Disk Galaxies

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1 Introduction and Goals

In this lecture, we discuss the disk galaxies. Dynamically, disks are very simple. Their equilibrium is primarily between gravity and rotation, so it is possible to study their gravitational potential and dark matter content with confidence. On the other hand, disks are highly dissipated structures, so much of the information about the early dynamical history of their baryons has been lost. In this sense, they are probably less useful than ellipticals as probes of events in the early universe. Another complication is that most disks are still forming stars, so their evolution (dynamical, structural and chemical) continues.

2 The Structure of Disk Galaxies

2.1 The Hubble Classification

Disk galaxies are classified according to the appearance of their spiral structure, the amount of star formation going on in their disks and the relative brightness of the bulge and disk. The basic Hubble classification proceeds from SO (very little star formation or spiral structure, and usually a large bulge) to Sa (tightly wound spiral structure, low level of star formation and large bulge) through to Sd (open spiral structure, much star formation and very small bulges). See Figure 1) The classification also recognises the irregular galaxies (Irr), most of which are disk-like, actively star forming and have insignificant bulges. Galaxies at the Sa end of the classification are called *early type*, and those at the other end are called *late type*. Important extensions of the basic Hubble scheme also recognize

- the significance of bars (SA, SAB, SB) and
- the inner and outer rings (r, R, s, rs), which are often seen, particularly in the barred spirals

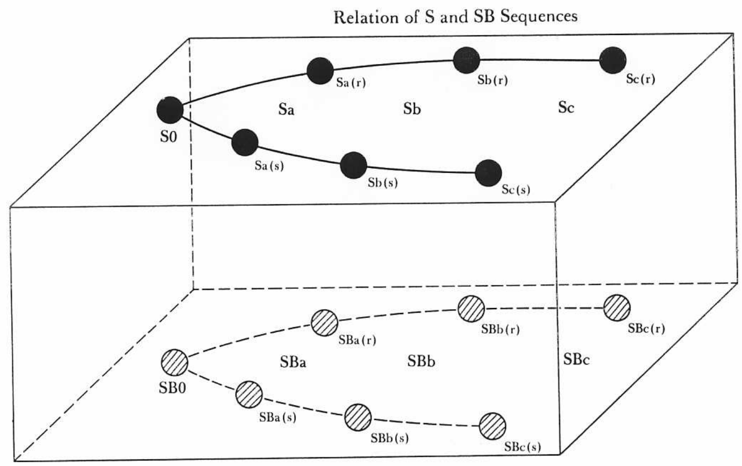

Figure 1: The Hubble sequence.

- a class of asymmetric galaxies like the Large Magellanic Cloud, denoted Sm.

Some disk galaxies have very substantial bulges and others do not have bulges at all. See Figure 2) for examples of galaxies with extreme bulge-to-disk ratios. The relative strength of the bulge and the disk is a major element of the Hubble classification, with the pure disk galaxies like IC 5249 (Figure 2) classified late in the Hubble sequence. It is clear that bulges are not an essential element of the formation of disk galaxies. The bulge-to-disk ratio is an important factor in determining the morphology of disk galaxies, not only in its own right as a classification criterion but also through its effect on the shape of the rotation curve and so on the optical morphology of the star-forming disk.

The relationship of the bulge-to-disk ratio to the Hubble type was clearly quantified by Simien & de Vaucouleurs (1986) who made bulge-disk decompositions of the surface brightness distributions of 98 galaxies. Figure 3 shows the relative brightness of the bulge and disk against the morphological type parameter T (T = −6 to −4 for ellipticals, −2 to −1 for S0 galaxies, and then increases from 0 at S0/a through 5 at Sc to 9 at Sm).

