3 The local group

The local group (LG) of galaxies is dominated by the bright spiral galaxies, the Milky Way and Andromeda (M31).

The LG may be defined as all galactic systems bound gravitationally to the MW and M31.

This can be difficult to demonstrate for all galaxies out to a radius of 1 Mpc of the MW/M31 barycentre. Therefore, a purely radial cut of 1 Mpc can also be applied.

The LG provides a close up view of galaxy related physics in action, e.g. interactions, mergers, star formation and globular cluster formation.

3.1 Taxonomy of members

The LG is dominated in terms of luminosity (mass) by the giant spirals M31 and the MW.

Then comes a small gap in the luminosity distribution before including the spiral M33 (aka Triangulum) and the LMC. Note that some researchers classify the LMC as a barred spiral (SBm) and others classify it as an irregular galaxy. This is an example of the subjective nature of morphological classification.

Dwarf galaxies can be defined as $-18 < M_V < -14$. Irrespective of where the exact line is drawn the important consideration is whether such dwarf galaxies are physically distinct compared to giants.

This does appear to be the case with the giant and dwarf ellipticals. The SB profiles of giant ellipticals are well described by de Vaucouleurs profiles. However, dwarf ellipticals show lower central surface brightnesses and overall are better fit be exponential profiles.

A more physically continuous description of the SB profiles is provided by the Sersic profile parametrised by the effective radius R_e and the radial fall-off n. Taking $n = 4$ generates a de Vaucouleurs profile, while $n = 1$ is an exponential profile.

Furthermore, HST ACS observations indicate that as one considers fainter ellipticals the rate of occurrence of bright, central nuclei increases. We shall consider this further in the lecture on Ellipticals. However, there do appear to be important structural differences, and thus clues to different formation histories, between giant and dwarf ellipticals.

A currently open question is whether dEs and dwarf spheroidals (dSphs) are physically related classes of objects. [in progress].

The distribution of the dwarf irregular galaxies within the LG may well be related to the ability of of such low mass, diffuse structures to survive as identifiable systems within the dynamically active inner regions of the LG. For example, a tidally disrupted and/or stripped dIrr galaxy may bell leave behind no recognisable structure (i.e. no GC-like nucleus) in the same manner that a dE/dSph will. All that may remain is a coherent stream of stars (see later).

3.2 Globular clusters

Globular clusters (GCs) mark a critical changeover point as we descend the mass scale of local group structures.

They can be as luminous as dwarf galaxies, with luminosities ranging from 10^3 to 10^6 $L_\odot$. However, their internal kinematics does not indicate the presence of a dark matter halo.

GCs are compact, dense stellar systems. Moreover the stellar population is very uniform and generally characterised as an old (effectively the age of the Universe), metal poor (as little as 100th solar metallicity) population.

Differences do exist. Blue, metal poor GCs appear to be the oldest systems and they preferentially reside in the halo of the MW. Red, metal rich (i.e. 1/10th solar) GCs represent younger (by a couple of gigayears) populations and reside in the bulge of the MW.

The existence of old GCs is not necessarily a problem for theories of galaxy formation: the Jeans mass in the post-recombination Universe is of the order of the mass of GC suggesting that GCs could have formed in an early, rapid burst of highly efficient star formation. However, the existence of a bi-modal population is currently not understood.

The MW possesses some 150 GCs with approximately 500 in M31. Giant elliptical galaxies may contain up to 13,000 GCs. Dwarf galaxies also contain GCs and the presence of GC in tidal streams of stars in the MW (e.g. the Sagittarius stream) indicates that giant galaxies can add to their GC population via gravitational capture.

Some of the brightest GCs may be the tidally stripped nucleus of dwarf galaxies that have interacted with the MW or M31 in the past, e.g. Omega Cen or G1. Evidence for this claim is the presence of multiple age stellar populations within such systems.

3.3 The discovery of new dwarf galaxies in the Local Group

The brighter members of the LG are of sufficiently high surface brightness to have been catalogued by Messier circa 1781.

The dwarf galaxies Sculptor and Fornax were discovered by Harlow Shapley in 1937 and 1938 respectively as faint nebula that could be resolved into individual stars.

Fainter and more distant dwarf galaxies lie well below the surface brightness limit of even deep CCD exposures, e.g. $\mu_B = 27 - 30$.

