Lecture 7 : Galaxy transformations
Interactions and mergers

We have so far considered galaxies as isolated systems, as 'island universe'. The 'elbow room' for galaxies in the universe is however much smaller compared to that of stars in a galaxy. The typical distance between stars in our Galaxy is $\sim 10^7$ times larger than their sizes, whereas the typical distances between galaxies ($l \sim 1$ Mpc) is only about ~ 20 times their size. Also the timescale $l/v \sim 5 \times 10^9$ yr, where $v \sim 200$ km/s is the typical relative velocity of field galaxy, is much shorter than the Hubble time. This means that galaxies are liable to interact with one another within the lifetime.

There are different regimes of interactions that one can consider to understand through analytical or computational means.

- When a small system moves through a larger one—we can use the concepts of dynamical friction in this case.
- 'Slow' encounters, when the relative velocity V is much smaller than the internal velocity dispersion of the systems, $V \ll \sigma$ —we can use the adiabatic approximation in this case.
- 'Fast' encounters, when $V \gg \sigma$—this is called the impulse approximation.

0.1 Spiraling satellites (BT pp.427-430)

We have already considered dynamical friction in detail. We can discuss some of its applications here. For a stellar system with Maxwellian distribution of velocities $f(v)$ (with dispersion σ), with individual masses m and number density n, we found that the drag force on mass M moving with velocity V is given by (with $X = V/\sigma\sqrt{2}$)

$$F_{drag} = -\frac{4\pi G^2 M^2 nm \ln\Lambda}{V^2}\left[\mathrm{erf}(X) - \frac{2X}{\sqrt{\pi}}\exp(-X^2)\right]. \quad (1)$$

Consider a satellite galaxy spiraling inward inside an isothermal galaxy with flat rotation curve $V_c = const$. The mass density profile is $\rho(r) = V_c^2/4\pi G r^2 (= nm)$, and $X = 1$ (since $\sigma = V_c/\sqrt{2}$), and one has $F_{drag} = -0.43 \ln\Lambda GM^2/r^2$. The angular momentum, $L \sim MV_c r$ changes according to $\dot{L} = F_{drag} \times r$, which gives,

$MV_c r\frac{dr}{dt} = -0.43 \ln\Lambda GM^2$. Solving this with the initial conditions $r = r_i$ at $t = 0$ and $r = 0$ at t_{infall}, one has,

$$\frac{1}{2}r_i^2 = \frac{0.43 \ln\Lambda GM}{V_c} t_{infall} \quad (2)$$

Using parameters for a typical globular cluster orbiting our Milky Way, $M \sim 10^6$ $M_\odot$, $V_c \sim 250$ km/s, $r_i = b_{max} = 2$ kpc (so that $\ln\Lambda \sim 10$), one gets $t_{infall} \sim 2.5 \times 10^{11}$ yr, implying that the orbits of globular clusters have not changed significantly over their lifetime.

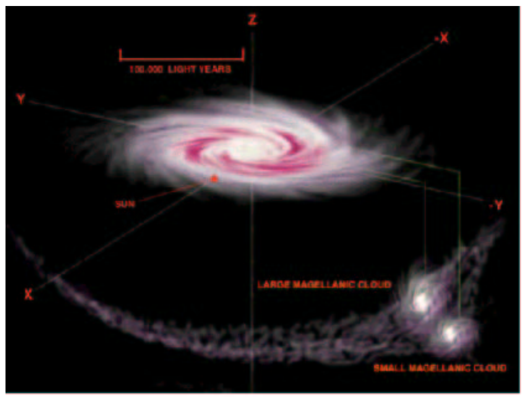

Figure 1: Artist's impression of the magellanic stream, of gas being pulled out of LMC and SMC. (movie at http://www.csiro.au/news/lmc.html)

If we use the parameters for the Large Magellanic Cloud, $M \sim 2 \times 10^{10}$ $M_\odot$ and $r \sim 60$ kpc (giving $\ln\Lambda \sim 3$), one has $t_{infall} \sim 3 \times 10^9$ yr. This estimate is however wrong as we have used circular orbits throughout. A more detail analysis (Murai & Fujimoto 1980) find a time scale of $\sim 10^{10}$ yr.

