Lecture 1 : Morphological classification and luminosity function

There are a few classification schemes for galaxies based on morphology (in a particular band, mostly blue band). They are naturally based on restricted and incomplete set of information and have many biases (like surface brightness bias etc). They are still useful since they do seem to be connected to physical properties of galaxies. The most commmonly used scheme is that of Hubble-Sandage system. It is based on four basic components—spheroid,disc,bar and arms—of galaxies. The presence and relative brightness of these components define the morphological class. There are also other systems ike that de Vaucouleurs (1959), Morgan (called the Yerkes system) and the DDO system (van den Bergh). Note that the Hubble system does not include dwarfs (which are the most common type of galaxies in the universe), interacting galaxies, low surface brightness galaxies and so on.

1 The Hubble sequence

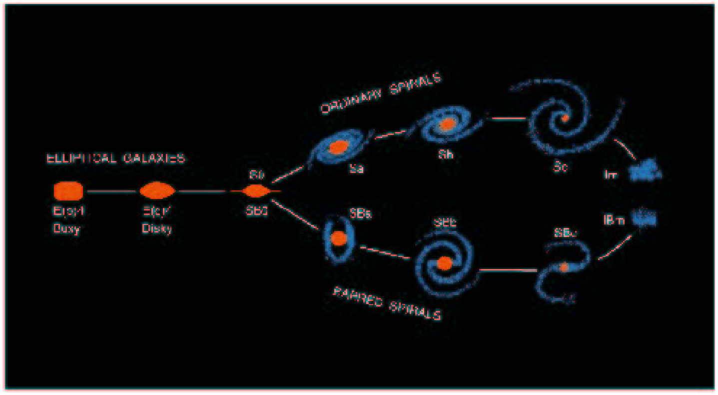


Figure 1: The (modified) Hubble tuning-fork sequence (Kormendy and Bender 1996, ApJ, 464, L119).

For historical reasons, one calls the galaxies on the left 'early' and on the right 'late' (which came from Jeans' theory of galaxy formation). This sequence is no longer thought to represent a simple evolutionary sequence.

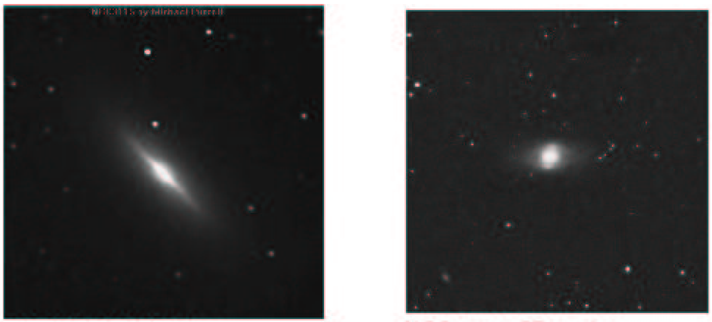
Ellipticals are characterised by a rapid decline in brightness with radius. They are named 'En' where $n = 10(1 - b/a)$ (e.g., E5 means b/a=0.5). There are not many ellipticals with $n \geq 6$. Deviations from pure elliptical shape is parameterized by a quantity a_4 (we will discuss this in lecture 3). Kormendy & Bender (1997) suggested a revision with increasing ‘disky-ness’ to the right.

Figure 2: Examples of E0 (M87) galaxy.

Figure 3: M110 is an E6 galaxy.

There are then *Lenticulars* or SO galaxies which have a central concentration (bulge) and an envelope (disc) of less steep gradient in surface brightness. They are difficult to classify though, unless one is seen edge-on.

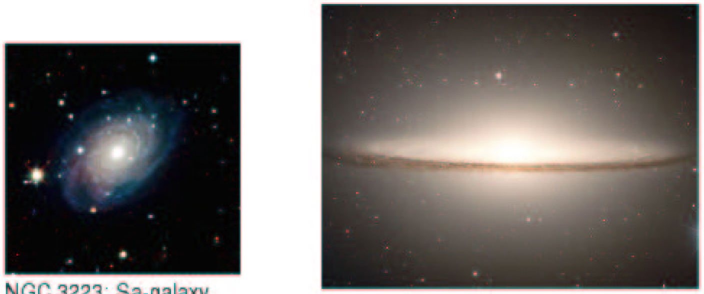
Spirals have bulges and discs with spiral arms. They are called Sa, Sb, Sc and so on according to (1) decreasing bulge/disc ratio (2) pitch angle (see lecture 4) and (3) resolution of arms into HII regions. It is now known that the spiral sequence is basically the sequence of bulge luminosity, which decreases with the