Such systems, starting with Sagittarius (Ibata et al. 1994) were detected on the basis of resolved star counts. Luminous red giant stars can be isolated on the HR diagram via colour cuts and by plotting the sky distribution of such luminous beacons one can identify distant stellar overdensities. Spectroscopy is then required to determine if stars making up a given overdensity form a dynamically coherent group (all moving at the same velocity).

Such resolved star counting methods have greatly decreased the effective surface brightness sensitivity to faint (resolved) galaxies, reaching $\mu_B \sim 31$.

Many new galaxies have been detected via this method including Sagittarius (1994) and Canis Major (2003) in the MW and numerous new systems in M31 detected via SDSS and the PANDAS surveys.

In addition to the detection of galaxies, resolved star counts have also revealed the existence of faint yet coherent streams of stars associated with the tidal disruption of dwarf galaxies as they encounter the giant galaxies of the LG. Examples include the Sagittarius stream (the "Field of Streams") and the stellar bridge linking M31 and M33 (Triangulum).

3.4 Evidence of interactions: tidal stripping, two-body relaxation and dynamical friction

The existence of streams of stars points to past interaction between galaxies of the LG. Galaxy interactions can be approached through three related concepts: the stripping of stars from a satellite galaxy due to the tidal field of the primary, the persistence of such tidal streams over long timescales and the eventual consumption of the satellite galaxy by the primary due to dynamical friction.

3.4.1 Tidal stripping

The tidal force of a massive body is defined as

$$\frac{\mathrm{d}F}{\mathrm{d}r} = -\frac{2GMu}{R^3} \tag{1}$$

where u is a test mass a distance R from a mass M.

Now consider the self gravity of a secondary body of mass m and extent r,

$$F_S = \frac{Gmu}{r^2}. \tag{2}$$

The tidal force experienced by the secondary mass as it orbits the primary is

$$F_T = -\frac{2GMu}{R^3} \times r \tag{3}$$

The size of the primary that will be stable against tidal stripping can be determined by setting $F_S = F_T$ and solving for r, i.e.

$$r_J = R\left(\frac{m}{2M}\right)^{1/3}, \tag{4}$$

where r_J is classically called the Jacobi radius or the Roche limit. Stars at radii $r > r_J$ will become unbound from the secondary. They will form a tidal stream – co-orbiting with the secondary but no longer bound to it.

We can consider the tidal stability of two satellites of the MW: the LMC and the Sagittarius DEG.

1. **LMC.** Taking $m_{LMC} = 10^{10}\ M_\odot$, $R = 50$ kpc, $M_{MW}(< R) = 5 \times 10^{11}\ M_\odot$ (use $V^2/R = GM(< R)/R^2$, we have

   $$r_{J,LMC} = 50 \text{ kpc} \times \left(\frac{10^{10}}{2 \times 5 \times 10^{11}}\right)^{1/3} \approx 11 \text{ kpc}. \tag{5}$$

   The physical extent of the LMC is approximate 4.5 kpc and we conclude that it is stable against tidal stripping.

2. **Sagittarius DEG.** The mass of the Sag DEG is not well known. Take $L_{Sag} = 8 \times 10^7\ L_\odot$ and $M/L = 10$ (not unreasonable for dwarf galaxies). Also take $R = 20$ kpc and $M(< R) = 2 \times 10^{10}\ M_\odot$. One then obtains

   $$r_{J,Sag} = 20 \text{ kpc} \times \left(\frac{8 \times 10^8}{2 \times 2 \times 10^{11}}\right)^{1/3} \approx 2.5 \text{ kpc}. \tag{6}$$

   The long axis of the Sag DEG is 2.6 kpc in extent and we conclude that this system is being actively stripped in the tidal field of the MW.

3.4.2 The persistence of stellar features: Two-body relaxation

How long might one expect a tidal streams of stars to exist as a coherent entity? As the streams pass through the MW they will suffer a combination of rare close encounters and frequent distant encounters with MW stars. One can set the condition that a star will suffer a significant collision (leading to orbital mixing) when it encounters the potential of a nearby star such that

$$\begin{aligned} \text{PE} &= \text{KE} \\ \frac{GM_*^2}{r} &= \frac{m_* v^2}{2} \\ r &< \frac{2Gm_*}{v^2}. \end{aligned}$$

Taking a 1 $M_\odot$ star of $v = 200$ kms^{-1} one obtains $r = 2 \times 10^{-7}$ pc.

