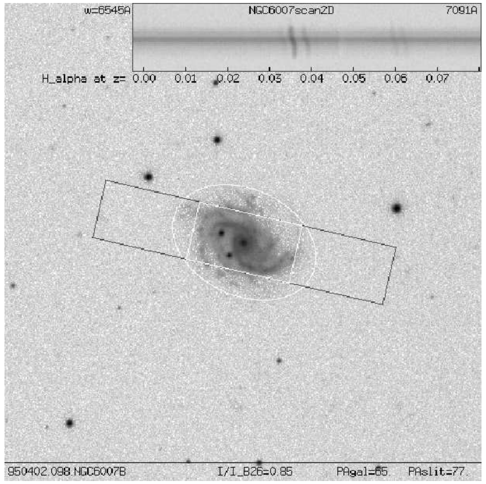
Galaxies: Dynamics, Masses & Clusters

Spiral Galaxies



NGC 6007 (Jansen)

Spectra of galaxies: sum of all constituent spectra (mainly stars plus some contribution from nebulae).

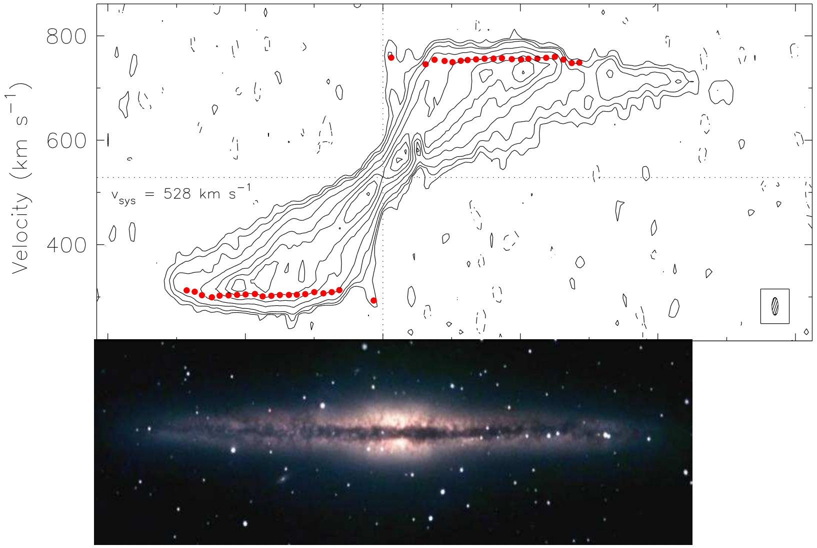
Absorption lines show clear shift $\Longrightarrow$ Doppler effect due to motion of stars around centre:

$$\frac{\Delta\lambda}{\lambda} = \frac{v_\mathrm{r}}{c} = \frac{v}{c}\sin i$$

where v_r: radial velocity, i: inclination (angle measured with respect to plane of sky).

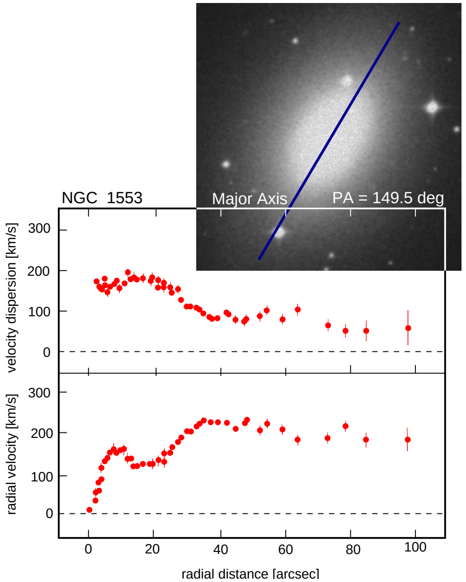
Typical rotation speeds are a few 100 km s^{-1}.

Spiral Galaxies



NGC 891 (Swaters et al., 1997, ApJ 491, 140 / Paul LeFevre, S&T Nov. 2002)

Spiral Galaxies



Spiral galaxy rotation curves are flat!

“Galaxy rotation problem”, first discovered by Vera Rubin (1970)

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← NGC 1553 (S0) (after Kormendy, 1984, ApJ 286, 116)

Rotation Curves: Interpretation

Newtonian interpretation of galaxy rotation curves:

Motion because of mass within r:

$$\frac{GM(\leq r)}{r^2} = \frac{v_{\text{rot}}^2(r)}{r}$$

such that

$$M(\leq r) = \frac{v_{\text{rot}}^2 r}{G}$$

therefore:

$v \sim$ const. implies $M(\leq r) \propto r$.

This assumption is approximately true even for nonspherical mass distributions.

NGC 891, KPNO 1.3 m
Barentine & Esquerdo

Rotation Curves: Interpretation

What mass distribution do we expect?

Intensity profile of disk in spiral galaxies can be well described by

$$I(r) = I_0 \exp(-r/h)$$

where r: distance from centre, h: "scale length".

Luminosity emitted within radial distance r_0:

$$L(r < r_0) = I_0 \int_0^{r_0} \exp(-r/h)\, 2\pi r\, \mathrm{d}r = 2\pi I_0 \left(h^2 - \exp(-r_0/h) h (h + r_0)\right)$$

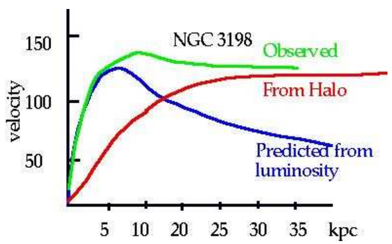
i.e., for $r_0 \longrightarrow \infty$: $L(r < r_0) \to$ const..

If all light comes from stars, i.e., light traces mass,

and the population of stars does not change with position

then $M/L \sim$ const., such that $M(< r) \sim$ const. outside a certain radius and $v \propto r^{-1/2} \Longrightarrow$ not what is observed!

Rotation Curves: Interpretation



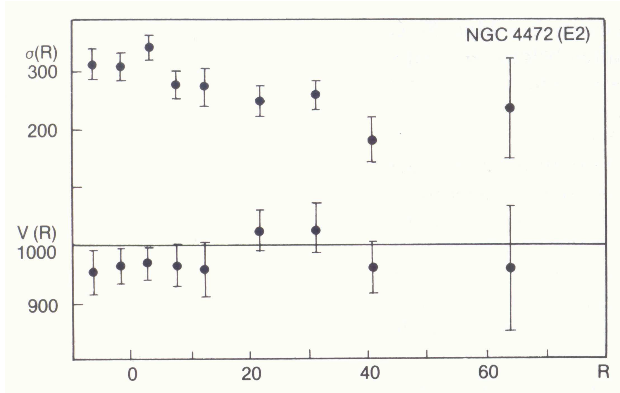
Distribution of dark matter

- luminosity to mass ratio: L/M = 4 (solar neighbourhood)
- convert luminosity to mass
- compute expected rotation curve form the mass distribution $v_{\text{lum}}(R)$
- distribution of dark matter: $M_{\text{dark}}(R) = \frac{M}{G}[v^2(R) - v_{\text{lum}}^2(R)]$

Canonical interpretation: a large fraction of gravitating material does not emit light $\Longrightarrow$ spiral galaxies have large and massive halos made of dark matter

Elliptical Galaxies

What determines the shape of elliptical galaxies?



