This week at Astro 3303

• Please pass in HW#7. Presentations next........

• HW #8-10 deal with your final project! (HW#8 is posted already)
  • The project counts 20% of the grade and is expected to be a significant piece of work.
  • HW#8 for next Wed: prepare a first outline.

• 2nd 30min test is Nov 11. Covers material through Wed Nov 6.

• Today:
  • Presentations: 3 fascinating galaxies
  • Large scale structure, groups and clusters, galaxy environments

• Reading:
  • Chapters 5 and 6
## HW #7 presentations

## HW #8-10 & final project

### Astro 3303 Final Project List

<table>
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<tr>
<th>Who</th>
<th>Science objective/facility</th>
<th>First link</th>
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<tr>
<td>Yoni</td>
<td>Constraints on dark energy with the Wide Field InfraRed Survey Telescope (WFIRST)</td>
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<td>Matthew</td>
<td>Detecting the first stars and galaxies with the James Webb Space Telescope (JWST)</td>
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<tr>
<td>Gianfranco</td>
<td>Constraints on dark energy from weak lensing with the Large Synoptic Survey Telescope (LSST)</td>
<td>LSST</td>
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Development of Large Scale Structure

Our cosmological model must explain how the structure developed to look this way (and not something else) and it has to do it in 13.7 billion years (not earlier, not later)

Smoother earlier on

Time =>

Galaxies, clusters, superclusters and voids today
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

*velocity dispersion: typical orbital velocity of a galaxy in the group/cluster
Large Scale Structure viewed from redshifts

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

If one galaxy has comoving coordinate, $x$, then the probability of finding another galaxy in the vicinity of $x$ is not random. They are Correlated.

Zone of avoidance

Courtesy of Michael Blanton.
LSS viewed in cone diagram

Cone opening angle = angle of sky sampled by “slice” survey
Clusters show up as “fingers of God” pointing towards origin
2dF = 2 degree field redshift survey
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?
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
## Morphological segregation

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<th>Spirals</th>
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<td>Smooth light distribution</td>
<td>Arms, disk, bulge</td>
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<tr>
<td>Brightest stars are red</td>
<td>Brightest are blue</td>
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<tr>
<td>Little/no star formation</td>
<td>On-going star formation</td>
</tr>
<tr>
<td>Little/no cool/cold gas</td>
<td>Molecular + atomic gas</td>
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<tr>
<td>Random motions</td>
<td>Circular rotation in disk</td>
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**S0 (lenticular):**

- Spiral-like: disk+bulge, rotation
- Elliptical-like: little gas/star formation; no spiral structure

*Found in cluster cores*           *Avoid cluster cores*
Elliptical versus Spiral Galaxies

Morphological segregation:
“Initial conditions” or evolution over time ???

Percent of total population

Low density Field | High density Cluster

E + S0
Spiral

Field

Cluster
Coma Cluster = A1656 (Gianfranco HW#4)

cz $\sim$ 7000 km/s

*Often used as “prototype rich cluster”*
Coma cluster in X-rays and optical
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.
Clusters of galaxies

Rich clusters of galaxies are the most massive virialized, high-overdensity systems known. In the optical light galaxy clusters have the following ranges of properties:

- **Richness** (number of cluster galaxies with luminosities 2 magnitudes dimmer than the third brightest cluster galaxies): 30-300 galaxies
- **Radius** (where the surface density of galaxies drops to 1% of the core density): 1-2 Mpc
- **Radial velocity dispersion**: 400-1400 km/s
- **Mass** (r<1.5 Mpc): $10^{14}-10^{15} M_\odot$
- **Optical B-Band luminosity**: (r<1.5 Mpc): $10^{11}-10^{13} L_\odot$
- **Mass-to-light ratio**: $\approx 300 M_\odot / L_\odot$
- **Cluster number density**: $10^{-5} - 10^{-6}$ Mpc$^{-3}$
- **Cluster correlation scale**: $22 \pm 4$ Mpc
- **Fraction of galaxies with L>L* in clusters**: ~5%

Some important optical cluster catalogues are:


From (deep) CCD (multicolor) images:


IMPRS Astrophysics Introductory Course

Fall 2007
Compact Groups:

Hickson 1982 & 1997 (ARAA 35, 357)

- High density but low mass/lum
- Richness: N>3 with m<m_1+3mag
- Isolation: R_{neighbor}>3R_{group}
- Compactness: \( \mu_G < 26 \) mag/arcsec^2
  - (selected off of red plates, so bias towards early types)