Most disks have a simple exponential surface brightness distribution of the form $I(r) = I_\circ e^{-r/h}$ where $I_\circ$ is the central surface brightness and h is the radial scalelength (*e.g.* Freeman 1970). This distribution typically extends out to about 5 radial scalengths, beyond which the disks are often truncated (*e.g.* van der Kruit 1988). What are the typical central surface brightnesses and scale lengths of disk galaxies ? This is an important issue, because these parameters for equilibrium disks reflect the disk's angular momentum and mass. Angular momentum transport between baryonic and dark matter during hierarchical galaxy formation

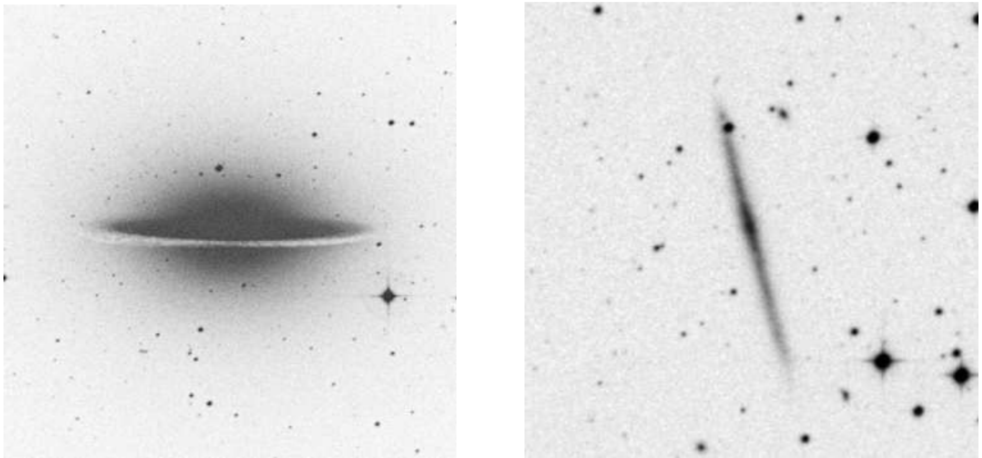

Figure 2: Examples of galaxies with a very large bulge (left: the Sombrero galaxy NGC 4594) and a very small bulge (right: IC 5249). Images from the DSS.

affects the angular momentum of the equilibrium disks, and theories of galaxy formation need to reproduce their typical surface brightnesses and sizes (which is currently a troublesome issue). Estimating the distribution of these parameters is not easy, because there are strong biases from the selection effects that go into defining samples of disk galaxies. For example, samples usually have some kind of selection limit on the apparent diameter, and explicit or implicit limits on the isophotal surface brightness. Samples are dominated by large galaxies of higher surface brightness, because such galaxies are included from a larger volume of space. It is necessary to correct the observed distributions of disk parameters for this *visibility volume* effect.

de Jong & Lacey (1999) have recently derived the bivariate distribution of absolute magnitude, surface brightness and scale length for disks, using a large diameter-limited sample of Sa to Sdm spirals with I-band surface photometry. The surface brightness profiles were decomposed into bulge + disk components, and the volume density of galaxies per Mpc^3 in $(M_I, h, I_\circ)$ was calculated, with correction for the visibility volume. Figure 4 shows a grey-scale representation of the density distribution of galaxies over effective radius r_e and effective surface brightness μ_e: the left panel shows the unweighted distribution and the right panel shows the luminosity-weighted distribution. We live in the kind of galaxy that contributes most to the luminosity of the local universe.

The possible existence of giant galaxies with low surface brightness as a major component of the galaxy population has been an issue for many years (see for example Impey & Bothun 1997). Although a few such galaxies are known, it seems from the work of de Jong & Lacey (1999) that such galaxies are relatively rare.