The time taken to "cross" the MW at a radius of 20 kpc can be crudely written as $t_{cross} = 6.2 \times 10^{20}\text{m}/2 \times 10^5\text{kms}^{-1} = 3 \times 10^{15}\text{s} = 9 \times 10^7\text{yrs}$.

How many MW stars will a stream star encounter on one pass? Consider an orbit going through the centre of the MW. The central SB is of order $I_0 \approx 300 L_\odot \text{pc}^{-2}$ (remember that this is the projection of a cylinder through the MW). Therefore $I_0 \times \pi r^2 = 4 \times 10^{-11}$ stars.

One would need to pass through the MW $\sim 3 \times 10^{10}$ times to encounter one star. This would take of order 3×10^{18} years, i.e. longer than the age of the Universe.

However, both giant and dwarf galaxies display coherent orbital motions. A significant level of relaxation must have occurred during their assembly. One invokes the idea of "violent" relaxation in order to explain this. During the earliest epochs of galaxy assembly the potential in which the stars orbited was changing rapidly (violently) as galaxies built up their masses via vigorous merging with satellites – driven by dynamical friction (see below). The rapidly changing potential erased the original dynamical properties of the stars.

3.4.3 Merging driven by dynamical friction

Although stellar streams can exist for a long time, the parent structures are – the dwarf galaxies themselves – can merge with the primary galaxy over much shorter timescales.

The process by which this occurs is dynamical friction. It results from the integrated effect of numerous weak stellar encounters between the satellite and primary.

Consider the perpendicular force imparted to the satellite by a single star in the primary:

$$F_\perp = \frac{GM_gM_*}{d^2}\cos\theta = \frac{GM_gM_*}{(b^2+v^2t^2)}\frac{b}{(b^2+v^2t^2)^{1/2}}. \tag{7}$$

The resulting perpendicular acceleration is

$$a_\perp = \frac{F_\perp}{M_g} = \frac{Gm_*b}{(b^2+v^2t^2)^{3/2}}. \tag{8}$$

The resulting total velocity change is

$$\Delta v_\perp = \int_\infty^\infty a(t)\ \mathrm{d}t = \int_\infty^\infty \frac{Gm_*b}{(b^2+v^2t^2)^{3/2}}\mathrm{d}t = \frac{2Gm_*}{bv}. \tag{9}$$

The momentum change of the galaxy is $\Delta p_g = 2GM_gm_*/bv$ and via conservation of momentum the change in the star velocity is $\Delta v_\perp^* = 2GM_g/bv$.

The change in perpendicular KE for the galaxy-star system is

$$\Delta K_\perp = \frac{M_g}{2}\left(\frac{2Gm_*}{bv}\right)^2 + \frac{m_*}{2}\left(\frac{2GM_g}{bv}\right)^2 = \frac{2G^2m_*M_g(m_*+M_g)}{b^2v^2}. \tag{10}$$

Energy is a scalar quantity and must be conserved. The forward motion of the galaxy must decrease – accompanied by an increase of the forward motion of the star, i.e.

$$\frac{M_gv^2}{2} = \frac{M_g(v-\Delta v)^2}{2} + \frac{m_*}{2}\left(\frac{M_g}{m_*}\Delta v\right)^2 + \Delta K_\perp. \tag{11}$$

Taking $\Delta v \ll v$ and $m_* \ll M_g$, one expands the squared terms and drops terms of order Δv^2 to obtain

$$\begin{aligned} M_gv\Delta v &= -\Delta K_\perp \\ \Delta v &= -\frac{\Delta K_\perp}{M_gv} \\ &= -\frac{2G^2m_*(m_*+M_g)}{b^2v^3} \\ &= -\frac{2G^2m_*M_g}{b^2v^3}. \end{aligned} \tag{12}$$

To obtain the total change in velocity one must integrate over all impact parameters

$$\begin{aligned} \mathrm{d}v &= -\int_{b_{min}}^{b_{max}} \frac{2G^2 m_* M_g}{b^2 v^3} \times n \times v\mathrm{d}t \times 2\pi b \mathrm{d}b \\ \frac{\mathrm{d}v}{\mathrm{d}t} &= -\int_{b_{min}}^{b_{max}} \frac{4\pi G^2 m_* M_g n}{v^2} \frac{1}{b} \mathrm{d}b \\ &= -\frac{4\pi G^2 m_* M_g n}{v^2} \ln(b_{max}/b_{min}) \quad [= \ln\Lambda], \end{aligned} \tag{13}$$

Noting that n is the number density of stars. Taking $b_{min} = r_g$ and $b_{max} = 3r_g$, $\ln(3) \approx 1$ and

$$\frac{\mathrm{d}v}{\mathrm{d}t} = -\frac{4\pi G^2 M_g \rho_*}{v^2}, \tag{14}$$

where $\rho_* = nm_*$.

