The Expanding Universe I

- The Universe beyond our Galaxy
- Cosmic distance ladder
- Hubble's discovery of expansion
- Relation of redshift to cosmic scale factor
- Hubble time and Hubble length

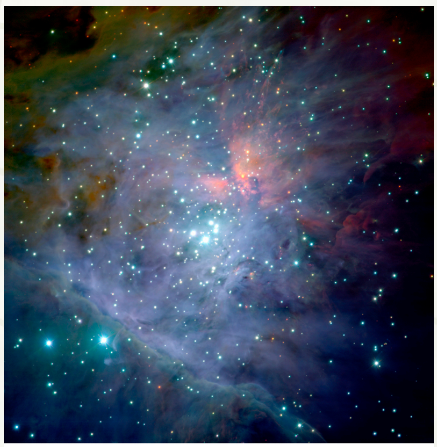
Beyond the Milky Way

- Philosopher Immanuel Kant (1775) was first to suggest that Milky Way was disk of stars, of which Sun is one
  - Kant imagined Universe consisting of many separate, grouped collections of stars like the MW, filling all space
  - Kant's views did not take hold, since there was no direct evidence yet of other galaxies

Spiral "nebulae"

- Many nebulae (fuzzy patches of light) were identified by Messier; published catalogue 1780
  - These were intended as aids to comet hunters to reject "uninteresting" objects
    - Some of Messier's nebulas are true clouds; now known as star forming regions illuminated by hot stars
    - Some looked different
- Herschel investigated nebulae further
  - Suggested they could be star collections like MW
- Lord Rosse first observed that some nebulae have spiral structure (1845)
  - Suggested that they are external "island universes"
- Others thought spiral nebulae were within MW
- Controversy continued through early 20th century

The Orion Nebula (M42)



The Orion Nebula and Trapezium Cluster
(VLT ANTU + ISAAC)

THE GLOBULAR CLUSTER M13

Credit: Yuugi Kitahara

Andromeda "Nebula" (M31)

M51a and b

- Lord Rosse's galaxy

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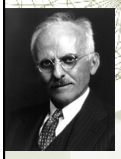

Early investigations in and beyond the MW

- Vesto Slipher (1912) showed, using spectral shifts, that some spiral nebulae have very large velocities relative to anything else known in MW (>1000 km/s), suggesting external objects
- Heber Curtis (1917) observed novae (strong flares in stars' light) in three spiral nebulae
  - Much fainter apparent brightness than other known novae, suggesting great distance
- Harlow Shapley showed, using globular clusters, that Sun is far out in disk of Milky Way
  - However, overestimated MW size by factor three
- "Great debate" between Curtis and Shapley in 1920 concerning whether spiral nebulae were inside (Shapley) or outside (Curtis) the MW
- Controversy was finally settled by E. Hubble in 1924
- Interstellar dust discovered by R. Trumpler in 1930
- Why the US? Because investment in science and technology led to building the largest telescopes here!

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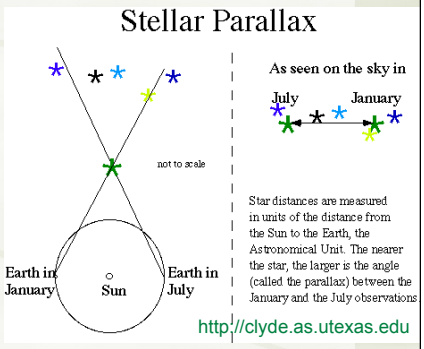
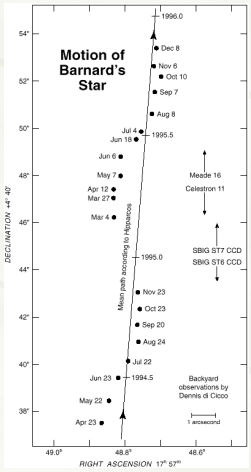
Cosmic distance ladder

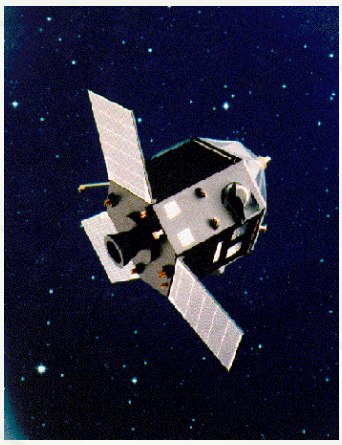
- The "first rung" in the cosmic distance ladder is based on parallax
  - Useful for stars relatively close to the Sun
  - Uses displacement in angle against more distant stars over the course of a year to determine distance *d*



