Oct 21, 2015

- Basic properties of groups and clusters of galaxies
  - Number density, structure
  - X-ray emission from hot ICM
  - Estimating cluster masses
  - Cluster scaling relations

- Impact of environment on galaxies
  - Galaxy-ICM interactions = ram pressure sweeping

- HW#6 is due; please pass it in.
- HW#7 is posted; it requires you to write out answers clearly and completely explaining your logic.

- (Hopefully) Arecibo remote observing Sat Oct 24 at 7:15 pm.

- HW#8 will focus on the final projects; discussion of topics on Monday (10/26) with assignments made on Wed (10/28)

There is a handout today
Explaining the universe

• How did the structures we see today form and evolve from the earliest times (CMB) to the galaxies of today?
• Do our cosmological models predict this behavior?
• Can we observe the development of structure over cosmic time?
Large Scale Structure viewed from redshifts

Galaxies are not randomly distributed in space => Galaxies tend to cluster

More luminous galaxies are over-represented in a flux-limited sample because of the Mahlquist bias.

If one galaxy has comoving coordinate, $\mathbf{x}$, then the probability of finding another galaxy in the vicinity of $\mathbf{x}$ is not random. They are correlated.

Zone of avoidance

Courtesy of Michael Blanton.
2dF = 2 degree field redshift survey
Large scale structure

Galaxy redshift survey

Cosmological simulation

Millennium Run
10,077,696,000 particles
Tracing large scale structure

Galaxies are not uniformly distributed in space. They rather form large filaments, sheets, and superclusters of galaxies, which surround regions with very low galaxy density (voids):

- What are the important characteristic scales (mass, size)?
- Is there a well-defined hierarchy?
- Where does the structure come from?
Large scale structure in the universe

- Galaxies trace hierarchical structures: groups, clusters and superclusters

- The **principal differences** between a group and a cluster is
  - the number (N) of members
  - the total mass of the group/cluster
  - the velocity “dispersion”*: of order ~250 km/s for a group and perhaps ~500-1000 km/s for a rich cluster

- The “typical radius” of a group or cluster is ~ 2 Mpc = 6.7 million light years (as determined by George Abell 50 years ago).

*velocity dispersion: typical orbital velocity of a galaxy in the group/cluster
Groups and clusters

• Groups and clusters are roughly the same size (radius = 2 Mpc)

• The basic difference is the number of galaxies $\Rightarrow$ density of galaxies (number per volume)
  • Morphological makeup
  • Presence of hot gas
Galaxies cluster:

Galaxies are found in different environments:

- The “field”
- Groups
- Cluster
- Superclusters (filaments)
Substructure in the Local Group

Galaxies mainly clustered around the two principal galaxies MW & M31

Diagram from Eva Grebel
M81 Group

TIDAL INTERACTIONS IN M81 GROUP

Stellar Light Distribution

21 cm HI Distribution

http://images.nrao.edu
M81 Group

http://www.atlasoftheuniverse.com
Leo I Group

Contains a few relatively bright spirals and some smaller dwarf galaxies (not unlike the Local Group)
Mass of Virgo cluster from velocities

- How can you use this information to calculate the total dynamical mass of the Virgo cluster?

Galaxies with measured $V < 3000$ km/s within $7.5^\circ$ of M87
Mass of Virgo cluster from velocities

- Why do some galaxies have negative heliocentric velocities?
- Why is the histogram skewed towards higher redshifts?
Mass of Virgo cluster from velocities

See lecture slides from Sep 23
Virial Theorem => Virial Mass

\[ M_{\text{tot}} = \frac{5R \sigma_r^2}{G} \]
Morphological segregation

**Ellipticals**
- Smooth light distribution
- Brightest stars are red
- Little/no star formation
- Little/no cool/cold gas
- Random motions

**Spirals**
- Arms, disk, bulge
- Brightest are blue
- On-going star formation
- Molecular + atomic gas
- Circular rotation in disk

- Found in cluster cores
- Avoid cluster cores

![Graph showing the distribution of Ellipticals and Spirals in low and high density fields.](image)
Clusters of Galaxies

- Clusters contain 100s to 1000s of galaxies per Mpc$^{-3}$ as well as hot (Temp~$10^8$ K) gas, detected as X-ray emission.
Coma Cluster = A1656

cz \sim 7000 \text{ km/s}

Often used as “prototypical rich cluster”
X-ray emission in clusters

Fig. 6.13. X-ray images of the Coma cluster, taken with the ROSAT-PSPC (left) and XMM-EPIC (right). The image size in the left panel is $2.7^\circ \times 2.5^\circ$. A remarkable feature is the secondary maximum in the X-ray emission at the lower right of the cluster center which shows that even Coma, long considered to be a regular cluster, is not completely in an equilibrium state, but is dynamically evolving, presumably by the accretion of a galaxy group.
Most of the baryons lie in the hot X-ray emitting gas which is in virial equilibrium with the DM potential well.

