Lecture notes 18: Galaxies and galaxy clusters

Immanuel Kant (1724?1824) and Thomas Wright (1711?1786) were among the first to recocnize the possibility that the Milky Way was indeed a stellar disk where the Sun was but one of many. Kant went on to propose that if the Milky Way were limited then perhaps the diffuse ?elliptical nebulae? seen in the night sky may also be distant disklike systems similar to our own but seperate. Kant called these objects *island universes*.

Charles Messier (1730?1817) compiled a list of 103 nebulae, many of these **Messier Objects** are indeed known today to be island universes or seperate galaxies, such as M31 in Andromeda.

The nature of the extragalactic nebulae (nor indeed that they were extragalactic) was not settled until Edwin Hubble (1889?1953) discovered a Cepheid variable in M31 allowing him to calculate the distance to that galaxy as being much greater than the dimensions of the Milky Way.

The Shapley ?Curtis debate

A debate was announced on April 26, 1920 at the Natiol Acadamy of Sciences in Washington D.C. to decide the issue of whether the spiral nebulae resided within the Milky Way or whether they were Kant?s island universes. Harlow Shapley and Heber Curtis were choses to represent opposite points of view. It is interesting to follow the arguments used in the face of poor or incomplete data. The three major questions were:

1. What are the distances to the spirals?
   Arguments for a small distance:
   (a) Von Maanen?s measurements of proper motion of rotation in M101 gave a velocity $> c$ if a large distance to M101 was used.
   (b) Brightness of S Andromedea (a SN) in M31 compared to Nova Persei.

   Arguments for a large distance:
   (a) Proper motion measurements may be in error.
   (b) Brightness of nova outbursts in M31 compared to those in the Milky Way.
2. Are spirals compoes of stars or gas?
   Arguments against stellar interpretation:
   (a) Milky Way in neighborhood of Sun has much greater M/L ratio (?.e. much smaller surface brightness) than central parts of most spirals.
   (b) Outer regions of spirals are bluer than their central portions.
3. Why do spirals avoid the plane of the Milky Way?
   Arguments against island-universe hypothesis:
   (a) Avoidance suggests influence, as do large velocities of recession.

(b) Both could be explained by postulating a new force of repulsion.

Arguments for island-universe hypothesis:

(a) Many edge-on spirals exhibit central belt of obscuring material.

(b) If Milky Way also ahs such a belt, and if Sun is embedded in the middle of such a belt, and if spirals are external to Milky Way system, the zone of avoidance could be explained.

(c) No immediate explanation for large recessional velocities except that ?such high speeds seem possible for individual galaxies?.

Nothing was decided by the debate itself, which was quite the thing in 1920 generating first page reports in major newspapers. Rather the issue was settled in 1923 by Edwin Hubble?s discovery that the Andromeda nebulae was actually the Andromeda Galaxy being 770 kpc from the Sun.

Galaxy Classification

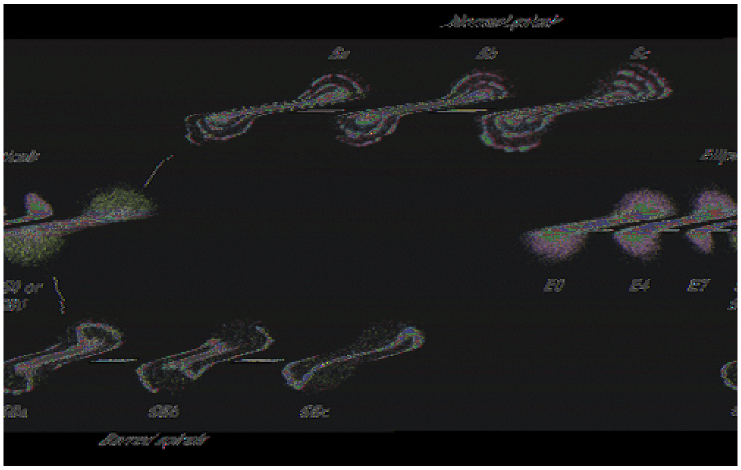

Figure 1: The Hubble sequence. Source: *Universe, fifth edition* , Kaufmann and Freedman.