- If star wobbles with amplitude of 1 arc-second (1/3600th of a degree – 1/2000th diameter of Moon), then it is at distance of **1 parsec** (definition of parsec).
  - 1pc = 3.26 lt-yr
  - In general,



- Until 1990s, could only detect parallax out to 50pc.
- Hipparcos satellite
  - Designed to measure parallax of stars
  - Can detect wobble out to distance of about 1kpc (1000pc)
  - Used to map out locations of nearby stars.
- GAIA satellite
  - Launched December 2013
  - Can map out positions and motions of stars across the whole galaxy!!
  - Will measure 1 billion stars



Hipparcos (ESA)

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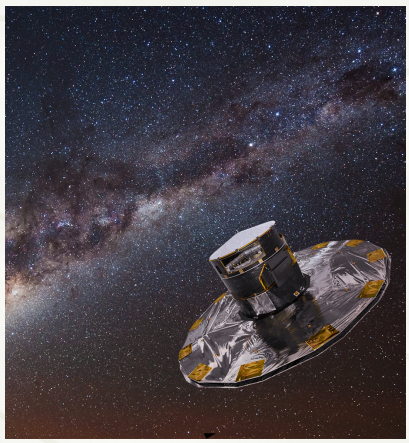

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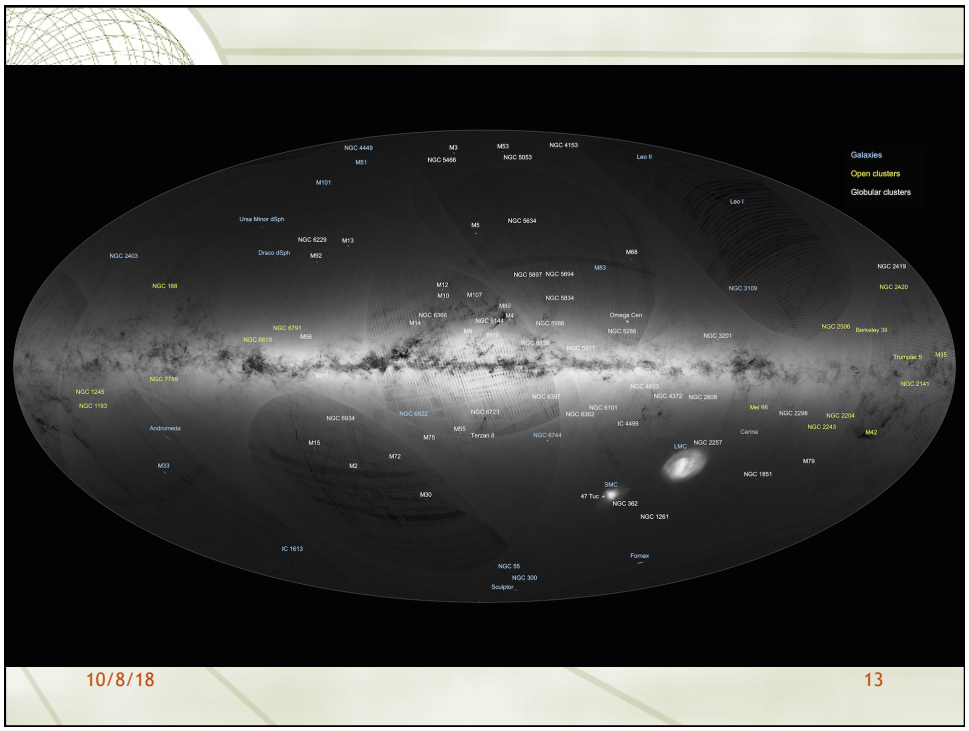


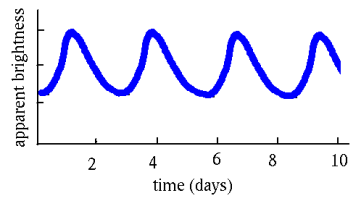
Distance-brightness relation of "standard candles"

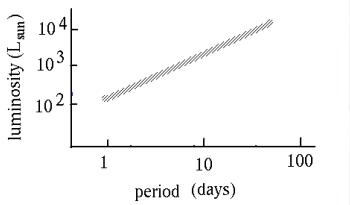
- Distance *d* based on parallax can be used to determine the intrinsic luminosity L_{std} of a star of given type with brightness *b* :
  $L_{std} = 4\pi\, d^2\, b$
- Once the intrinsic luminosity L_{std} of a given type of object is known, it can become a "standard candle"
  - For given observed brightness *b* , distance is then derived as

