Our place in the Galaxy

- We live in a large disk galaxy, towards the edge (8kpc~25,000 lyr out)

Projected onto the sky, this disk of stars looks like a band

of light that rings the sky… the Milky Way

This realization came somewhat slowly…

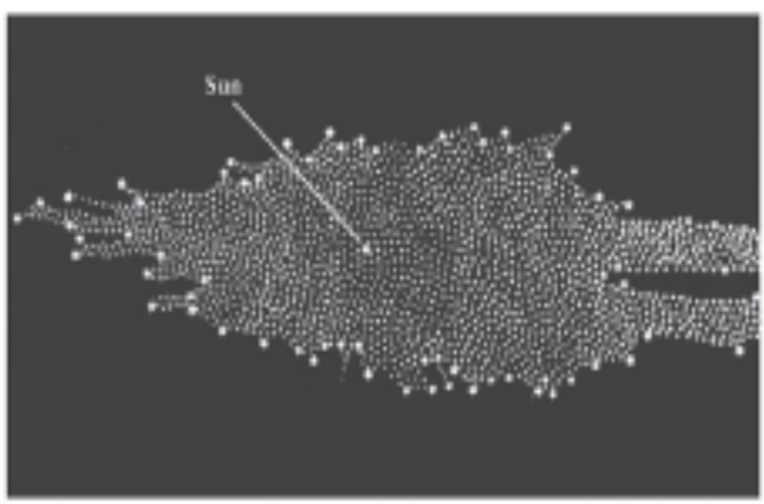
Disk-like nature of galaxy realized by Thomas Wright (1780);

refined by Kant (1775)

First attempt to map out galaxy made by William Herschel

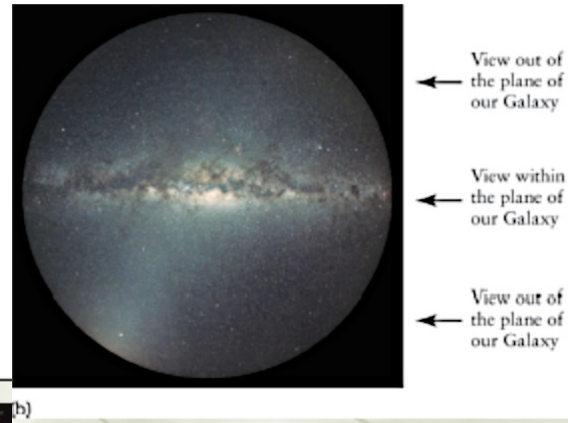
(1785); refined by Kapteyn in 1920

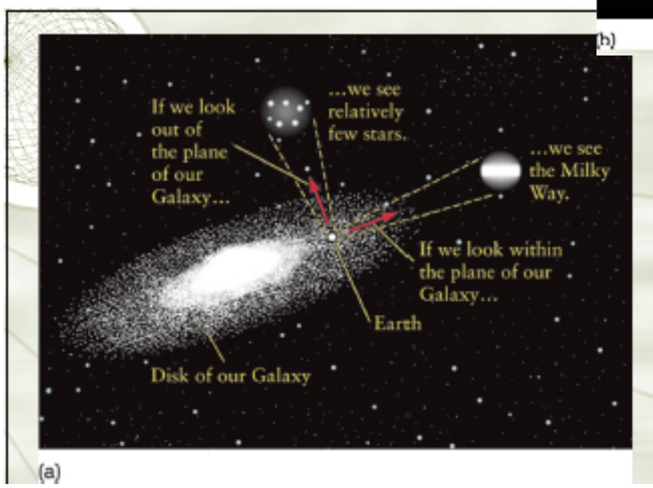
- Herschel came to the conclusion that we sit at the center of the Galactic disk. In fact, **he was wrong**… had not accounted absorption by dust! *(something that he did not know about)*



Herschel's map of the Galaxy

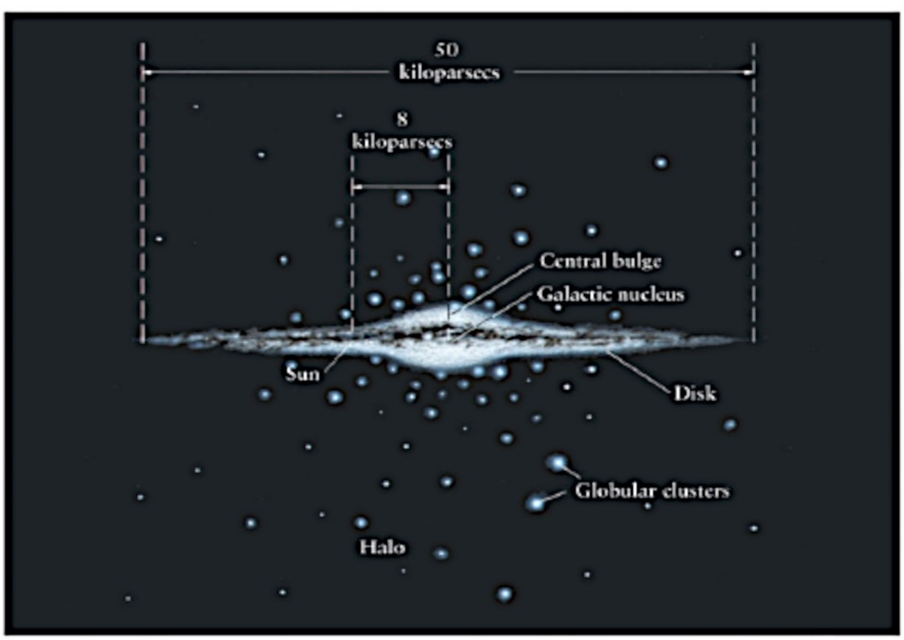
View of MW
from earth- in
'galactic coordinates'
plane of MW is made the
equator of the image