Karttunen

No rotation!

Large velocity dispersion

statistical motion of stars

correlation of the central velocity dispersion with absolute brightness

$L \sim \sigma_c^4$

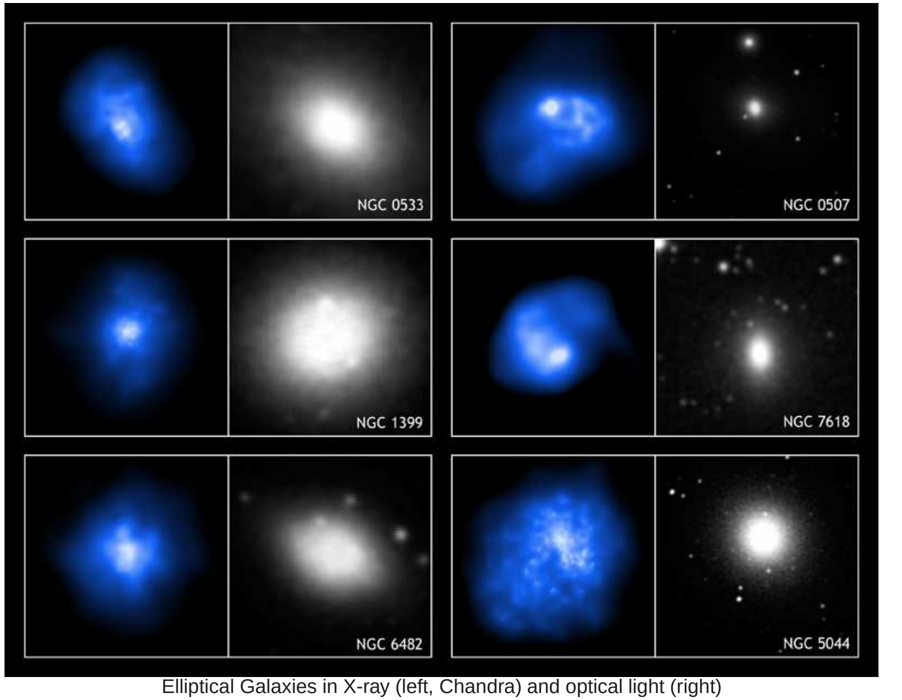
(Faber-Jackson-relation)

Masses of Elliptical Galaxies

No rotation!

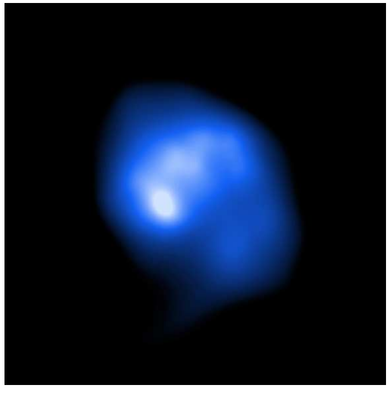
- virial theorem: time averaged $\bar{E}_{\rm kin} = -\frac{1}{2}\bar{E}_{\rm pot}$
- requires hydrostatic equilibrium
- elliptical galaxy of $M_G \langle v^2 \rangle = G \int_0^{R_G} \frac{M(R) dM(R)}{R} = a \frac{G M_G^2}{R_G}$
- homogeneous sphere $a = 3/5$
- $\langle v^2 \rangle = \sigma^2 = a \frac{G M_G}{R_G}$
- Kinematical mass larger than mass of luminous matter

Dark Matter also in Elliptical Galaxies



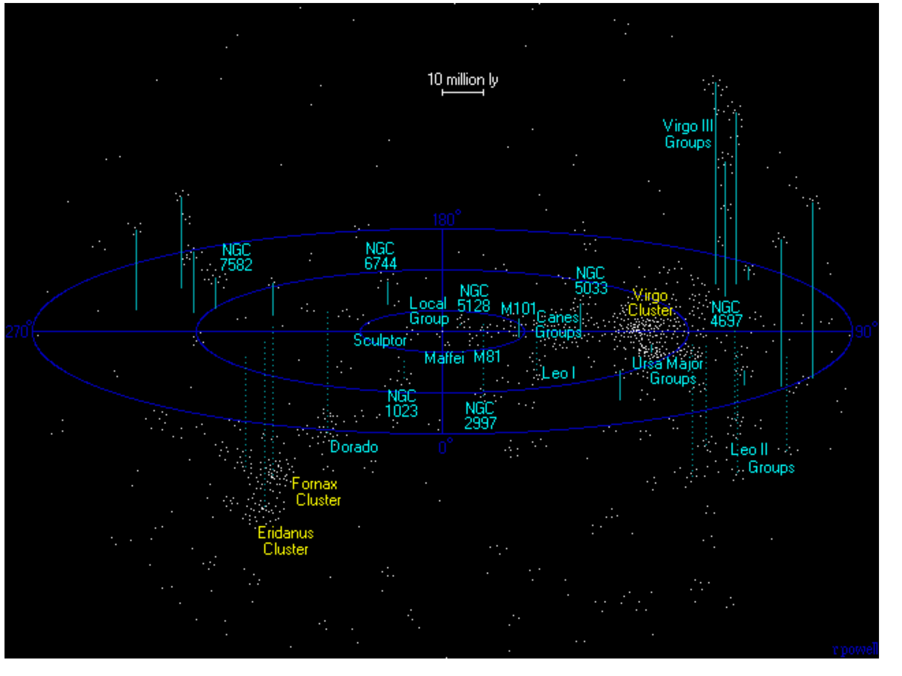
Elliptical Galaxies in X-ray (left, Chandra) and optical light (right)

Hot X-ray gas



NGC 7618 (Chandra)

- Elliptical galaxies have very little gas and dust
- Diffuse X-rays detected
- Temperatures: 10...100 Million K
- Gas expelled and heated by Supernovae(?)
- Mass: 5% of total galaxy
- High escape velocity
- Dark Matter required to keep X-ray gas bound



