Lecture 4 : Spiral galaxies

We now move on to spiral galaxies, which are more complex systems than ellipticals. They are complex not only because there is a large range of morphological appearances, but also because there is range in the stellar populations, with old, intermediate and young stars; with a wide range in stellar dynamics (cold, rotationally supported disk stars and hot, dispersion supported halo stars). There is also a significant amount of ISM.

1 Basic Components

- Disc–It contains metal rich stars. Mainly circular orbits with very small random motion. There is current star formation, and it also contains HI, molecular clouds, dust.
- Bulge–It contains metal poor to very metal rich stars. Rotation is not significant. Centrally concentrated.
- Stellar halo–Has metal poor stars, with little or no rotation, has low surface brightness, contains globular clusters, X-ray gas, and low density HI-HII gas.
- Dark halo–It dominates the mass content, especially outside ~ 10 kpc. It is perhaps mildly flattened.

2 Surface brightness profile

The bulges follow the de Vaucoulers $r^{1/4}$ profile as ellipticals. The discs however follow an exponential profile,

$$I(r) = I_0 e^{r/R_0} \tag{1}$$

where R_0 is the scale length. It follows that $L_{tot} = 2\pi I_0 R_0^2$. Typically $R_0 \sim 2-5$ kpc. Large discs generally have lower surface brightness. It was earlier thought (Freeman 1970) that the central blue surface brightness is a constant $I_{B,0} \sim 21.65 \pm 0.3$ mag/ss, but **low surface brightness (LSB)** galaxies have recently been discovered.

The vertical profile is also fit well by exponential law, with a vertical scale height.

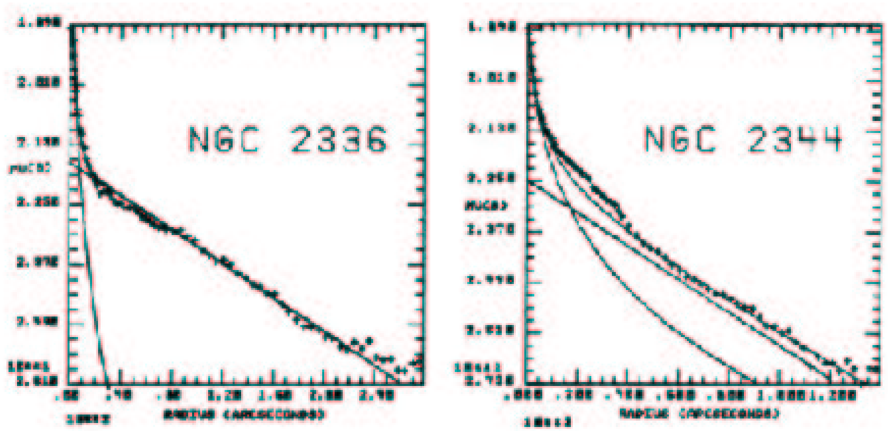

Figure 1: Averaged bulge and disc profiles for 26 spiral galaxies (Boroson 1981 ApJS, 46, 177).

2.1 Disc/Bulge ratio

Along the Hubble sequence, the ratio of total Disc and Bulge luminosity (D/B) increases monotonically : from 0.7 for S0, to 3 for Sb to 50 for Sd galaxies. The ratio of bulge to the total luminosity decreases accordingly from 0.57 for S0s to 0.24 for Sb to 0.02 for Sd galaxies. These are only average values (actual data has a large scatter). (Simien, de Vaucouleurs 1986, ApJ, 302, 564)

3 Velocity field of disc matter

The most prominent motion of gas and stars in spiral galaxies is that of rotation, random speeds in HI gas being of order only $\sim 8-10$ km/s. Suppose one observes a purely rotating disc tilted at an angle i to face-on. We can specify the position of a star by its radius r and azimuth ϕ measured from the diameter AB lying perpendicular to our viewing direction. The radial velocity is then $v_r(r,i) = v_c(r)\sin i \cos\phi$. If one draws the contours for equal values of the radial velocity v_r they will connect points with equal values of $v_c(r)\cos\phi$ and will form a *spider diagram*. The line AB will be the kinematic major axis. In the central region, $v_c(r) \propto r$ (see below) the contours are parallel to the minor axis, and further out, where $v_c(r)$ is mostly flat, they run radially away from the centre. If v_c falls, the extreme velocity contours close back on themselves.