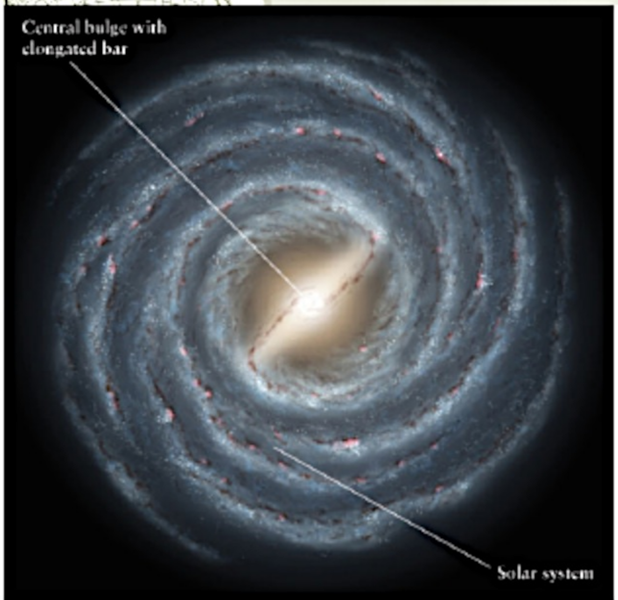


Artists view of MW in space

Edge on View of MW



1 kiloparsec=3.26×10^{3} lightyears=3.08×10^{19}m



(a) The structure of the Milky Way's disk

(b) Closeup of the Sun's galactic neighborhood

Artists view of the Milky Way system
'top' down

A Little History

- Early 20th century…
  - Knew that we lived in a large disk galaxy
  - But what was the nature of the **larger** Universe?
- Two opposing ideas:
  - Our galaxy is *alone,* sitting in the middle of otherwise empty space
  - Our galaxy *is one of many galaxies* that fill space (so-called "Island Universes")
- The debate rapidly focused on the nature of the 'nebulae'*

*Dictionary definition: any celestial object that appears nebulous, hazy, or fuzzy, and extended in a telescope view.

What are nebulae??

- Nebulae have been studied since the invention of the telescope (M31/Andromeda is a naked eye nebulae as are the LMC/SMC)- see

http://messier.seds.org/xtra/history/deepskyd.html for a history)

- Messier (1780)

  Systematically catalogued over 100 bright nebulae (M objects)
  - Main reason for doing this was so that comet hunters knew which "fuzzy patches= nebulae" to ignore!
- But what were these nebulae? :
  - Glowing patches of gas (e.g., M42 Orion)
  - Clusters of many stars within our Galaxy (e.g., the Globular cluster M13)
  - Whole other galaxies!!
- Of special interest were the "spiral nebulae" (Lord Rosse 184)5 that showed Milky Way like spiral structure… the brightest spiral nebulae was the Andromeda nebula Messier 31

MW, Magellanic Clouds and a Comet

ngm.nationalgeographic.com670 × 522Search by image Miloslav Druckmüller.