The merging timescale from dynamical friction may be defined as the time required to slow the satellite to zero velocity, i.e.

$$t_{merge} \sim \frac{v}{\mathrm{d}v/\mathrm{d}t} = \frac{v^3}{4\pi G^2 M_g \rho_*}. \tag{15}$$

One notes that $t_{merge} \propto 1/m_g$, i.e. more massive systems are consumed faster than less massive systems. Dwarf galaxies are consumed faster than GCs.

In addition, $t_{merge} \propto 1/\rho_*$, i.e. denser galaxies consume their satellites more rapidly.

For a satellite galaxy with $v = 200$ kms^{-1} and $M_g = 10^{10} M_\odot$ orbiting a galaxy at $R = 10$ kpc and $M(< R) = 10^{11} M_\odot$ (remember $\rho_* = 10^{11} M_\odot/4/3\pi(10 \text{ kpc})^3$) then $t_{merge} \sim 3 \times 10^8$ yrs.

One could refine this calculation further but, for instance, taking $M_g = 10^8 M_\odot$, i.e. more applicable to the Sagittarius DEG, one obtains $t_{merge} \sim 10^{10}$ yrs. This indicates that it is reasonable to observe dwarf galaxies in close proximity to giants in the LG today: the merging time is of the order of the age of the Universe.

See the Dubinski simulation for a visual impression of dynamical friction and two-body relaxation in action.

3.5 The chemistry and star formation history of dwarf galaxies in the LG

Not going to say too much about chemistry here. See section in lecture on spiral galaxies. Dwarf galaxies are low metallicity objects - down to 1/10th to 1/30th solar. This is due to the binding energy of metals produced in SN ejecta. See analysis by Dekel and Silk.

All dwarf elliptical and spheroidal galaxies contain old stars. However, many contain younger stellar populations associated with both short and extended periods of star formation. No dwarf ellipticals or spheroidals contain stars younger than 2-3 Gyr. There is no clear pattern to the star formation histories of such dwarf galaxies. They appear to be stochastic and potentially driven by interactions with the giant galaxies in the LG.

3.6 The Local Group in context

The LG can be thought of as a low mass group of galaxies. Such structures may well dominate the mass density of galaxies in the Universe (Fukugita et al. 1998 – counting both gas and galaxies).

The LG is therefore a small part of a steadily increasing scale of structure in the Universe. This is confirmed observationally and within computational N-body simulations.

N-body simulations are important because they predict the distribution of dark matter halos – both parent and satellite – within computational analogues of the LG.

Since Klypin et al. 1999 (and Moore et al. 1999) it has been realised that such DM-only simulations over predict the abundance of DM halos as a function of mass (the halo mass function) compared to observations.

The "missing satellite" problem has been discussed from two perspectives: firstly, the cold dark matter hypothesis underpinning the computer simulations may be flawed at some level. Solutions include mixing warm and cold dark matter to simulations to modulate the halo distribution.

Alternatively, our census of the LG dwarf galaxy population may be incomplete. This is plausible given both the low luminosity and the fragility to disruption of dwarf galaxies.

Furthermore, consideration of the M/L ratio of dwarf galaxies as a function of luminosity indicates that dwarf galaxies may reside in approximately constant mass halos with steadily increasing M/L ratios as a function decreasing luminosity. This in turn may be related to the efficiency of star formation in very low mass galaxies.

One of the lowest luminosity dwarf galaxy candidate in the LG is Segue 1 (Geha et al 2009) with a luminosity $L_V = 340\ L_\odot$ (approximately that of a single red giant star) and a mass $M = 4.3 \times 10^5\ M_\odot$. The implied M/L ratio is greater than 1000.

Observations of such systems are challenging in a number of ways: the velocity of Segue 1 with respect to the Earth is 206 kms^{-1} and the velocity dispersion, measured from several tens of stars, is approximately 3.5 ± 1 kms^{-1}. In addition, the debate continues as to whether such "galaxies" are bound or are in the process of disruption.

However, overall these observations may point to a mass threshold, below which a galaxy will either no longer form stars, or it will form them but not retain them. Only when this question is understood will the missing satellite problem be considered answered.