- Ratio of gas to stellar mass is typically 2-10 to 1
- The ICM is enriched in heavy elements => by products of stellar evolution in the galaxies in the cluster
- Strong relation between T of gas and total mass of cluster
X-ray from hot ICM in clusters

- Clusters of galaxies are the most common bright extragalactic X-ray sources; clusters have very high $L_X \sim 10^{43-45}$ erg s$^{-1}$ but the range of $L_X$ is very high. Emission is by thermal bremsstrahlung (breaking) radiation also known as free-free emission due to the hot gas. We deduce that the emission is bremsstrahlung from its spectrum:

$$4\pi\varepsilon(\nu) = 6.8 \times 10^{-38} \frac{n_e \exp(-h\nu/kT)}{\sqrt{T}}$$

where $n_e(r=0) \sim 10^{-3}$ cm$^{-3}$, $T \sim 10^8$ K

- For a thermal plasma with solar abundance, the total bremsstrahlung emission depends on the temperature $T$ of the hot gas and the density $n_e$ as:

$$\epsilon^{\text{ff}} = \int_0^\infty d\nu\epsilon^{\text{ff}}_\nu \approx 3.0 \times 10^{-27} \sqrt{\frac{T}{1\text{K}}} \left(\frac{n_e}{1\text{ cm}^{-3}}\right)^2 \text{erg cm}^{-3}\text{s}^{-1}.$$  

(6.32)
Hot gas in clusters

- The X-ray surface brightness is usually described by a “beta” β-model

\[ S(R) = S(0)(1 + \frac{R^2}{r_{core}^2})^{-3\beta + 1/2} \]

**Fig. 6.23** Surface brightness contours of the X-ray emission for four different groups or clusters of galaxies. Each image is about 30'' on a side. *Upper left:* the galaxy group NGC 5044, at redshift \( z = 0.009 \), with an X-ray temperature of \( T \approx 1.07 \) keV and a virial mass of \( M_{200} \approx 0.32h^{-1} \times 10^{14} M_\odot \).

*Upper right:* the group MKW4, at \( z = 0.02 \), with \( T \approx 1.71 \) keV and \( M_{200} \approx 0.5h^{-1} \times 10^{14} M_\odot \).

*Lower left:* the cluster of galaxies A 0754, at \( z = 0.053 \), with

\( T \approx 9.5 \) keV and

\( M_{200} \approx 13.1h^{-1} \times 10^{14} M_\odot \).

*Lower right:* the cluster of galaxies A 3667, at \( z = 0.056 \), with

\( T \approx 7.0 \) keV and

\( M_{200} \approx 5.6h^{-1} \times 10^{14} M_\odot \). The X-ray data were obtained by ROSAT, and the optical images were taken from the Digitized Sky Survey. These clusters are part of the HIFLUGCS survey, which we will discuss more thoroughly in Sect. 6.4.5. Credit: T. Reiprich, Argelander-Institut für Astronomie, Universität Bonn.
“Beta model”

- X-ray distribution centered on cluster center, as determined by the galaxy distribution, or on active galaxy in the cluster.
- Favored model: isothermal, hydrostatic
  - Both gas and galaxies are assumed to be:
    1. Isothermal
    2. Bound to cluster
    3. In equilibrium

\[ \Rightarrow \text{Galaxies assumed to have an isotropic velocity dispersion, but the gas & galaxies are NOT assumed to have the same velocity dispersion} \]

\[ \beta \equiv \frac{\mu m_p \sigma_r^2}{kT_{\text{gas}}} \]

where \( \mu = \text{mean molecular weight in amu} \)
\( m_p = \text{mass of proton} \)
\( \sigma_r = \text{1-D velocity dispersion} \)
\( T_{\text{gas}} = \text{gas temperature in K} \)

