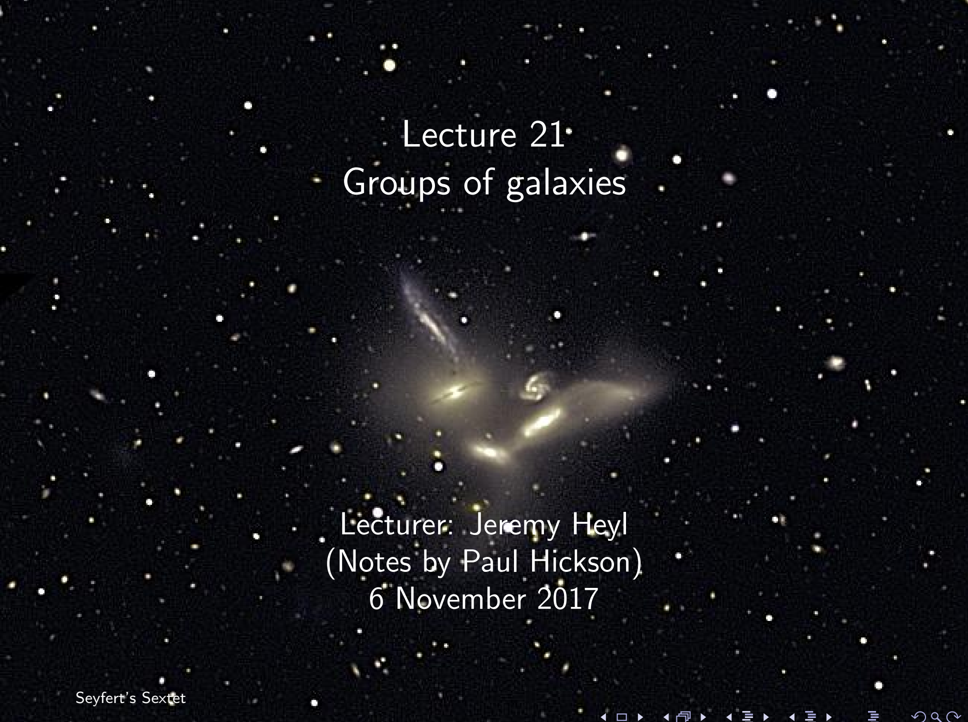
Lecture 21
Groups of galaxies



Seyfert's Sextet

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(Notes by Paul Hickson)
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Groups

At least half of all galaxies are found in small groups, such as the Local Group.

These are bound systems of galaxies, typically about a Mpc across, that no longer expand with the Universe

Groups typically contain less than ~ 50 members and have total mass less than $\sim 10^{14} M_{\odot}$.

Most groups contain primarily spiral galaxies. However, elliptical and S0 galaxies may be found in the denser groups.

Groups have a range of densities, extending from **loose groups** like the Local Group, to **compact groups** in which the galaxies may appear to overlap.

Stephans Quintet is ~ 85 Mpc distant and 80 kpc across (3.2 arcmin). South is at the top and east is to the right. NGC 7319, the barred spiral, has an active nucleus: it is a Seyfert 2 galaxy. The large spiral in the top right, NGC 7320, is not a group member; it is in the foreground and has a much smaller redshift.

Compact groups

Compact groups are the highest-density galactic systems in the Universe. They generally have four to 8 galaxies of comparable luminosity, apparently within a few galaxy radii of each other.

One frequently finds signs of gravitational interactions in these systems. These can include tidal plumes or ‘tails’, asymmetric or disturbed shapes, active nuclei, star-bursts and mergers.

For example, Stephan’s Quintet consists of two interacting galaxies, a barred spiral, and an elliptical galaxy (plus one foreground galaxy). Extended tidal plumes can be seen, and a prominent arc of star forming regions over 100 kpc long. The group is enveloped in about $10^9 M_\odot$ of hot X-ray emitting gas with $T \sim 10^7$ K.

The X-ray gas was heated by shock waves produced when the two gas-rich spiral galaxies collided. Tidal forces also pulled cool gas (about $10^{10} M_\odot$) out of one of the galaxies. This long plume of gas was compressed and is now forming stars.

Loose groups

Even low-density groups may show signs of interactions when examined closely.

For example, the M81 group consists of two spirals and a small elliptical galaxy. One of the spirals (M82) is classified as a peculiar galaxy due to its unusual amorphous shape. In fact it is a **starburst galaxy**, that is presently forming stars ten times faster than is the Milky Way.