Hubble went on to classify the galaxies he observed into **ellipticals**, **spirals** and **barred spirals**, and **irregulars**.

Elliptical galaxies were classified according to their degree of ellipticity as Ex galaxies where x is $x = 10$ with

$$\equiv 1 ? \beta/\alpha, \qquad (1)$$

α and β representing the apparent major and minor axies fo the ellipse projected onto the plane of the sky. Ellipticals have an enormous range of variation of their physical parameters with masses $10^{7} ? 10^{13}$ M_S and diameters $0.1 ? 100$ kpc.

The spirals were subdived into the sequence Sa ? Sc and SBa ? SBc for the barred spirals. The range in parameters for these galaxies is smaller: masses $10^{9} ? 10^{12}$ M_S and diameters $5 ? 100$ kpc.

Hubble ordered the various galaxies into his famous **tuning fork diagram**, see figure 1, which he originally thought also represented could be interpreted as an evolutionary sequence for galaxies. This turned out to be not the case. However, one still refers to the elliptical galaxies as ?early? galaxies and spirals and barred spirals as ?late? galaxies.

Irregular galaxies span from masses $10^{8} ? 10^{10}$ M_S and diameters $1 ? 10$ kpc. Hubble split these galaxies into two classes Irr i, both the Large (figure 2) and Small Magellenic Clouds are examples of this class, and Irr ii (an example is M82 see `http://www.seds.org/messier/m/m082.html`). But see below for more modern classifications schemes for irregulars.

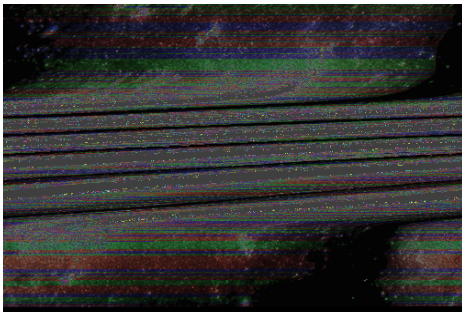

Figure 2: The Large Magellenic Cloud is 50 000 pc away is one the closest companions to the Milky Way. It is a galaxy fo type . Note the Hii region, 30 Doradus or the *Tarantula Nebulae*, to the upper left of the image, with diameter 250 pc and mass $5 ? 10^{6}$ M_S it is the largest known such region. Source: Anglo-Australian Observatory and *Universe, fifth edition* .

In addition to the classifications given above a **luminosity class** from i ? v is given spiral and barred spiral galaxies according to how well defined the arms are, with i representing the best defined arms. Those galaxies previously known as Irr i are now designated Sd (SBd), Sm (SBm) or Im (where ?m? stands for Magellenic type). The LMC is now classified as SBmiii and the SMC as Imiv-v. The remaining irregular galaxies are simply designated Ir (such as M82).

Spirals and Irregular Galaxies

Hubble?s classification scheme works well for late-type galaxies. The bulge to disk ratios, the tightness of the spiral arms, and the ability to resolve the arms into stars and H ii regions correlate well with Hubble type, as do many other physical properties such as the amount of gas and dust in the disk.

The surface brightness of the bulges of spiral galaxies and large ellipticals follows

$$\log_{10}[I(r)/I_e] = -3.33[(r/r_e)^{1/4} - 1] \tag{2}$$

where I is given in units of L_S/pc^2 and r_e is the radius within which 1/2 of the bulges light is emitted. On the other hand it seems that when the contribution from the bulges are removed and the disks brightness contribution is extrapolated to the center one finds a surprisingly small range in central surface brightnesses: this is **Freeman's law** .

