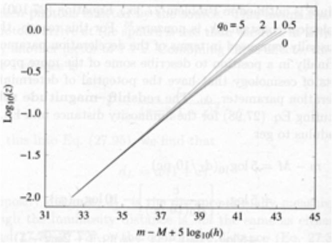
Table 7.3 Andromeda Galaxy (M31) distance estimates

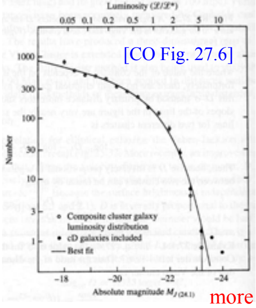
Method	Distance/kpc
Cepheids	760 ± 50
RR Lyrae	750 ± 50
Planetary Nebula Luminosity Function	750 ± 50
Globular Cluster Luminosity Function	700 ± 60
Novae	710 ± 80

Former Goal:
Calibrate Brightest Cluster Galaxies

- To get out to large distances ➔ want most luminous possible objects.

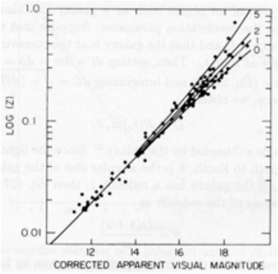
Schecter Luminosity Function





[CO Fig. 27.6]

more
luminous



Disaster!

- But large distances ➔ large lookback time ➔ evolution effects.