0.2 Tidal evaporation

The sharp edges of globular clusters is difficult to understand unless one takes into account the large scale gravitational field in which it is placed, and the tidal interactions with it. Otherwise one would expect that over a long period of time any sharp edge in the density distribution would be erased. It is believed that the outer stars are **tidally evaporated**. Since the system is orbiting the galaxy, the tidal radius is *not* where the r^{-2} force due to the galaxy and the system is

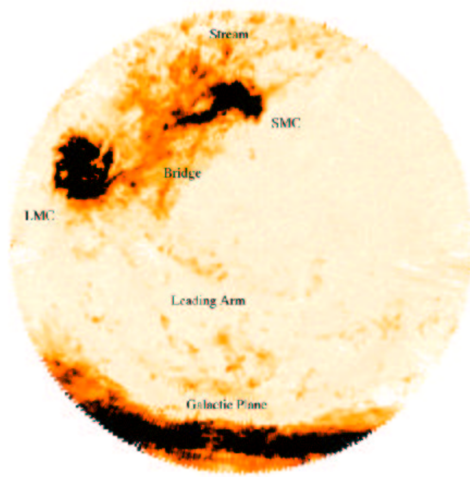

Figure 2: HI map of the region near LMC and SMC (Putman/ATNF).

balanced; there would be pseudo-forces in the rotating frame of the system. What is conserved in this frame is the Jacobi ingtegral,

$$E_J = \frac{1}{2}V^2 + \Phi_{eff}(r)\,, \tag{3}$$

where the effective potential in the rotating frame is $\Phi_{eff}(r) = \Phi(r) - \frac{1}{2}|\blacksquare \times \mathbf{r}|^2$. The derivative of Φ_{eff} gives rise to the coriolis and centrifugal forces. The equipotential contours (BT, figure 7-8) shows a saddle point between the two masses, which is the tidal radius. For the limit of a very small stellar system orbiting a large galaxy, $m \ll M$, we can write the effective potential along the line connecting the two point masses, which are separated by R, with origin at the smaller mass, as

$$\Phi(x) = -\frac{GM}{(R-x)} - \frac{Gm}{x} - 1/2\Omega^2(x-R)^2\,, \tag{4}$$

where $\Omega^2 = G(M+m)/R^3 \sim GM/R^3$ from Kepler's third law. Differentiating and equating to zero, one finds the tidal radius (the **Jacobi limit**) as, (see BT, pp. 451-452 for a more general derivation)

$$r_J \approx R\left(\frac{m}{3M}\right)^{1/3} \tag{5}$$

Stars with energy $E_J \geq \Phi_{eff}(r_j)$ will be lost to the system (evaporated). For satellites approaching a big galaxy, r_J and $\Phi_{eff}(r_J)$ decreases with time and the satellite will continually lose stars.

0.3 Slow encounters

During a slow encounter, orbits of stars with $t_{orbit} \ll t_{en}$ are not changed significantly. Here $t_{en} \approx \frac{\max(r_1,r_2,b)}{V}$, where r_1, r_2 are the sizes of the two interacting systems and b is the impact parameter and V is the relative velocity at closest approach.As the tidal field slowly changes, the orbit responds slowly (adiabatically). For distant and slow encounters (flyby), rapid orbits slowly modify but return to their original form after the tidal field decays after the flyby. The stars on rapid orbits, near the galactic centre, are not greatly affected by such encounters.

0.4 Fast encounters

At the other extreme is the regime when $t_{orbit} \gg t_{encounter}$, when $\sigma \ll V$. Stars do not move much during these encounters, so that there is no significant change in the potential energy. They however feel an impulse (force acting over a short time), which changes both the internal velocity dispersion, and the velocity of the centre of mass. The internal KE therefore changes, and in fact, the change is positive (BT pp.434-435). Essentially, the effect of this 'tidal shock' is to 'heat' hte stars. After the shock passes, the increased KE of the system causes it to expand and cool.

