Lecture 16
Spiral galaxies

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(Notes by Paul Hickson)
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M101, the Pinwheel Galaxy

Disk rotation

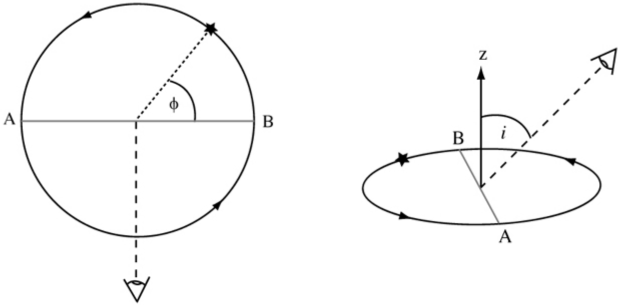

Fig 5.18 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

In order to estimate rotation velocities of spiral galaxies, one must consider the effect of galaxy inclination. The angle between the rotation axis and the line of sight is the **inclination angle** i.

The radial velocity is related to the circular velocity V by

$$V_r(R, \phi, i) = V_0 + V(R) \sin i \cos \phi.$$

Disk rotation

Contours of constant V_r correspond to constant values of $V(R)\cos\phi$, leading to "spider diagrams".

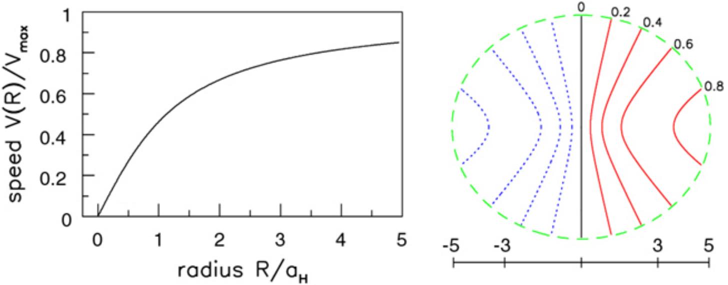

Fig 5.19 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Left, the rotation curve $V(R)$ for the density distribution $4\pi G\rho = V_H^2/(r^2+a^2)$, in units of V_H. Right, the spider diagram of $V_r - V_0$ for $i = 30^\circ$; contours are marked in units of $V_H \sin 30^\circ$, with negative velocities shown dotted.

HI line profiles

If V_{max} is the maximum value of $V(R)$, the velocity width of the H1 emission line profile will be

$$W = V_r \text{ max} - V_r \text{ min} = 2V_{\text{max}} \sin i.$$

By measuring the velocity width of the 21 cm line, we can estimate the maximum rotation velocity of a galaxy. If the inclination is not known, taking $\sin i = 1$ gives a lower bound to the velocity.

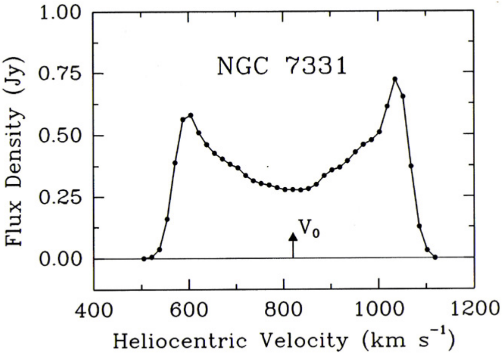

Fig5.22 (K. Begeman) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Rotation curves

If the galaxy is spatially resolved, we can estimate the inclination, and measure the rotation velocity as a function of radius. This gives the **rotation curve** for the galaxy.

One typically finds that after a rapid rise in the centre, the rotation velocity is nearly constant.

The angular velocity $\omega(R) = V(R)/R$ decreases as R increases, so the period of the orbits increase with R. The disk does not rotate like a solid body but instead is in **differential rotation**.

One finds that the observed rotation velocity $V(R)$ exceeds that required by the mass associated with the visible light, particularly at large radii.

In a typical large spiral galaxy, dark matter dominates the mass density beyond about 20 kpc.

