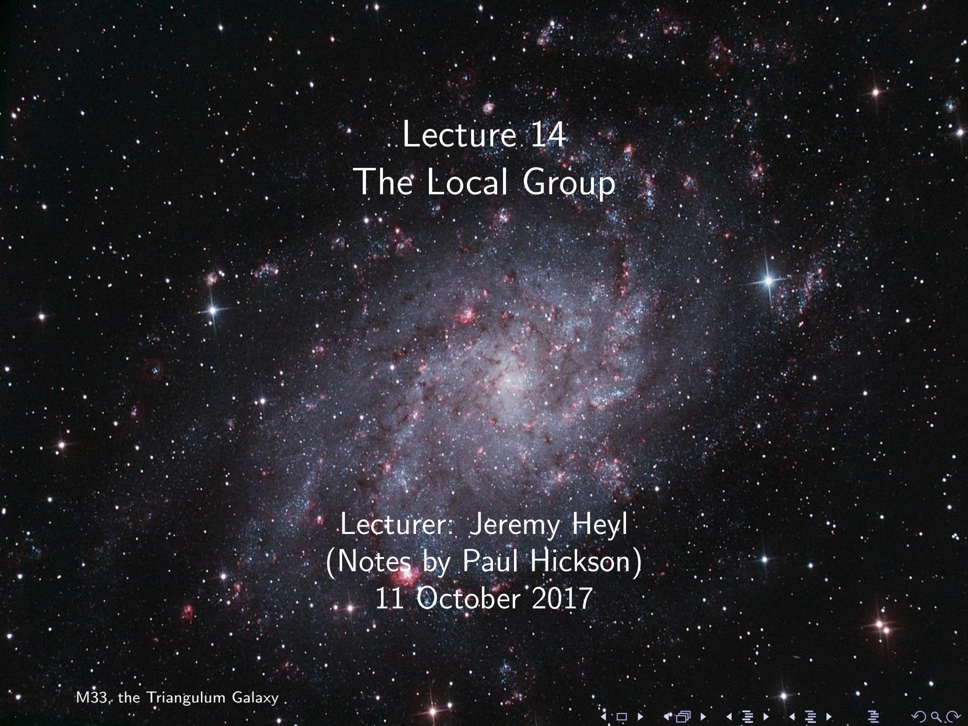
Lecture 14
The Local Group

Lecturer: Jeremy Heyl
(Notes by Paul Hickson)
11 October 2017



M33, the Triangulum Galaxy

The Andromeda Galaxy

M31 is larger than the Milky Way, with a luminosity that is about 50% greater, and a higher rotation velocity (~ 260 km/s).

It has ~ 300 globular clusters, twice as many as the Milky Way, and more satellite galaxies.

Its nucleus has two central concentrations of stars, about 2 pc apart. One of these contains a black hole of mass $M \sim 3 \times 10^6 M_\odot$. The other is likely a star cluster that is spiraling into the centre.

The halo of M31 contains many metal-rich stars, about 6 Gyrs old, showing systematic rotation. These are believed to be the result of M31 accreting a smaller galaxy.

There is a pronounced ring of star formation, at $R \simeq 10$ kpc.

The Andromeda Galaxy

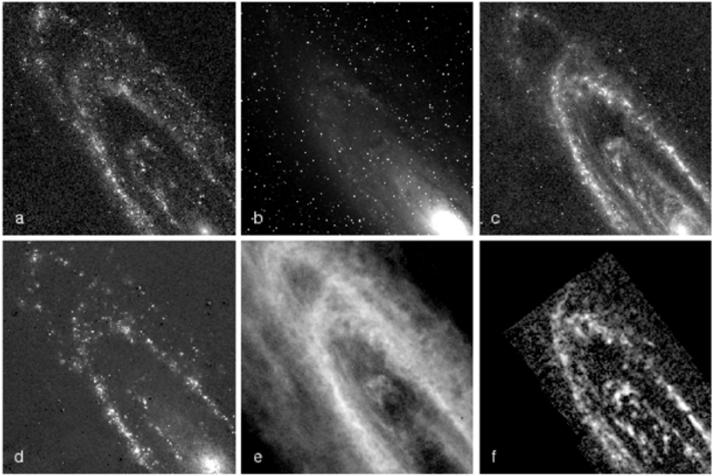


Fig 4.11 (K. Gordon) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

M31: (a) in ultraviolet light; (b) B-band image shows the prominent bulge; (c) infrared light of warm dust at 24 um; (d) H_α image shows the ring of fire and HII regions; (e) HI gas; and (f) emission of CO tracing dense molecular gas.

The Andromeda Galaxy

M31 is classified as an Sb galaxy. It's spiral arms are tightly wound, with no clear global pattern, and it has a relatively large large bulge compared to the Milky Way.

Its disk is not entirely flat, but has a noticeable warp in the outer regions. Warps like this are quite common and are produced by gravitational encounters with other galaxies.

The disk contains about $4 - 6 \times 10^9 M_\odot$ of neutral hydrogen, about 50% more than the Milky Way.