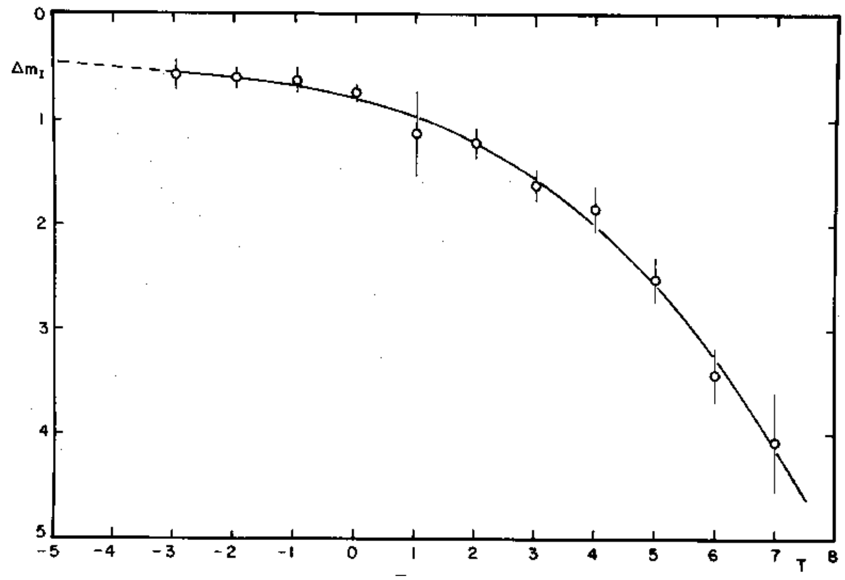

Figure 3: Mean values of the relative brightness in magnitudes between bulge and disk *vs.* the morphological type parameter T. Note the continuity between the lenticular (T $<$ 0) and the spiral sequences. (From Simien & de Vaucouleurs 1986).

In simulations of the growth of density fluctuations in the expanding universe, blobs of matter acquire angular momentum from each other by tidal torques. The dimensionless parameter $\lambda = J|E|^{\frac{1}{2}}G^{-1}M^{-\frac{5}{2}}$ is a measure of the ratio (rotational velocity)/(virial velocity) for a blob. (Here J, E and M are the angular momentum, binding energy and mass of the system). For disks in centrifugal equilibrium, $\lambda \simeq 0.45$. Simulations of hierachical galaxy formation show that the typical value of λ is 0.05 ± 0.03 (*e.g.* Zurek *et al.* 1988). In the absence of significant transport of angular momentum from the disk to the dark halo as the galaxy is forming, λ is a useful measure of the collapse factor for the baryons, and hence for the surface brightness of the ensuing disk. Simple arguments (Fall & Efstathiou 1980), assuming that the specific angular momentum of the dark matter and baryons are similar, show that the collapse factor for the baryons is $r_t/h = \sqrt{2}/\lambda \simeq 30$ where r_t is the truncation radius of the halo. For our Galaxy, $h \simeq 4$ kpc so the truncation radius of the dark halo should be about 120 kpc. This is consistent with the observed extent of the galactic dark halo (*e.g.* Freeman 1996). If the baryons and dark matter maintain the same specific angular momentum throughout the collapse of the disk, disks with higher λ-values are initially closer to centrifugal equilibrium, have a smaller collapse factor and lead to disks of lower surface density. The distributions of surface brightness and scale length from de Jong & Lacey (1999) indicate that the initial spread in λ may be smaller than given by the cosmological simulations (if the assumptions

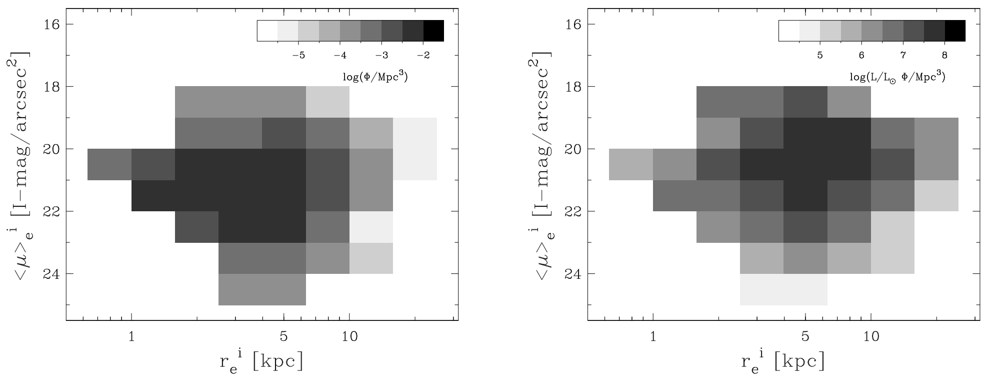

Figure 4: The density distribution of Sa-Sm galaxies over effective radius r_e and effective surface brightness μ_e: the left panel shows the unweighted distribution and the right panel shows the luminosity-weighted distribution (from de Jong & Lacey 1999).

about conservation of specific angular momentum are correct).

