Clusters of Galaxies

Galaxies are not randomly strewn throughout space. Instead the majority belong to groups and clusters of galaxies. In these structures, galaxies are bound gravitationally and orbit a common center of mass.

Groups: have less than $\sim$50 members with a size of $\sim$2 Mpc. They have velocity dispersions $\sim$150 km/s and total mass $2-3 \times 10^{13}$ M$_{\odot}$. They have mass-to-light ratios of $\sim$300-400 M$_{\odot}$/L$_{\odot}$.

Clusters: have $\sim$50 members (a poor cluster) to as many as 1000 members (a rich cluster). They have sizes of 6-8 Mpc, velocity dispersions of $\sim$800-2000 km/s and total mass of $1-3 \times 10^{15}$ M$_{\odot}$. They have mass-to-light ratios of $>500$ M$_{\odot}$/L$_{\odot}$.

Superclusters: clusters of clusters of galaxies, and so on.
The Local Group

There are about 35 galaxies within roughly 1 Mpc of the Milky Way and these have velocities implying they are all bound to a common center of mass (about 460 kpc in the direction of Andromeda). The most prominent members are the Milky Way (us), and the Andromeda (M31) and Triangulum (M33) galaxies.
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Figure 1. A scaled 3-D representation of the Local Group (LG). The dashed ellipsoid marks a radius of 1 Mpc around the LG barycenter (assumed to be at 462 kpc toward $l = 121.7$ and $b = -21.3$ following Courteau & van den Bergh 1999). Distances of galaxies from the the arbitrarily chosen plane through the Milky Way are indicated by solid lines (above the plane) and dotted lines (below). Morphological segregation is evident: The dEs and gas-deficient dSphs (light symbols) are closely concentrated around the large spirals (open symbols). DSp/h/dIrr transition types (e.g. Pegasus, LGS 3, Phoenix) tend to be somewhat more distant. Most dIrrs (dark symbols) are fairly isolated and located at larger distances. Also indicated are the locations of two nearby groups.
The Local Group

Andromeda has a “blueshift”. It has a negative recessional velocity of roughly -300 km/s. Given the current distance of 770 kpc, they should collide in 2-3 Gyr.

What would this look like?
The Local Group

Using the orbital speeds and distances of galaxies in the local group, you can estimate how much mass their is in the local group. The answer is \( \textit{at least} \ 4 \times 10^{12} \ M_\odot \). Using all the light we see, this gives a mass to light ratio of \( \sim 60 \ M_\odot/L_\odot \).

The mass-to-light ratio of “luminous matter”) in the the Milky Way \( \sim 3 \ M_\odot/L_\odot \) in the Solar circle) is much, much smaller. Luminous matter accounts for \( \sim 5\text{-}10\% \) in the Local Group.
The Virgo Cluster

First recognized by William Herschel where the constellations Virgo and Coma meet. The cluster covers 10 x 10 degrees on the sky (the Full Moon cover 0.5 x 0.5 degrees). The center of the cluster is ~18 Mpc from Earth.

The Virgo Cluster contains >250 large galaxies and more than 2000 smaller ones contained within an area 3 Mpc across.

The largest galaxies are all ellipticals (M87, M86, M84) and these have sizes equal to the distance between the Milky Way and Andromeda. These are “giant” Ellipticals (gE).
Central Part of Virgo Cluster

Sky.google.com

Virgo Cluster of Galaxies

Tuesday, April 17, 2012
The Coma Cluster

The Virgo Cluster is small compared to the Coma Cluster.

The Virgo Cluster contains >250 large galaxies and more than 2000 smaller ones contained within an area 3 Mpc across. Most of the large galaxies are spirals in Virgo.

The Coma Cluster is 15° of Virgo, in the constellation Coma Berenices, and is ~90 Mpc away. It has an angular diameter of ~4° which at 90 Mpc away is a linear diameter of 6 Mpc.

Coma contains possibly more than 10,000 galaxies. Of the >1000 large galaxies, only 15% are spirals. The majority are ellipticals (and some S0’s).
The Coma Cluster

In 1933 Fritz Zwicky measured the doppler shift velocities of galaxies in the Coma Cluster.

He measured the velocity dispersion (average velocity) of cluster galaxies to be $\sigma = 977$ km/s.

This gives a Virial Mass of $M = 5\sigma^2 R / G = 3.3 \times 10^{15} M_\odot$.

Comparing this to all the luminosity from the galaxies in the cluster, $L_{\text{tot}} = 5 \times 10^{12} L_\odot$ gives a mass-to-light ratio of

$$M/L \approx 660 M_\odot/L_\odot.$$ 

The Luminous matter in Coma accounts for $1/660 = 0.1\%$ of the mass! Zwicky argued in 1933 that Dark Matter must dominate clusters. Turns out it does, but at the time no one believed Zwicky.....
The Coma Cluster

A portion of Zwicky’s “Missing Mass” was discovered in the X-rays. In 1977 the High Energy Astronomical Observatory (HEAO) satellites indicated that clusters contain an intracluster medium (ICM). This includes a hot intracluster gas that is so hot it emits in the X-rays (by thermal Bremsstrahlung radiation).
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X-ray spectrum of bremsstrahlung for the Coma cluster (Henriksen & Mushotzky 1986)
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For Bremsstrahlung radiation, the Luminosity density (energy per second per unit volume) is

\[ \mathcal{L}_X = 1.42 \times 10^{-40} n_e^2 T^{1/2} \text{ W m}^{-3} \]

For Coma, consider that the radius of the gas is \( R = 1.5 \) Mpc (one-half the actual radius), the X-ray spectrum is best-fit with a gas of temperature \( T = 8.8 \times 10^7 \) K.