Early type galaxies show a wide range of maximum rotational velocity within the disk. Typical examples are $V_{\max} = 299$ km/s for type Sa, $V_{\max} = 222$ km/s for type Sb, and $V_{\max} = 175$ km/s for type Sc; with ranges on the order of 100 km/s or more. The corresponing velocities for irregulars is significantly lower, ranging from 50 km/s to 70 km/s, perhaps indicating a minimum velocity required for the formation of a spiral.

Tully-Fisher relation is a relationship between a spiral galaxies luminosity L and maximum rotational velocity $V_{\max}$. The velocity may be measured by measuring the Doppler broadening of the H i 21 cm radio emission line which typically shows a double peak due to the approaching and receding sides of the rotating galactic disk.

$$\frac{\Delta\lambda}{\lambda_{\mathrm{rest}}} \quad \frac{v_r}{c} = \frac{V \sin i}{c} \tag{3}$$

where v_r is the radial velocity and i is the angle of inclination between the observer and the perpendicular to the disk. The Tully-Fisher relation may be understood in principle from

$$M = \frac{V_{\max}^2 R}{G} \tag{4}$$

where M is the mass of the galaxy within radius R. If the mass to light ratio is the same for all spirals: $(M/L \equiv 1/C_{ML})$ then

$$L = C_{ML} \frac{V_{\max}^2 R}{G} \tag{5}$$

and continuing, if one assumes that Freeman's law is valid so that all spirals have the same surface brightness then $L/R^2 \equiv C_{SB}$. Eliminating R then gives

$$L = \frac{C_{ML}^2}{C_{SB}} \frac{V_{\max}^4}{G^2} = C V_{\max}^4. \tag{6}$$

The ratio M/L_B decreases with later Hubble type, from 6.2 for Sa, via 4.5 for Sb, and 2.6 for Sc, suggesting that Sc's have a greater fraction of massive mains-sequence stars reltative to earlier spirals. A fact that fits well in with the fact that Sc's are bluer than Sb's and Sa's. Irregular are the bluest of all galaxies. For example the LMC and SMC still appear to be making globular clusters in their disks.

Spiral Structure

Grand desing spirals (an example is M51 `http://www.seds.org/messier/m/m051.html`) are seen to account for 10% of all spirals, multiple arm galaxies number 60% while the flocculent spirals (an example is NGC 2841 `http://www.seds.org/ spider/ngc/ngc.cgi?n2841`) number 30%. The former are presumed to be caused by **quasistatic density waves**, while the latter are caused by **stochastic, self-propagating star formation**. Both processes are probably active in most spiral galaxies.

Elliptical Galaxies

In contradiction to the spiral galaxies, the Hubble type does not correlate well with any of the physical properties of elliptical galaxies. These galaxies were until recently to be among the simplest galaxies but are now considered to be the most complex and diverse group. There are a number of types:

- **cD galaxies** are immense bright objects with diameters that can approach 1 Mpc. These galaxies are found near the center of large dense clusters and contain up to 10^{13} ? 10^{14} M_S and may be surrounded by on the order 10^4 globular clusters. The mass to light ratio of these galaxies is also immense, 750 $\mathrm{M}_S/\mathrm{L}_S$, indicating large quantities of dark matter.
- **Normal elliptical galaxies** are further seperated into giant elliptical (gE?s), ellipticals (E?s) and compact ellipticals (cE?s). Masses range 10^8 ? 10^{13} M_S, diameters 1 ? 200 kpc and M/L ranges 7 ? 100 $\mathrm{M}_S/\mathrm{L}_S$.
- **Dwarf elliptical galaxies** (dE?s) fundamentally different from the normal sequence of ellipticals, with much lower surface brightness than the cE?s of the same luminosity. Masses range 10^8 ? 10^9 M_S, diamters 1 ? 10 kpc and these galaxies seem to have lower metallicities than normal ellipticals.
- **Dwarf spheroidals** (dSph?s) are low luminosity, low surface brightness end of dE sequence. These galaxies have only been found in the vicinity of the Milky Way. Masses range 10^7 ? 10^8 M_S, diameters 0.1 ? 0.5 kpc.
- **Blue compact dwarf galaxies** (BCD?s) are small galaxies that are unusually blue, and are presumably undergoing vigorous star formation. Masses of order 10^9 M_S, diameter of order 3 kpc and have a large abundance of gas: $M_{\mathrm{HI}} = 10^8$ M_S and $M_{\mathrm{HII}} = 10^6$ M_S. Mass to light ratios may be as low as 0.1 $\mathrm{M}_S/\mathrm{L}_S$.

