Milky Way & Galaxies

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Dr. Bill Pezzaglia Updated: May 28, 2007

Milky Way & Galaxies

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A. The Milky Way

B. Galaxies & Cosmography

C. Galaxy Types & Evolution

A. The Milky Way

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1. The Galactic Equator
2. Galactic Core
3. Spiral Arms & Dark Matter

A1a. Milky Way

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A1b. Milky Way: Galactic Equator

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2a. Galileo Galilei (1564-1642)

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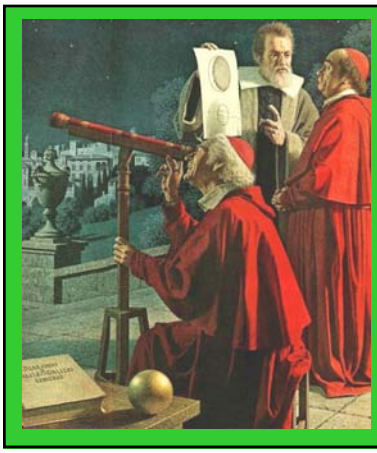


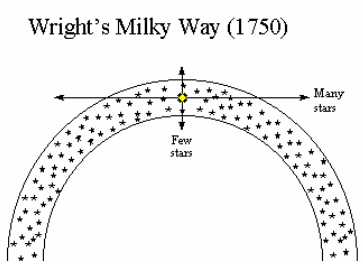
Galileo was one of the very first scientists to do *experiments* to understand Nature

He was the first astronomer to use a telescope (in 1610) to study the sky.

Sees that the Milky Way is made of stars

A1c. 1750 Thomas Wright

7



Milky Way is thin shell of stars, which explains why we see a band across the sky.

A1c. 1784 Herschel's Telescope

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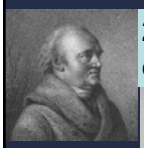
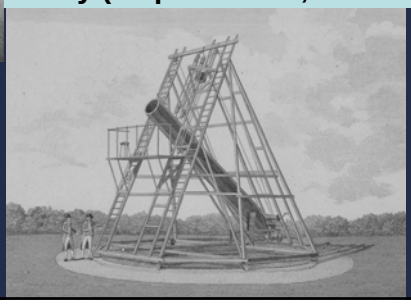


20 year study of 2400 regions of sky (maps over 90,000 stars)



A1c. The Galactic Equator

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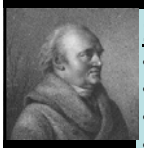
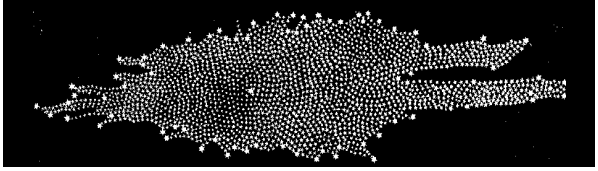


1784 Herschel's Star Gauging

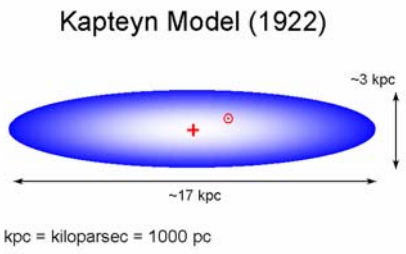
- Counts stars in 683 regions
- Estimates universe is disk shaped
- Diameter is 5 times thickness
- Sun appears to be at the center



A1c. Kapteyn Universe

10

1897 measured that stars move (rotate around universe)



(Parsec=3.26 light years=200,000 x distance to sun)

Globular Cluster of Stars

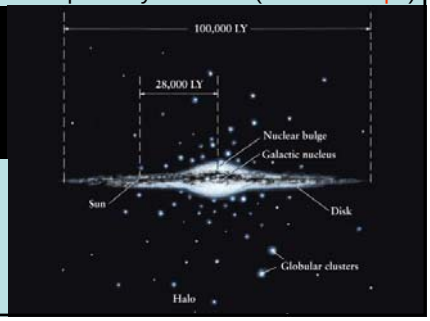
11

A2a. Shapley Core (1914-17)

12

- Postulates globular clusters orbit galactic core
- More in direction of Sagittarius
- Estimates core is 15kpc away from sun (error: its 9 kpc)

Overestimated distances, because did not know about absorption of light by galactic dust



A1c. Robert Trumpler

13

1930 (Lick Observatory) shows that there is dust in the galaxy which absorbs light.