3 Star Formation Law in Disks

Theories of galaxy formation need a prescription for the star formation rate as a function of gas density and physical conditions. At this time, star formation is not well understood, and empirical prescriptions are needed. Kennicutt's law (1989) is widely used for the star formation in galactic disks. Kennicutt showed that the local rate of massive star formation, as measured by the Hα surface brightness, follows the HI surface density $\Sigma_{\rm HI}$ with a relation of the Schmidt law form

$$SFR \propto \Sigma_{\rm HI}^{1.3\pm0.3}$$

in dense regions. This law breaks down at lower gas densities; below a critical threshold density (which is typically about a few $M_\odot$ pc^{-2} and varies from galaxy to galaxy), massive star formation is completely suppressed. Figure 5 gives examples of the functional dependence of star formation rate against the HI surface density for several galaxies, showing the variable threshold. A more recent study (Kennicutt 1998) of the disk-averaged star formation rate and gas densities gives a law

$$SFR \propto \Sigma_{\rm HI}^{1.4\pm0.15}$$

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Kennicutt argued that this threshold is associated with the onset of gravitational instability of the disk, as given by Toomre's criterion

$$\Sigma_{\rm HI} \simeq \frac{\kappa c}{3.36}$$

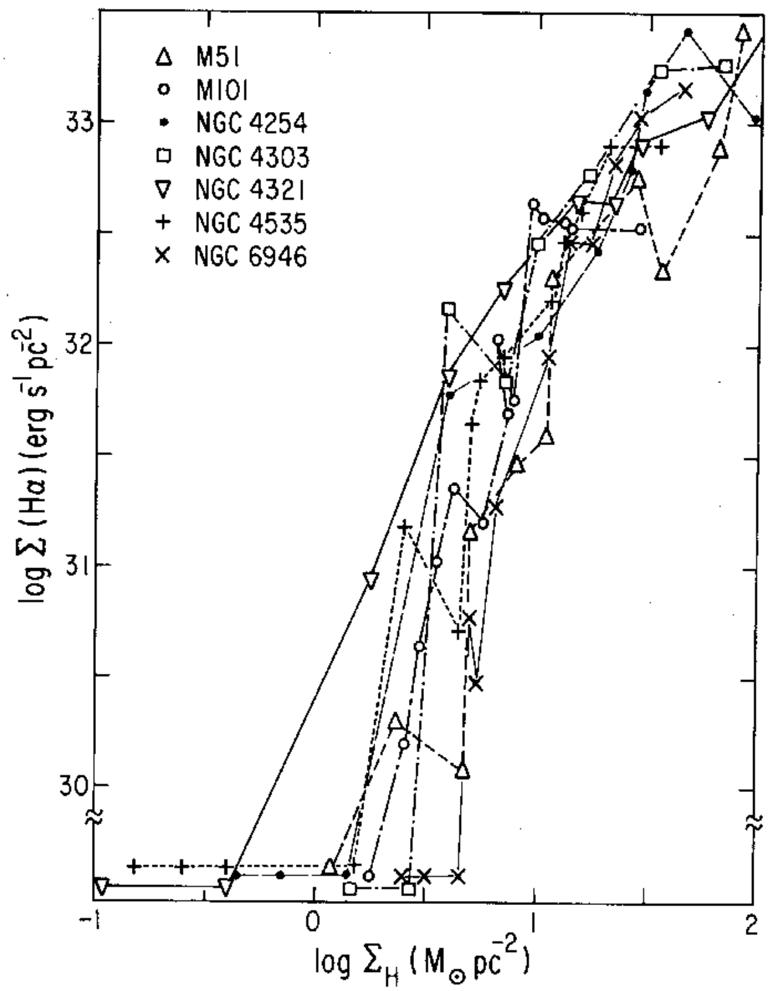

Figure 5: Examples of Hα surface brightness against HI surface density within several galaxies. The points at the bottom show regions below the star formation threshold, where no Hα emission was detected (from Kennicutt 1989).

, where κ and c are the epicyclic frequency and the velocity dispersion of the gas. (Toomre's criterion is for the local instability of a rotating disk to axisymmetric modes).