The universe out to the Virgo Cluster

source: `http://www.atlasoftheuniverse.com/virgo.html`

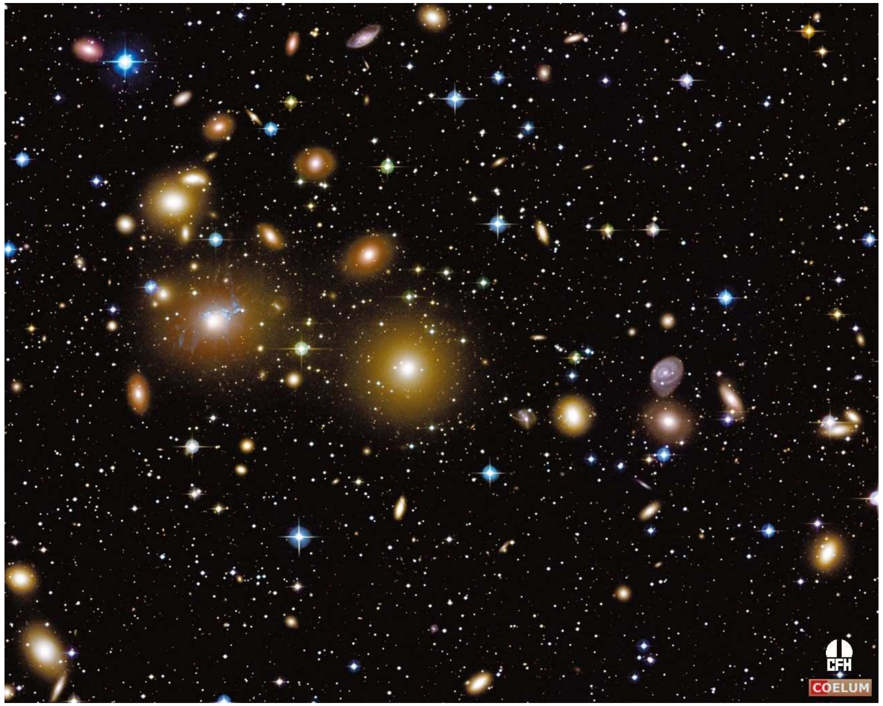
Coma cluster of galaxies (Misti/APOD)

Clusters of Galaxies: largest gravitationally bound structures in the universe.

Typical numbers: up to a few 1000 galaxies, masses: 10^{14} to $10^{15}\,M_\odot$

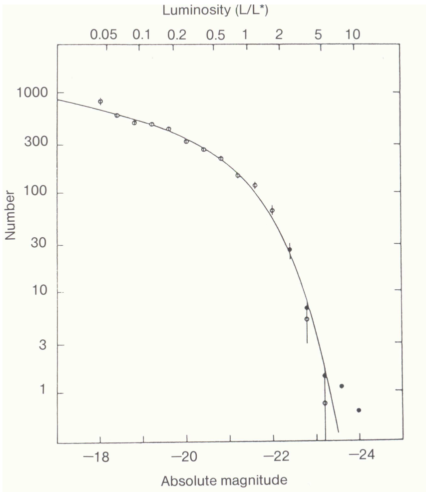
Densest clusters: visually found, “Abell clusters”

Groups of galaxies: few MPc, few 10s of galaxies



Perseus Cluster: 660 gal in field, number of spirals increases outwards

Luminosity Function



“Schechter Function” of 13 clusters (Karttunen)

Analysis of clusters finds that galaxies have wide distribution of absolute magnitudes

Generally described in terms of the luminosity function, $\Phi(L)$, where $\Phi(L)dL$ = number of galaxies per unit volume in luminosity bin $[L, L+dL]$, can be described by the Schechter function:

$$\Phi(L)dL = \Phi^* \left(\frac{L}{L^*}\right)^\alpha \exp\left(-\frac{L}{L^*}\right)\frac{dL}{L} \quad (16.1)$$

where typically $\Phi^* \sim 4 \times 10^{-2}\,\mathrm{Mpc}^{-3}$, $\alpha \sim -1$ and where L^* is a characteristic luminosity (in magnitudes, $M^* \sim -20\,\mathrm{mag}$)

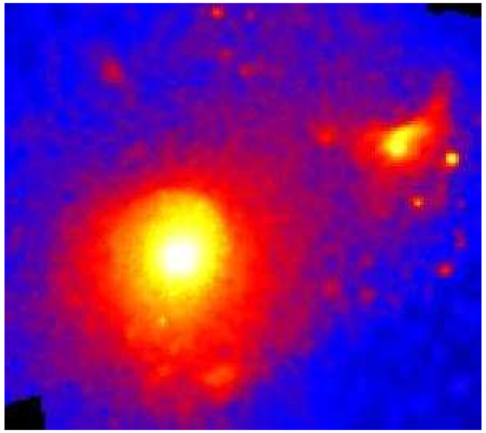
Masses of Clusters of Galaxies

Fritz Zwicky

- Virial masses (as for elliptical galaxies)
- Zwicky (1933): Coma cluster: $\sigma \sim 1000\,\mathrm{km/s}$
- virial mass 10 times larger than luminous mass
- Dark Matter halo
- Masses of clusters of galaxies: $10^{12} \dots 10^{15}\,M_\odot$
- Masses of stars: 5% of the cluster mass

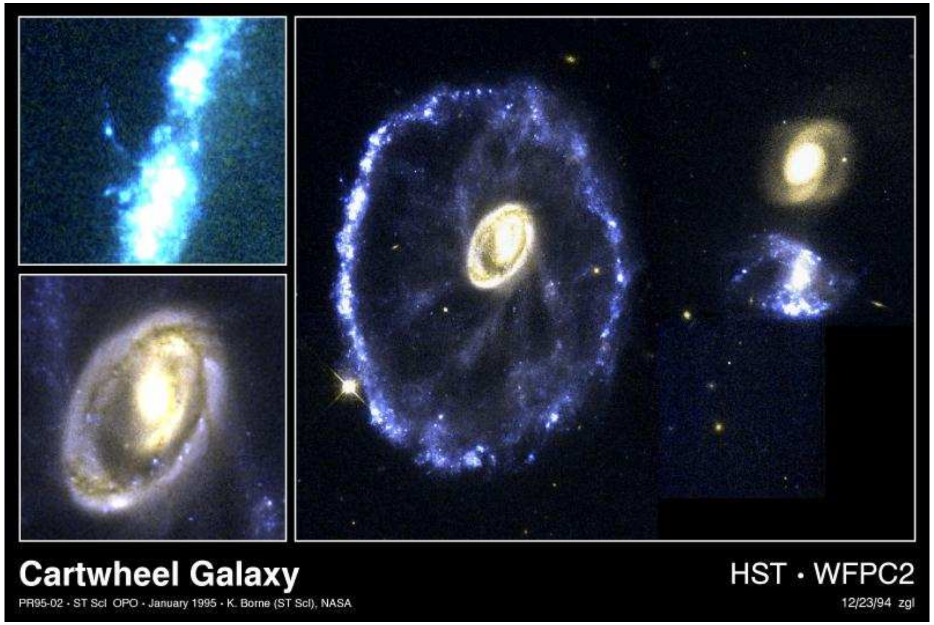
Dark Matter also in clusters of Galaxies