Messier actually cared about comets

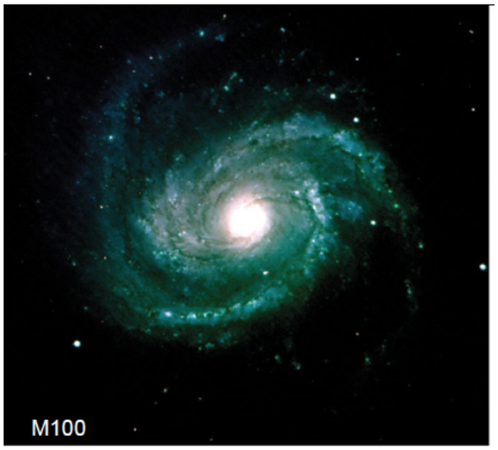
Credit : A. Dimai

- *The Orion Nebula (M42)- first discovered nebulae with a telescope 1610*

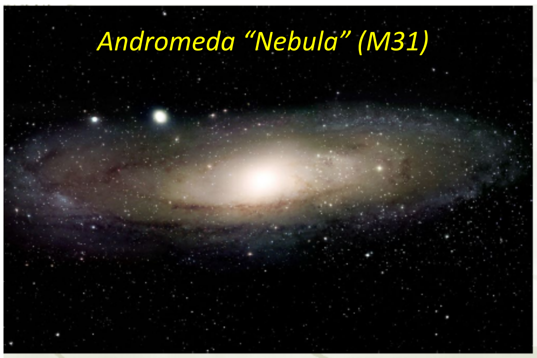
Some Nebulae

Globular cluster (M13)
r~10-20pc, d~10kpc, θ~1-30' , M~10^5-$10^6$$M_\odot$

Credit: Yuugi Kitahara



Nearby galaxies ~5-60' in size



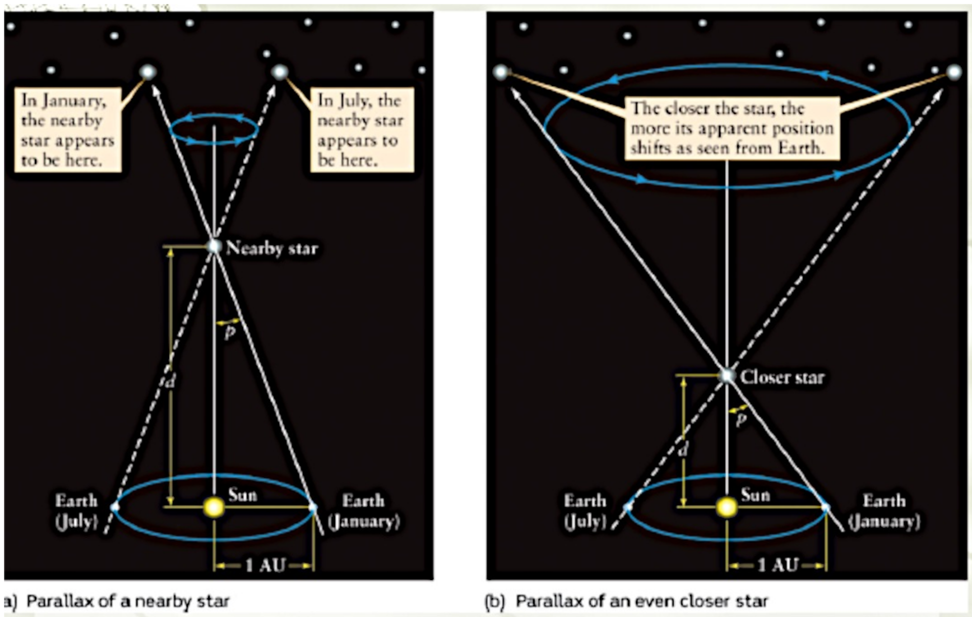
Are Some Nebulae Nearby Galaxies ?
1920 :
Shapley & Curtis in the "Great Debate" (see article by V. Trimble on web site)

If this were true it drastically changed the scale of the universe! Things were much bigger and further away

How to Tell What Things Are- Measuring Distances in Astronomy

- The distance to any astronomical object is a basic parameter
- Require knowledge of distance in order to calculate just about any other property of the object
- Distance is often difficult to determine!
- Most direct method for measure distances to "nearby" stars uses an effect called parallax (remember lecture 3?? and homework)
- As Earth orbits Sun, we view a star along a slightly different line of sight This causes the star to appear to move slightly with respect to much more distant stars
- We can currently use this technique to measure stellar distances out to ~3000 light years from Earth

Reminder of Parallax



a) Parallax of a nearby star (b) Parallax of an even closer star

If star wobbles with amplitude of 1 arc-second, then it is at distance of 1 parsec (definition of parsec). 1pc = 3.26 lt-yr

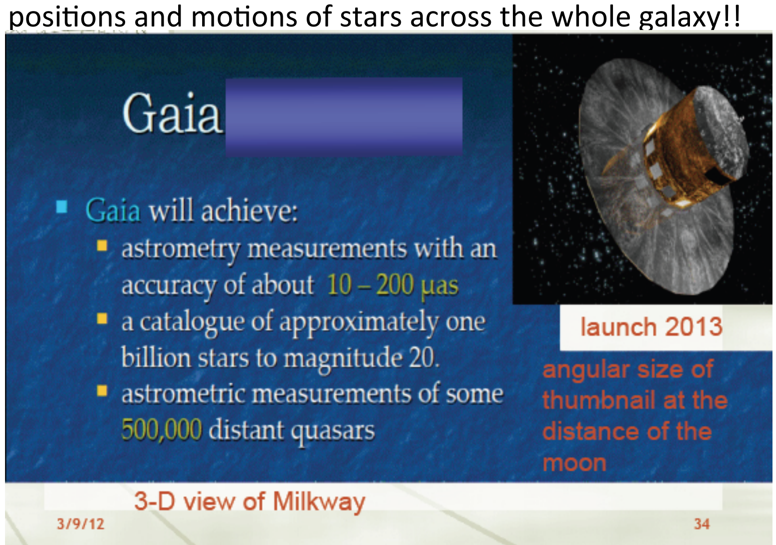
In general,

$$D(\text{pc}) = \frac{1}{\theta_{wobble}(\text{arcsec})}$$

13

Improvement in Parallax Measurements

- Until 1990s, could only detect parallax out to 50pc.
- Hipparcos satellite: Designed to measure parallax of stars
  - detect wobbles out to distance of about 1kpc
  - Mapped out locations of nearby stars.
- GAIA satellite: launched Dec 2013
- Can map out positions and motions of stars across the whole galaxy!!