Applying virial theorem to the origin ('o') and the final ('f') relaxed systems, we can write $E_o = -KE_o$ and $E_f = -KE_f$. Initially after the encounter, we have $KE_i = KE_o + \Delta KE$ and $E_i = E_o + \Delta KE = -KE_o + \Delta KE$. After the relaxation, we can write, (since $E_f = E_i$) $-KE_f = -KE_o + \Delta KE$ implying that $KE_f = KE_o - \Delta KE$. This means that the system has cooled by an amount ΔKE. We know that the system was heated by the encounter by ΔKE, therefore the system cools during relaxation by $-2\Delta KE$. The system has then expanded and increased the PE by ΔKE.

If the encounter is distant, then one can determine the chenge in the energy of a spherical system of mass M and size r, as a mass m passes by at distance b with speed V (BT pp.437-438), as,

$$\Delta E \approx \frac{4G^2M^2mr^2}{3b^4V^2}. \tag{6}$$

The spherical system is deformed to an ellipsoid, with the major axis pointing toward the point of closest approach (like the way Moon raises tideas on the oceans on Earth).

During such tidal shocking in galaxies in clusters, for example, discs of galaxies get heated, which increases their thickness and the corresponding Toomre's Q parameter, inhibiting spiral arm formation. Such **galaxy harassments** lead to spiral galaxies appear to have earlier Hubble type (Sb can be turned into Sa, e.g.).

When galaxies have penetrating encounters, that is, when b is close to zero, the change in energy can be significant. It is easy to work out the case when the galaxies are assumed to have density distribution as in Plummer model,

$$\rho(r) = (3Ma^2/4\pi)(r^2 + a^2)^{-5/2}, \tag{7}$$

where M is the total mass, a is the scale length and r is the spherical radius. The force is ($\Phi = -GM/\sqrt{r^2+a^2}$),

$$F_r(r) = -GMr(r^2 + a^2)^{-3/2}. \tag{8}$$

The lateral speed that a test particle at distance D develops after the penetrating galaxy rushes past with a large and almost constant speed U, is given by, (in a cylindrical coordinate system, we have the vertical distance of the perturber as $z_p = \sqrt{r^2 - D^2} = Ut$)

$$\begin{aligned} v_\perp(D) \quad &= \int_{-\infty}^{\infty} F_r(r)(D/r)dt = (2GMD/U)\int^{\infty} \frac{dz_p}{(z_p^2 + D^2 + a^2)^{3/2}} \\ &= (2GMD/U)\Big[\frac{z_p}{(D^2+a^2)\sqrt{z_p^2 + D^2 + a^2}}\Big]_0^{\infty} = \frac{2GMD}{U(D^2+a^2)} \end{aligned} \tag{9}$$

This depends only on the distance from the perturber's axis. This tidally induced motion of stars would amount to a change in kinetic energy (in terms of the surface mass density profile $\Sigma(r)$),

$$\Delta E = \frac{1}{2}v_\perp^2 dM = \pi\int_0^{\infty} v_\perp^2 \Sigma(r) r dr = \frac{G^2M^3}{3V^2a^2}. \tag{10}$$

The surface mass density in this case is (writing $\lambda^2 = w^2 + a^2$)),

$$\begin{aligned} \Sigma(w) \quad &= 2(3Ma^2/4\pi)\int_0^{\infty} \frac{dz}{(z^2 + w^2 + a^2)^{5/2}} \\ &= 2(3Ma^2/4\pi)\Big[\frac{1}{3\lambda^2}\frac{z}{(z^2+\lambda^2)^{3/2}} + \frac{2z}{3\lambda^4\sqrt{z^2+\lambda^2}}\Big]_0^{\infty} \\ &= Ma^2/(\pi(w^2+a^2)^2) \end{aligned} \tag{11}$$

The integral for the energy change is then easily verified, since,

$$\int_0^\infty \frac{r^3 dr}{(r^2+a^2)^4} = \int_0^{\pi/2} \sin^3\theta \cos^3\theta d\theta = 1/12 . \quad (12)$$

Figure 3: Ring in cartwheel galaxy.