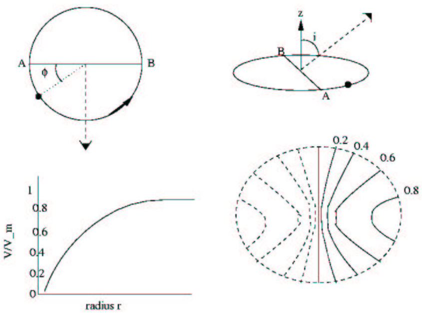

Figure 2: Upper panels: rotating disc viewed from above. Below left: rotation curve and right : spider diagram of contours of equal values of $v \sin 30^\circ$ for a disc viewed at angle 30 degrees from face-on.

4 Mass estimates from rotation

For rotation velocity $v_c(r)$ one in general has,

$$M(<r) = \beta \frac{r v_c^2(r)}{G}, \tag{2}$$

where β is a factor depending on geometry, with $\beta = 1$ for a spherical distribution of mass. One can show that for a flattened disc (in the inner region, for $r < 4R_0$),

$$v_c^2(r) \sim 0.77 \frac{GM}{R_0} \frac{0.44(r/R_0)^{1.3}}{1 + 0.235(r/R_0)^{2.3}} \tag{3}$$

This has a maximum value of v_c at $r \sim 2.2R_0$ and for $r \geq 6R_0$ the velocity falls off in a Keplerian way, as $r^{-1/2}$.

In the 1960s, the rotation curve documented by Burbidge and colleagues from Hα assumed Keplerian fall-off beyond their data. In 1970s and 80s Rubin's data showed that v_c was flat till $2-3R_0$, and concluded extra, dark matter. Kent (1986) however found that rotation curves derived from light profiles (exponential) match the observed data. With HI data however one can go deeper, to $\sim 5R_0$ and it showed that v_c hardly declined. This implies dark matter, especially in the outer regions. The dark matter naturally has a profile $\rho \propto r^{-2}$ in the outer region. In the simplest case, one assumes that,

$$\rho = \rho_0 \frac{a^2}{a^2 + r^2}, \tag{4}$$

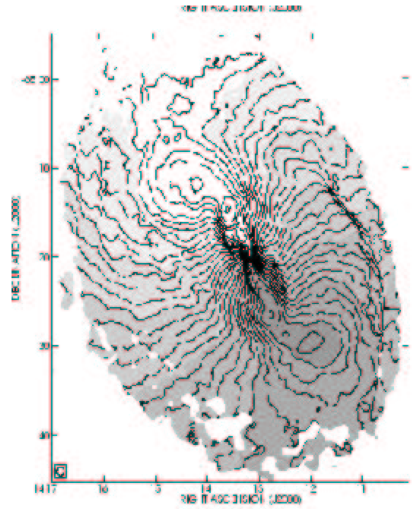

Figure 3: Observed spider diagram of the Circinus galaxy (Jones et al 2001)

which gives a mass within r, $M(<r) = 4\pi\rho_0 a^3(\frac{r}{a} - \arctan\frac{r}{a})$, therefore the circular velocity is given by $v_c^2(r) = GM(r)/r = 4\pi G\rho_0 a^2(1 - \frac{a}{r}\arctan\frac{r}{a})$. This has the asymptotic behaviour, $v_c \to \sqrt{4\pi G\rho_0 a^2} =$ constant for $r \gg a$ and $v_c \propto r$ for $r \ll a$. Notice that $M(r) \propto r$ and is divergent.

In general, one can account for the inner rotation curve with bulge and disc matter, with $M/L_B \sim 3-5$, but one needs a dark matter halo for the outer rotation curve, with a total $M/L_B \sim 30$. One therefore has five times more dark matter than total baryonic mass.

One interesting aspect of the rotation curves is that most curves are flat after a rapid rise, which implies that it is flat in both regions, where v_c is determined by disc matter and where it is determined by the halo dark matter. It is intriguing to note that matter in these two different regions are somehow matched to produced the same rotation velocities. This is called the **disc-halo conspiracy**. Perhaps this has some important clue about the formation process of spiral galaxies.

