Announcements

- Homework #9 is due today
- Course Evaluations available on line now
- Post-test Survey for "At Play in the Cosmos" now ready

For extra credit:

- must complete all 8 missions by Dec 10
- must complete the post-game survey by Dec 10
- Campus observatory Friday Dec 2nd if clear



Campus Observatory

Friday @ 7pm

you are here

Clusters of Galaxies and Large Scale Structure

Outline

- 1. Classifying Clusters
- 2. Morphology-Density Relation
- 3. Intracluster Gas
- 4. Dark Matter and Gravitational Lensing
- 5. Superclusters

Most galaxies are in clusters or groups. Clusters contain hundreds to thousands of galaxies.



Cluster Abell 1185 showing a galaxy interaction

Classifying clusters:

1) "rich" clusters vs. "poor" clusters

Poor clusters include galaxy groups (few to a few dozen members) and clusters with 100's of members. Masses are 10¹² to 10¹⁴ solar masses.

Rich clusters have 1000's of members. Masses are 10¹⁵ to 10¹⁶ solar masses. Higher density of galaxies.

2) "regular" vs. "irregular" clusters

Regular clusters have spherical shapes. Tend to be the rich clusters.

Irregular clusters have irregular shapes. Tend to be the poor clusters.

Example:

Distribution of galaxies (2500 or so) in the Virgo cluster. It is moderately rich but not very regular.

Large extension to the south makes it irregular. Also, these galaxies have velocities offset from the main cluster. This is a whole subcluster that is merging with the main cluster.

Despite great age of universe, most clusters are still evolving!

<u>The Morphology – Density Relation</u>

The higher the density of galaxies, the higher the fraction of ellipticals.

Coma cluster: thousands of galaxies, high elliptical fraction

Hercules cluster: about a hundred galaxies, high spiral fraction

Spirals dominate isolated galaxies, groups, poor clusters. Ellipticals and SO's dominate rich clusters, especially dense central parts.

Black Hole Mass - Velocity Dispersion

Kormendy et al.

Why this relation between morphology and galaxy density?

Explanation: denser environment => more mergers => more ellipticals made as bulges grew. Most mergers happened long ago when galaxies were closer together.

At cluster centers lie the largest ellipticals: "cD" galaxies. They have digested many companions. Masses up to 10¹⁴ solar masses (remember: Milky Way about 6 x 10¹¹ solar masses)!

Are these cores of swallowed companions or galaxies seen in projection?

What sort of galactic environment is our own Milky Way Galaxy in?

- A: completely isolated no other galaxies within 100 Mpc
- B: a small group of ~30 galaxies
- C: a moderately rich cluster of ~300 galaxies
- D: a super dense cluster of ~3000 galaxies

What sort of environment do you often find cD galaxies in but very rarely find any spiral galaxies in?

- A: In isolation
- B: In small groups of galaxies.
- C: At the outskirts of modest galaxy groups.
- D: In the center of very rich clusters.

There is more mass between galaxies in clusters than within them

Abell 2029: galaxies (blue), hot intracluster gas (red)

X-ray satellites (e.g. ROSAT, Chandra) have revealed massive amounts of hot (10^7-10^8 K!) gas in between galaxies in clusters ("intracluster gas"). A few times more than in stars!

One consequence of intracluster gas: "Ram Pressure Stripping"

As a spiral galaxy moves through a cluster, the gas <u>in</u> the galaxy runs into the intracluster gas, dragging some of it (especially from the outskirts) from the galaxy. Stars not affected – they are more like bullets)

Virgo cluster galaxy showing stripped atomic gas (contours are 21-cm emission).

AGN Feedback

AGNs feedback energy to the cluster gas, heats it up

Studies of nearby clusters \Rightarrow In Perseus and in M87 directed energy from jets is being redistributed more isotropically via bubbles blown, compression waves,

Chandra 900 ks image of Perseus cluster, unsharp-masked at right (Fabian et al. 2006)

NASA animation of sound waves produced by 3C84

Cluster Dominant Galaxy (cD)

Fabian et al. 2003

Chandra + VLA

What is the origin of intracluster gas? Possibilities:

- 1) "Leftover" gas from the galaxy formation process
- 2) Gas lost from galaxies in tidal interactions, ram pressure stripping, supernova explosions, and jets from active galactic nuclei

High density of galaxies in clusters means that tidal interactions are common

How could you tell between 1) and 2)?

Take a spectrum! Many lines of elements produced by nucleosynthesis in stars. Can't be mostly "leftover" gas.

Most mass in clusters is in Dark Matter

Recall Escape Velocity: needed to completely escape the gravity of a massive object.

$$v_{escape} = \sqrt{\frac{2 G M_{object}}{R}}$$

Mass in visible matter (galaxies and intracluster gas) $2 \ge 10^{14}$ solar masses. Size 3 Mpc. Escape speed then 775 km/s.

But typical velocity of galaxy within cluster observed to be 1000 km/s, and many have 1000-2000 km/s! Must be more mass than is visible (85% dark matter inferred).