M82, NASA/ESA/HST

Deep 21-cm observations reveal plumes of HI gas connecting all three galaxies. These were drawn out of M81 by a recent close passage of the smaller companion.

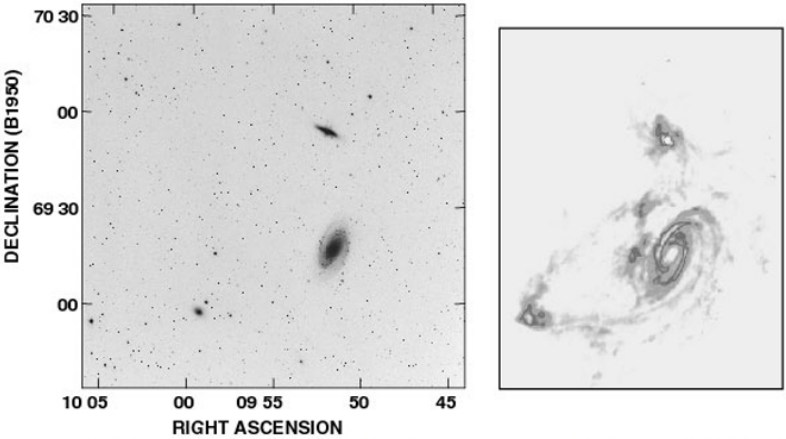


Fig 7.2 (M. Yun) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The group around the large Sc spiral galaxy M81, about 3.5 Mpc distant. Left, negative image in visible light; the elongated object north of M81 is starburst galaxy M82; NGC 3077 is to the southeast. Right, map in HI to the same spatial scale.

Hot gas in groups

About 50% of groups show X-ray emission, originating from gas at $T > 3 \times 10^6$ K.

These tend to have more galaxies, and at least on elliptical.

This gas has lower metallicity, typically a few tenths of the solar metallicity.

NGC 2300 group optical+X-ray, NASA/CHANDRA

Estimating the mass

X-ray emission from hot gas gives us another way to estimate the mass. Combining the equation of hydrostatic equilibrium,

$$\frac{dP}{dr} = -g\rho = -\frac{GM(r)}{r^2}\rho$$

and the ideal gas equation of state

$$P = \frac{\rho k T}{\mu m_{\mathsf{H}}}$$

one gets

$$M(r) = \frac{k}{\mu m_{\mathsf{H}}} \frac{r^2}{G\rho(r)} \frac{d}{dr}(-\rho T)$$

The density and temperature profile can be deduced from the X-ray emission. The value of μ, the mean molecular weight, is ~ 0.6.

One finds mass-to-light rations in the range $80 - 300$ in solar units, which is considerably larger than that of individual galaxies.

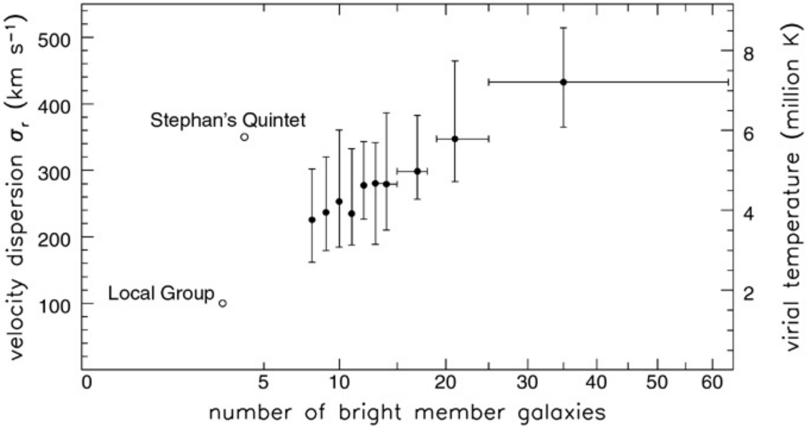


Fig 7.3 (van den Bosch & Yang) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

For groups chosenfrom the 2dF galaxy catalogue, the average velocity dispersion σ_r of the galaxies, and hence the virial temperature, increase with the number of members. The vertical bar shows the range in σ_r within which half the galaxies fall.

Dynamical friction

Gravitational encounters between a massive object (in this case a galaxy) and many low-mass objects (stars or dark matter) result in the massive object loosing energy. This is **dynamical friction**.