Then
\[ \rho_{\text{gas}} \propto \rho_{\text{gal}}^\beta \]

See: Schneider 6.4.2
Assume a galaxy distribution has a “King” analytic form (truncated isothermal sphere=> finite mass)

\[
\text{Space density: } \quad n(r) = n_o \left[ 1 + \left(\frac{r}{r_c}\right)^2 \right]^{-3/2}
\]

\[
\text{Surface density: } \quad \Sigma(b) = \Sigma_o \left[ 1 + \left(\frac{b}{r_c}\right)^2 \right]^{-1}
\]

\[\Sigma_o = 2 \, n_o \, r_c \quad \text{where } r_c \text{ is the core radius}\]

Then the X-ray surface brightness I_X goes as

\[I_X(b) \propto \left[ 1 + \left(\frac{b}{r_c}\right)^2 \right]^{-3\beta + \frac{1}{2}}\]

- Typical fits to X-ray SB yield
  \[<\beta> \sim 0.65 \quad \Rightarrow \text{gas more extensively distributed than galaxies}\]
  \[r_c \sim (0.1 \text{ to } 1.2 \text{ Mpc}) \Rightarrow \text{wide range}\]
Close relations between X-ray \( L \) and \( T \) and velocity dispersion of cluster

\[
L_X \propto \sigma^{4.4}
\]

\[
L_X \propto T_X^3
\]

\[
T(\text{keV}) = \frac{1.602 \times 10^{-9} \text{ erg}}{1.38 \times 10^{-16} \text{ erg K}^{-1}} = 1.16 \times 10^7 \text{ K}
\]

from Mulchaey (2000)
Scaling relations for clusters

- The central galaxy density is higher for higher $L_x$
- The fraction of spirals is lower for higher $L_x$
- The temperature $T$ (of order $10^8$ K) is proportional to $L_x$.
- The gas metallicity is lower for higher $T$ and typically $1/3$ solar
- The ratio of gas-mass to galaxy-mass increases with $T$ up to 5 or more

\[ T \propto \frac{M_{\text{vir}}}{r_{\text{vir}}} \propto r_{\text{vir}}^2 \propto M_{\text{vir}}^{2/3} \]

\[ M_{\text{vir}} \propto \sigma_v^3 \]

Fig. 6.28. For the galaxy clusters in the extended HIFLUGCS sample, the X-ray luminosity in the energy range of the ROSAT satellite is plotted versus the mass of the cluster. The solid points show the clusters of the HIFLUGCS sample proper. For the full sample and for the main HIFLUGCS sample, a best-fit power law is indicated by the solid line and dashed line, respectively.
Global correlations in clusters

- The central galaxy density is higher for higher $L_x$.
- The fraction of spirals is lower for higher $L_x$.
- The temperature $T$ is proportional to $L_x$ and typically $10^8$K.
- The gas metallicity is lower for higher $T$ and typically $1/3$ of solar.
- The ratio of gas-mass to galaxy-mass increases with $T$ up to 4 or more.

- The dominant component in all clusters is dark matter, as measured by the dynamics of the galaxies, the hydrostatic equilibrium of the X-ray gas and from gravitational lensing.
Masses of clusters: Methods

**From dynamics:**

**Virial Theorem:**

\[
M = \frac{r_G \langle v^2 \rangle}{G}
\]

where \( r_G = \frac{\sum m_i}{\sum_{i \neq j} \rho_i r_{ij}} \) and \( \langle v^2 \rangle = \frac{\sum m_i (v_i - \bar{v})^2}{\sum m_i} \)

**From X-rays:**

**Hydrostatic equilibrium:**

\[
\frac{1}{\rho_g} \frac{dP}{dr} = -G \frac{M(<r)}{r^2}
\]

As for elliptical galaxies:

\[
M(<r) = -\frac{kT(r) r^2}{G \mu m} \left[ \frac{d \ln \rho_g(r)}{dr} + \frac{d \ln T(r)}{dr} \right]
\]

See also Heisler, Tremaine & Bahcall (1985) for alternative mass estimators.
Typical cluster components

**Dark matter**
80-87% of the total mass
determines gravitational potential and dynamics
“backbone” of the system
detailed predictions only from simulations
only indirect observations possible

**Intracluster medium**
11-14% of the total mass
dominates baryonic mass
completely fills potential well
very thin and hot plasma ($\sim 10^7$ K)
emits x-rays