Gravitational Lensing

Remember from Einstein's Theory of General Relativity that gravity causes light to follow curved paths, e.g.

Saturn-mass black hole

So gravity acts like a lens.

Clusters of galaxies also bend the light of more distant galaxies seen through them

From the lensed galaxy images, you can figure out the total mass of the cluster. Results: much greater than mass of stars and gas => <u>further</u> evidence for dark matter!

The Bullet Cluster

Dark matter predicted not to interact with ordinary matter, or itself, except through gravity. Gas clouds, by contrast, can run into each other. A collision of two clusters provides dramatic evidence for dark matter:

cluster trajectory

red shows hot gas from two clusters, seen with Chandra Xray observatory. The gas clouds have run into each other, slowing each one down

cluster trajectory

blue shows inferred distribution of cluster mass from gravitational lensing of background galaxies. The dark matter has gone straight through with no interaction, like the galaxies have. Can MOND explain this? Recall, MOND asserts that on large scales, a given mass has more gravity than Newton's Law predicts, so less mass is needed to explain large scale accelerations, which may get rid of exotic Dark Matter.

So red is still hot intracluster gas clouds slowed down by their collision.

But in MOND, blue is ordinary non-radiating matter that has passed through with essentially no collisions to slow it down.

However, MOND allows for "ordinary" Dark Matter, such as dead stellar remnants, known elementary particles (e.g. neutrinos), i.e. something in which collisions are rare, allowing the two concentrations to pass through each other. So this is a large challenge for MOND, but hasn't buried it.

Assemblages of clusters and groups

The Local (or Virgo) Supercluster

More Superclusters – note the filamentary shapes

Where in the Universe are we?

103 Regener Hall
University of New Mexico
Albuquerque, NM 87131
United States of America
Earth
The Solar System, 8000 pc Orion Arm spur
The Milky Way Galaxy
The Local Group
The Virgo Supercluster

Simulating the Universe

Growth of structure - The Cosmic Web

Z=28.62

Most of the mass in galaxy clusters is in the form of:

A: Stars, which collectively form the galaxies in the cluster.

B: Cold gas, which exists between the stars in galaxies and we measure in the radio.

C: Hot gas, which exists mostly between galaxies and we measure in X-rays.

D: Dark matter, which we infer from the velocities of galaxies and from gravitational lensing.

What is the origin of the intra-cluster gas in clusters of galaxies?

A: It is left-over material from the formation of the cluster.

B: It is material ejected or stripped out of galaxies long after the formation of the cluster.

C: It is material spontaneously created since the formation of the cluster.

D: It is material created from the decay of dark matter since the formation of the cluster.

What is the name of the supercluster that contains our local group:

- A: The Coma Supercluster
- B: The Virgo Supercluster
- C: The Centaurus Supercluster
- D: The Leo Supercluster.

In 1920's, Hubble used Cepheids to find distances to some of these receding galaxies. Showed that <u>redshift</u> or <u>recessional velocity</u> is proportional to <u>distance</u>:

$$V = H_0 \times D$$
 (Hubble's Law
velocity (km / sec) Distance (Mpc)

Hubble's Constant (km / sec / Mpc)

Current estimate: $H_0 = ~75 \text{ km/sec/Mpc}$ If $H_0 = 75 \text{ km/sec/Mpc}$, a galaxy at 1 Mpc moves away from us at 75 km/sec, So by getting the <u>spectrum</u> of a galaxy, can measure its <u>redshift</u>, convert it to a <u>velocity</u>, and determine <u>distance</u>.

Results from a mid 1980's survey.

Assumes $H_0 = 65 \text{ km/}$ sec/Mpc. Note how scale of structure depends on this.

Hubble's Law now used to unveil <u>Large Scale Structure</u> of the universe. Result: empty <u>voids</u> surrounded by <u>shells or filaments</u>, each containing many galaxies and clusters. Like a froth.

Results from further surveys: two large "pie-slices" of the sky, one from N. Hemisphere, one from S. Hemsiphere.

Finding Large Assemblages of Galaxies through Motions of Tracer Galaxies

<u>Uniform</u> Hubble expansion as seen from our point of view.

a galaxy recedes with a speed proportional to its distance. Same in every direction <u>Departure</u> from Hubble expansion due to large cluster to the right.

these galaxies have <u>excess speed</u> for their distance because they are falling in to massive cluster (distances from, e.g., Tully-Fisher relation, <u>not</u> Hubble's Law)

From measuring such departures, we've found:

Milky Way and Andromeda approaching each other 1)

Where is the Great Attractor? Hard to characterize because it crosses the plane of the Milky Way. Galactic dust obscures our view.

The Deep SkyRadio survey of galaxies shows
more. But implied mass of
galaxies much less than thought.

Clusters are Very Large Magnets

Faraday Rotation

Carilli & Taylor 2002 (ARA&A)

 $B \thicksim 10 \ \mu G$

Faraday Rotation Measures

Hydra A

 $B \sim 30 \ \mu G$

Astrophysics Majors at UNM

BS in Astrophysics
Astro 270 and 271
BA in Physics and Astrophysics
Astro 270 and 271

See me for more details