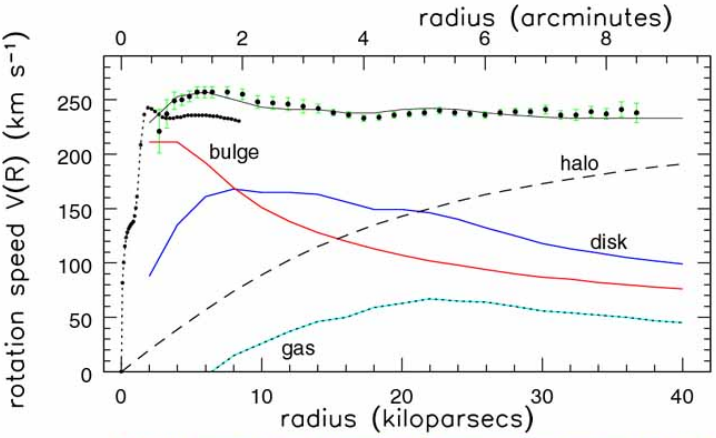

Fig 5.20 (Begeman, Sofue) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Points give the rotation curve of NGC 7331; vertical bars show uncertainty. CO gas (dotted), observed with a finer spatial resolution, traces a faster rise. The lower solid curves show contributions to $V(R)$ from the gas disk, the bulge, and the stellar disk. A dark halo (dashes) must be added before the combined rotation speed (uppermost curve) matches the measured velocities.

Dark matter

The mass fraction of dark matter, within the region probed by HI measurements, ranges from about 50% in Sa and Sb galaxies to $80 - 90\%$ in Sd and Sm galaxies.

There is likely dark matter beyond this region, so these numbers are actually lower bounds on the total dark matter mass fraction.

Typical spiral galaxies have mass-to-light ratios (M/L_B), within the HI region, in the range $3 - 15$.

Multiplying this by the observed blue luminosity density of the local Universe, about $1.5 \times 10^8 L_\odot$ Mpc^{-3}, one finds

$$\rho_{\mathsf{gal}} \sim (0.5 - 2.5) \times 10^9 M_\odot \ \mathsf{Mpc}^{-3}.$$

Dark matter

This is less than 0.02 of the critical density

$$\rho_{\text{crit}} = \frac{3H_0^2}{8\pi G} \simeq 1.4 \times 10^{11} M_{\odot} \text{ Mpc}^{-3}$$

needed to halt the expansion of the Universe.

The helium abundance requires that the ratio of baryons to photons is $\sim 10^9$. This requires a baryon density in the range

$$0.03\rho_{\text{crit}} \lesssim \rho_{\text{B}} \lesssim 0.07\rho_{\text{crit}},$$

which is more baryons than we see in galaxies.

It is likely that the missing baryons are in the hot diffuse intergalactic medium found in clusters of galaxies.

The Tully-Fisher relation

Brent Tully and Richard Fisher discovered that the HI line width W, and therefore V_{max}, correlates with the optical luminosity of a galaxy,

$$L \propto V_{\mathsf{max}}^{\alpha},$$

where $\alpha \sim 4$.

The **Tully-Fisher relation** was later refined by using infrared luminosities, which are less affected by recent star formation.

An important application of this relation is that it allows luminosities, and therefore distances, to be estimated from 21-cm observations of HI.

The Tully-Fisher relation

Using the theoretical relation relation,

$$M \propto V^2 R,$$

and the observed approximate correlations

$$M \propto L, \quad M \propto R^2,$$

we get

$$L \propto V^2 \sqrt{L}$$

and thus

$$L \propto V^4,$$

which is the Tully Fisher relation.

However, the relation is a still puzzling as rotation speed is determined mostly by the dark matter, while luminosity comes from the baryons. Somehow, the two are related.