NGC 3115: S0-galaxy

NGC 4371: SB0-galaxy

Figure 4: Examples of SO and SBO galaxies



NGC 3223: Sa-galaxy

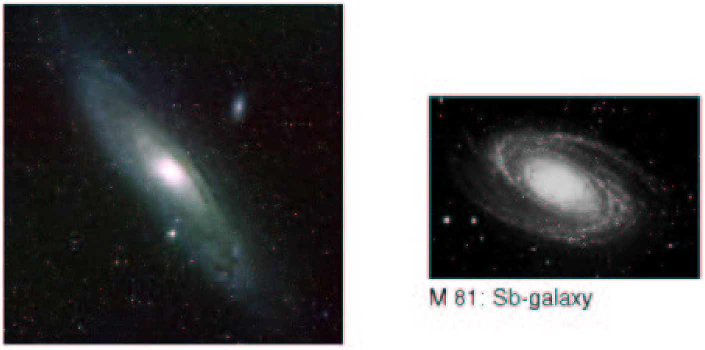
M 104 (Sombrero), Sa-galaxy

Figure 5: Examples of Sa galaxies

spiral type. There are nuclear rings in some galaxies, connected to star formation and are probably linked with resonances (lecture 5). If there is an inner ring, then arms usually start from the ring.

There are also **barred galaxies**, and there is a replica of spiral stages with bars, with SBa, SBb, SCb and so on. Then there are **irregular galaxies** like the Magellanic clouds, which have no nucleus and have low luminosity in general. There are also **Dwarf galaxies** – dwarf irregulars (dIrr) have no clear disc or nucleus, have patchy star formation and are often HI rich; dwarf ellipticals (dE) and dwarf spheroidals (dSph) appear to be small versions of ellipticals, but they do not follow the typical relations of ellipticals.

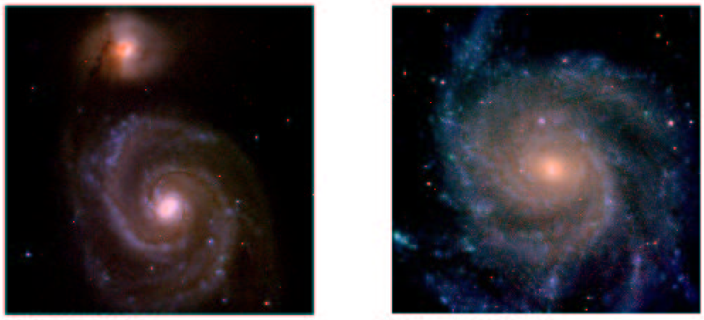
How common are the different types of galaxies? From the RSA catalogue, one finds that the E+E/SO galaxies comprise about 17%, S0+S0/a about 14%, Sa/Sab about 12.5%, Sb/Sbc about 19%, Sc about 30% of the total population and



M 31 (Andromeda-galaxy): Sb-galaxy

M 81: Sb-galaxy

Figure 6: Examples of Sb galaxies.



M 51: Sc-galaxy

M 101: Sc-galaxy

Figure 7: Examples of Sc galaxies.

about a fourth of all spiral galaxies (of each type) being barred.

2 M/L ratios

The ratio of mass to luminosity is expressed in terms of the values for the Sun. Typically, for a 0.5 solar mass star, $M/L \sim 10 M_\odot/L_\odot$ and for 2 solar mass star, $M/L \sim 0.1 M_\odot/L_\odot$. In galaxies, the mass is dominated by low mass stars and the brightness is dominated by massive stars. The luminous parts of typical galaxies have $M/L \sim 10 M_\odot/L_{B,\odot}$, and is usually in the range $2 < M/L_B < 20$.

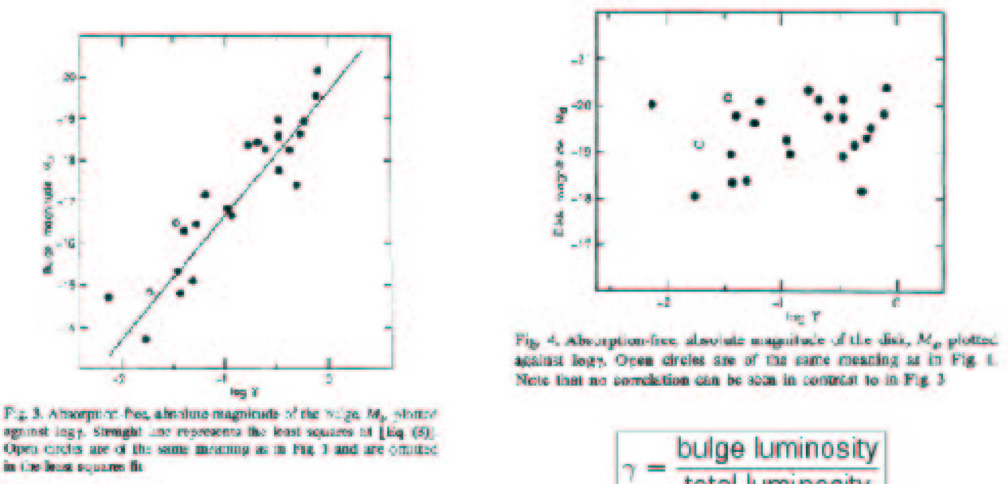


Fig. 3. Absorption-free absolute magnitude of the bulge, M_b, plotted against log γ. Straight line represents the least squares fit [Eq. (5)]. Open circles are of the same meaning as in Fig. 1 and are omitted in the least squares fit