Hence, clusters appear fainter, and more distant than they actually are.

Shapley's size of universe is 40% too big!

2c. Interstellar Reddening

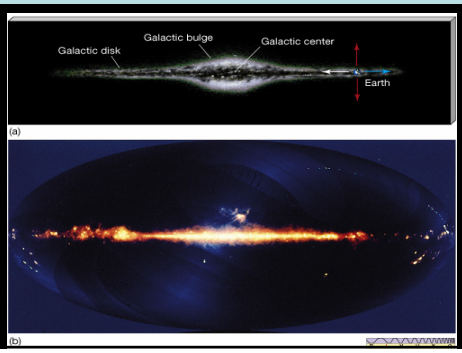
14

Note NGC3603 (left) is more red than NGC3576 (right) because it is twice as far away. Short wavelength Blue light is absorbed more than Red

A2b. The Central Bulge

15

Central Bulge is 4kpc in size, with a small 5 pc bright radio source "Sagittarius A", also bright in the IR (see below)

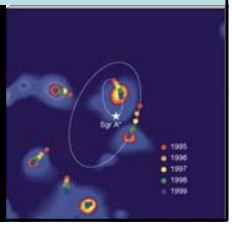


A2c. Black Hole?

16

In the center of the 5 pc Nucleus is an X-Ray source smaller than 100 AU

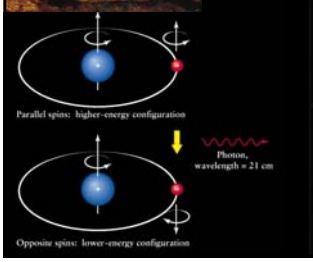
Recent measurements of orbits of stars around this core imply that there is a 2.6 million solar mass black hole!



A3a. Mapping Spiral Arms (1960)

17

- 1944, Hendrik van de Hulst predicted Neutral Hydrogen gas will emit a 21 cm "spin flip" spectral line
- 1951 First Observed with radio telescope
- 1960 Used to map spiral arms of our galaxy



A3b. Our place in the Galaxy

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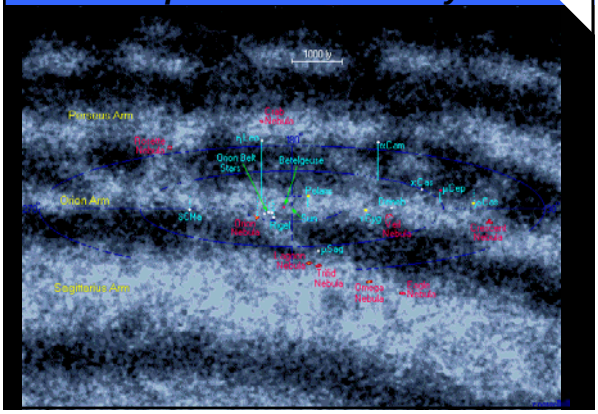


A3c. Rotations of Galaxies

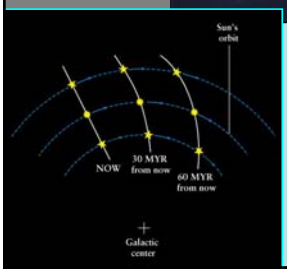
19

- Spiral Galaxies Rotate Slowly
- Sun takes 226 million years to go around (220 km/sec or 1 AU in 8 days)

- The rotation speed can be measured by the Doppler effect on the 21 cm radio line

A3d. The "Winding Dilemma"

20

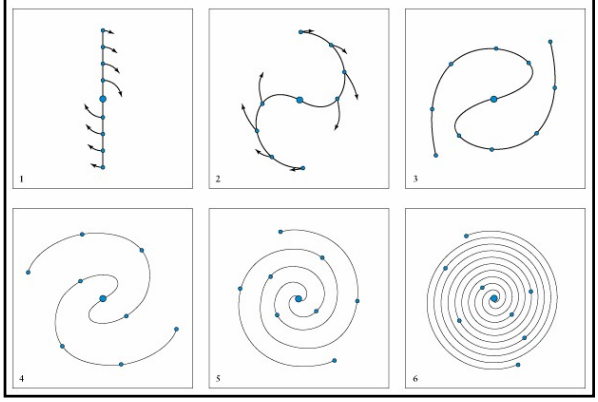


Outer stars move slower.