Like the Milky Way, it contains high-velocity clouds of gas in its halo. These contain $10^5 - 10^6 M_\odot$ and were presumably captured from another galaxy.

M33

M33 is a small Sc or Scd galaxy, with open spiral arms and a small bulge.

It has a high mass-fraction of gas, extending to more than 3 Holmberg radii (about 30 kpc). The outer part of the disk is warped.

Its nucleus contains a dense star cluster with luminosity $\sim 2.5 \times 10^6 L_\odot$, but there does not appear to be a black hole, unless its mass is less than $10^4 M_\odot$.

However, the nucleus of M33 contains a bright X-ray source, with luminosity equivalent to several X-ray binary stars.

Formation of the Local Group

Galaxies formed as the primordial gas was drawn towards concentrations of dark matter that were growing due to gravitational instability.

Initially, the matter was expanding with the universe, but less rapidly. Eventually, gravity was able to halt the expansion and the gas and dark matter in the denser regions.

Only density concentrations that exceeded a certain level were able to collapse. As a result, galaxies tended to form in clusters and groups.

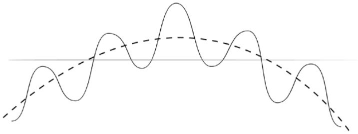


Fig 4.12 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Small galaxies form near large ones: the density of matter (wavy solid line) is a combination of small clumps within a large region that is denser than average (dashed line). Regions dense enough to collapse on themselves (above the horizontal line) tend to be clustered together.

Galaxy rotation

Initially, the matter was expanding with the universe, but not quite as fast. Eventually, gravity was able to halt the expansion and the gas and dark matter began to contract.

Irregular-shaped concentrations of dark matter and gas would exert torques on one another, giving rise to rotation.

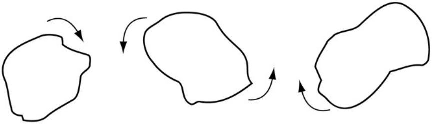


Fig 4.13 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Simulations indicate that rotation velocities that are about 5% of those needed for circular orbits can be produed.

As these concentrations continued to collapse, their rate of rotation increased, due to conservation of angular momentum.

The first stars

The first stars would have formed once the Universe cooled enough to allow gas clouds to collapse, typically a few hundred Myr after the Big Bang.

These first stars, called **population III**, had no heavy elements, and would have been massive and luminous. Their supernovae explosions would have enriched the interstellar gas with metals.

These first stars would have been very luminous, producing many UV photons. These photons would have ionized the surrounding gas, producing giant, expanding HII regions.

Today we observe that the intergalactic medium is highly ionized, at least to redshifts as high as $z \sim 6$, so the first stars must have formed well before this time.

We have not yet been able to detect the first stars, but it is hoped that the next generation of space and ground-based telescopes might be able to see them.

Formation of the galactic disk

When gas clouds collide, they dissipate their kinetic energy in shock waves producing heat and radiation. However, angular momentum is conserved so the ratio of orderly rotation to random motion increases. The result is a rotating disk of gas.

Stars that form from the gas after this collapse have primarily circular orbits, as these have the maximum ratio of angular momentum to energy.

If tidal torques provide only 5% of the velocity needed for a circular orbit, the initial cloud must have been ~ 20 times larger than the present galactic disk (since $L_z = RV = constant$). So the gas in our galaxy probably originated in a cloud that was several hundred kpc in diameter.

Because Globular clusters have random orbits with no systematic rotation, they must have formed from small dense gas clouds, before dissipation could occur.

Formation of the bulge

The galactic bulge contains very few stars older than $8 - 10$ Gyrs. These must have formed after the globular cluster and halo populations, perhaps in the dense centre of the rotating protogalactic gas.

Alternatively, these stars might have formed from gas clouds falling into the galaxy at later times. Such clouds would be compressed as they collide with the gas in the disk which would trigger star formation.

Or, the bulge might be the result of star clusters or dwarf galaxies captured by the galaxy. Such clusters would spiral in towards the centre due to **dynamical friction**.

Dark matter

The dark matter in the Galaxy is more extended than the luminous matter. It comprises a greater fraction of the total mass as radius increases.

A possible reason for this is that, unlike gas particles, dark matter does not interact and so cannot dissipate orbital energy. It remains extended.

The gas on the other hand dissipates energy and therefore move inward to orbits of lower total energy. From the virial theorem,

$$E = \frac{1}{2}U \simeq -\frac{GM^2}{R}.$$

As energy is lost, E becomes more negative, so R must decrease.

The gas therefore becomes more centrally condensed than the dark matter, and so are the stars that form from it.

The buildup of heavy elements

Stars pollute the interstellar medium with heavy elements in several ways.

Stars produce carbon during helium burning phases, and nitrogen and oxygen from the CNO cycle. Those that are only slightly more massive than the Sun transport some these elements to the surface by convection. They are then released into the ISM by stellar winds or ejected in late phases of stellar evolution.

AGB stars can produce heavy elements by a process in which stable nucleii are built up slowly by the capture of neutrons (the *s-process*)

Massive stars produce elements up to iron in their cores. They then explode as supernovae, releasing these elements into the ISM.