5 Tully-Fisher relation

It was discovered by Tully and Fisher in 1977 that the maximum rotation velocity v_m (derived from rotation curves or integrated profiles of HI 21 cm) is correlated with the total luminosity as $L \propto v_m^\alpha$ with $\alpha \sim 3-4$. Like the Faber-Jackson relation

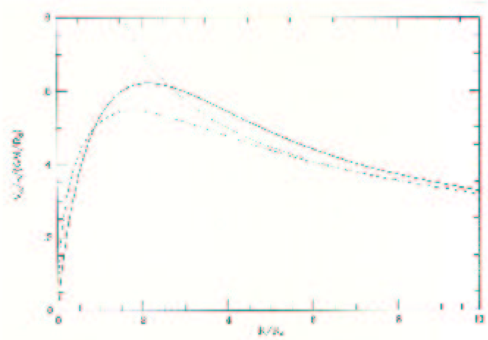

Figure 4: Rotation curve of an exponential disc (solid curve) BT. Fig 2-17

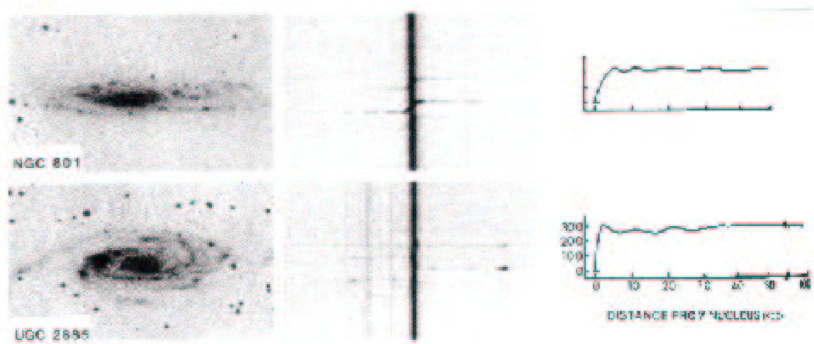

Figure 5: Rotation curves from Rubin (1983) (BT. p. 600)

for ellipticals, this perhaps arises from virial arguments. If $v_c^2 \propto M/r$ and $L \propto I_0 r^2$, then one gets T-F relation if $(M/L)^{-2} I_0^{-1}$ is roughly constant, which is more or less true.

Usually one uses the TF relation for longer wavelengths (I or H bands) for which the scatter is small. This is because the luminosity at about $1-2\mu$ is less sensitive to star formation and dust, and follows older stars which dominates mass and which have a homogeneous M/L ratio.

TF relation is very important for distance measurements.

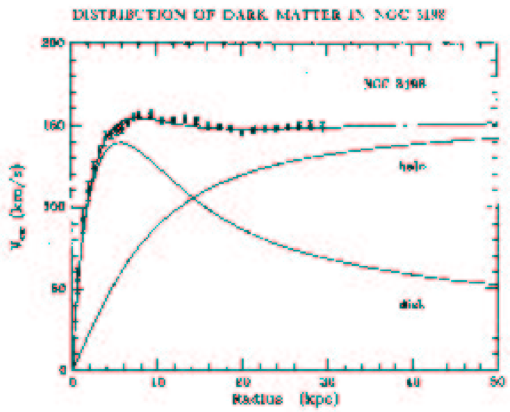

Figure 6: Fit to rotation curve of NGC 3198 (van Albada et al 1985, ApJ, 295, 305)

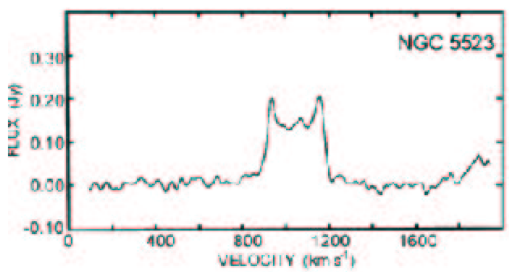

Figure 7: Observed 21cm profile of NGC 5523 (Shostak ,1975, ApJ, 198, 52)

