Large-Scale Structure

- Evidence for Dark Matter
- Dark Halos in Ellipticals
- Hot Gas in Ellipticals
- Clusters
- Hot Gas in Clusters
- Cluster Galaxy Velocities and Masses
- Large-Scale Distribution of Galaxies
Evidence for Dark Matter on Large Scales

- Spiral Galaxies $\rightarrow$ dark halos
  - Flat rotation curves (covered previously)

- Elliptical Galaxies $\rightarrow$ dark halos
  - Velocities of planetary nebulae in halos of giant Es
  - Rotation of embedded H I disks (in a few peculiar Es)
  - Confinement of hot ($T \approx 10^7$ K) gas

- Rich Clusters of Galaxies $\rightarrow$ large unseen mass
  - Velocities of individual galaxies, virial theorem
  - Confinement of very hot ($T > 3 \times 10^7$ K) gas

- As size scale increases, M/L increases from $\sim 5$ to $\sim 200$
  - Evidence for a large dark mass component that has a shallow density profile.
  - Hot gas may account for missing baryons, but not most of the “missing mass”
Dark Halos in Ellipticals

• At $R < R_{25}$ in ellipticals, $M/L_\nu \approx 5$
• A few peculiar Es have cold H I disks
  $\rightarrow$ H I 21-cm gives $M/L = 10 - 20$ at $R = 25 - 50$ kpc
• Planetary nebulae are bright, compact sources of emission lines (e.g., [O III] $\lambda$5007)
  – Detected at distances of 20 – 30 kpc from cores of giant Es
  – Dispersions and radial velocities flat at large distances
  $\rightarrow$ $M$ (at $r > 30$ kpc) $\geq 10^{12}$ $M_\odot$ in these ellipticals: $M/L \approx 50$

Planetary nebulae on the outskirts of NGC 1399
- [O III] filter and CCD on CTIO 4-m telescope
• X-ray missions (Einstein, ROSAT) discovered hot \( (T \approx 10^7 \text{ K}) \) gas in nearby giant Es (now studied with Chandra and XMM).

• Gas is almost completely ionized – cooled by bremsstrahlung.

**Cooling curve for gas with solar composition and \( n_H = 1 \text{ cm}^{-3} \)**

![Cooling curve](image)

solid – luminosity density, dashed – cooling time
ASCA X-ray Spectrum of Hot Gas around M87

(Sparke & Gallagher, p. 272)

- H and He-like emission lines in addition to bremmstrahlung
- $Z = 0.5 \, Z_{\odot} \rightarrow$ material ejected by RG and AGB stars
  
  \( (1 - 2 \, M_{\odot} \, \text{yr}^{-1} \, \text{per} \, 10^{10} \, L_{\odot}) \)
Why is the gas so hot?

• Gas clouds are on random orbits like their progenitor stars
• Collisions between gas clouds:

\[ kT = m_p \sigma^2 \rightarrow T = 6 \times 10^6 \left( \frac{\sigma}{300 \text{ km s}^{-1}} \right)^2 \text{ K} \]

• The cooling time is: \( t_{\text{cool}} \approx n_H^{-1} T^{1/2} \) at these high temperatures.
• At centers of giant E’ s, the gas may be dense (\( n_H = 0.1 \text{ cm}^{-3} \)) enough to cool in ~1 Gyr \( \rightarrow \) new star formation in core
• However, see the cooling flow problem for clusters
• Is the hot gas enough to provide the “missing mass”?

\[ \rightarrow \text{no, the mass is only } 10^9 - 10^{11} \text{M}_\odot \text{ in giant E’ s} \]

However, to keep the hot gas confined out to ~50 kpc, \( M/L \approx 20 - 50. \)
Rich Clusters of Galaxies

• About ½ of all galaxies are in rich clusters (others in “groups”)
• Thousands of gravitationally bound galaxies within a few Mpcs
• Typically 50 to 100 galaxies with $L > L^*$ in central Mpc
• Abell (1958, 1989) catalogs: list 4073 rich clusters
• Strongly differentiated: core dominated by ellipticals, spirals are scarce and mostly on the outskirts

Coma Cluster
Hot Gas in Clusters

• X-ray observations: hot ($T = 3 \times 10^7$ to $10^8$ K) intracluster gas
  – 3 to 6 times the stellar mass!
  – must come from intergalactic medium (IGM).