Why haven't the spiral arms wound up and disappeared a long time ago?

A3e. The "Winding Dilemma"

21



A3f. Density Wave Theory

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Bertil Lindblad

1925 Shows stars further from center of galaxy should move slower due to weaker gravity

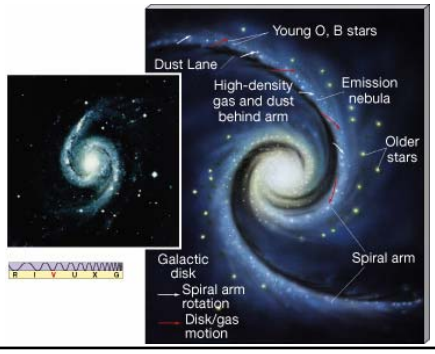
1927 Jan Oort proves this with observations

1940 Lindblad Proposes "density wave theory" to explain spiral arms (resolve the winding paradox)

A3f. Density Wave Theory

23

A compression wave through the galaxy causes stellar birth; the bright short-lived O,B stars show the crest of the wave.



A3f. Density Wave Theory

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A3f. Emission Neb in M51

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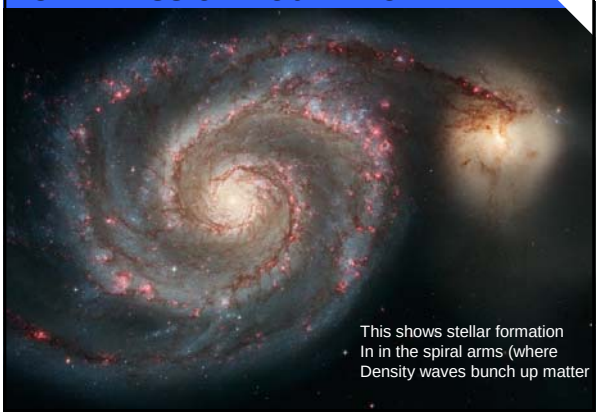

This shows stellar formation
In in the spiral arms (where
Density waves bunch up matter

A3f. Emission Nebulae

26

Red is ionized hydrogen gas
Emission nebulae are where stars
have recently formed.

A4a. Rotation Curves

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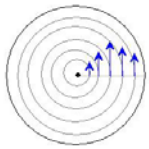
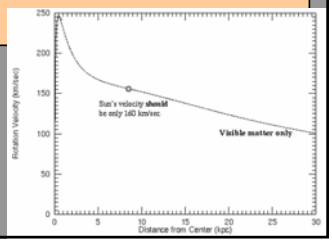
- Assuming most of mass of galaxy is in the core
- Velocity of a Star predicted by Newton's Gravity:

$$V^2/R = GM/R^2$$

- Or: $V \propto 1/\sqrt{R}$





A4b. Rotating Rong?

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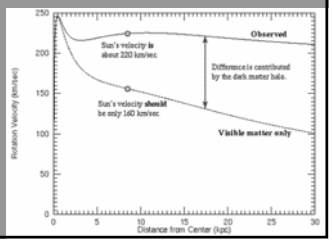
- 1980 Vera Rubin shows rotation curves of galaxies are nearly constant!
- Implies a lot of "missing" (dark) matter surrounds galaxies.

Pivotal Paper:
Rotational Properties of 21 Sc Galaxies with a Large Range of Luminosities and Radii from NGC 4605 (R=4kpc) to UGC 2885 (R=122kpc)," *Astrophys. J.* 238: 471 (1980), V.C. Rubin, W. K. Ford, Jr. and N. Thonnard.



A4c. What IS Dark Matter?

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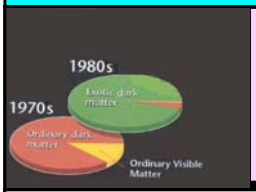

- MACHOs (**Ma**ssive **C**ompact **H**alo **O**bjects) were looked for:
  - White Dwarfs
  - Brown Dwarfs
  - Black Holes
- But its not enough!

- WIMPs (**W**eakly **I**nteracting **M**assive **P**articles): Must propose exotic things like a neutrino, but with BIG mass (10 to 10,000x that of proton).