The total Luminosity is \( L_x = \frac{4}{3} \pi R^3 \mathcal{L}_X = 5 \times 10^{37} \) W from observations.

The value of the number density of free electrons, \( n_e \), is

\[ n_e = \left[ \frac{3L_X}{4\pi R^3 T^{1/2} (1.42 \times 10^{-40} \text{ W m}^{-3})} \right]^{1/2} = 300 \text{ m}^{-3} \]

Recall that giant molecular clouds have \( n_H \sim 10^8 \) to \( 10^9 \) m\(^{-3}\).
The Coma Cluster

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Using $n_e = 300 \, m^{-3}$ and $R=1.5 \, Mpc$, the total mass for ionized hydrogen (there is one free proton for every free electron in the gas) we get the total mass of the X-ray emitting gas:

$$M_{\text{gas}} = \frac{4}{3} \pi R^3 n_e m_H = 1.05 \times 10^{14} M_\odot$$

This is 10x higher than the Mass of the galaxies in the cluster ($M_{\text{galaxies}} \sim 10^{13} M_\odot$, for $L=5 \times 10^{12} L_\odot$ and $M/L \sim 3 M_\odot/L_\odot$).

And, this is still much, much less than the mass from the dynamical measurement, $M_{\text{total}} = M_{\text{gas}} + M_{\text{galaxies}} + M_{\text{??}} = 3.3 \times 10^{15} M_\odot$.

>90% of the mass of the cluster is in the form of some kind of dark matter.
Superclusters
As the name suggests, superclusters are seen in the distribution of clustering of galaxies and clustering of clusters. These are structures on scales of \(~100\) Mpc.

The Milky Way sits at one end of the **Local Supercluster**, which is \(~50\) Mpc long.
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As the name suggests, superclusters are seen in the distribution of clustering of galaxies and clustering of clusters. These are structures on scales of $\sim 100$ Mpc.

The Milky Way sits at one end of the **Local Supercluster**, which is $\sim 50$ Mpc long.


The Milky Way is at the center of the circle and runs in the triangular regions with no galaxies (can’t see them in the plane of the galaxy).
Redshift Surveys

Many galaxy surveys measuring the angular position (RA and Decl) and redshift (the *distance*) have been carried out. These show strong clustering in all dimensions. The galaxy distribution is far from random.

Angular coordinate on sky (in hours, there are 24 hrs in a complete circle)

This “slice” is 6 degrees thick (in the page), from $26.5^\circ < \delta < 32.5^\circ$.

$v = c \, z \, ( = H_0 \, d)$

$d = 70 \, \text{Mpc for } v=5000 \, \text{km/s}$
Redshift Surveys

Coma Cluster
\[ z = 0.023 \text{ (6900 km/s)} \]
390 sources modified

“finger” transformed into gaussian sphere
Superclusters

Cross section of the Universe with cz < 12,000 km/s (120h⁻¹ Mpc) with 9325 galaxies (da Costa et al. 1994).

Coordinates for the top slice are RA=8-17h, Decl=8.5-44.5d.

Coordinates for the bottom slice are RA=20.8h - 4h, Decl=-40 - 2.5d.
z = 20.0

50 Mpc/h

Courtesy V. Springel
Modern survey: Sloan Digital Sky Survey, probes out to nearly 1000 Mpc.

This spans almost the “whole sky”, except for where the Galaxy blocks our view....

Courtesy of Michael Blanton.
Summary: Evidence for Dark Matter

1. Rotation Curves in Galaxies: The rotation velocities of galaxies at large radii are constant. This is not what one would expect if the luminous matter (stars and gas) were all the matter. One can work out what the Dark Matter “Halo” looks like from this.

2. Velocities in Clusters of Galaxies: Average velocities of cluster galaxies is $\sim 1000$ km/s, which implies very large masses, $\sim 10^{15}$ solar masses, which comes from the Virial Theorem. The gas and stars add up to only 10% of this, so 90% of matter is “Dark” in clusters.

3. Cluster and galaxy masses from gravitational lensing. This is from General Relativity, which predicts that as the light from distant objects passes near massive objects, it will get bent. The observed phenomenon is exactly as General Relativity predicts, but it implies that galaxies and clusters have dark matter that accounts for $\sim 90\%$ of the mass.
The **Bullet Cluster.** This object appears to be two galaxy clusters that have merged.
The Bullet Cluster

See Clowe et al. 2006

Orange: stars  Red: X-ray gas  Blue: Mass from lensing measurements
Evidence for Dark Matter

The **Bullet Cluster**. This object appears to be two galaxy clusters that have merged. Most of the galaxies passed through each other, but the hot X-ray-emitting gas smashed into each other and stopped in its tracks.

The gravitational lensing analysis of background galaxies shows that all the mass (the dark matter) has followed the galaxies. The Dark Matter is acting solely as point sources that interact only by gravity. No other known model for gravity can explain this except Dark Matter.
The Bullet Cluster

Orange: stars
Red: X-ray gas
Blue: Mass from lensing measurements

See Clowe et al. 2006
The Bullet Cluster

Orange: stars
Red: X-ray gas
Blue: Mass from lensing measurements

See Clowe et al. 2006
The Bullet Cluster

Orange: stars, Red: X-ray gas, Blue: Mass from lensing measurements

See Clowe et al. 2006
The Bullet Cluster

Orange: stars
Red: X-ray gas
Blue: Mass from lensing measurements

See Clowe et al. 2006