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, $M/L_V \approx 5$
- 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 ($T \approx 10^7$ 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 $n_H = 1$ cm$^{-3}$

![Diagram showing cooling curve for gas with solar composition and $n_H = 1$ cm$^{-3}$]
- H and He-like emission lines in addition to bremsstrahlung
- $Z = 0.5 \, Z_\odot \rightarrow$ 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 → new star formation in core
- However, see the cooling flow problem for clusters
- Is the hot gas enough to provide the “missing mass”?

→ no, the mass is only \( 10^9 – 10^{11} \text{M}_\odot \) 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 $\frac{1}{2}$ 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).
  $\Rightarrow$ 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
  $\Rightarrow$ 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 $\sim 16$ Mpc
- Home of cD galaxy (and AGN) M87 in core
- Central luminosity density $\sim 3 \times 10^{11} \, L_{\odot} \, \text{Mpc}^{-3}$
- Relatively loose and irregular in shape
- Kinematics: infalling galaxies at edges – still growing

Chandra X-ray Image  HST Visible Image
Coma Cluster

• Distance $\approx 70 \, h^{-1} \, \text{Mpc}$
• 3 – 4 times more luminous than Virgo
• Core is dominated by a pair of giant E’s
• Much more spherical than Virgo
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: \( r_c = 200 \text{ kpc}, \sigma_r = 1000 \text{ km s}^{-1} \)

\( M \approx 10^{15} M_\odot \), \( M/L = 200 M_\odot/L_\odot \) inside the core radius

(note the extent of the Coma cluster is \( \sim 10 \text{ Mpc} \))
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:
  \rightarrow 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 \sim 50 \text{ 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)
  \rightarrow \text{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): \( v \approx 1000 \, \text{km} \, \text{s}^{-1} \)
    Crossing time = 3 Gyrs! \rightarrow \text{Clusters are still coming together}
Positions of Bright Galaxies - Supergalactic Coordinates

(Sparke & Gallagher, p. 315)

- Clusters and many nearby galaxies lie close to a great circle at $l = 140^\circ, 320^\circ$ → defines local (Virgo) supercluster and “supergalactic plane” (X,Y)
- Z axis ($l = 47.4^\circ, b = 6.3^\circ$); X ($l = 137.3^\circ, b = 0^\circ$) → 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

- Use \( cz \) as distance indicator (approximately \( \sim \) 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

(Sparke & Gallagher 1st ed., p. 286)
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
Measures of Galaxy Clustering

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

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

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?):

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

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

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

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

- peak at ~20 h⁻¹ Mpc
- useful for comparison with structure-formation models
CDM Model (matches COBE power spectrum)

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

• Sloan Digital Sky Survey (http://www.sdss.org/)
  – 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 $R \sim 1000$

• 2DF Survey (http://www.mso.anu.edu.au/2dFGRS/)
  – 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
  \( (v = 371 \text{ km s}^{-1} \text{ towards } l = 264^\circ, b = +48^\circ) \)
- 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