Even though 96% of the universe is made of it, not a single piece of it is in this room.

- Or maybe there is something wrong with our theory of gravity?

B. Galaxies

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1. Curtis Shapley & Hubble
2. Clusters, Dark Matter
3. Large Scale Structure

Messier Catalog

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Charles Messier (1730-1817) was hunting for comets. People kept reporting the same fuzzy blobs that were NOT comets, so from 1758-1782 he made a catalog of about 100 of these fuzzy things to "ignore".

In fact, these 110 objects are nebulae, star clusters and galaxies, which are the best things to look for in an amateur telescope!

e.g. "M31" is the Andromeda Galaxy

Some Galaxies in Messier Catalog

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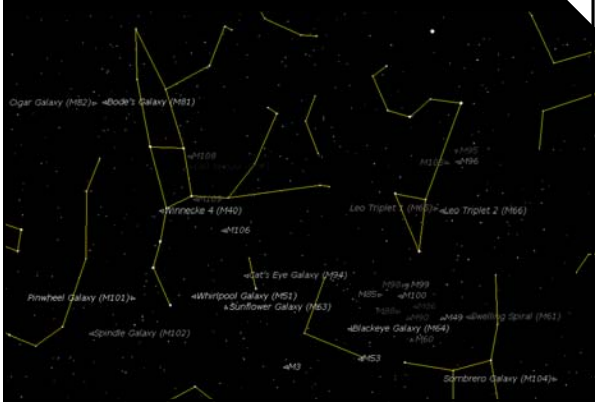


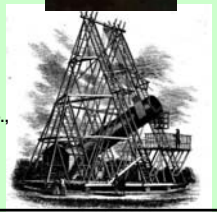
William Herschel

33

- 1785 Catalog of 1000 objects
- 1788 another 1000 objects
- 1802 another 500 objects

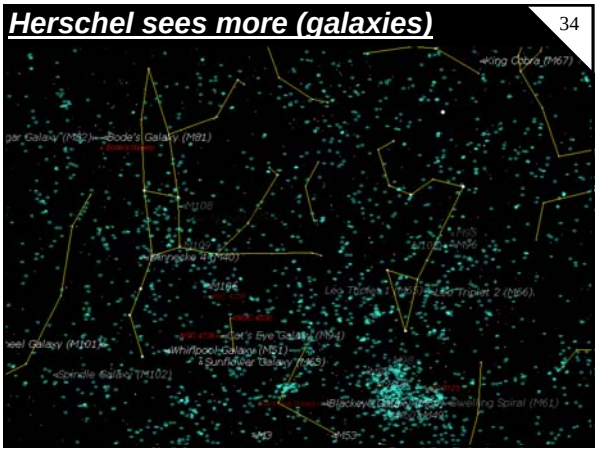
Classifies objects into star clusters and nebulae. The "types" were:

1. **Bright Nebulae**
2. **Faint Nebulae**
3. **Very faint Nebulae**
4. **Planetary Nebulae**
5. **Very large Nebulae**
6. **Very compressed and rich star clusters**
7. **Compressed clusters of small and large (i.e., faint and bright) stars**
8. **Coarsely scattered clusters of stars**



Herschel sees more (galaxies)

34



B1a. Spiral Nebulae

35

1845 Lord Rosse using his 72 inch *Leviathan* telescope sees spiral arms in M51 (Whirlpool Galaxy).

Sketches also M99, M101 and M33, calls them "Spiral Nebulae"

Lord Rosse sketch of M51

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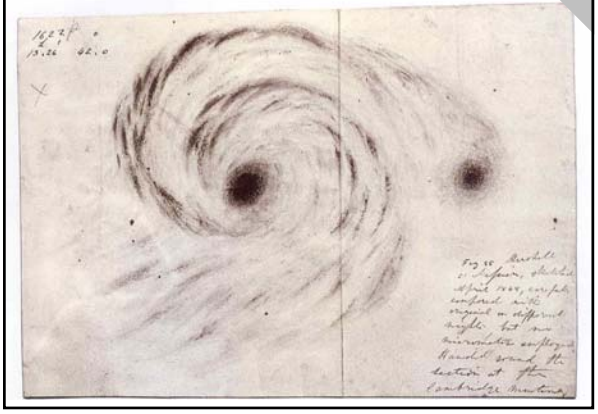

NGC: New Galactic Catalog

37

- 1864 Herschel's son John publishes the "GC", Galactic Catalog of 5079 objects.
- 1888 J. L. E. Dreyer publishes the "New Galactic Catalog" for use in Lord Rosse's observatory (the 72" Leviathan Telescope). It will take 45 years for people to realize the "spiral nebulae" seen by Lord Rosse are in fact galaxies.