Henrietta Leavitt
ph.credit: AAVSO

Cepheid variables

- Henrietta Leavitt discovered (1912) that a certain class of variable stars called Cepheids had properties that meant they could be used as standard candles
  - she found Cepheids' luminosity is related to the period of fluctuations in brightness
  - instrinsic luminosity can then be obtained using their apparent brightness and distance based on parallax





graphics: University of Oregon Astronomy Dept

Edwin Hubble

Hubble's observations

- In studying Andromeda "spiral nebula" with 100-inch telescope on Mt. Wilson, Edwin Hubble first observed a variable star with properties of a Cepheid in 1924
- Hubble determined that Andromeda must be well outside MW!
  - modern measurement: 2 million lyr
  - Distance to Andromeda > 20× MW diameter

- Hubble, with Milton Humason, systematically began to study many other galaxies
- Obtained distances using Cepheids and other estimates
- Obtained redshifts from stellar spectra
- The "redshift" may actually be either $z > 0$ (redder, longer wavelength) or $z < 0$ (bluer, shorter wavelength)

Redshift-distance relation

- Ordinarily, a Doppler shifted spectrum is interpreted as a relative velocity of emitter with respect to observer, with $v = cz$
- By plotting redshift versus distance, Hubble (1929) found a linear relationship!

Apparent velocity = c×z

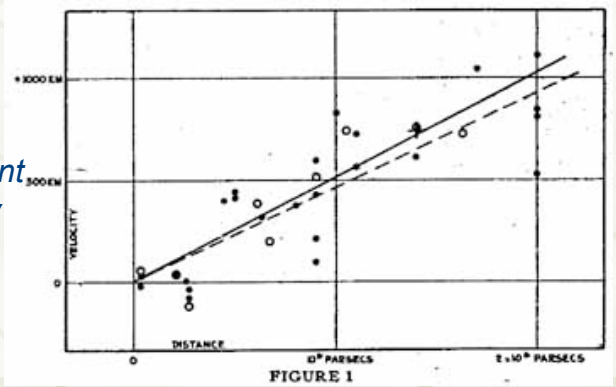


FIGURE 1

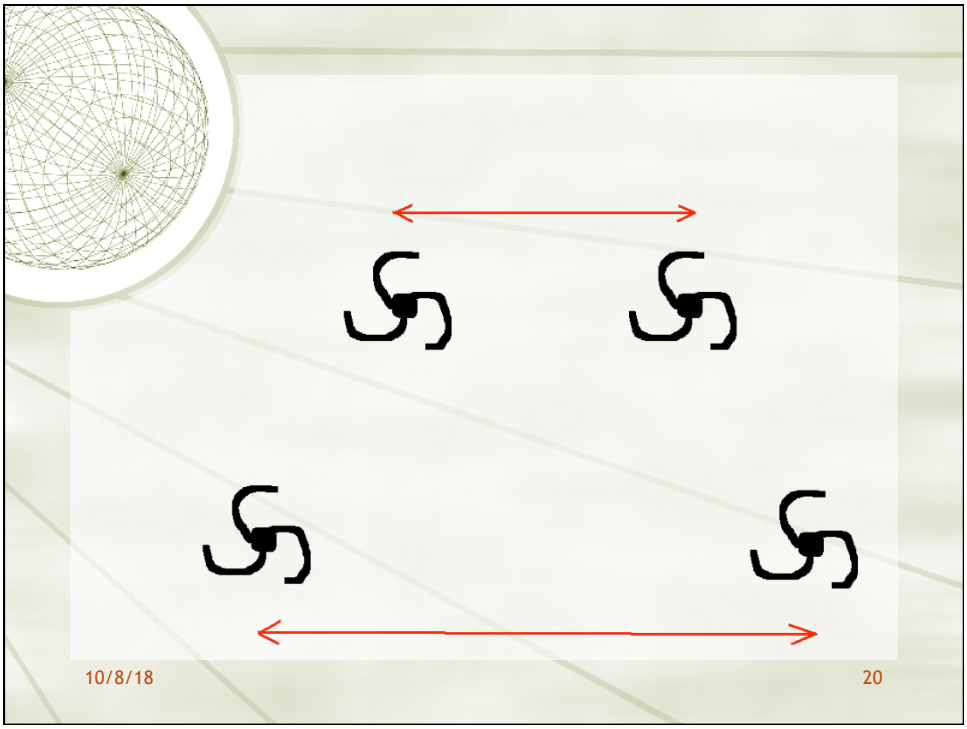
Distance

Hubble's Law

- Hubble interpreted redshift-distance relationship as a linear increase of the recession velocity of external galaxies with their distance
- Mathematically, the Hubble law is