14

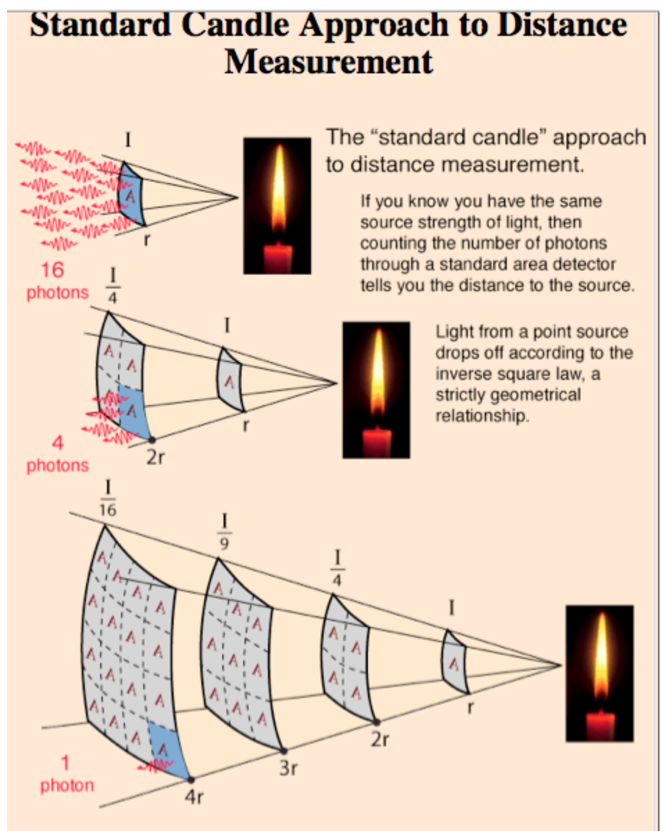
Beyond parallax!

- Definition : The observed flux (F) of a star is the energy received from the star per unit time per unit area.
- Definition : The luminosity (L) of a star is the energy per unit time (i.e. power) emitted by the star
- If the star is at distance D and emits equally in all directions (i.e. it emits isotropically), then the observed flux F and luminosity L are related by

$$L = 4\pi D^2 F \quad \text{or} \quad F = \frac{L}{4\pi D^2}$$

Suppose we *know* the luminosity of some object… then we can use its measured **flux** to determine the distance! Objects with *known luminosities* are called **standard candles**.

- So the problem boils down to how to find and define a standard candle
- Question: how would you do this??



http://hyperphysics.phy-astr.gsu.edu/Nave-html/Faithpathh/astdat.html

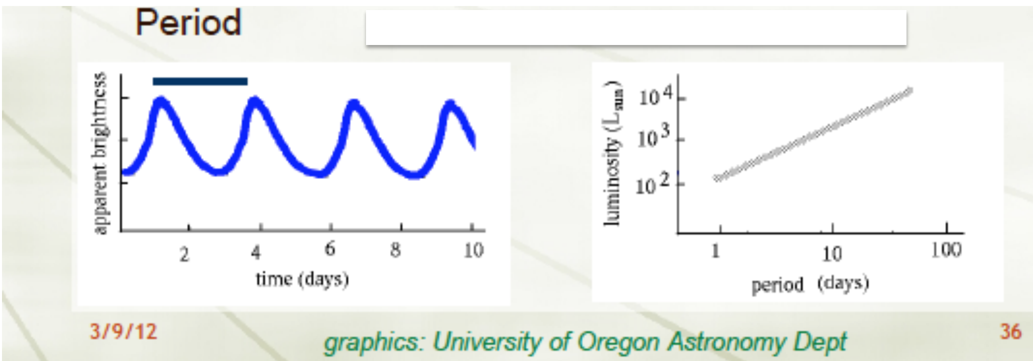

Henrietta Leavitt
ph credit: AAVSO

Cepheid variables

Henrietta Leavitt discovered (1912) that a certain class of variable stars called Cepheids had properties that allowed their use as standard candles

She studied Cepheids that are all are 'more or less' the same distance in the Magellanic clouds… found that the luminosity is related to the period of fluctuations in brightness

So, if you measure the period of a Cepheid, you can determine its luminosity. Measuring flux then gives you distance, even if its too far for parallax



Cepheids

- Very lucky that Cepheid's are intrinsically very luminous stars

(10^3-10^5 times the luminosity of the sun) so that even in the early 20th century they could be measured in the Magellanic clouds

Relative vs. Absolute Distances

- It wasn't until 1997 that the parallax was directly to the nearest Cepheids using the Hipparcos satellite-
  - the closest Cepheids have parallaxes of **milliarc** secs
- Before then the distances to Cepheids was estimated using a less reliable technique