B1b. Curtis-Shapley Debate (1920)

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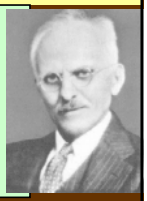
Shapley (Mt. Wilson Observatory)

•Milky Way is 100 kpc in size

•Spiral nebulae are inside the Milky Way

Curtis: (Lick Observatory)



•Milky Way is 10 to 20 kpc in size

•Spiral Nebulae are "Island Universes" (i.e. Galaxies), well outside of the Milky Way.

Debate took place 26 April 1920 at National Academy of Sciences in Washington

B1c. Curtis-Shapley Debate (1920)

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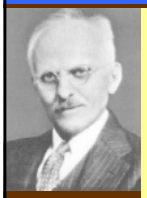


Curtis: (Lick Observatory)

•1917 Nova seen in "spiral nebula", was very faint, implies very far away

•Argues: If M31 (Andromeda Galaxy) is 20 kpc in size

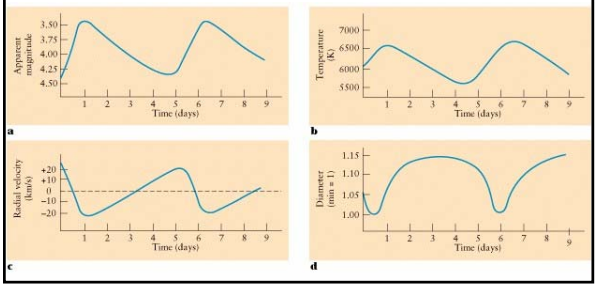
•Then 2 degree angular size implies it must be 600 kpc away (well outside Milky Way)

•1930 Trumpler shows that absorption of light by galactic dust made Shapley overestimate size of Milky Way

(2b) Cepheid Variable Stars

40

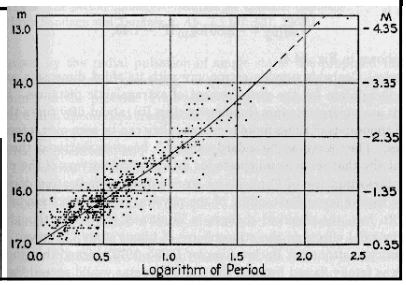
- 1784, John Goodricke discovers star in Cepheus which varies regularly in brightness by about 1 magnitude in 5.37 days
- Corresponds to both change in size and temperature
- Very bright, can be seen 50 MPC away



(3b) Period Luminosity Relation

41

- 1912 Henrietta Leavitt notes Cepheids with longer periods are brighter (bigger)
- 1913 Ejnar Hertzsprung measures distance to Polaris (which is a Cepheid variable), calibrating the period-luminosity relation.
- Cepheid variables can be used to measure distances to clusters and closer galaxies!



Edwin Hubble (1889-1953)

42

- 1919 invited to Mount Wilson Observatory
- 1925 publishes work that supports idea of existence of galaxies.
- Develops classification scheme for galaxy types
  - Elliptical
  - Spiral
  - Irregular

B1d. Edwin Hubble (1889-1953)

43

•1923 Resolves M31/M33 into stars

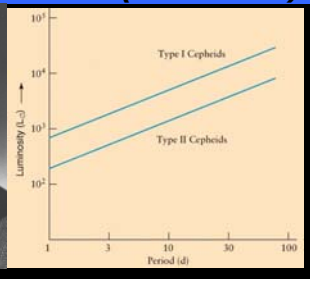
•1924 Finds Cepheids in both, estimates distance to be 285 kpc (4 times too small!)

•Supports Curtis view that spiral nebula are "island universes", i.e. galaxies, well outside of the Milky Way

•Error in calibration of Cepheids (didn't know there were two types) was not corrected until Baade's work in 1944. This changed all distances by a factor of 3.