**Galaxies**
2-5% of the total mass
100s-1000s galaxies
move like test particles in the dark matter potential
population mix different from field galaxies
observations in optical and NIR
Interactions, Tides and Mergers
Morphological alteration mechanisms

- **Gravitational mechanisms**
  - Galaxy-galaxy interactions
    - Direct collisions
    - Tidal encounters
    - Mergers
  - Galaxy-cluster interactions
    - Harassment (multiple rapid tidal encounters)

- **Gravity**

- **Galaxy-intracluster medium interactions**
  - Thermal evaporation
  - Ram pressure sweeping

**Intracluster Gas**
The Virgo Cluster
Virgo: Nearest rich cluster to Local Group

- At center of Local Supercluster
- Not very “rich” compared to most “Abell clusters” but nearest to Local Group
- Distance ~ 16.7 Mpc
- Ellipticals form relaxed core; spirals still in-falling

See: ACS Virgo cluster survey

Next Generation Virgo Survey (underway)
The Virgo Cluster:

- Morphological peculiarities
- Substructure in space and velocity
- Ellipticals show narrow, Gaussian distribution (σ~500 km/s) while Sp/Im show flatter velocity distribution (σ~800 km/s => still infalling)
Interaction of a spiral galaxy with its environment

- Gravitational interaction: galaxy - cluster

- Gravitational interaction: galaxy - galaxy

- Ram pressure: galaxy ISM - intracluster medium (ICM)

VLA Survey of Virgo in Atomic Gas: VIVA
www.astro.yale.edu/viva/

(Böhringer et al. 1994)

(Kenney et al. 1995)

(Kenney et al. 2004)
NGC 4522

nearly edge-on disk about 1 Mpc from center

Contours: 6 cm pol (Vollmer et al. 2004)
Greyscale: B band

Contours: 6 cm cont
Greyscale: HI (Kenney et al. 2004)
Ram pressure sweeping

- Spirals in Virgo are HI deficient.
- Hydrodynamical simulations show effectiveness of ram pressure stripping
- Stripping occurs if $\rho_{ICM} V^2 > 2\pi G \Sigma_{gas} \Sigma_{stars}$

- Ram pressure exerted by stationary gas on moving galaxy
- $V$ is velocity of galaxy with respect to cluster

- Gravitational "restoring" force of stars and gas in galaxy
- $\Sigma$ is surface density

Vollmer et al. 2001
Ram Pressure Stripping

- Ram Pressure Stripping can remove the gas supply of galaxies that pass through clusters
  - Interaction between ISM and ICM
  - Could explain metal content of the ICM
  - Episodes of starburst?

Animation by Bengt Vollmer

- The arrow which appears represents the “turn-on” of ram pressure as the galaxy moves in the opposite direction (towards the cluster center, in the lower left)
Ram pressure stripping animation

http://www.hubblesite.org/newscenter/archive/releases/2014/14/video/b
Peculiar morphologies

What are the main processes responsible for morphological peculiarities?
Gravitational encounters
“N-body” simulations: binary stars

1. Adopt the masses of the 2 objects (so here $N=2$)

2. Adopt characteristics of the orbits (eccentricity, inclination, orientation)

3. Apply the laws of gravity to predict the relative positions of the two objects after every time step.
“N-body” simulations: Sun-Earth-Moon

1. Adopt the masses of the 3 bodies (so here N=3)

2. Adopt characteristics of the orbits (eccentricity, inclination, orientation)

3. Apply the laws of gravity to predict the relative positions of the N objects after every time step.

- Each of the 3 bodies exerts a gravitational force on the other two
- Each of the 3 bodies feels the gravitational force from the other two
- They are all in motion!
Toomre & Toomre 1972

- The galaxy’s mass is concentrated at a point
- The outer disk particles are arranged in 5 rings
- They do not interact with each other (no self-gravity)
- All passages involve two galaxies that have a close, slow moving parabolic approach
- Each time unit is 100 million years

Although much more sophisticated codes exist today, T&T72 demonstrated the overall damage done by tides.
Toomre$^2$ results

- Galaxy encounters are not accidental; most pairs are bound already
- Direct encounters cause more damage than retrograde ones
- Tails (nice) are easier to make than bridges (messy)
- Viewing geometry is critically important
Chris Mihos’ GalCrash Applet

http://burro.cwru.edu/JavaLab/GalCrashWeb/