- May be stage in evolution to cluster core, field early type, “fossil group”, or “dry merger remnants”
- Strong local density enhancement but velocity dispersion similar to loose groups (~250 km/s)
- Condensation w/in looser, prolate-like elongated systems; members on orbits aligned with long axis

e.g. Tovmassian et al 2006 A&A 456, 839
Fossil Groups:

e.g Jones et al. 2003, MNRAS 343, 627

• Idea: Fossil groups are end result of galaxy merging within a normal group, leaving X-ray halo

• Identified by combination of rather high $L_X$ and very low richness, with single galaxy with $L > L_*$
  • Extended X-ray source with $L_X > 10^{42} h_{50}^{-2} \text{erg/s}$ (comparable to Virgo cluster)
    • This limit precludes individual galaxies
  • Optical counterpart is a bound system of galaxies with $\Delta m_{12} > 2.0 \text{mag}$ (difference in abs mag of 1$^{\text{st}}$ and 2$^{\text{nd}}$ brightest galaxies, within half projected virial radius)
    • This limit insures the brightest galaxy dominates
Poor clusters:

e.g MKW: Morgan, Kayser & White 1975, ApJ 199, 545

• Surface density enhancements in CGCG (nearby)
  • Contain dominant giant elliptical galaxy
  • Exhibit a range of $L_X$ (wider than fossil groups)
  • But fewer members overall than “rich” clusters
X-ray properties of rich clusters

Temperature: $2 - 14 \text{keV}$ or $2 \times 10^6 - 10^8 \text{ K}$
Luminosity: $10^{42.5} - 10^{45} \text{ erg/s}$
Core radius: 0.1-0.2 Mpc
Central electron density: $n_e \simeq 10^{-3} \text{ cm}^{-3}$
Gas mass: $M_{\text{gas}} \simeq 10^{13} - 10^{14} M_\odot$
Fe abundance: $\approx 1/3$ solar

For the center of the Coma cluster:

$L \simeq 10^{44} \text{ erg/s}$ \hspace{1cm} $\tau_{\text{cool}} \simeq 10^{10} \text{ yrs}$
$\overline{n}_e \simeq 10^{-3} \text{ cm}^{-3}$ \hspace{1cm} $M_{\text{gas}} \simeq 10^{13} M_\odot$

Important X-ray catalogues:

Böhringer et al. (2001, 2004): clusters with $z<0.45$ from the ROSAT all-sky survey
Rosati et al. (1998): clusters with $z<1.2$ from ROSAT pointed observations

Masses of clusters

From dynamics:

Virial Theorem:

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

where \( r_G = \frac{\sum m_i}{\sum i \neq j \frac{m_im_j}{r_{ij}}} \)

and \( \langle v^2 \rangle = \frac{\sum m_i(v_i - \bar{v})^2}{\sum m_i} \)

See also Heisler, Tremaine & Bahcall (1985) for alternative mass estimators

From X-rays:

Hydrostatic equilibrium:

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

As for elliptical galaxies:

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

\[ \frac{dP}{dr} = -G \frac{M(<r)\rho}{r^2} \]
Close relations between X-ray $L$ and $T$ and velocity dispersion of cluster

$$L_X \propto \sigma^{4.4}$$

$$T_X \propto \sigma^2$$

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

from Mulchaey (2000)
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.
- Typical ratios are:
  galaxies: X-ray gas: dark matter = 1:4:25
X-ray observations of hot ICM in clusters

• Clusters of galaxies are the most common bright extragalactic X-ray sources.
• Cluster have very high $L_X \sim 10^{43-45}$ erg s$^{-1}$.
• The range of $L_X$ is very high.
• Clusters are the most luminous class of X-ray sources, except for quasars.
• X-ray sources associated with clusters are extended, typical $R_X \sim 200$ kpc to 3 Mpc.
• Clusters show X-ray spectra that show no strong evidence of low E photo-absorption.
• X-ray emission from clusters is not time-variable.
• Emission is by thermal bremsstrahlung (breaking) radiation also known as free-free emission due to the hot gas.
Bremsstrahlung = free-free radiation

**Fig. 6.16.** X-ray emission of a hot plasma. In the top panel, the bremsstrahlung spectrum is shown, for three different gas temperatures: the radiation of hotter gas extends to higher photon energies, and above $E \sim k_B T$ the spectrum is exponentially cut off. In the central panel, atomic transitions and recombination radiation are also taken into account. These additional radiation mechanisms become more important towards smaller $T$, as can be seen from the $T = 1$ keV curve. In the bottom panel, photo-absorption is included, with different column densities in hydrogen and a metallicity of 0.4 in Solar units. This absorption produces a cut-off in the spectrum towards lower energies.
Thermal bremsstrahlung