Hot X-ray gas in clusters of Galaxies

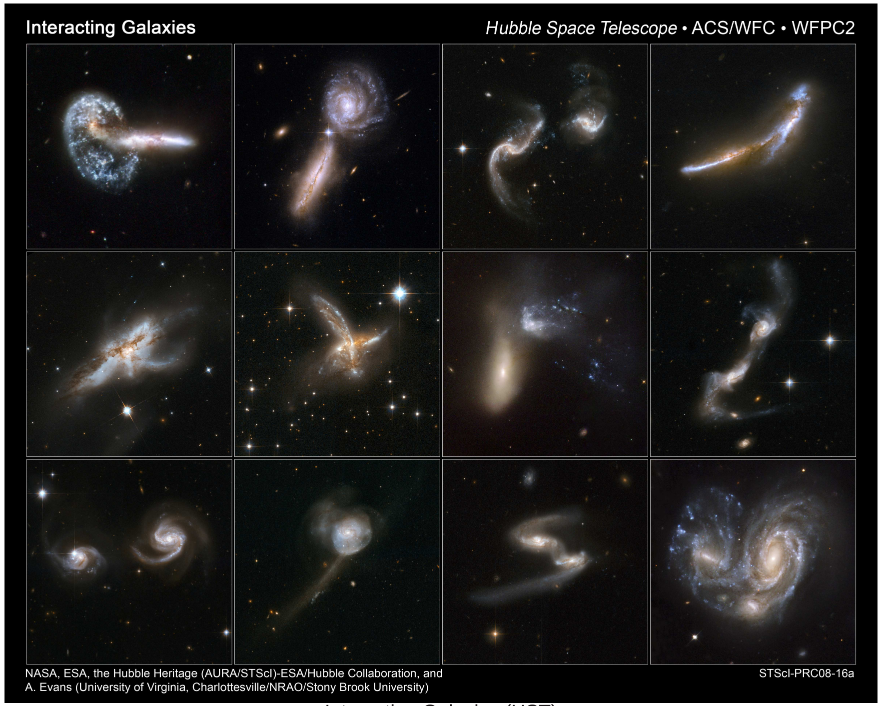


Virgo cluster in X-ray light (ROSAT)

- Diffuse intra cluster X-rays detected
- Temperatures: 10...100 Million K
- Mass: 10% of total mass of galaxy cluster
- Dark Matter required to keep X-ray intracluster gas bound to the cluster

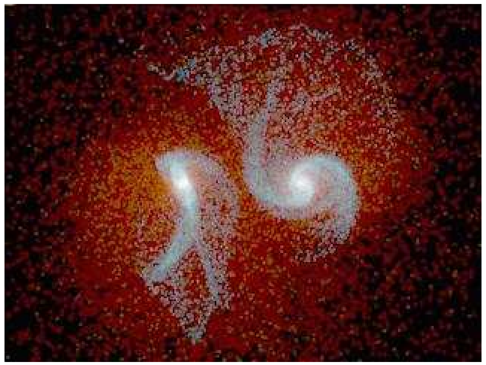


colliding galaxies: Cartwheel Galaxy (HST)



Interacting Galaxies (HST)

Interacting Galaxies

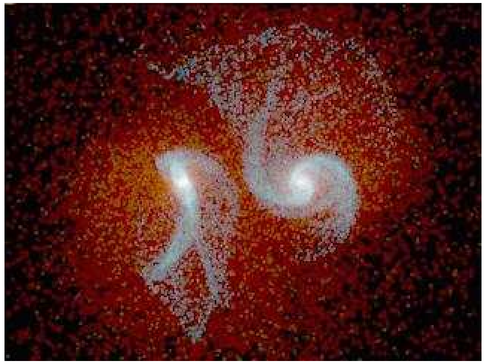


http://ifa.hawaii.edu/~barnes/transform.html

Numerical Merger Experiments

- two identical spiral galaxies
- bulge : disc : halo = 1 : 3 : 16
- gas: 10% of disc mass
- exponential scale length: 3.3 kpc
- rotation curve as in Milky Way
- parabolic orbit
- closest encounter: 8.8kpc after 250 Myrs

Interacting Galaxies



http://ifa.hawaii.edu/~barnes/transform.html

Numerical Merger Experiments: Results

- gas collapses into the central 100pc of the merger
- tidal arms form; bridges between galaxies
- morphology of peculiar galaxies (e.g. The Mice) can be explained by two merging disc galaxies

Elliptical galaxy results from a merger of two disc galaxies

The Astronomical Distance Ladder

Introduction

Distances are required to determine properties such as the luminosity or the size of an astronomical object.

Only *direct* method:

1. Trigonometric parallax

Most other methods based on “standard candles”, i.e., use known absolute magnitude of an object to derive distance via distance modulus.

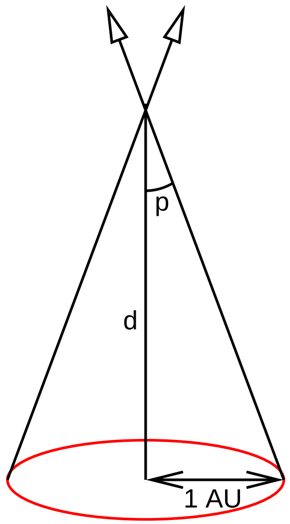
2. Main Sequence Fitting
3. Variable stars: RR Lyrae and Cepheids
4. Type Ia Supernovae
5. Tully-Fisher for spiral galaxies
6. D_n-σ for ellipticals
7. Brightest Cluster Galaxies

For the farthest objects, can also use expansion of universe:

8. Hubble’s law

Methods are calibrated using distances from the previous step of the distance ladder.

Trigonometric Parallax



Motion of Earth around Sun $\Longrightarrow$ Parallax
Produces apparent motion of star; projected on sky see angular motion, opening angle

$$\tan p \sim p = \frac{r_{\text{Earth}}}{d} = \frac{1\,\text{AU}}{d}$$

p is called the trigonometric parallax.

Note: requires several observations at several positions of the Earth

Measurement difficult: $\pi \lesssim 0.76''$ (α Cen).

Define unit for distance:
Parsec: Distance where 1 AU has $p = 1''$.

$1\,\text{pc} = 206265\,\text{AU} = 3.086 \times 10^{16}\,\text{m} = 3.26\,\text{ly}$

Trigonometric Parallax

Best measurements to date: Hipparcos satellite (1989–1993)

- systematic error of position: $\sim$0.1 mas
- effective distance limit: 1 kpc
- standard error of proper motion: $\sim$1 mas/yr
- photometry
- magnitude limit: 12
- complete to mag: 7.3–9.0

Results available at `http://astro.estec.esa.nl/Hipparcos/`:

Hipparcos catalogue: 120000 objects with milliarcsecond precision.

Tycho catalogue: 10^6 stars with 20–30 mas precision, two-band photometry

Standard Candles

Assuming isotropic emission, the flux measured at distance d from object with luminosity L is given by the "inverse square law",

$$f(d) = \frac{L}{4\pi d^2}$$

note that f is a function of the d.