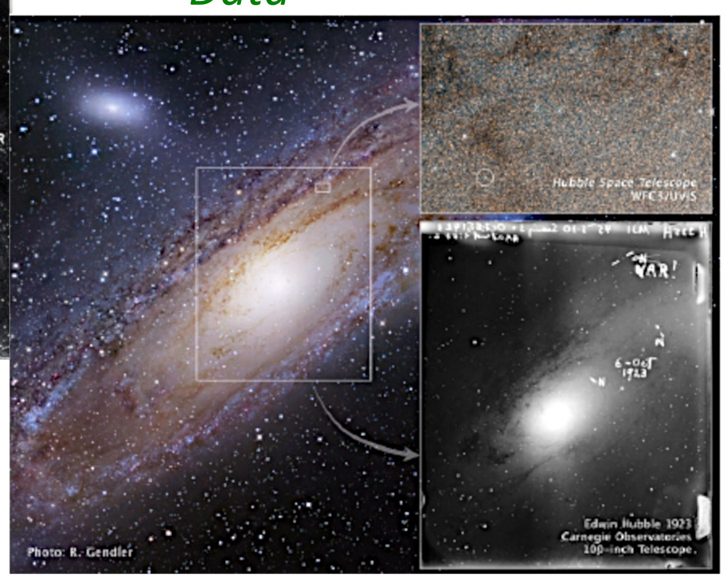
- *Edwin Hubble*

The Opening Up of the Universe

Hubble's observations

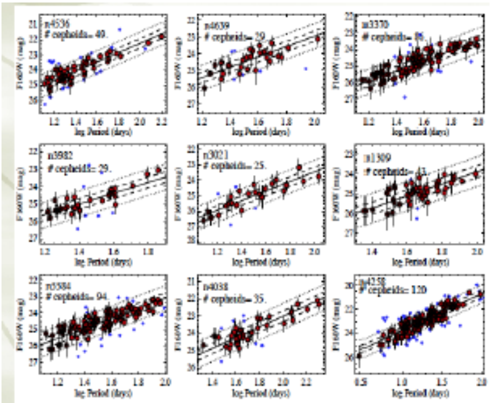
Hubble found Cepheid Variables in Andromeda Nebulae (M31)
Measured period and flux, and hence distance relative to the Magellanic clouds
Andromeda must be well outside of the Milky Way Galaxy
Thus, the Great Debate was settled… the MW is just one of many many many galaxies
Modern measurements Distance to Andromeda 744 ± 33 kpc 4%error
About 2x MW diameter

Hubble's Original Data

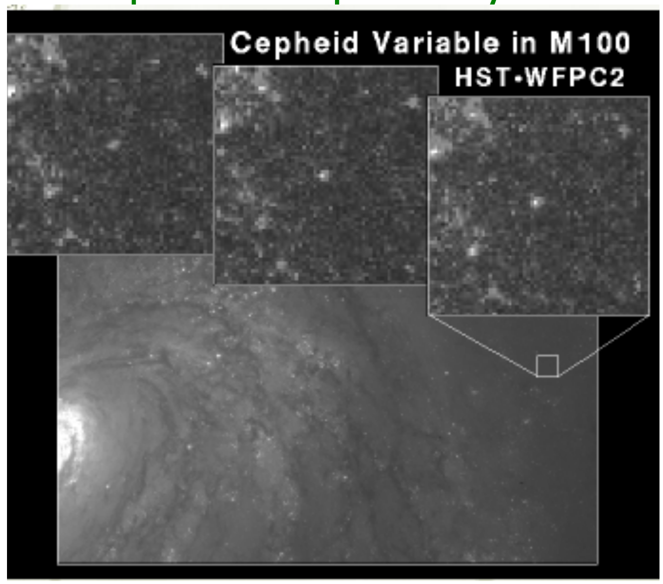


Hubble's original Cepheid observed with Hubble Space Telescope

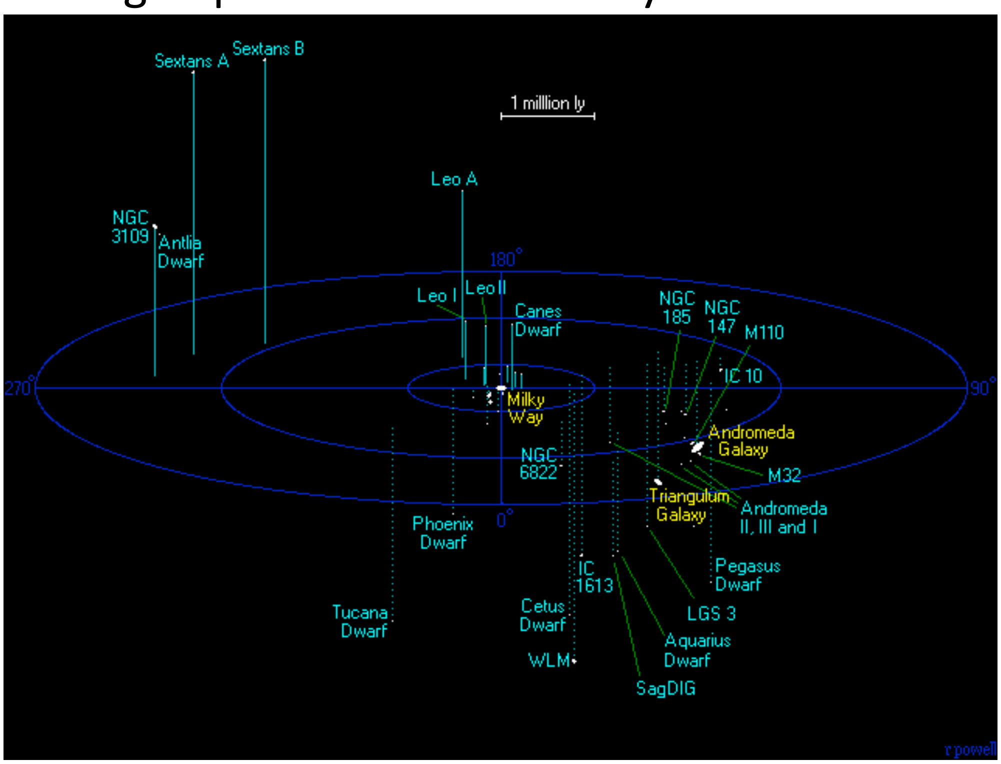
Hubble Space Telescope (HST) Can Measure Cepheids in Galaxies Up to 30 Mpc Away