  \Rightarrow \text{ongoing collapse of large-scale structure on these scales}

• $Z \approx 1/3 \, Z_{\odot} \Rightarrow$ enrichment of early IGM plus cluster SN
• Gas in core is dense enough to cool in Hubble time
  \Rightarrow \text{cooling flows}

• However, cooling flows are rarely observed \Rightarrow gas likely heated by AGN feedback.

• Ram pressure as galaxies move through cluster gas
  – Strips neutral gas in spirals, hot gas in E’s; pushes back radio lobes

• Large mass needed to confine hot gas in clusters:
  $M/L \approx 200$ to $300$
3C 465 in Abell 2634

VLA 4.9 GHz image
Virgo Cluster

- Nearest rich cluster at ~ 16 Mpc
- Home of cD galaxy (and AGN) M87 in core
- Central luminosity density ~ $3 \times 10^{11} \, L_\odot \, \text{Mpc}^{-3}$
- Relatively loose and irregular in shape
- Kinematics: infalling galaxies at edges – still growing

Chandra X-ray Image  HST Visible Image
Coma Cluster

- Distance $\approx 70 \, h^{-1} \, Mpc$
- 3 – 4 times more luminous than Virgo
- Core is dominated by a pair of giant E’s
- Much more spherical than Virgo

X-ray

Visible
Distribution of Galaxies in Coma Cluster

(Sparke & Gallagher, p. 295)
Masses of Clusters from Galaxy Velocities

• Virial Theorem – assumes clusters are bound:

\[ 2 \text{K.E.} = -\text{P.E.} \]

\[ \frac{3}{2} M \sigma_r^2 = \frac{GM^2}{2r_c} \] (for spherical cluster)

where \( \sigma_r^2 = \left\langle v_r^2 \right\rangle \), \( r_c = \) core radius (Sparke & Gallagher, p. 105)

\[ M = \frac{3 \sigma_r^2 r_c}{G} \]

• For the Coma cluster: \( r_c = 200 \text{ kpc}, \sigma_r = 1000 \text{ km s}^{-1} \)

\[ \Rightarrow M \approx 10^{15} M_\odot, \text{ M/L } = 200 M_\odot/L_\odot \text{ inside the core radius} \]

(note the extent of the Coma cluster is ~10 Mpc)
Gravitational Lensing (Abell 2218 Cluster)

- Gravitational lensing of distant galaxies: Cluster M/L ~200

  • For galaxy core $\rightarrow$ galaxy halo $\rightarrow$ Local Group $\rightarrow$ rich cluster:
  • M/L increases: 5 $\rightarrow$ 10 $\rightarrow$ 50 $\rightarrow$ 200
  • Slow drop in density from cluster cores ($\rho \sim r^{-1}$)
Large-Scale Distribution of Galaxies

• In the past, clusters were thought to be in superclusters
• Redshift surveys over the past decade:
  ➔ galaxies arranged like connecting bubbles (or a sponge)
  – Clusters and superclusters are at the edges of 2 or more intersecting bubbles
• “Voids” are on the order of ~50 Mpc across
• How concentrated are the galaxies into filaments/walls?
  – Core of Virgo Cluster: \( L = 3 \times 10^{11} \, L_\odot \, \text{Mpc}^{-3} \)
  – Average (Schechter lum. fct.): \( L \approx 1.4 \times 10^8 \, L_\odot \, \text{Mpc}^{-3} \)
    (averaged over large volume, including voids)
  ➔ Variation in galaxy density spans a factor of >1000
• Galaxy velocities: most clusters are still collapsing at edges
  Ex) Galaxy at edge of Coma cluster (3 Mpc): \( v \approx 1000 \, \text{km s}^{-1} \)
  Crossing time = 3 Gyrs! ➔ Clusters are still coming together
Clusters and many nearby galaxies lie close to a great circle at $l = 140^\circ, 320^\circ$ which defines local (Virgo) supercluster and “supergalactic plane” $(X,Y)$.