Remember that the magnitude is defined through comparing two fluxes,

$$m_2 - m_1 = 2.5 \log_{10}(f_1/f_2) = -2.5 \log_{10}(f_2/f_1)$$

To allow the comparison of sources at different distances, define

absolute magnitude M = magnitude if star were at distance 10 pc

Because of this

$$M - m = -2.5 \log_{10}\left(f(10\,\mathrm{pc})/f(d)\right) = -2.5 \log_{10}\left(\frac{L/(4\pi(10\,\mathrm{pc})^2)}{L/(4\pi d^2)}\right) = -2.5 \log_{10}\left(\frac{d}{10\,\mathrm{pc}}\right)^2$$

The difference $m - M$ is called the distance modulus,

$$m - M = 5 \log_{10}\left(\frac{d}{10\,\mathrm{pc}}\right)$$

Standard Candles

To obtain distance, use standard candles

Standard candles are defined to be objects for which their absolute magnitude is known.

Requirements:

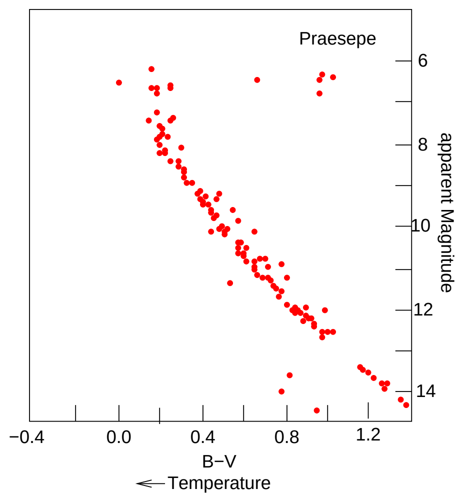
- physics of standard candle well understood (i.e., need to know *why* object has certain luminosity).
- absolute magnitude of standard candle needs to be calibrated, e.g., by measuring its distance by other means (this is a *big problem*)

To determine distance to astronomical object:

1. find standard candle(s) in object,
2. measure their m
3. determine $m - M$ from known M of standard candle
4. compute distance d

Often, distances are given in terms of $m - M$, and not in pc, so last step is not always performed.

Main Sequence Fitting



MS fitting applied to Praesepe
(after VandenBerg & Bridges 1984)

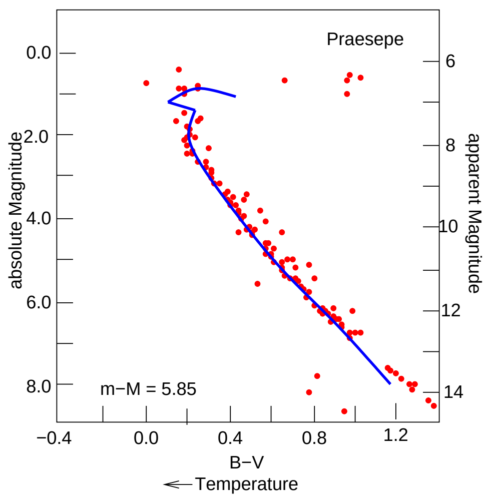
Clusters: if Main Sequence in Hertzsprung Russell Diagram determinable:

Shift observed HRD until main sequence agrees with location of MS measured for stars in solar vicinity $\Longrightarrow$ distance modulus.

Currently: distances to $\sim$200 open clusters known

Distance limit $\sim$7 kpc.

Main Sequence Fitting



MS fitting applied to Praesepe
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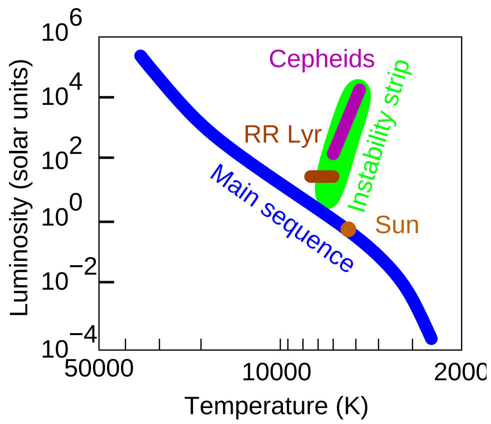
Introduction



Instability strip in the Hertzsprung-Russell Diagram

Certain regions of HRD: stars prone to instability:

Ionization of Helium: transparency of outer parts of star changes

$\Longrightarrow$ size of star changes

$\Longrightarrow$ surface temperature and luminosity variations

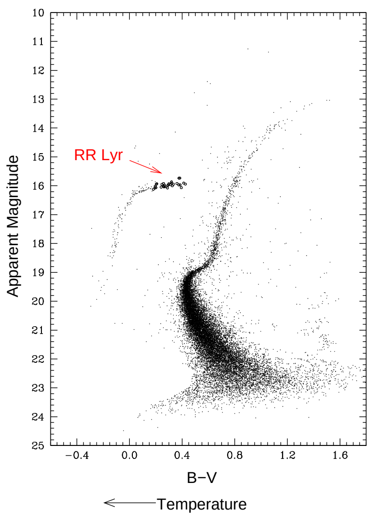
Most important variables of this kind:

1. RR Lyr variables

   mainly in globular clusters: lower metallicity of clusters ("population II") allows stars to enter instability strip

2. δ Cepheids

RR Lyrae



HRD of Globular Cluster M2
(after Lee et al., 1999, Fig. 2)

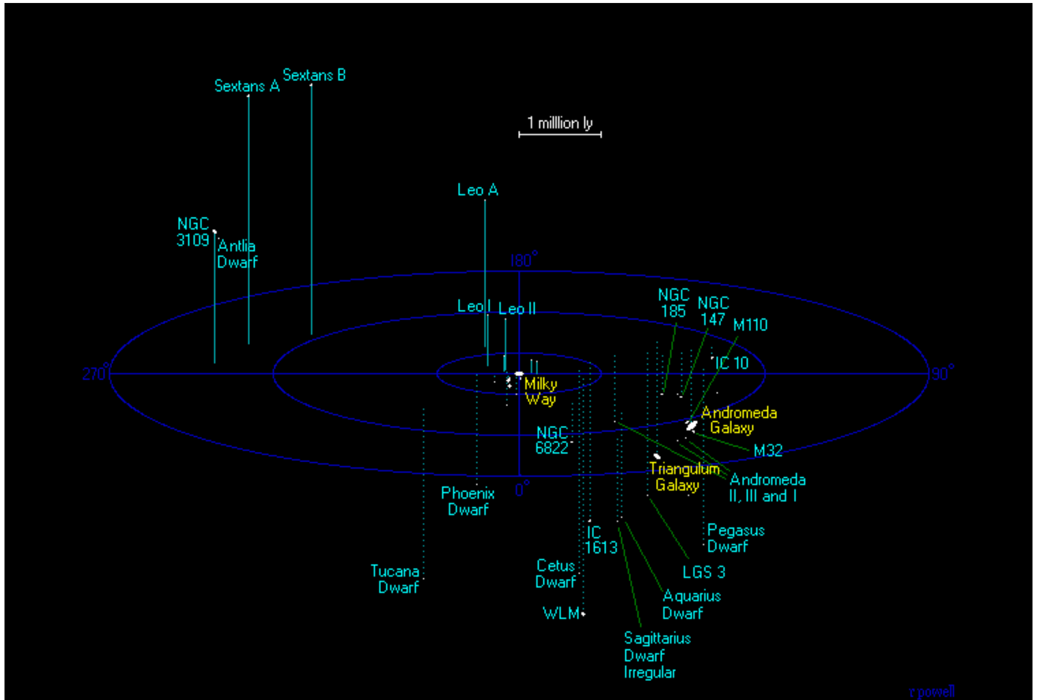
RR Lyrae variables:

- Variability ($P \sim 0.2 \dots 1$ d)
- Mainly temperature change
- RR Lyr gap clearly observable in globular cluster HRD

Absolute magnitude of RR Lyr gap:
$M_{\rm V} = 0.6$ mag, $M_{\rm B} = 0.8$ mag, i.e.,
$L_{\rm RR} \sim 50\,L_\odot$.