Fig. 4. Absorption-free absolute magnitude of the disk, M_D, plotted against log γ. Open circles are of the same meaning as in Fig. 1. Note that no correlation can be seen in contrast to in Fig. 3

$$\boxed{\gamma = \frac{\text{bulge luminosity}}{\text{total luminosity}}}$$

Figure 8: Bulge luminosity is plotted on left against γ the ratio between bulge and total luminosity, and the disc luminosity is plotted against γ (Yoshizawa, Wakamatsu 1975, A&A, 44, 363)

3 Luminosity function

The luminosity function (LF) describes how the relative number of galaxies varies with luminosity. One defines $\phi(L)dL$ as the number density of galaxies with luminosities in the range $L, L+dL$. Schechter proposed a form of the LF, motivated by the theoretical Press-Schechter mass function (Schechter 1976, ApJ, 203, 297), as,

$$\phi(L)dL = n_* \left(\frac{L}{L_*}\right)^\alpha \exp(-L/L_*) d(L/L_*) \,. \tag{1}$$

There are several versions of it using magnitude instead of L. The power law dominates at low luminosities and the exponential cutoff is prominent at high luminosities, for $L > L_*$, implying that very luminous galaxies are rare. L_* is the luminosity at the break between these two regimes.

It is important to have a complete sample of galaxies to estimate LF. Usually samples are limited by magnitude or surface brightness. It is possible to check the completeness by the V/V_{max} test. Here V is the volume out to an object and V_{max} is the volume to the object if it is assumed to be at the limiting magnitude of the sampIle. For an uniform density of objects (which need not be true though), a sample is complete for this limiting magnitude is the average V/V_{max} is 0.5. Clas-

Figure 9: Examples of SBa galaxies.

sically one estimates the LF by multiplying the number in each apparent magnitude bin by $1/V_{max}$, which corrects each magnitude bin to the same effective volume (Felten 1977). This however assumes a uniform space density. The differential/cumulative ratio method (Kirshner et al 1979) avoids this assumption. One here assumes that the shape of LF does not depend on the position/environment. One argues that $N(M) = \phi(M) \times D(x,y,z)$ where $D(x,y,z)$ is a position dependent total galaxy density and $\phi(M)$ is the LF, expressed as a probability. One then integrates over M, and argues that $N(M)/N(>M) = \phi(M)/\phi(>M)$. Now $\phi(M)$ and $\phi(>M)$ are evaluated as before and from this ratio the Schechter function is estimated.

Typically one has $L_* \sim 10^{10} h^{-2} L_{B,\odot}$ (in the field), $\phi_* \sim 0.01$ Mpc^{-3} h^3 and $\alpha \sim -1 -- 1.3$. The integrated luminosity per unit volume is given by,

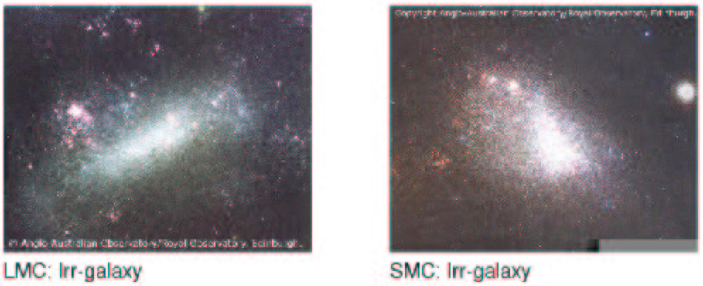
$$j = \int_0^\infty L\phi(L/L_*)d(L/L_*) = \Gamma(\alpha+2)\phi_* L_* \sim 10^8 L_\odot Mpc^{-3}. \qquad (2)$$

Using a typical M/L=10 one then gets a mass density of $\rho_* \sim 10^9$ M$_\odot$ Mpc^{-3}, which implies $\Omega \sim 0.004$.

NGC 1365: SBc-galaxy

NGC 613: SBc-galaxy

Figure 10: Examples of SBc galaxies.



LMC: Irr-galaxy

SMC: Irr-galaxy

Figure 11: Examples of irregular galaxies.