- Z axis ($l = 47.4^\circ, b = 6.3^\circ$); $X (l = 137.3^\circ, b = 0^\circ) \rightarrow Y$ near NGP
- Supergalactic latitude $= 0$ in X-Y plane, longitude $= 0$ in X direction
Projected Distances of Nearby Ellipticals on the Supergalactic Plane (X, Y)

clusters are not very concentrated: → still coming together

(Sparke & Gallagher, p. 317)
Redshift Surveys - Las Campanas

(Sparke & Gallagher 1st ed., p. 286)

- Use cz as distance indicator (approximately ~ distance at low z)
- Las Campanas survey covered 6 strips, each 1.5° wide
- number of galaxies decrease at large velocities \(\rightarrow\) magnitude limit
- number of galaxies small at low velocities \(\rightarrow\) small volume sampled
Luminosity Distribution for Las Campanas Survey

(Sparke & Gallagher 1st ed., p. 287)

Dashed line – faint magnitude limit = 17.7
Dotted line – bright magnitude limit = 15.0
"Great Wall"
- The sharpness of the peak is exaggerated: extra mass in the wall pulls galaxies on either side toward it.
- Peculiar velocities conspire so that cz is close to that of the Wall

(Sparke & Gallagher 1st ed., p. 288)
Measures of Galaxy Clustering

Two-point Correlation Function ($\xi$):

Given an average spatial density of galaxies $n$ ($\#/\text{Mpc}^3$)

Probability of finding a galaxy in a volume $\Delta V_1$ is $\propto n\Delta V_1$

Joint probability of finding 2 galaxies in the 2 volumes $\Delta V_1$, $\Delta V_2$:

$$\Delta P = n^2 \left[ 1 + \xi(r_{12}) \right] \Delta V_1 \Delta V_2$$

If $\xi(r) > 0 \rightarrow$ galaxies are clustered

Typically, described as a power law (what else?):

$$\xi(r) = \left( \frac{r}{r_0} \right)^{-\gamma} \quad r_0 = \text{correlation length}$$

Can also use the Fourier transform of $\xi(r) \rightarrow$ power spectrum:

$$P(k) = 4\pi \int_0^\infty \xi(r) \frac{\sin(kr)}{kr} r^2 dr$$
Two-Point Correlation Function
(Las Campanas Survey)

(Sparke & Gallagher 1st ed., p. 290)

\[ r_0 = 5h^{-1}\text{Mpc}, \ \gamma=1.8 \]

Strong clustering (\(\xi > 1\)) at \(r < 20\) Mpc
Power Spectrum (Las Campanas)

(Sparke & Gallagher 1st ed., p. 290)

- peak at \(\sim 20 \, \text{h}^{-1} \, \text{Mpc}\)
- useful for comparison with structure-formation models
CDM Model (matches COBE power spectrum)

(Sparke & Gallagher, 1st ed. p. 311)
Redshift Surveys

  – Positions and brightnesses for $10^8$ objects
  – Colors and redshifts for $10^6$ galaxies, $10^5$ quasars
  – Survey covers $\frac{1}{4}$ of the sky
  – 2.5-m telescope at Apache Point, NM
  – Companion 0.5-m monitors the seeing and transparency
  – 30 CCDs, 5 filters to scan the sky
  – Galaxies and quasars isolated on color-color diagrams
  – Follow-up multi-object spectroscopy at $R \sim 1000$

  – Spectra of $\sim 250,000$ galaxies near the galactic poles
  – Multi-object spectrograph with the AAT (4-m)
  – Final data release in June, 2003
SDSS
2dF “Wedge”
- Cosmic Microwave Background (CMB) Explorer, resolution ~7°
- “Absolute” motion of galaxy relative to CMB: strong dipole radiation
  \( v = 371 \text{ km s}^{-1} \) towards \( l = 264^\circ, b = +48^\circ \)
- Due to Local Group, Virgo Infall, and “Great Attractor” (Centaurus supercluster) and Shapley supercluster motions (Mould et al. 2000, ApJ, 529, 786)

- after subtraction of dipole: unresolved Temperature variations
- Wilkinson Microwave Anisotropy Probe, resolution $\sim 0.3^\circ$
- temperature variations of CMB: 2.73 K average, amplitude $\sim 2$ mK
- tiny variations in structure after Big Bang led to current large-scale structure
- agrees with inflationary theory and cold dark matter models
Accelerating Universe from Type Ia Supernovae

http://www.astro.ucla.edu/~wright/sne_cosmology.html
Constraints on Accelerating Universe