When discussing stellar relaxation, we showed that for weak encounters, the change in perpendicular velocity component of a mass M moving with speed V, passing by a mass m with impact parameter b is

$$\Delta V_{\perp} = \frac{2Gm}{bV}$$

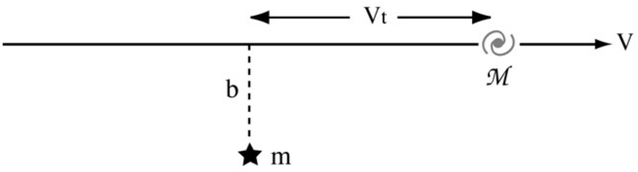


Fig 7.4 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Dynamical friction

The change in perpendicular momentum is $\Delta p = M\Delta V_\perp$ which must be balanced by an equal and opposite change in momentum of the mass m.

Since, for on object of mass m, the kinentic energy is $K = p^2/2m$, the total energy transferred to perpendicular motions is

$$\Delta K = \left(\frac{1}{2M} + \frac{1}{2m}\right)\left(\frac{2GmM}{bV}\right)^2 = \frac{2G^2mM(M+m)}{b^2V^2}.$$

This energy must come from the forward motion of the mass M.

For multiple encounters, we must integrate over the impact parameter, as before. This gives the energy loss rate

$$\frac{d\ln E}{dt} = \frac{1}{E}\frac{dE}{dt} = -\frac{2}{MV^2}\int_{b_{\text{min}}}^{b_{\text{max}}} nV\frac{2G^2mM(M+m)}{b^2V^2}2\pi b db$$
$$= -\frac{8\pi G^2(M+m)\rho\ln\Lambda}{V^3}.$$

where $\rho = nm$ is the mass density of the small objects.

Dynamical friction

Note that the rate of energy loss is inversely proportional to V^3. This result assumes that the large mass is moving considerably faster than the smaller objects m.

The reciprocal of this equation gives the **dynamical friction timescale**

$$t_{\mathrm{df}} = \left| \frac{d \ln E}{dt} \right|^{-1} = \frac{V^3}{8\pi G^2 (M + m) \rho \ln \Lambda}.$$

This can be simplified using the virial theorem, $G M_{\mathrm{tot}} \simeq V^2 R$. Assuming $m \ll M$,

$$t_{\mathrm{df}} \simeq \frac{M_{\mathrm{tot}}^2 V^3}{8\pi G^2 \rho M M_{\mathrm{tot}}^2 \ln \Lambda} \simeq \frac{M_{\mathrm{tot}}^2}{8\pi V R^2 \rho M \ln \Lambda} \simeq \left(\frac{M_{\mathrm{tot}}}{M} \right) \left(\frac{t_{\mathrm{cr}}}{6 \ln \Lambda} \right).$$

where we have assumed that the small objects dominate the total mass, $M_{\mathrm{tot}} = 4\pi \rho R^3 / 3$.

Galaxy dynamical evolution

The dynamical friction timescale for galaxies in small groups can be much shorter than the age of the Universe.

As a result, galaxies can loose energy when moving through the dark matter and spiral inwards.

This leads to tidal interactions which culminate in mergers. Typically two galaxies will merge after just a few close encounters.

Dynamical friction also causes the orbits of satellite galaxies to decay. They typically spiral in to their hosts over a timescales of a few few orbital periods.

The energy lost by galaxies to dynamical friction is converted into kinetic energy of the smaller objects. These then move to higher-energy orbits, causing the halo to become more extended.

‘The Mice’ interacting galaxies

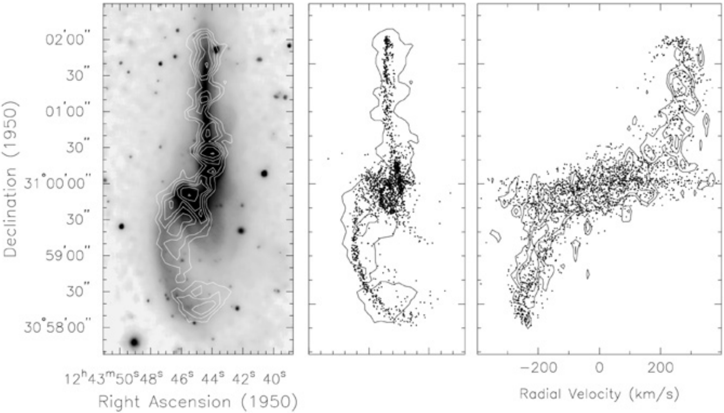


Fig 7.5 (J. Hibbard, J. Barnes) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The galaxy pair NGC 4676, known as ‘the Mice’. Left, an R-band optical image, with white contours showing neutral hydrogen gas in the tails; center, results of a gravitational N-body simulation following two disks of stars. Positions of the stars are shown on top of the outer HI contour. Right, velocities of the stars compared with the gas at each position along the tail.