Modern Cepheid Data
Have 30-300 Cepheids
per galaxy- Reiss et al 2011



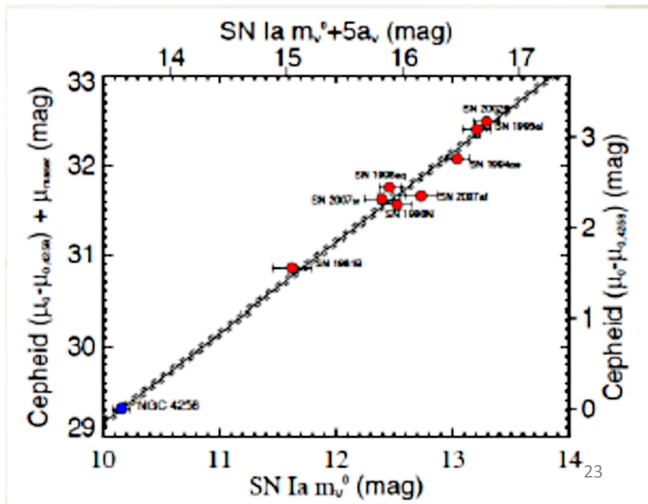
Using Cepheids Get Geometry of Local Volume



Going Further

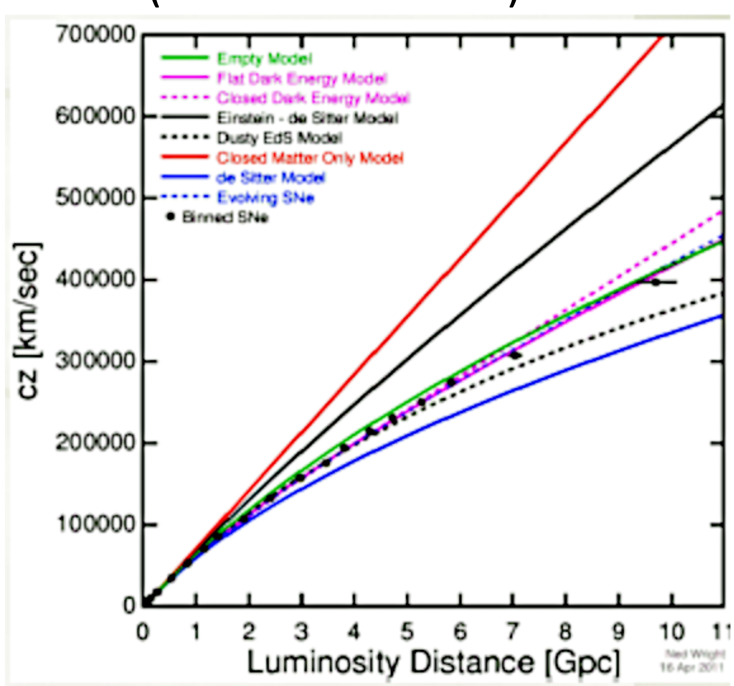
- Need more luminous 'standardizable' candles
- Turns out that type I SuperNovae (SNIa) can be 'made' standard candles (Nobel Prize 2011)
- This allow 'absolute' distances to ~5000 Mpc

Comparison of SN Ia and Cepheid distances in strange astronomers units



Going Real Far (a Future Lecture)

Using type Ia SN to measure absolute distance out to 10,000 Mpc (10Gpc-G stands for Giga)



Midterm On Thursday

Any questions ?
before the mid-term
Continue reading Ch 10

THE DOPPLER EFFECT-Recap of a few lectures ago

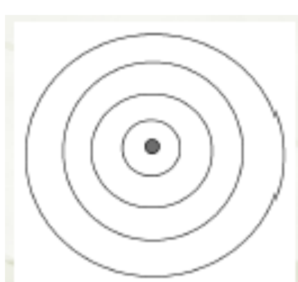
Think about sound waves

Let ν=frequency (number of waves passing certain fixed point in one second)

Let λ=wavelength (distance between two "crests" of the wave)

Let c_s=speed of the wave

$c_s = \nu \lambda$



pattern of waves if sources is **stationary**

THE DOPPLER EFFECT-Recap of a few lectures ago

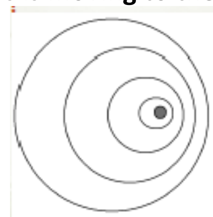
Suppose source is moving towards you with speed V

Waves get squeezed in direction of motion (I.e., λ decreases)

c_s stays same (i.e. speed of sound fixed)

So, frequency ν must go up!