This is the other extreme regime of galactic encounters. In this case of bull's eye collision, one can show that (for galaxies with singular isothermal spheres, with circular velocities V_c) the shock imparts a change in speed of stars in the radial direction, of $\Delta V_r \approx -\pi V_c (V_c/V)$. Stars then move inward immediately after the encounter, but they rebound when they hit the angular momentum barrier. Basically it sets up an epicyclic motion around the guiding centre, the pre-collision orbit. The period of these epicyclic oscillation increases with r in the disc (in a flat rotation curve disc, $\kappa \propto \nu/r$ so that the period $P \propto r$). Therefore when the stars at a given radius have rebounded and begun to move outwards, those at a slightly larger radius are still moving inwards. Consequently there would be a crowding of stellar orbits. These caustics can cause 'ring' like structures (Lynds & Toomre 1976). (BT pp.447-449)

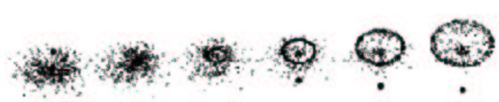

Figure 4: From Lynds and Toomre's simulation.

1 Results from numerical simulations

Tidal tails : The first simulations by Toomre & Toomre (1972) showed that long thin features of, say, the Antennae galaxy (NGC 4038/9), are the results of tidal interactions and were created from cold discs (and no jets or explosions, as were suggested earlier). It makes a big difference whether or not the galaxy rotates in the same direction as the perturber is moving : in the case of same direction, one gets strong tidal tails and one gets muted tails in the other case (BT, Figures 7.13 and 7.14). The reason is that in the first case, the stars on the near side move in the same direction, making the relative velocity small so that tidal perturbation acts for a long time, creating a strong tail. The gas, on the other hand, shocks and forms stars, and moves inward after losing angular momentum. Such flybys are usually associated with enhanced nuclear star formation.

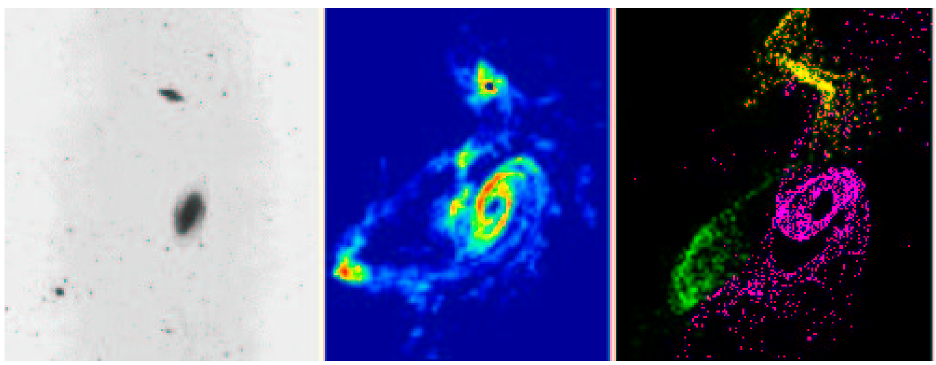

Figure 5: Left panel shows the optical image of M81/M82/NGC 3077 group. M81 is the brightest galaxy and M82 is at top (which is a starburst galaxy). The middle panel shows a 21cm HI map of the same field. The right panel shows a computer model of the system (Min Yun?NRAO).

Gas in ISM often extends beyond the observable stars and therefore HI studies often show dramatic tidal tails.

Major mergers : It appears that merger timescale can be very short, of order a few orbital times. Dark matter in the halo plays an important role in these mergers, by absorbing most of the angular momentum and making the dynamical friction very effective.

Discs are very fragile systems and are destroyed during major mergers. An interesting result is that the final density distribution is found to be close to the $R^{1/4}$ law (Schweizer 1982; see NGC 7252). This strongly suggests that (at least some)