B1e. Walter Baade (1893-1960)

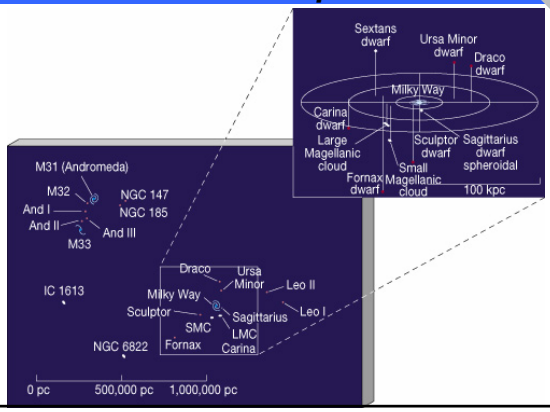
44



•Population II (1st generation stars) are in globular clusters, metal poor. Shapley had calibrated the period-luminosity curve to these.
•Population I (2nd generation stars) are in the spiral arms of the galaxy, have lots of metals. Cepheids Hubble saw in M31 were these, brighter than type I, so he underestimated distances

B2a. The Local Group

45



B2b. Magellenic Clouds

46

Discovered by Magellan 1519 in his trip around the world

B2c. The Andromeda Galaxy M31

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B2d. The Triangulum Galaxy M33

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This is about 10x smaller than M31

B2e. Clusters of Galaxies

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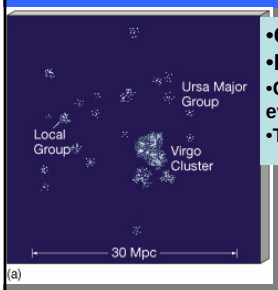
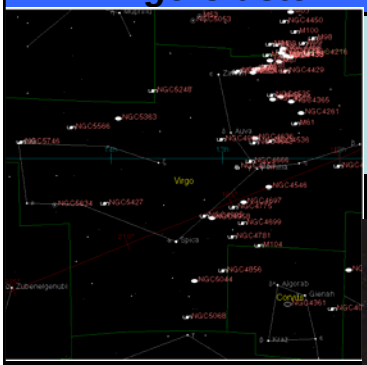


- Galaxies are in groups
- Local group has 40 galaxies
- Clusters may have hundreds or even thousands of galaxies
- Typical Size 8 MPC

- The nearest cluster to ours is in Virgo

B2f. Virgo Cluster

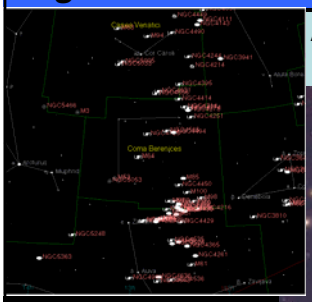
50



- Discovered 1781 by Messier
- 8 degrees in size
- Centered near M87
- 1000+ galaxies
- About 20 MPC away

B2g. Coma Cluster

51

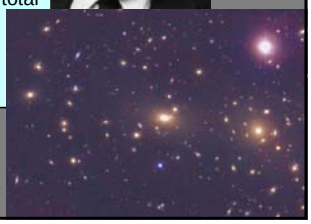


About 100 MPC away

B2h. Dark Matter

52

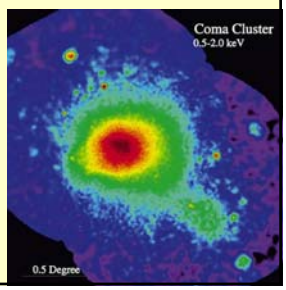
- 1933 Fritz Zwicky
- Galaxies orbiting Coma Cluster moving much faster than could be explained by mass of cluster
- Luminous Mass is only 10% of total
- Other 90% mass is "missing"
- Coined term **"Dark Matter"**



B2i. Dark Matter in Clusters

53

- 1970s Ultra Hot "X-ray gas" filling the space between the galaxies in a cluster
- Hot gas would have very high velocity, and would escape unless there is sufficient gravitational mass keeping it there.
- The mass of all the visible galaxies is only 10% of the required amount to explain the trapped gas.
- Again 90% must be **Dark Matter**