cD?s and normal ellipticals have surface brightnesses that closely follow the $r^{1/4}$ law (equation 2).

dE?s and dSph?s seem to have been stripped of all gas and dust. On the other hand it seems that contrary to popular belief gas and dust is to be found

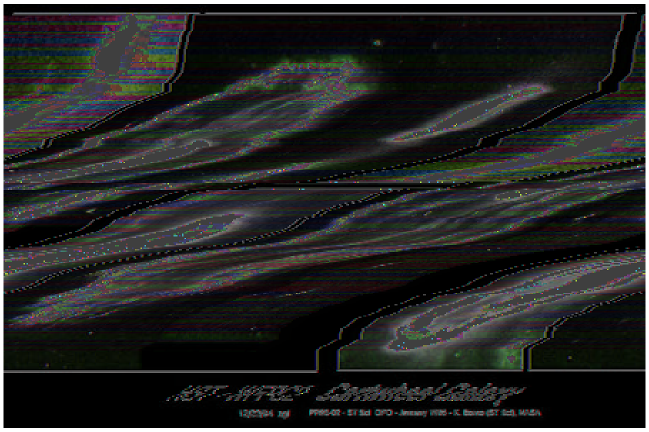

Figure 3: The Cartwheel Galaxy, left lower panel: galactic center, left upper panel: a shocked ring of star formation. A rare and spectacular head-on collision between two galaxies appears in this Hubble telescope picture of the Cartwheel Galaxy, located 150 Mpc from the Milky Way in the constellation Sculptor. The striking ring-like feature is a direct result of a smaller intruder galaxy possibly one of two objects to the right of the ring that careened through the core [close-up image at lower left] of the host galaxy. Like a rock tossed into a lake, the collision sent a ripple of energy into space, plowing gas and dust in front of it. Expanding at 200,000 mph, this cosmic tsunami leaves in its wake a firestorm of new star creation. Hubble resolves bright blue knots that are gigantic clusters of newborn stars and immense loops and bubbles blown into space by exploding stars (called supernovae) going off like a string of firecrackers. Source/stolen from: Kirk Borne (STScI), and NASA.

in most normal ellipticals, though at smaller abundances than what is found in spirals.

dE?s, dSph?s and E?s all follow the **Faber-Jackson** relation

$$L \quad \sigma_0^4 \tag{7}$$

where σ_0 represents the central value of the velocity dispersion. There is considerably more scatter in this relation than in the Tully-Fisher relation. Fixes have been attempted to rectify this by including a second parameter into the fit, the effective radius r_e, with greater success.

What is the source of the shape of ellitical galaxies shape? It is not due to rotation, rather to anisotropies in the velocity dispersion.