  $v = H \times d$

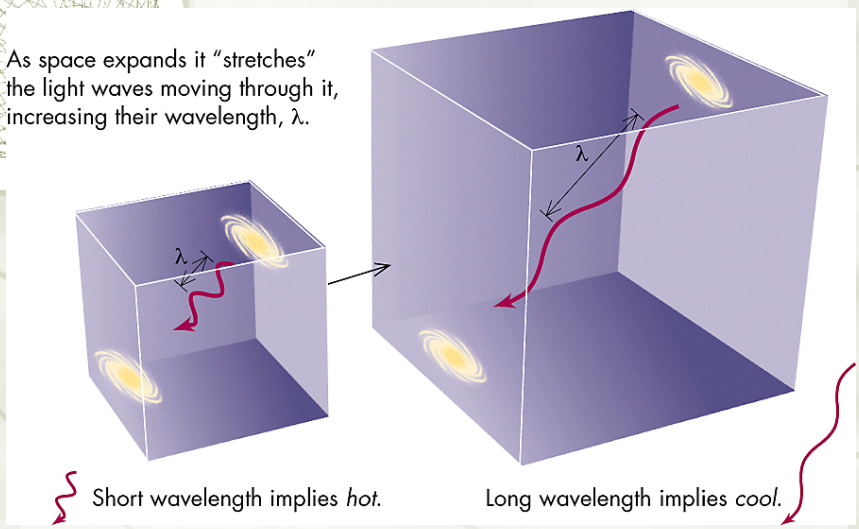
  where v=velocity and d=distance
- Modern measurement gives the Hubble constant as H = 70 km/s/Mpc
- In fact, Hubble's interpretation is only "sort of" correct
- What **really** increases linearly with distance from the MW is simply wavelength of light observed, and this redshift is due to the *cosmological expansion of space over the time since the light left the distant galaxy and arrived at the Milky Way!*



Interpretation of Hubble law in terms of relativity

- New way to look at redshifts observed by Hubble
- *Redshift is not due to velocity of galaxies*
  - Galaxies are (approximately) stationary in space…
  - **Galaxies get further apart because the space between them is physically expanding!**
  - The expansion of space, as *R(t)* in the metric equation, also affects the wavelength of light… as space expands, the wavelength expands and so there is a redshift.
- So, cosmological redshift is due to cosmological expansion of wavelength of light, not the regular Doppler shift from local motions.

Redshift from the expansion of space



Relation between z and R(t)

- Using our relativistic interpretation of cosmic redshifts, we write

$$\lambda_{obs} = \left(\frac{R_{present}}{R_{emitted}}\right)\lambda_{em}$$

- Redshift of a galaxy is defined by

$$z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$

- So, we have…

$$z = \frac{R_{present}}{R_{emitted}} - 1 = \frac{R_{present} - R_{emitted}}{R_{emitted}} \approx \frac{\Delta R}{R}$$

Hubble Law for "nearby" (z<0.1) objects

- Thus $$cz \approx \frac{c\Delta R}{R} = c\Delta t \times \frac{(\Delta R/\Delta t)}{R} = d_{light-travel} \times H$$

where Hubble's constant is defined by

$$H = \frac{1}{R}\frac{\Delta R}{\Delta t} = \frac{1}{R}\frac{dR}{dt}$$

- But also, for comoving coordinates of two galaxies differing by space-time interval $d = R(t) \times D_{comoving}$, have

$$v = D_{comoving} \times \Delta R/\Delta t = (d/R) \times (\Delta R/\Delta t)$$

- Hence $v = d \times H$ for two galaxies with fixed comoving separation

Peculiar velocities

- Of course, galaxies are **not** precisely at fixed comoving locations in space
- They have local random motions, called "peculiar velocities"
  - e.g. motions of galaxies in "local group"
- This is the reason that observational Hubble law is not exact straight line but has scatter
- Since random velocities **do not** overall increase with comoving separation, but cosmological redshift **does,** it is necessary to measure fairly distant galaxies to determine the Hubble constant accurately

