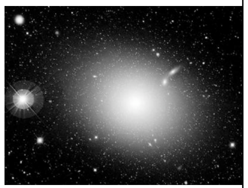
FORMATION AND EVOLUTION OF GALAXIES

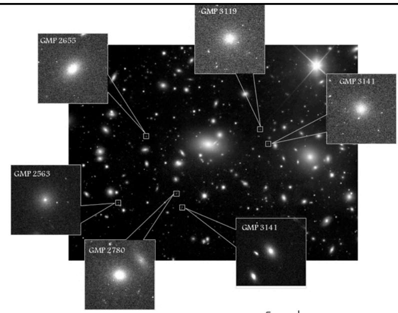
- Virial theorem
  - Faber-Jackson and Tully-Fisher
- Processes that transform galaxies
  - Dynamical friction
  - Tidal disruption

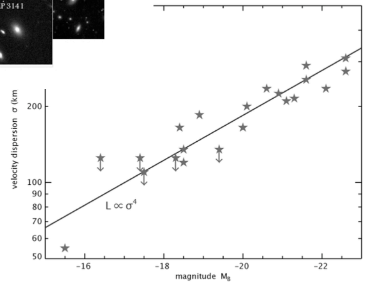


Lecture 12:

EXTRA LECTURE: Tuesday 22 Feb
Nuffield G13

Elliptical galaxies: Faber-Jackson relation





Ellipticals: Faber-Jackson

The luminosity of an elliptical roughly scales as its average velocity dispersion as the *Faber-Jackson relation*

$$L \propto \sigma^4, \tag{6.2}$$

and is often used to measure distances to ellipticals (this was the relation used by the 'Seven Samurai', for instance, in the study that found evidence for a 'Great attractor' in our neighbourhood). But it turns out that all ellipticals don't obey the F-J relation in the same way–the surface brightness of the elliptical plays a role as well.

If we assume that the velocity dispersion of stars σ and the M/L ratio is constant throughout an elliptical galaxy, we can use the virial theorem to infer a relation between the global measurable parameters of ellipticals. From the virial theorem we have $2T + V = 0$, or, approximately,

$$Mv^2 - \frac{3}{5}\frac{GM^2}{R} = 0.$$

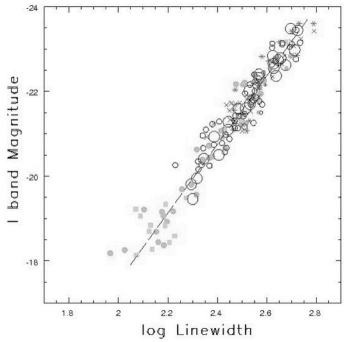
$$M \sim v^2 R/G. \qquad \Sigma \equiv M/R^2 \sim \frac{v^2}{GR},$$

$$M \propto L$$

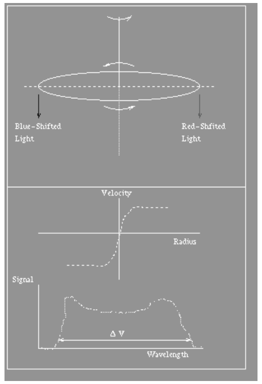
$$R \propto \frac{LG}{\sigma^2} \qquad L \propto 4\pi\left(\frac{LG}{\sigma^2}\right)^2 \Sigma$$

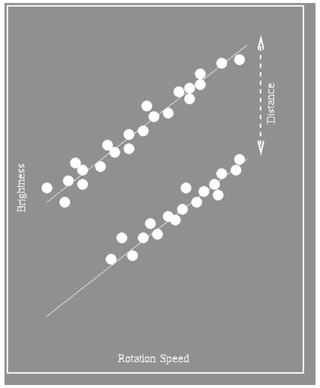
$$L \propto \frac{\sigma^4}{4\pi G^2\,\Sigma}$$

Spirals: Tully Fisher relation



Spirals: Tully Fisher relation





2) 'Parameter Relations' in (Present-Day) Galaxies

Many parameters with which to describe the stellar component of galaxies are tightly correlated

(though such correlations are/were not 'expected')

Most of them can be cast as

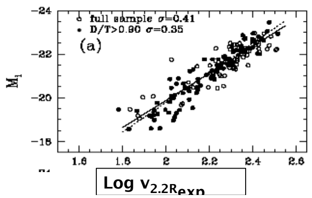
(stellar) luminosity/mass vs

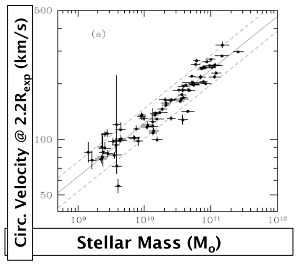
- size
- characteristic velocity (Tully-Fisher; Faber-Jackson)
- 3D - shape
- (radial) concentration, black hole mass

These correlations are important constraints on galaxy formation mechanisms

The 'Tully-Fisher' Relation for Disk Galaxies

- Tully&Fisher 1977
  - HI linewidth correlates well with absolute magnitude of spiral galaxy.
- In general:
  - Correlation between circular velocity and stellar luminosity
  - L_{opt} can predict v_{circ} to ~5-8%
    - $M_*, L_{opt} \sim v_c^{3-4}$
- Historically: extremely important distance indicator
- Now: also constraint on galaxy formation





Explanations for a Tully-Fisher-like relation

- Let's consider the self-gravitating case

$$v_{max}^2 \sim G\Sigma_0 R_d \quad \text{with } \Sigma_0 \text{ central mass density and } R_d \text{ scale length}$$

$$\Rightarrow L \sim v_{max}^4 I_0^{-1} \Gamma_{disk}^{-2} \quad \text{with } I_0 = \Sigma_0/\Gamma_{disk}$$