Finally we should say that galaxies should not solely be studied in isolation: the luminosity function of various galaxy types varies according to postion in the universe. In general we may say that dE?s and dwarf Ir constitute the largest fraction of galaxies. Of the bright galaxies, spirals number roughly 70% and

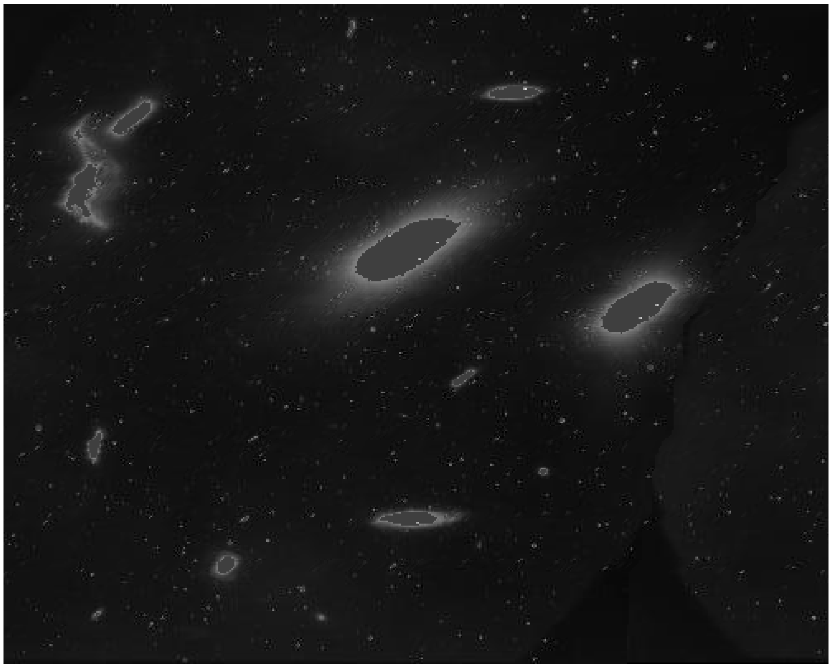

Figure 4: he Virgo cluster of galaxies includes the elliptical galaxies M84 and M86. Thousands of galaxies form a rich, loose, irregular cluster which is not strongly concentrated towards the center. KPNO 4-meter Mayall telescope, 1974 Credit: OAO/AURA/NSF.

ellipticals 30%. But in the Virgo cluster there are more ellipticals and S0?s; the fractions are 12% E?s, 26% S0?s, and 62% S and Ir. In the rich Coma cluster we ?nd 44% E?s, 49% S0?s and only 7% S and Ir?s.

Galactic collisions and other interactions

The typical distances between galaxies is not very much larger than typical galactic dimensions and galactic collisions cannot be ignored in galactic evolution. The average distance between stars *is* fairly large, so such collisions do not increase the probability of stellar collisions - but the gas and dust contained in galaxies will be strongly perturbed. The gas will be compressed and the temperature of the gas can rise to 10^7 ? 10^8 K, this can result in greatly enhanced star formation: so called **starburst galaxies**.

The cD galaxies one ?nds at the center of rich, regular clusters presumably grow by absorbing the minor galaxies in orbit around the cluster center, this process **galactic cannibalism** proceed by the process of **dynamical friction** which tends to move the heaviest bodies towards the center. We also ?nd both in the Virgo cluster and to an even greater extent in the Coma cluster that the proportion of elliptical galaxies is greater ? probably a result of galactic collisions.