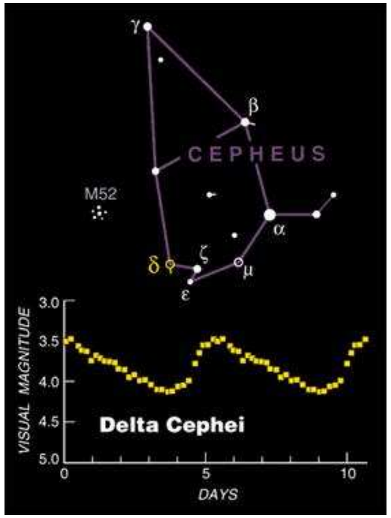
Works out to LMC ($d \sim 50$ kpc) and other dwarf galaxies of Local Group, mainly used for globular clusters and Local Group.

Example: M5: gap at $m = 16$ mag $\Longrightarrow m - M = 15.4$ mag $\Longrightarrow d = 12$ kpc.



source: `http://www.atlasoftheuniverse.com/localgr.html`
The neighbourhood of the Milky Way:

Cepheids



John Goodricke (1764–1786):

- deaf after scarlet fever at the age of five
- special education at Edinburgh
- at the age of 13 academy near York
- 1781: worked with Edward Pigott as astronomer
- 1782: discovery of Algol as eclipsing binary
- 1784: discovery of δ Cep

Cepheids

© ASP

Henrietta Leavitt (1868–1921):

- Graduated from Radcliffe College
- from 1895: volunteer at Harvard Observatory
- was ill and partially deaf from that
- 1902: back at Harvard Obs
- discovered 1777 variable stars in LMC
- 1912: discovered Period-Luminosity relation of Cepheids in SMC, but was not allowed (!) to follow this up
- later: defined Harvard photographic magnitude system
- died of cancer in 1921

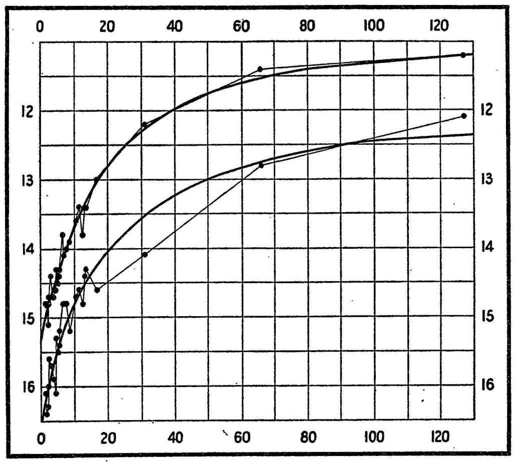


Fig. 1.

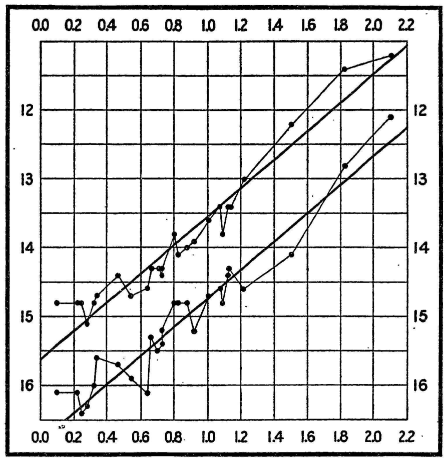
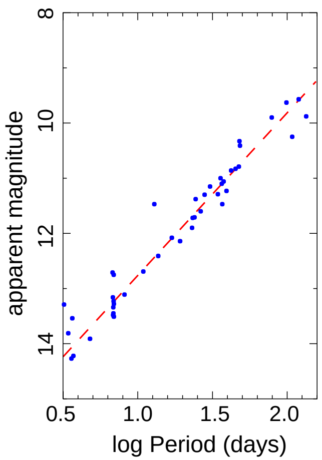


Fig. 2.

X-axis: period in days, Y-axis: magnitude

Leavitt & Pickering, 1912, Periods of 25 Variable Stars in the Small Magellanic Cloud, Harvard College Observatory Circular, vol. 173, pp. 1–3

Cepheids



Period-Luminosity relation for the LMC Cepheids

after Mould et al. (2000, Fig. 2)

Henrietta Leavitt(1912):

Cepheids have a period luminosity relationship: $M \propto -\log P$

Low luminosity Cepheids have lower period

Observations find:

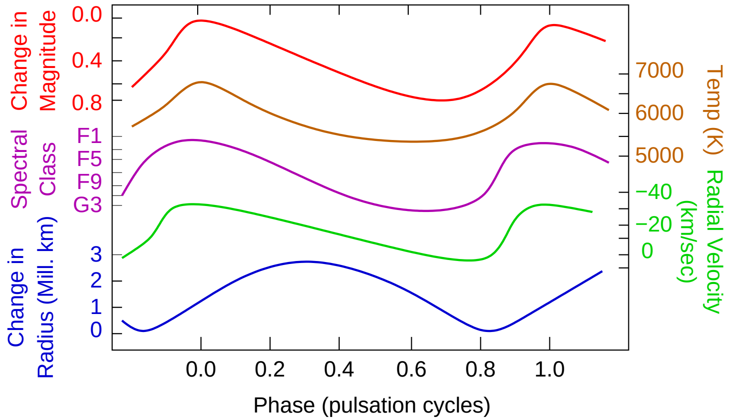
$$\langle M \rangle = -2.76 \log P - 1.40$$

(P in days)

Calibrated from observing Large Magellanic Cloud Cepheids (see figure), and determining LMC distance from other means (MS fitting, RR Lyr,...) to find absolute magnitudes...

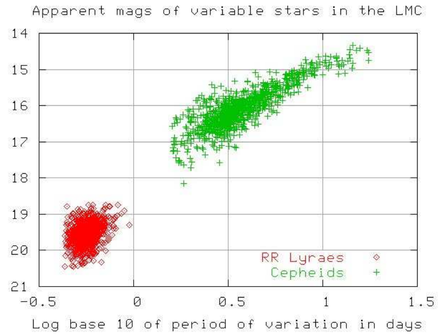
With HST: works out to Virgo cluster ($d = 16.5$ Mpc).