pattern of waves if sources is **moving to the right**



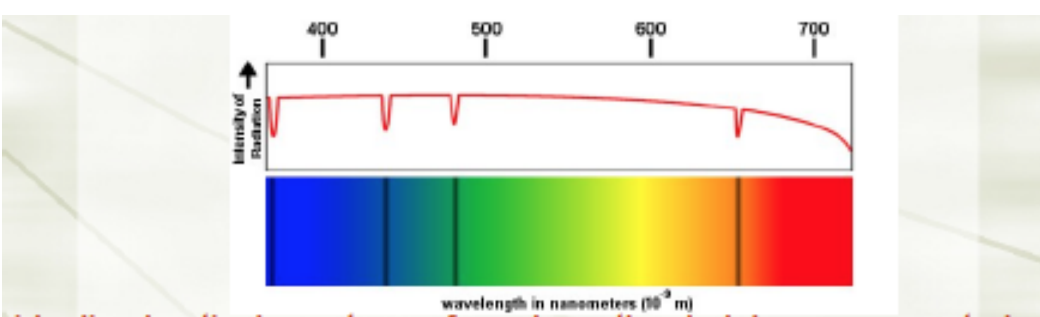
$(\lambda_{moving}-\lambda_{still})=V/c$ (non-relativistic)

The Doppler effect works on any wave

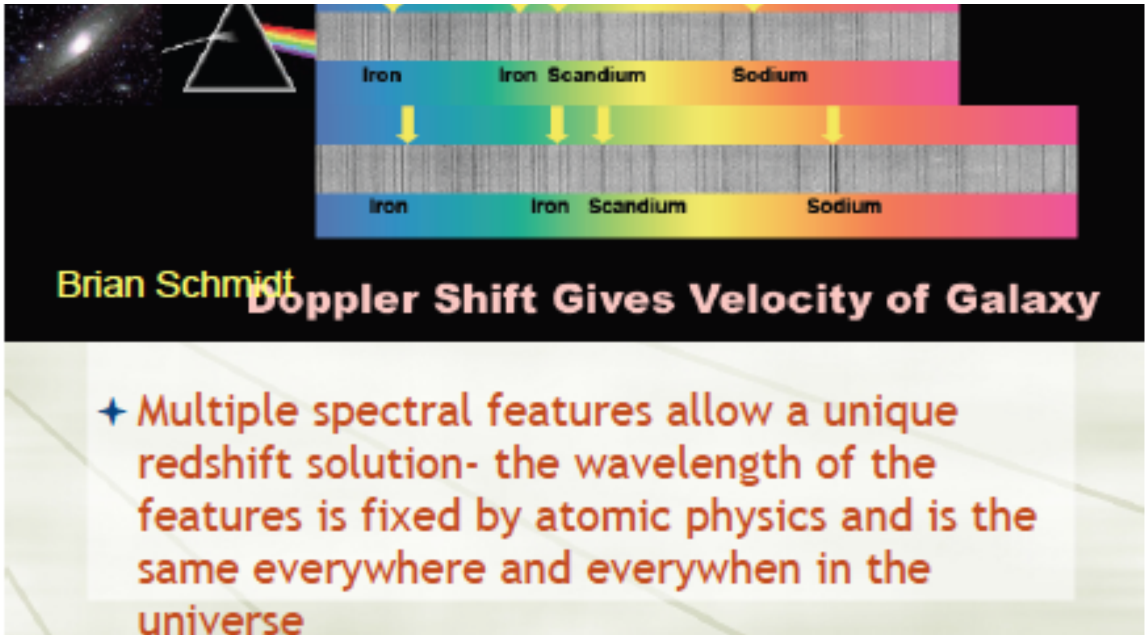
– including light waves! (where c_s =c(speed of light))

MEASURING APPARENT VELOCITIES OF GALAXIES

- Technique for measuring a galaxies velocity:
- Measure the spectrum of light from the galaxy
- Look for characteristic features in the spectrum
- Compare to known features and see if they are shifted by Doppler effect



idealized optical spectrum of a galaxy- the dark bars are spectral features due to certain elements in the atmospheres of stars



Full relativistic relation

$h\nu_0 = h\nu/\gamma \quad \gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$

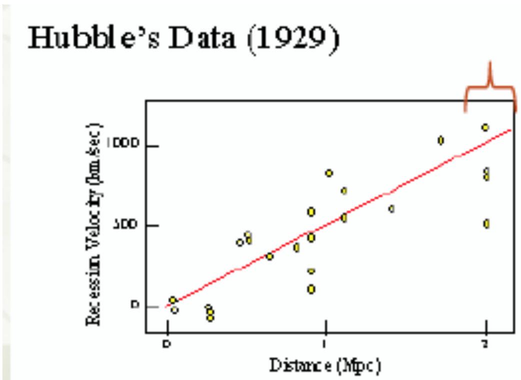
Blueshifts and Redshifts

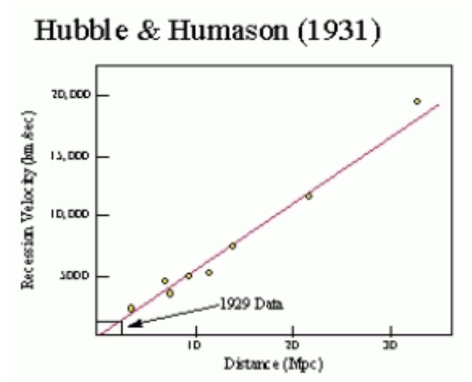
- If galaxy is moving towards us, wavelengths are shortened **spectrum blueshifted**
- If galaxy is receding from us, wavelengths are lengthened **spectrum redshifted**
- Slipher measured velocities of nearby galaxies (spiral
- nebulae) – by 1922, he found that 36 out of 41 were moving away from us!-
- "For us to have such motion and the stars not show it means that our whole stellar system moves and carries us with it. It has for a long time been suggested that the spiral nebulae are stellar systems seen at great distances ... This theory, it seems to me, gains favor in the present observations".
- This, was 8 years before Hubble.
- The first hint of Hubble's remarkable result