Galaxy pair NGC 4676: the computer simulation of Figure 7.5.

Left, motion in the galaxies initial orbital plane; center, view along our line of sight.

Right, radial velocity V_r of particles at each declination.

Time is in Myr from closest first approach, distance in kpc. Material at the tips of the tails is still travelling outward at the end of the run; it will not fall back onto the galaxies for many Gyr.

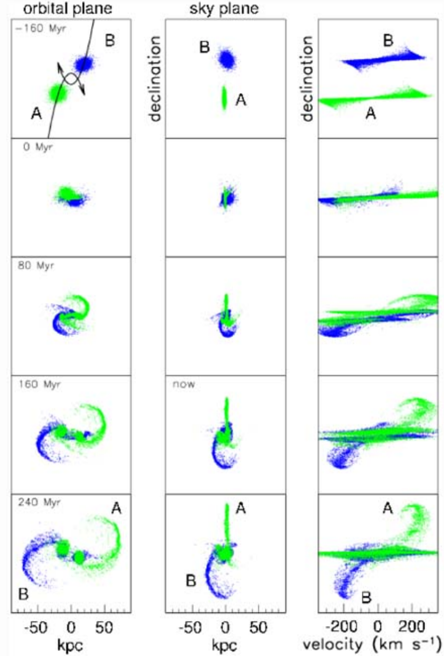


Fig 7.6 (J.Hibbard, J.Barnes) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

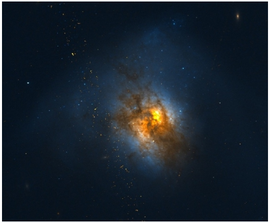
Starburst galaxies

Starbursts occur when interactions allow cool gas to flow into the central region of a galaxy. The gas is compressed, triggering star formation at a rate that can be as much as two orders of magnitude higher than in the disk of the Milky Way.

Such galaxies emit strongly in the infrared, as dust grains are heated by the UV continuum. Galaxies that have an infrared luminosity $L_{\mathsf{FIR}} \gtrsim 10^{11} L_\odot$ are called **luminous infrared galaxies** (LIRGs) .

An example is Arp 220, which appears to be a late-stage merger. With an infrared luminosity of $L_{\mathsf{FIR}} \sim 1.5 \times 10^{12} L_\odot$, its star-formation rate is $\sim 200 M_\odot$/yr.

The most luminous infrared galaxies, with $L_{\mathsf{FIR}} \gtrsim 10^{13} L_\odot$, are called **ultraluminous infrared galaxies** (ULIRGs).



Arp 200,
NASA/ESA/HST.

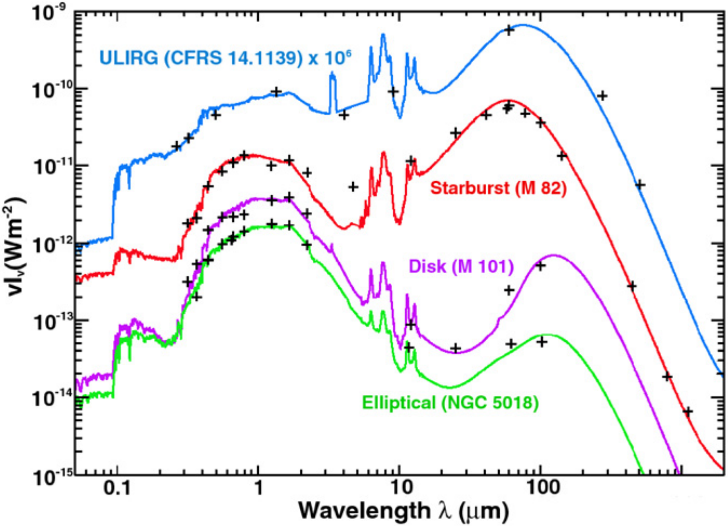


Fig 7.7 (P. Chanial, G. Lagache) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Normal elliptical and disk galaxies are brightest in the visible and near-infrared, at $\lambda < 2$ um. Most dust grains are cooler than 30 K, and their emission peaks beyond 100 um. In the starburst M82 and the ULIRG, dust intercepts far more of the light, and it is hotter, radiating mainly at $\lambda < 100$ um.