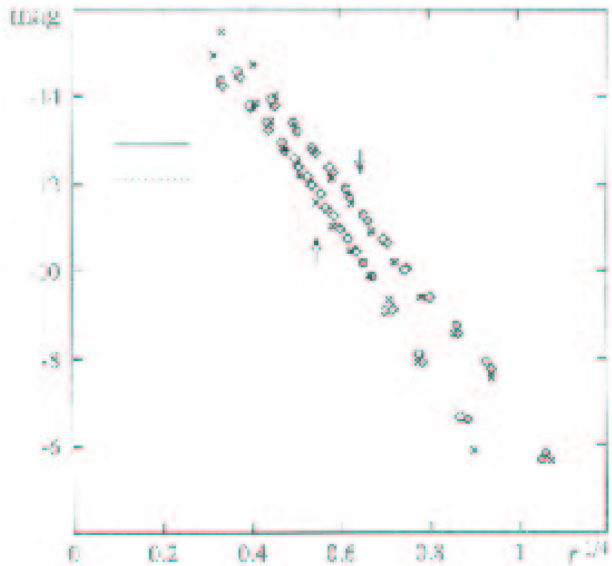

Figure 6: Surface brightness profiles of merger remnants are close to $r^{1/4}$ profiles (from Barnes 1989 Nature, 338, 123).

ellipticals were created by mergers. There are however some counter-arguments to this : (1) ellipticals are mostly found in clusters, where the relative velocity is too large for mergers (but then in hierarchical structure formation, ellipticals form earlier in smaller groups, which merge to form clusters?); (2) ellipticals have more globular clusters than spirals (but then globular clusters form during mergers); (3) the phase space density of ellipticals is larger than spiral, (but gas dissipation and ensuing star formation can increase the phase space density).

Gas: The dissipational nature of gas allows it to fall towards the centre quickly. It is found that the interaction forms a **bar**, and the gas gets shocked while passing through the bar, and loses most of its angular momentum due to offset between stars and gas and the resulting gravitational pull. One therefore expects high star formation rates (starbursts). In some cases the gas angular momentum can be opposite to the stellar angular momentum. In this way counter-rotating cores can be formed, similar to those found in some ellipticals (Franx and Illingworth 1988 APJLett 327, L55; Bertola and Bettoni 1988 ApJ 329, 102) and spirals (Braun et al. 1992 Nature 360, 442). It appears that the fraction of such ellipticals with a 'kinematically distinct core' is as large as $\sim 25\%$.

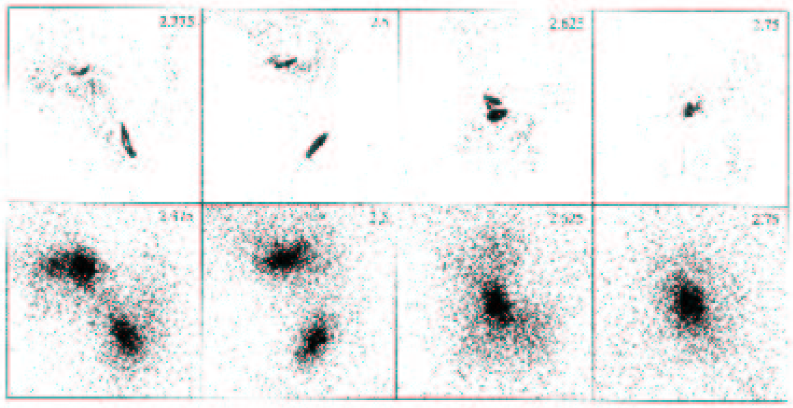

Figure 7: The upper row shows the fate of gas and the lower row shows the evolution of the stellar system (Barnes 1995).

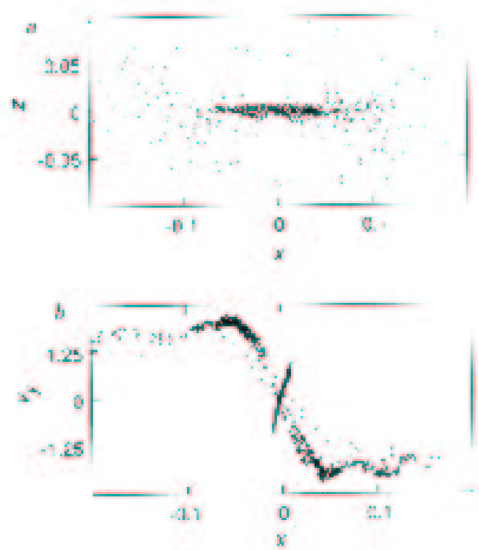

Figure 8: Gas distribution in remnant is shown at top (edge-on) adn the rotation curve at the bottom (Hernquist & Barnes 1991, Nature, 354, 210).