Cepheids

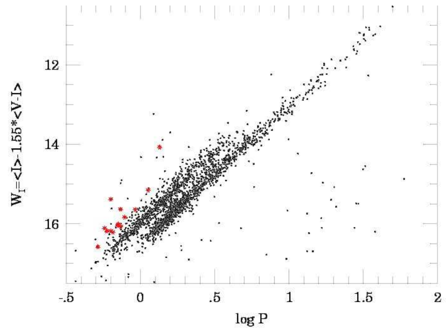


Cepheids: Luminous stars ($L \sim 1000\,L_\odot$) in instability strip with large luminosity amplitude variation, $P \sim 2 \ldots 150$ d (easily measurable).

The distance to the LMC



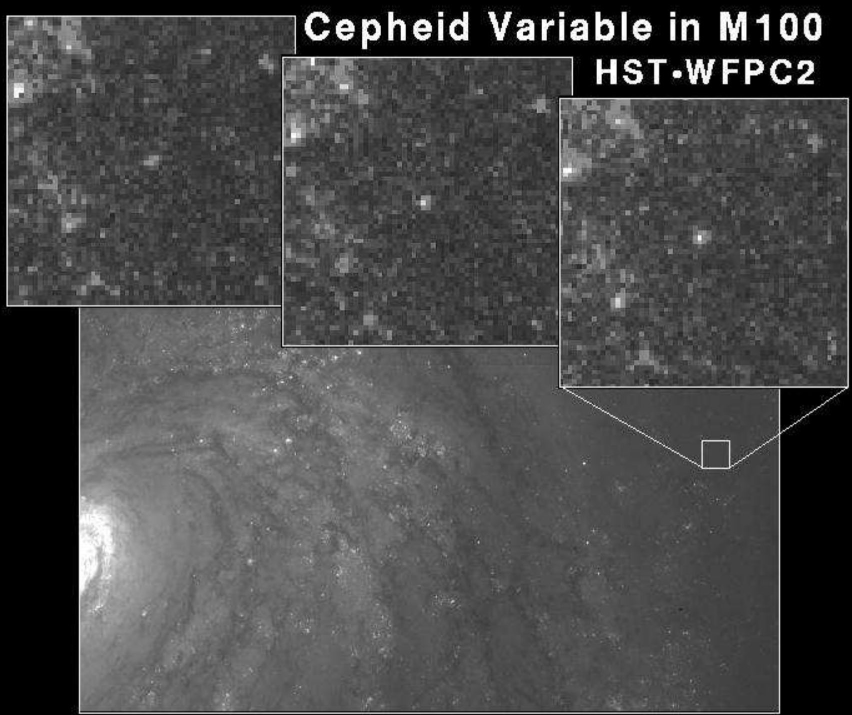
RR Lyra (old stellar population) & δ Cep stars (young population)

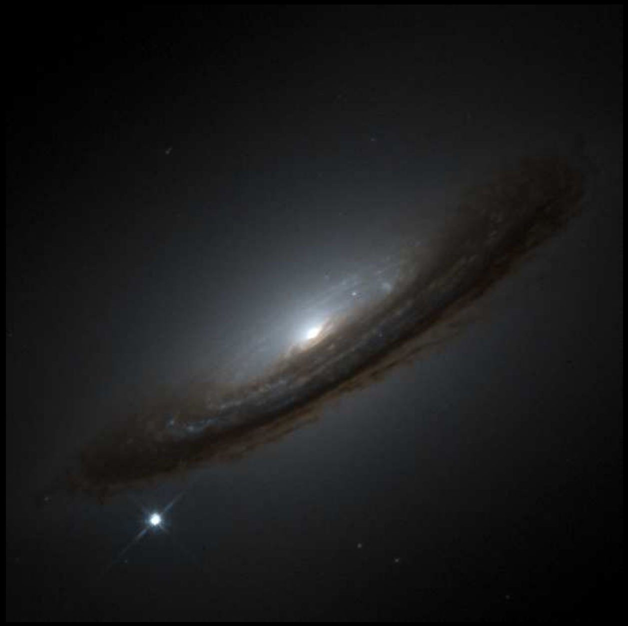


problem: overtone pulsators

Additional methods: Eclipsing binaries, star clusters, Miras, tip of red giant branch, Supernova 1987A,...

Distance to the LMC: 50 kpc

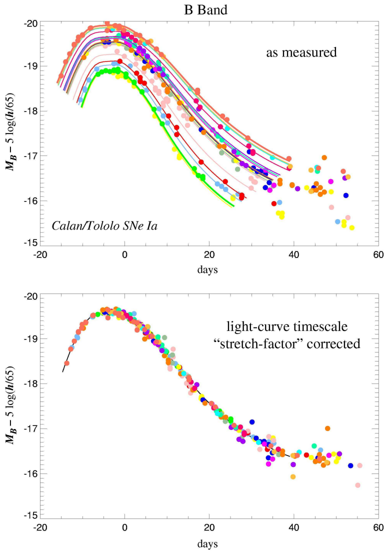




SN1994d (HST WFPC)

Supernovae have luminosities comparable to whole galaxies: $\sim 10^{51}$ erg/s in light, 100× more in neutrinos.

Supernovae



Kim, *et al.* (1997)

After correction of systematic effects and time dilatation (expansion of the universe, see later):

SN Ia lightcurves all look the same

$\Longrightarrow$ standard candle

Supernovae

SN Ia = Explosion of CO white dwarf when pushed over Chandrasekhar limit (1.4 $M_\odot$) (via accretion?).

$\Longrightarrow$ Always similar process

$\Longrightarrow$ Very characteristic light curve: fast rise, rapid fall, exponential decay (“FRED”) with half-time of 77 d.

77 d time scale from radioactive decay $\mathrm{Ni}^{56} \to \mathrm{Co}^{56} \to \mathrm{Fe}^{56}$

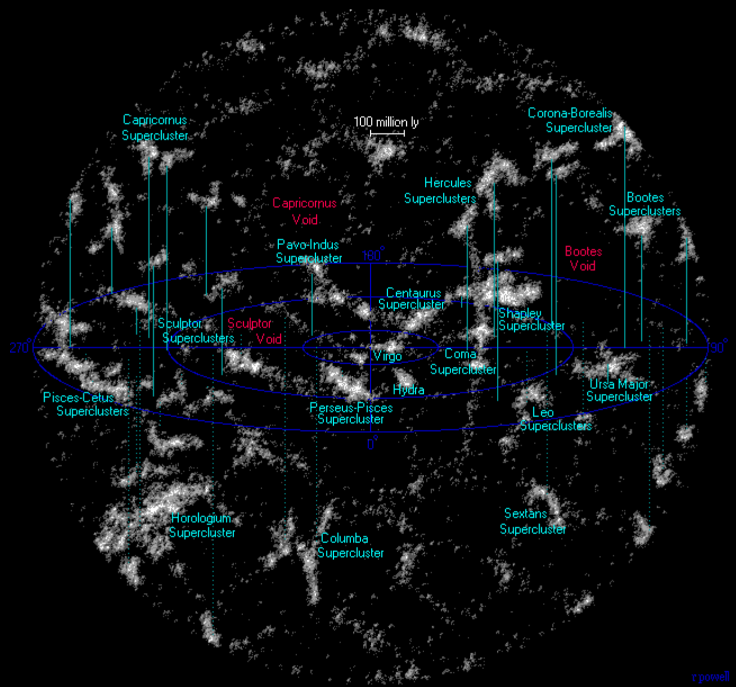
(“self calibration” of lightcurve if same amount of Ni^{56} produced everywhere)

Calibration: SNe Ia in nearby galaxies where Cepheid distances known.