The luminosity function depends strongly on the environment. In general cluster LF is easier to estimate since galaxies are at the same distance. The power law α for cluster LF is often steeper than in the field, with $\alpha \sim -1.3$. There is a slight dip at $M_B \sim -16$. This basically arises from a different mix of spirals, SOs, ellipticals and dwarfs. In clusters, one has more E,SO and dEs. The dip occurs between the changeover from normal to dwarf galaxies.

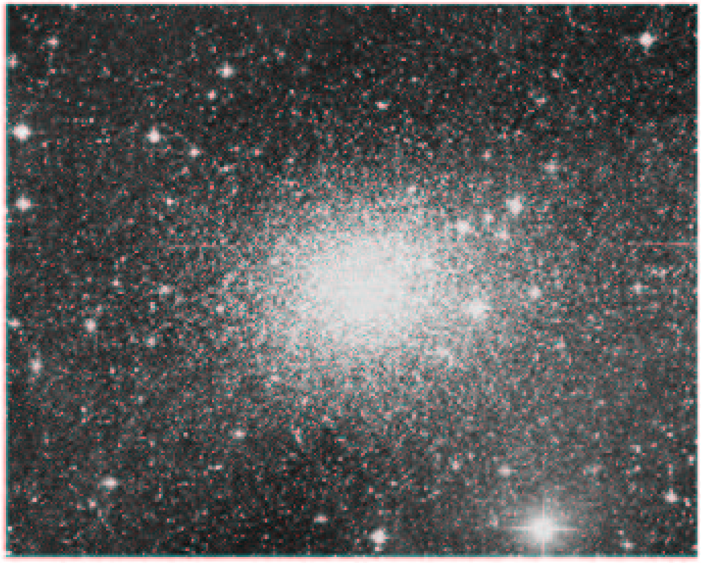


Figure 12: Example of a dE galaxy (Sculptor dwarf; a companion of Milky Way).

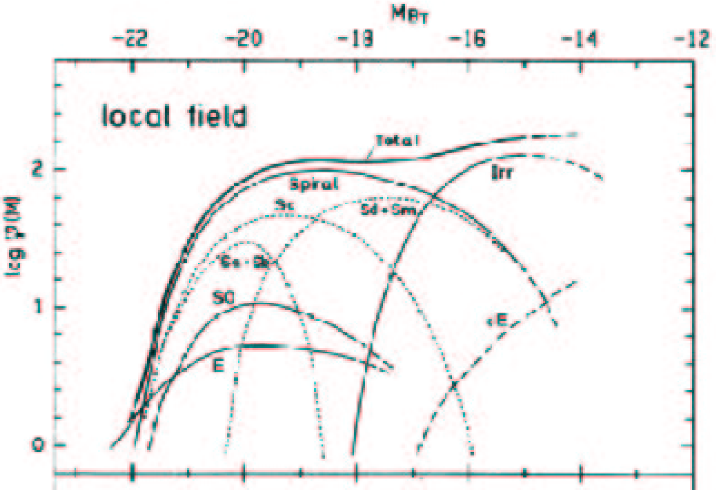


Figure 13: The field luminosity function (Bingelli, Sandage, Tamman 1988 ARAA 26, 509).

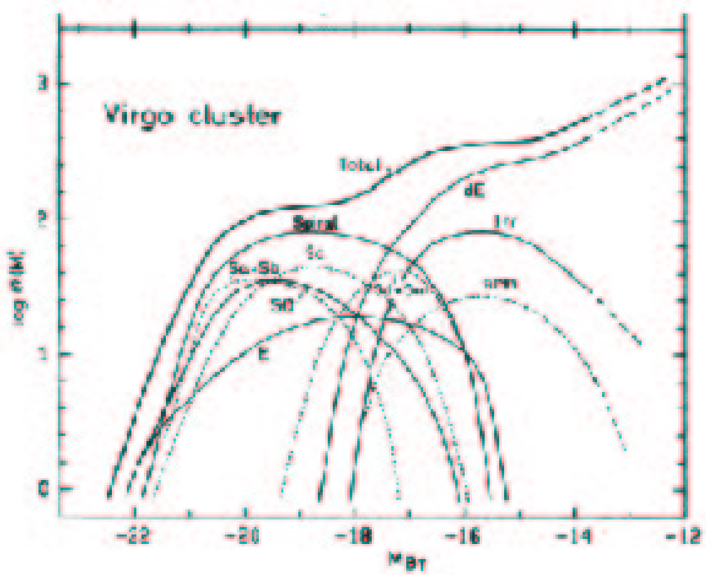


Figure 14: The LF for Virgo cluster (Binggeli, Sandage, Tamman 1988 ARAA)