Redshift-distance relation

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Apparent velocity = c×z

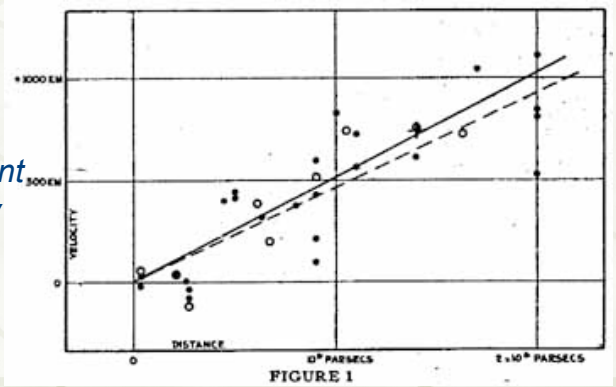


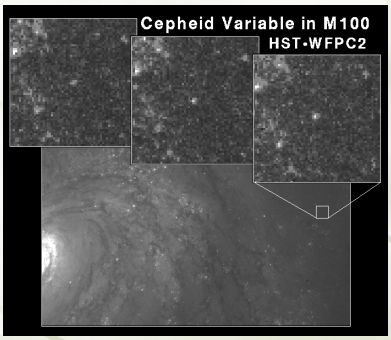
FIGURE 1

Distance

Distance determinations further away

- In modern times, Cepheids in the **Virgo galaxy cluster** have been measured with Hubble Space Telescope (16 Mpc away…)

Virgo cluster



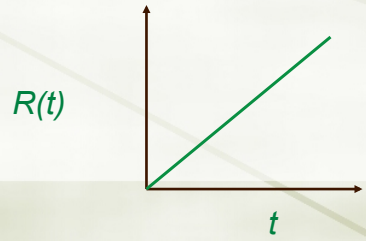
Tully-Fisher relation

- Tully-Fisher relationship (spiral galaxies)
  - Correlation between
    - width of particular emission line of hydrogen,
    - Intrinsic luminosity of galaxy
  - So, you can measure distance by…
    - Measuring width of line in spectrum
    - Using TF relationship to work out intrinsic luminosity of galaxy
    - Compare with observed brightness to determine distance
  - Works out to about 200 Mpc (then hydrogen line becomes too hard to measure)

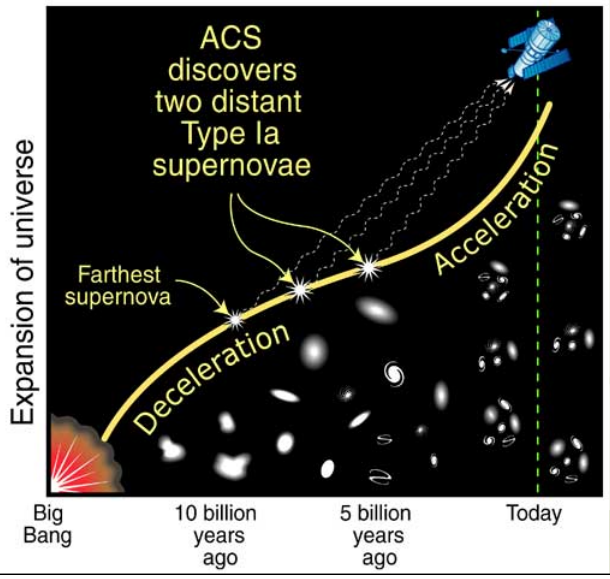
Hubble time

- Once the Hubble parameter has been determined accurately, it gives very useful information about age and size of the expanding Universe…
- Recall Hubble parameter is ratio of rate of change of size of Universe to size of Universe:

- ***If*** Universe ***were*** expanding at a constant rate, we would have $\Delta R/\Delta t$ = *constant* and $R(t) = t \times (\Delta R/\Delta t)$; then we would have $H = (\Delta R/\Delta t)/R = 1/t$
- *ie* $t_H = 1/H$ *would be age of Universe since Big Bang*



The expansion of the Universe is speeding up from "dark energy"



Reminder

- Midterm **Thursday, October 18th**
- Material covered:
  - lectures through October 16th
  - Textbook Ch. 1-3, 6-8
  - HW 1-4
- **Bring a calculator and a pencil**

MIDTERM

- Bring a scientific/graphing calculator
- No phones/computers
- No notes, closed books