At maximum light:

$$M_\mathrm{B} = -19.3 \pm 0.11 \quad \Longleftrightarrow \quad L \sim 10^{9\ldots10}\,L_\odot$$

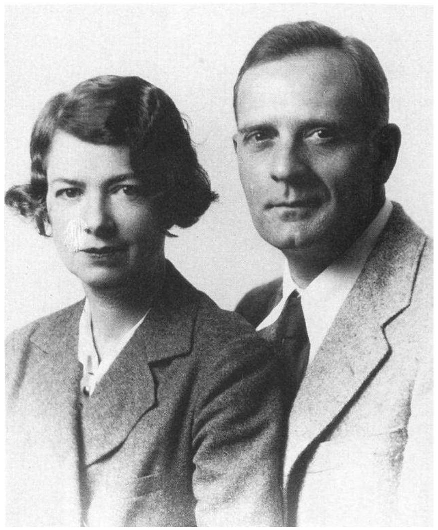
Observable out to $\gtrsim$1 Gpc $\Longrightarrow$ covers almost the whole universe. . .



Superclusters in our vicinity

source: `http://www.atlasoftheuniverse.com/superc.html`

Edwin Hubble



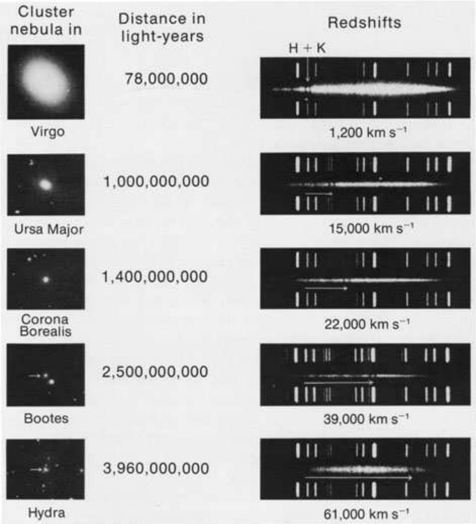
Christianson, 1995, p. 165

Edwin Hubble (1889–1953):

- Realization of galaxies as being outside of the Milky Way
- Discovery that universe is expanding

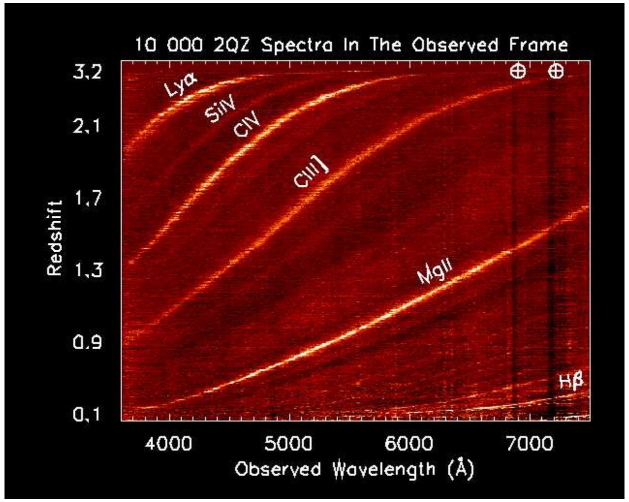
Founder of modern extragalactic astronomy

Redshifts



Hubble: spectral lines in galaxies are more and more redshifted with increasing distance.

Redshifts



2dF QSO Redshift survey

Redshift:

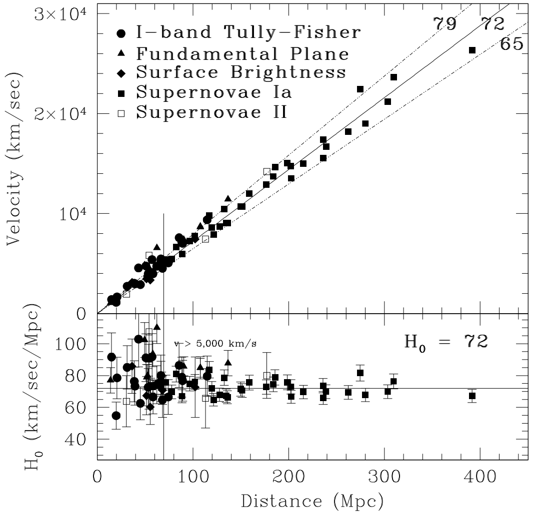
$$z = \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}}$$

interpreted as velocity:

$$v = cz$$

where $c = 300000\,\mathrm{km\,s^{-1}}$ (speed of light)

Hubble Relation



(Freedman, 2001, Fig.4)

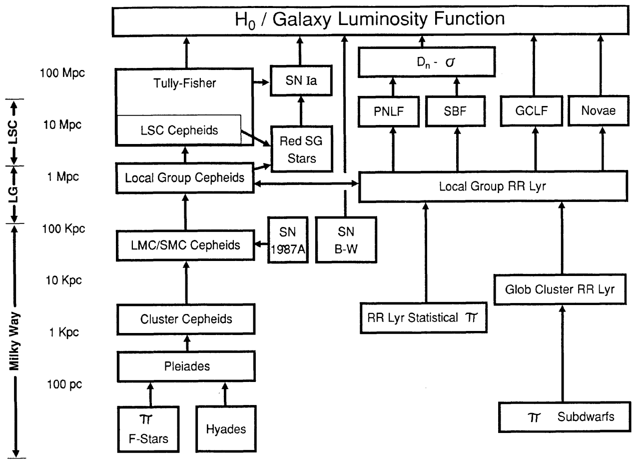
Hubble relation (1929):

The redshift of a galaxy is proportional to its distance: $v = cz = H_0 d$

where H_0: "Hubble constant".
Measurement: determine v from redshift (easy), d with standard candles (difficult) $\Longrightarrow H_0$ from linear regression.
Hubble Space Telescope key project finds

$$H_0 = 72 \pm 8\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Summary: Distance Ladder



Pathways to Extragalactic Distances

Jacoby (1992, Fig. 1)