- Thermal bremsstrahlung spectrum

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

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

Deceleration of free electron leads to emission of photon "breaking radiation"
Hot gas in clusters

The baryonic gas is compressed in the deep cluster potential wells and shock-heated up to X-ray emitting temperatures $T$. For bremsstrahlung from a $10^8$ K gas, the emissivity at frequency $\nu$ is:

$$\varepsilon(\nu) = \frac{32\pi Z^2 n_e n_i}{3m_e c^3} \sqrt{\frac{2\pi}{3k m_e T}} \exp\left(\frac{-h\nu}{kT}\right) g_{ff}(T,\nu)$$

where $g_{ff}$ is the Gaunt factor (quantum mechanical factor $\sim 1$). Integrating over frequency one gets the volume emissivity:

$$\varepsilon = 2.4 \times 10^{-27} T^{-1/2} n_e^2 \left[\frac{\text{erg}}{\text{cm}^3\text{s}}\right]$$

The cooling time of the plasma is:

$$t_{\text{cool}} = \frac{3n_e kT}{\varepsilon} \approx \frac{10^{11}}{n_e} T^{1/2} \text{[s]}$$

Can be $< t_{\text{Hub}}$

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

$$S(R) = S(0) \left(1 + \frac{R^2}{r_{\text{core}}^2}\right)^{-3\beta + 1/2}$$
X-ray observations of hot ICM in clusters

- 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
  \[ \implies \text{Galaxies assumed to have an isotropic velocity dispersion, but the gas and galaxies are NOT assumed to have the same velocity dispersion} \]
  \[ \beta = \frac{\mu \ m_p \ \sigma_r^2}{kT_{\text{gas}}} \]
  where \( \mu = \text{mean molecular weight in amu} \)
  \( m_p = \text{mass of proton} \)
  \( \sigma_r = \text{1-D velocity dispersion} \)
  \( T_{\text{gas}} = \text{gas temperature in K} \)
  \[ \rho_{\text{gas}} \propto \rho_{\text{gal}}^\beta \]
X-ray observations of hot ICM in clusters

Assume a galaxy distribution has a “King” analytic form (truncated isothermal sphere)

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

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

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
\[ <\beta> \sim 0.65 \Rightarrow \text{gas more extensively distributed than galaxies} \]
\[ R_c \sim (0.1 \text{ to } 1.2 \ Mpc) \Rightarrow \text{wide range} \]

**Cooling flows:** If the rate of cooling of the IC gas is sufficiently rapid, then gas may cool and flow into the center of the cluster (Sarazin 1986). Evidence

1. Peaks in soft Xray SB at cluster center
2. Measurement of inverted temp gradient \( dT/dr > 0 \)
3. Soft X-ray line emission of low ionization lines at center
   \( (T \sim 10^{6-7} \ K \text{ at center}) \)
Sunyaev-Zel'dovich effect

Graphs showing intensity and wavelength relationships.
Sunyaev-Zel’dovich effect

The photons of the CBR suffer Inverse Compton scattering against the hot electrons of the intracluster medium, preferentially gaining energy. The CMB spectrum gets shifted to higher frequencies: at wavelengths <1.4 mm the clusters appear as bright patches in the CMB.

To first order, the CMB distortion is proportional to the integral along the line of sight of the electron density times its thermal energy:

$$\frac{\Delta I}{I} = 2y, \quad y = \int n_e \sigma_T \frac{kT}{m_e c^2} dl$$

Carlstrom, Holder & Reese, 2002, ARAA, 40, 643
**Sunyaev-Zel'dovich effect**

Fig. 6.24. Sunyaev–Zeldovich maps of three clusters of galaxies at $0.37 < z < 0.55$. Plotted is the temperature difference of the measured CMB relative to the average CMB temperature (or, at fixed frequency, the difference in radiation intensities). The black ellipse in each image specifies the instrument’s beam size. For each of the clusters shown here, the spatial dependence of the SZ effect is clearly visible. Since the SZ effect is proportional to the electron density, the mass fraction of baryons in clusters can be measured if one additionally knows the total mass of the cluster from dynamical methods or from the X-ray temperature. The analysis of the clusters shown here yields for the mass fraction of the intergalactic gas $f_g \approx 0.08 \, h^{-1}$

**Xray emission + SZE measurement:**

- Can be used to find clusters independent of redshift
- Therefore can be used to determine when clusters form $N(M,z)$