$\Gamma = M/L$

Right slope, but central surface brightness/mass density should be a 3rd parameter

- Let's assume the disk is a small fraction assembled from a DM halo

For the halo

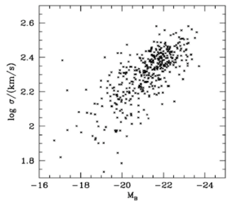
$$r_{vir} = \sqrt{\frac{2}{\Delta_{vir}(z)}}\frac{V_{vir}}{H(z)} \quad \text{and} \quad M_{vir} = \sqrt{\frac{2}{\Delta_{vir}(z)}}\frac{V_{vir}^3}{GH(z)} \qquad \rho_{crit} = 3H^2(z)/(8\pi G)$$

$\Delta_{vir}(z)$: Factor by which density within virial radius exceeds mean density of the universe

$$M_d \approx 1.3 \times 10^{11} h^{-1} M_\odot \left(\frac{m_d}{0.05}\right)\left(\frac{V_{vir}}{200\,\mathrm{km\,s^{-1}}}\right)^3$$

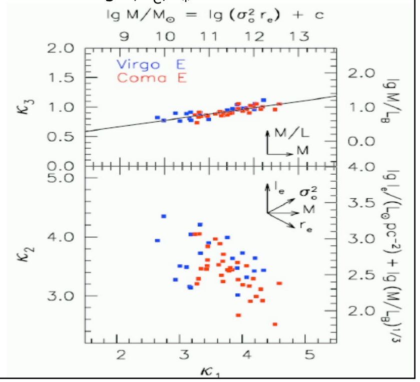
with NO surface brighness/mass dependence!

Parameter relations for (massive) spheroids: Faber-Jackson and the ‘fundamental plane’



Faber-Jackson relation between central velocity dispersion and total magnitude of elliptical galaxies ($L_B \sim \sigma^4$).

One version of the ‘fundamental plane’, involving L, R_e, σ_*



- **For spheroids: → 3-parameter relation!!**
- M/L = f(M)

Processes that transform galaxies

a) **Dynamical friction**

b) **Tidal disruption**

c) **Violent relaxation**

d) **Mergers, or how galaxies become spheroids**

a) Dynamical friction

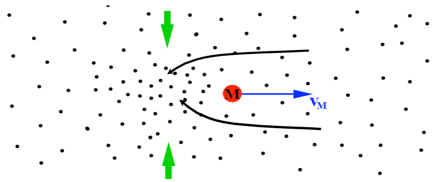
Chandrasekhar 1943

A “heavy” mass, a satellite galaxy or a bound sub-halo, will experience a slowing-down drag force (dynamical friction) when moving through a sea of lighter particles

Two ways to look at the phenomenon

a) A system of many particles is driven towards “equipartition”, i.e. $E_{kin}(M) \sim E_{kin}(m)$
=> $V^2_{\text{of particle M}} < V^2_{\text{of particle m}}$

b) Heavy particles create a ‘wake’ behind them



$$F_{dyn.fric} = -\frac{4\pi G M^2}{V_M^2}\rho_m \cdot \ln\Lambda$$

Where m << M and ρ_m is the (uniform) density of light particles m, and $\Lambda = b_{max}/b_{min}$ with $b_{min} \sim \rho_M/V_2$ and $b_{max} \sim$ size of system typically lu $\Lambda \sim 10$

Effects of dynamical Friction

a) Orbital decay: $t_{df} \sim r / (dr/dt)$

$V_{circ}\, dr/dt = -0.4 \ln \Lambda\, \rho_M/r$

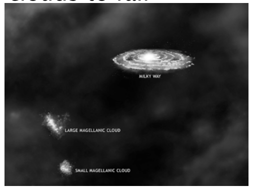
or

$$t_{df} \approx \frac{1.2}{lu\Lambda}\frac{r_i^2 V_c}{\rho M}$$

Dynamical friction effective for
- high (host galaxy) densities
- Low mass (v_c) hosts
- small (orbital) radii
- Massive satellites (M)

Example: orbital decay of a satellite galaxy in MW Halo

How long will it take for the Magellanic clouds to fall into the Milky Way?

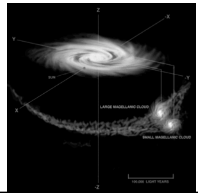


$V_{cir}(MW) = 220$ km/s

$M_{LMC} = 2 \times 10^{10}\ M_{SUN}$

$R_{LMC} = 50$ kpc

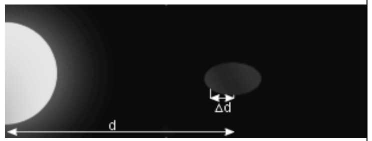
$\Rightarrow\ T_{df}(LMC) = 1.2$ Gyr



b) Tidal disruption

Wikipedia!

Roche limit for the existence of a satellite, its self-gravity has to exceed the tidal force from the 'parent'



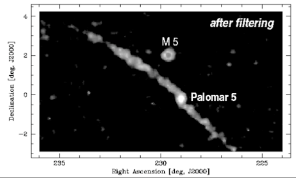
$$V_T = -\frac{3GM}{2d^3}\Delta d^2$$

Tidal radius:

$$R_{tidal}(satellite) = f\left[\frac{M_{satellite}}{M_{host}(< R_{peri})}\right]^{1/3} \times R_{peri} \quad \text{with } f \approx 2/3[1-\ln(1-e)]^{-1/3}$$

In cosmological simulations, many DM sub-halos get tidally disrupted.

- How important is it, e.g. in the Milky Way?
- The GC Pal 5 and the Sagittarius dwarf galaxy show that it happens



Tidal stripping of Sagittarius dwarf