- http://astronomy.nmsu.edu/tharriso/ast110/class25.html

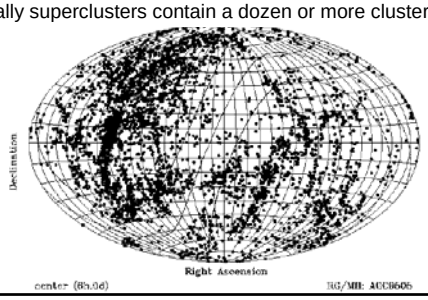
B2j. Hercules Cluster

54

B3a. Superclusters

55

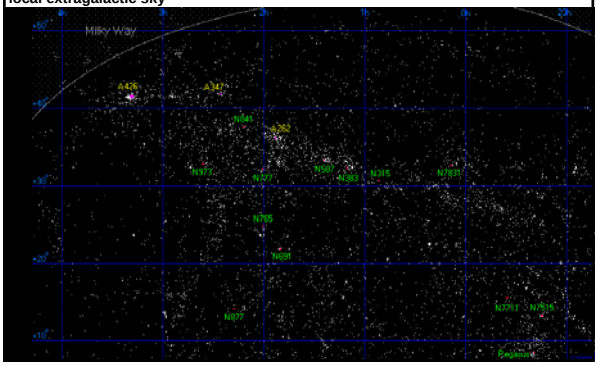
Clusters of Galaxies group together into Superclusters. Our local supercluster is has the Virgo Cluster near its center, and our local group at one end. Its about 40-50 MPC in size, with thousands of galaxies. It similar in shape to a flattened ellipse (pancake). Typically superclusters contain a dozen or more clusters.



B3b. Perseus Supercluster

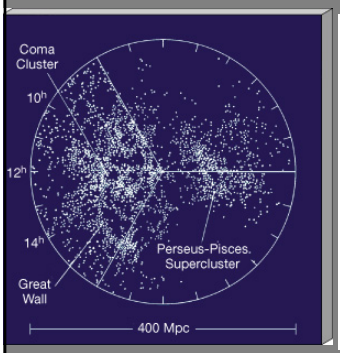
56

The Pisces-Perseus supercluster is one of the most prominent structures in the local extragalactic sky



B3c. Large Scale Structure

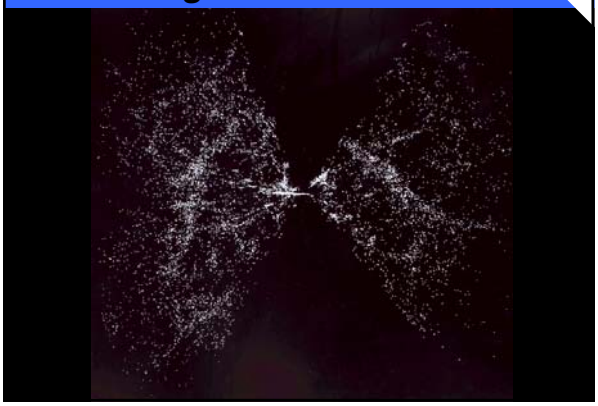
57



Deep redshift surveys reveal a very bubbly structure to the universe with galaxies primarily confined to sheets and filaments. Voids are the dominant feature and have a typical diameter of about 25Mpc. They fill about 90% of space and the largest observed, Bootes void, has a diameter of about 124Mpc. Other features that have been observed are the `Great Wall', an apparent sheet of galaxies 100Mpc long at a distance of about 100Mpc.

B3dc. Large Scale Structure

58



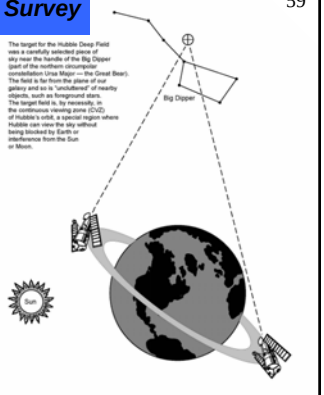
B3e. Hubble Deep Field Survey

59

•10 days in December 1995

•Focus on one small "average" part of the sky and count all the galaxies out to the edge of the universe.

•Area is about 0.04 square degrees (the size of a dime viewed at 75 feet, or one-27th-millionth of the complete sky



B3f. Hubble Deep Field Survey

60

•Found at least 3000 galaxies

•Hence there must be about 3000 x 27,000,000 =80 billion galaxies in the universe.