Clusters of Galaxies

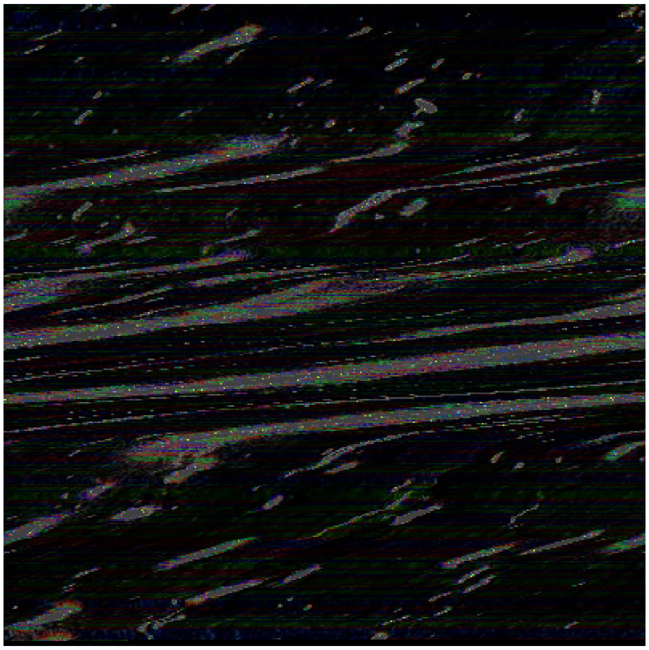

Figure 5: Galaxy Cluster CL0024+1654 serving as a gravitational lens. The Hubble Space Telescope has captured a striking image of the galaxy cluster which lies some 1.5 Gpc away in the constellation Pisces. The oblong, blue objects on the outskirts of the cluster are all in fact a mirage of the same galaxy. Credit: STScI NASA.

Galaxies are arranged into **clusters**. These can be rich or poor. A typical poor cluster is our own Local Group, that consists of the Milky Way, the Andromeda Nebula
(M31 `http://www.seds.org/messier/m/m031.html`), the LMC and SMC, and a number of dwarf galaxies among them the Sagittarius dwarf and the Antlia galaxy. There are roughly 30 galaxies all together and the diameter of the local group is some 750 kpc.

The nearest rich cluster is the Virgo cluster. This cluster is more than 15 Mpc away with a diameter of 3 Mpc and consists of more than 2000 galaxies.

Cluster can also be *regular*; *i.e.* strongly concentrated toward the center.

One such cluster is the Coma cluster, 90 Mpc away with more than 10 000 members. 80% of these are elliptical galaxies, and the galaxies are spherically arranged. Another well known rich, but irregular cluster is the Hercules cluster, 200 Mpc away, consisting of equal numbers of elliptical and spiral galaxies.

Superclusters, groups of a dozen or so galaxy clusters with diamters on the order of 30 Mpc, are the largest structures in the Universe, or actuallly it is the voids between the superclusters that are the largest structures with typical diameters of 120 Mpc. Superclusters are arranged as the soapy film in a froth of soapy water around the voids.

At scales larger than 100 Mpc the galaxies (matter) seems evenly distributed.

Gravitational lenses and dark matter. Galactic cluster dynamics show that there is a great amount of dark matter: there is not enough luminous matter, even when considering the very hot intergalactic gas clouds, to bind galaxies together. Another method of assessing the mass of galaxy clusters is by studying the gravitational lensing of light passing through the cluster. These observations give the same result: luminous matter is of order 10% of all gravitational matter in the Universe. Gravitational lensing also shows that the dark matter is ordered in much the same way as luminous matter is.

Hubble's law and the expansion of the Universe

When observing galaxies at ever greater distances from the Milky Way it becomes apperant that galaxies are *receding* at a velocity v (actually a red-shift $z \approx v/c$ for small v) that increases proprotionally with distance d

$$v = H_0 d \tag{8}$$

The constant of proportionality H_0 is called **Hubble's constant** . The current best value of this constant is $H_0 = 70$ km/s/Mpc. A good value for this number has been among the most sought after quanteties in astrophysics. The difficulty in establishing a good value lies in acheiving good measurments of galactic distances using the **distance ladder**. The distance ladder consist of classes of objects (RR Lyrae stars, Cepheids, globular clusters, Tully-Fisher compliant galaxies, type ia supernovae) with known intrinsic luminosities L, such that a measurment of their flux f gives a distance $d = \sqrt{L/4\pi f}$. A a ladder because calibration between such sources must be done and are dependent on all the steps that come before. . . much of this problem has been solved during the last decade with the observation of large numbers of SN ia as discussed in the cosmology chapter.

Naïvely comparing Hubble's law with the equation for distance travelled at a constant velocity $r = vt$ allows us to obtain an age of the univer H_0^{-1} assuming that the mutual gravitational attraction of galaxies has not slowed the universal expansion.