HUBBLE'S RESULTS

Hubble measured distance (some derived from Cepheids, some less accurate estimates) and plotted it against velocity of the galaxy

Just a few years later the data got a lot better





Everything's rushing away! Hubble's law

- Hubble found that all distant galaxies are rushing away from us!
- **The speed of recession V is proportional to distance of galaxy d (Hubble's law)**

$$V = H_0\, d$$

or

$$d = V/H_0$$

- H_0 is called Hubble's constant.
  - Hubble's original value was H=500km/s/Mpc… way off the real value. He had mistakenly identified bright nebulae in other galaxies with bright stars, thereby making them seem closer.
- Modern measurements : H_0=69km/s/Mpc
  - think about the units for a bit, in MKS units this is =2.2×10^{-17} m/s/m

Redshift

Redshift z = $(\lambda_{observed}-\lambda_{emitted})/(\lambda_{emitted})$

- 1+z= sqrt{(1+v/c)/(1-v/c)} or for v<<c ; z~(v/c).

or $1+z=\gamma\{1+(v/c)\}$

Hubble Expansion

we will later show that the redshift is related to the scale factor change of the universe (how big the universe is at different times)

A Redshift Digression

- As shown later the cosmological redshift is related to the expansion of the universe

$1+z=R_{then}/R_{now}$

Where R is the size of the universe at different times

Calculation of redshift, z

Based on wavelength	Based on frequency
$z = \frac{\lambda_{obsv} - \lambda_{emit}}{\lambda_{emit}}$	$z = \frac{\nu_{emit} - \nu_{obsv}}{\nu_{obsv}}$
$1 + z = \frac{\lambda_{obsv}}{\lambda_{emit}}$	$1 + z = \frac{\nu_{emit}}{\nu_{obsv}}$

Doppler redshift

$$1 + z = \left(1 + \frac{v}{c}\right)\gamma.$$

Gravitational redshift

$$1 + z = \frac{1}{\sqrt{1 - \frac{2GM}{rc^2}}},$$

Modern redshift data

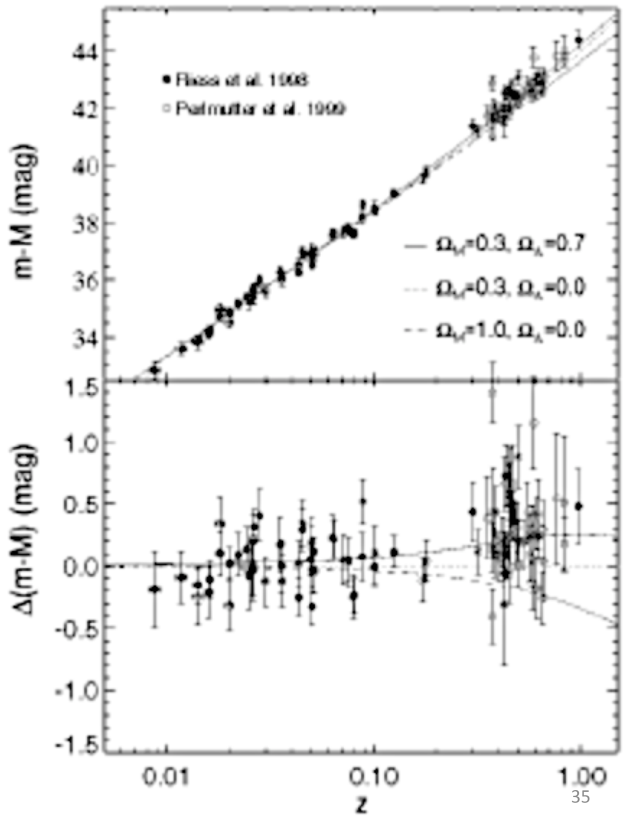
In terms of redshift

$$z = \frac{(\lambda_{Galaxy} - \lambda_{rest})}{\lambda_{rest}}$$

Clearly, we are seeing some very fast galaxies!

m-M is one way that some astronomers measure distance (we don't need the details of this)

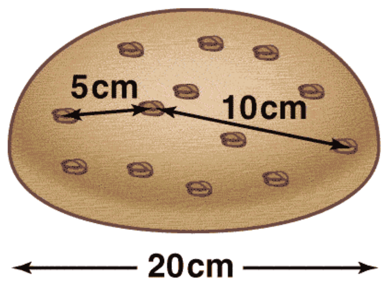
$$1 + z = \left(1 + \frac{v}{c}\right)\gamma.$$



Cosmological and Gravitational Redshift

- Doppler shifts imply a certain velocity
- Gravitational redshifts: a certain mass and size

  $1+z = \mathrm{sqrt}(1/1 - 2GM/Rc^2)$
- The cosmological redshift is due to the **expansion of space itself**- every galaxy is moving away from every other- there is no center
- Because this is NOT a velocity effect galaxies can move apart from each other faster than the speed of light- this is not a violation of Einstein



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