Tully Fisher relation

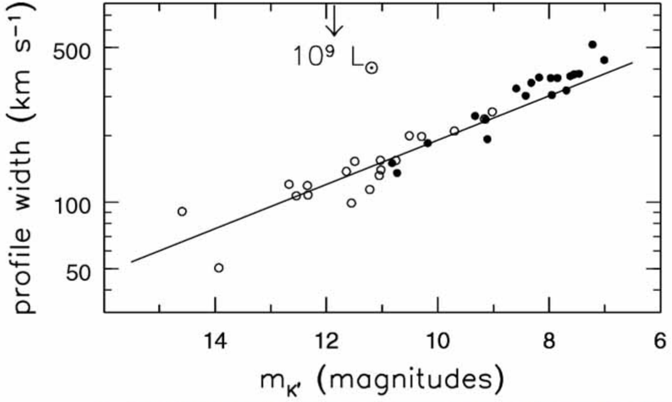

Fig 5.23 (M. Verheijen) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

For galaxies in the Ursa Major group: from the HI global profile, width $W/\sin i \simeq 2V_{\text{max}}$ plotted against apparent K'-magnitude. LSB galaxies (open circles) follow the same relationship as do those of high surface brightness (filled circles). The solid line passing through $L = 3 \times 10^{10} L_\odot$, $V_{\text{max}} = 205$ km s^{-1} has slope $L \propto V_{\text{max}}^4$.

The spiral sequence

Properties of different spiral types are summarized in Table 5.1 of Sparke and Gallagher.

Generally, this is a sequence of decreasing total luminosity, decreasing bulge fraction, and increasing star formation rate.

Galaxy spectra reflect this, showing older stellar populations in early types and bluer stars and gas emission lines in later types.

Starburst galaxies have enhanced rates of star formation, triggered by tidal interactions and mergers.

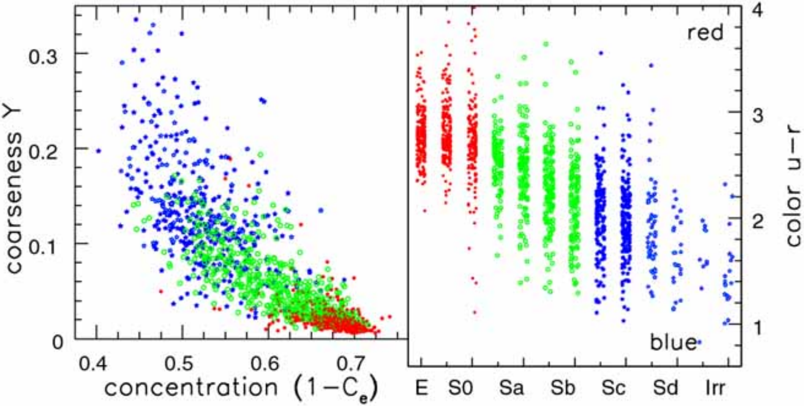

Fig 5.25 (C. Yamauchi) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

For 1421 galaxies of the Sloan Digital Sky Survey, the left panel shows how far the r-band light is concentrated to the centre, and the coarseness or deviation from a smooth image. Elliptical and S0 galaxies (filled dots) are the most concentrated, while Sc, Sd, and irregular galaxies (stars) are lumpiest, with Sa and Sb galaxies (open dots) between them. Right, average color becomes bluer along the sequence from S0 to Sd – C.

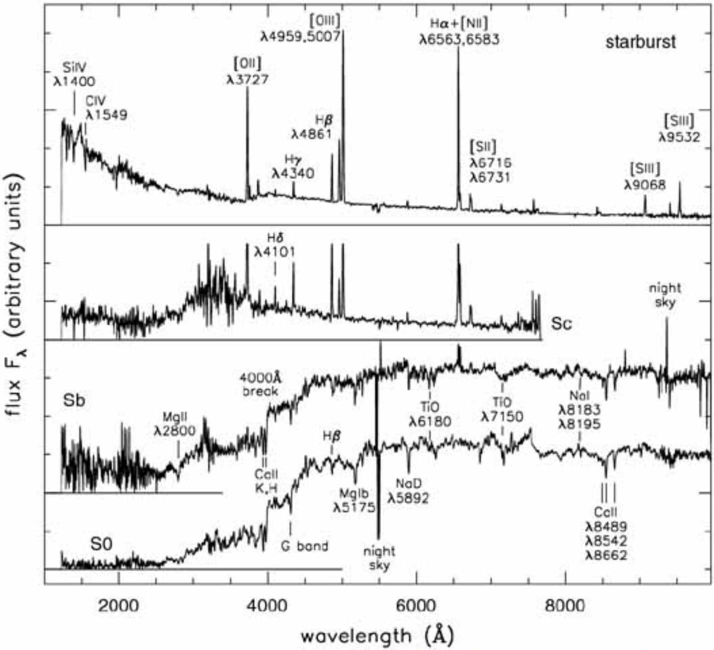

Fig 5.24 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007