6 Spiral pattern

6.1 Observed pattern : winding problem

Spiral arms stand out in blue colour and also in Hα emission from HII regions of young stars. The patterns stand out most clearly in the case of *grand design* spirals which can be tranced over many radians in angle. Using galactocentric polar coordinates (R,ϕ) one can describe the shape of an m-armed spiral by the equation,

$$\cos(m[\phi + f(R,t)]) = 1\,, \tag{5}$$

where the function f describes how tightly the arms are wound (if $|df/dR|$ is large the arms are tightly wrapped). The *pitch angle* i, the angle between the arm and

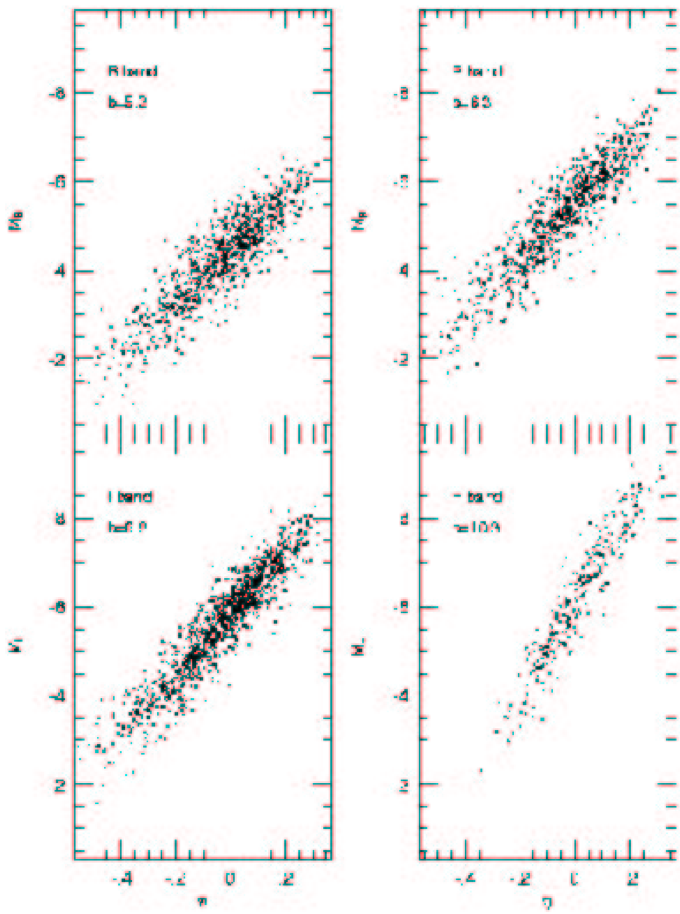

Figure 8: Tully-Fisher relation in four bands (B, R, I, H).

the tangent to the circle at radius R is defined as $1/\tan i = |R\frac{\partial\phi}{\partial R}| = |R\frac{\partial f}{\partial R}|$. For Sa spirals, $i \sim 5°$ and for Sc's, $10 < i < 30$. One calls a spiral to be *leading* if the tips of the arms point forward in the direction of galactic rotation, and *trailing* if otherwise. Most often the spiral arms are found be trailing, although it is not easy always to determine the sense of rotation.

A problem with arms is that if they are parmanent features then they would soon get wound up. For example, in the solar neighbourhood, where $v_c(r) \sim 200$ km/s, and is constant upto ~ 8 kpc, the pitch angle would tighten according to,

$$\cot i = R|\frac{d\Omega(R)}{dR}|t \approx \frac{200}{8}(t/1\,Gyr)i \quad (6)$$

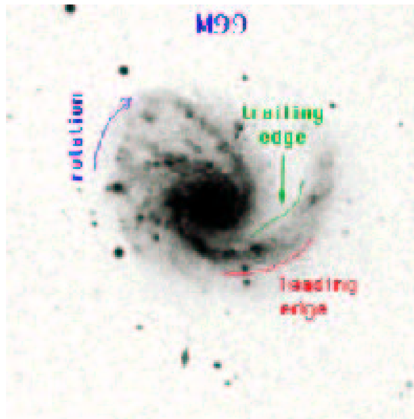

Figure 9: For example, the spiral arms of M99.

Or,

$$i \sim 2^{\circ}(t/1\,Gyr) \tag{7}$$

which means that a spiral arms would get wound up in very short time scales. Any initial spiral pattern would therefore get very tightly wound up.