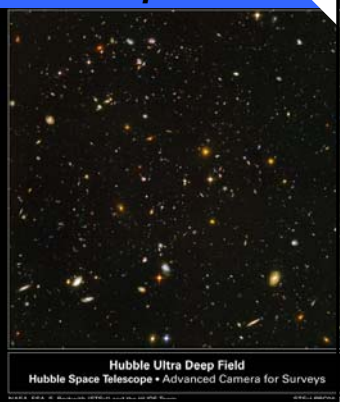
B3g. Hubble Ultra Deep Field

61

•in March 2004 -- the Hubble Ultra Deep Field survey probed even more deeply an area about three minutes of arc square, shows 10,000 galaxies.

•The nearest galaxies - the larger, brighter, well-defined spirals and ellipticals - thrived about 1 billion years ago.

•The smallest, reddest 100 galaxies, the most distant, existed when the universe was just 800 million years old. These are possibly the first galaxies to emerge from the so-called "dark ages," the time shortly after the big bang when the first stars reheated the cold, dark universe.



B3h. Mass of Universe

62

•A Galaxy is approximately 100 billion stars

•Mass of Typical Star is: $2x10^{30}$ kg

•Total Mass of Universe: $1.6x10^{52}$ kg

•Neutrinos and photons might contribute some energy (equivalent to mass), but estimates are that its not significant (less than 0.1% of stellar mass)

•We are ignoring "dark matter" here

B3i. Size of universe

63

- If photons started at the big bang, then how far have they travelled during the lifetime* of the universe?
- $R = c/H_0 = 4225$ MPC
  $(3x10^5$ km/sec)/(71 km/s-MPC) = 4225 MPC
- $R=1.3x10^{26}$ meters

*Note age of universe is the **"Hubble Time"** = $1/H_0$

B3j. Is the Universe a Black Hole

64

$$\frac{2GM}{c^2R} = \begin{cases} <1 & \text{Open} & \text{+ curved} \\ =1 & \text{Asymptotic} & \text{Flat} \\ >1 & \text{Closed} & \text{- curved} \end{cases}$$

- **The Schwarzschild radius of the Universe is about 18% of its present size: $2GM/(Rc^2) = 0.18 = 1/5.5 < 1$**
- **Universe is hence "open", not a black hole, it should expand forever.**
- **To be closed need $2GM/(Rc^2) > 1$**
- **Would need to propose the universe is 82% "dark matter", only 18% regular matter.**

B3k. Critical Mass

65

Problem with Hubble's Deep Field Survey:

•Far away galaxies might be too faint to see, or obscured by gas/dust

•Far away is also far in past, there may have been fewer galaxies then

•Curved space might affect the galaxy count

Most likely our estimate will undercount the mass in universe. So maybe there is enough normal matter to make the universe "closed"

B3l. Critical Density

66

Alternative Approach: make estimate of density of matter in nearby universe, assume it's the same everywhere.

•Density: ρ=(mass)/(volume) = $M/[4/3\ \pi R^3]$
•$R = c/H_0 = R=1.3x10^{26}$ meters

•Substitute into $2GM/(Rc^2)=1$, and solve

$$\rho_c = \frac{3H^2}{8G\pi} = 9.5x10^{-27}\ kg/m^3$$

This is the critical density for the universe to be a Black Hole

B3m. Density Parameter

67

If the measured density ρ is greater than this "critical density" ρ_c then the Universe in closed.

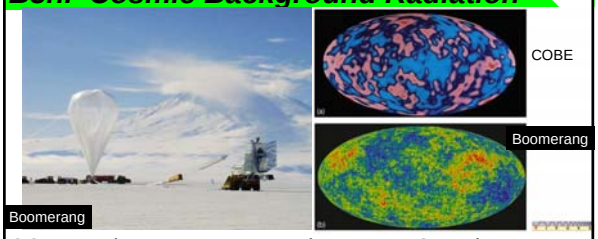
Density Parameter: $\Omega = \rho/\rho_c$

- **Ω >1 Closed (+ Curved)**
- **Ω =1 Flat (0 Curved)**
- **Ω <1 Open (- Curved)**

Measured Density gives **Ω=0.27**, a factor of 5 short of making the universe closed.

B3n. Cosmic Background Radiation

68



COBE and Boomerang experiments on Cosmic Background Radiation, the afterimage of the Big Bang Explosion, imply Ω=1 ± 2% (FLAT UNIVERSE)

Hence, there must be at least 5x more matter out there (another argument for DARK MATTER)