Other heavy elements are formed during the supernova explosion itself, by rapid neutron caputure (the *r-process*). Here the neutron flux is so great that unstable nuclei can capture another neutron before they have time to decay, and thereby become stable.

The buildup of heavy elements

Massive stars end their lives as core-collapse supernovae. These release mostly light elements (such as oxygen, silicon and magnesium) into the ISM. Heavier elements such as iron are retained by the remnant neutron star or black hole.

These stars have short lifetimes (< 100 Myr), so the light elements build up relatively rapidly.

Type 1a supernovae result when a white dwarf, accreting matter from a companion star, exceeds the Chandrasekhar mass (about $1.4 M_{\odot}$ and collapses.

This heats the interior triggering fusion that blows the star apart. All its elements, including a great deal of iron, are released into the interstellar medium.

So most of the iron comes from Type Ia supernovae. But these are produced by lower mass stars, which typically take a billion years or more to evolve to this stage.

The buildup of heavy elements

The production of both light and heavy elements can be modelled, and measurements of metal abundances provide input to these models.

A simple example, the *closed box model*, is described in Sparke and Gallager. One assumes that as stars evolve, they produce supernovae that lock up a certain fraction of the mass in remnants (black holes, neutron stars) and release a fraction p of that mass as metals into the interstellar medium.

This model predicts that, at any given time, the fraction of stars that have metallicity less than Z is given by

$$M_*(< Z) = M_g(0)\{1 - e^{[Z-Z(0)]/p}\},$$

where $M_g(0)$ is the initial mass of gas and $Z(0)$ is the initial metallicity.

Modeling heavy elements

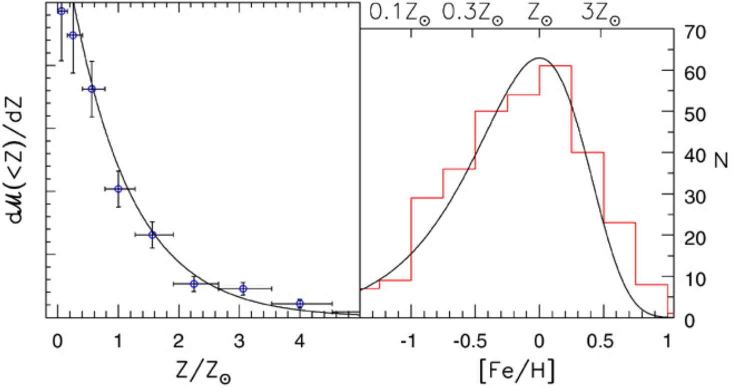


Fig 4.16 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Metal abundance in G and K giant stars of the Galactic bulge. Left, relative number in each range of metal fraction Z; right, number in each bin of $[Fe/H] = \log 10(Z/Z_\odot)$. Solid curves show the prediction of a closed-box model with $p = Z_\odot$ and gas that is initially free of metals: note the tail at high Z.

The mass of the Local Group

Presently, we are falling towards M31 and M31 is falling towards us, with $v_r = -120$ km/s. Our present separation is ~ 770 kpc.

We can make a simple estimate of the total mass as follows. Shortly after the Big Bang, M31 and the Galaxy were close together and moving apart. At the present speed, they will collide in less than $770,000/120 = 6.4$ Gyr. Therefore the period of this near-radial orbit is $P < 6.4 + 13.6 = 20$ Gyr.

We don't know the maximum distance between us, but it was at least as large as 770 kpc, so the semi-major axis of the orbit is $a > 770/2 = 385$ kpc.

This gives an upper limit to the total mass from Kepler's third law,

$$M \equiv M_{\text{M31}} + M_{\text{MW}} = \frac{4\pi^2 a^3}{GP^2} > 1.2 \times 10^{12} M_\odot.$$

The mass of the Local Group

A better estimate can be found by solving the equation of motion,

$$\frac{d^2r}{dt^2} = \frac{L_z^2}{r^3} - \frac{GM}{r^2}.$$

The solution is the parametric equation for a *cycloid*,

$$r = a(1 - e\cos\eta), \quad t = \sqrt{\frac{a^3}{GM}}(\eta - e\sin\eta), \quad a = \frac{L_z^2}{GM(1-e^2)}.$$

The speed is given by

$$\frac{dr}{dt} = \frac{dr/d\eta}{dt/d\eta} = \sqrt{\frac{GM}{a}}\frac{e\sin\eta}{1 - e\cos\eta} = \frac{re\sin\eta(\eta - e\sin\eta)}{t(1 - e\cos\eta)^2}.$$

Assuming that the galaxies are falling together for the first time, $\pi < \eta < 2\pi$. For $e = 1$ (a radial orbit), $t = 13.6$ Gyr, $r = 770$ kpc, and $\dot{r} = -120$ km/s, this equation gives $M = 5 \times 10^{12} M_\odot$. This gives a mean $M/L \sim 100$, which is an order of magnitude larger than values found from galactic rotation. There must be dark matter throughout the Local Group.