4 Star Formation History of Disks

As the gas dissipated to form the disk, it seems likely that star formation started in the inner disk where the surface density was highest, and then propagated outwards as disk settling continued. Many disk galaxies still have extended envelopes of HI, in which star formation has not yet begun. Bell & de Jong (1999) have attempted to measure the radial age gradient in the disks of spirals. Measuring the ages of stellar populations from their integrated properties is difficult, because changes in age and in metallicity have similar effects on the spectra of composite stellar populations. This *age-metallicity degeneracy* can be broken by using particular combinations of spectral lines or some combinations of broad band colors. Bell & de Jong used optical and near-IR colors and stellar population synthesis models to partially break the degeneracy and estimate the radial variation of mean stellar age within a sample of disk galaxies.

They find that most spiral galaxies have stellar population gradients, in the sense that their inner regions are older and more metal rich. The star formation history of the stellar population appear to correlate most strongly with the K-band central surface brightness: galaxies of higher surface brightness have weaker radial age gradients, and their mean age at the disk half-light radius is older. While galaxies with a central surface brightness $\mu_K(0) = 16$ K mag arcsec^{-2} have a mean age at $1r_e$ of about 10 Gyr, the corresponding age for galaxies with $\mu_K(0) = 20$ is only 6 Gyr. The mean radial age gradients range from near zero at $\mu_K(0) = 16$ to -1.2 Gyr per disk scale length at $\mu_K(0) = 20$. The gas fraction for the high surface brightness disks is near zero, and rises rapidly to about 60% at $\mu_K(0) = 20$, which is consistent with the age gradient pattern. The luminosity of the galaxy appears to have less effect on its star formation history of its disk, although the mean metallicity of the disk does show the usual metallicity-luminosity relation. The dependence of mean age, gas fraction and metallicity on the K-band surface brightness are shown in Figure 6.

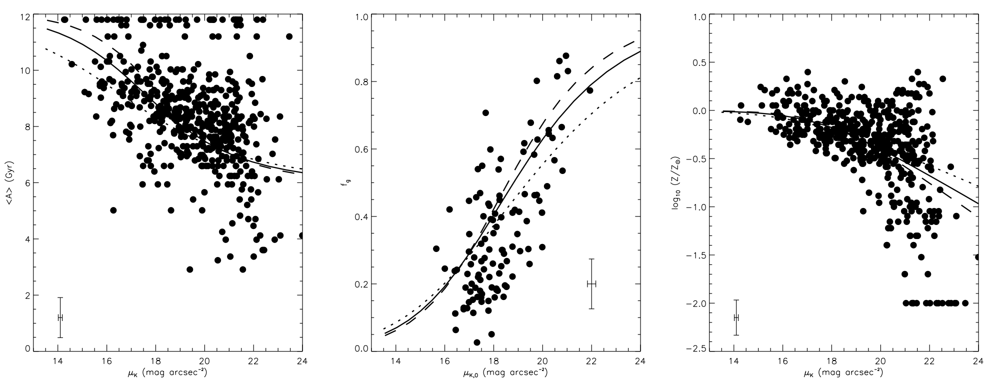

Figure 6: Local average age (left), gas fraction (middle) and metallicity (right) against K-band surface brightness. The curves show some simple star formation history models: see Bell & de Jong (1999).

5 The Tully-Fisher Law

The Tully-Fisher law for disk galaxies is the analog of the Faber-Jackson luminosity–velocity dispersion law for ellipticals. Tully & Fisher (1977) discovered a correlation between the global HI profile width and the absolute magnitude of disk galaxies. This law is now widely used as a distance indicator, with the HI profile width or the amplitude of the optical rotation curve as the luminosity estimator. Both work well, as one might expect from the typical (flat) shape of rotation curves.

What kind of luminosity - velocity relation would we expect ? For isolated exponential disks, simple equilibrium arguments lead to

$$L \propto V^4/[I_\circ(M/L)^2]$$

where $I_\circ$ is the central surface brightness of the disk and M/L its mass to light ratio, and we have seen that both are roughly constant from galaxy to galaxy. This is close to the observed Tully-Fisher law, at least for the I-band and the near-IR. Sakai *et al.* (1999) have made a recent calibration of the Tully-Fisher law in the BVRIH bands. They find that the slope of the relationship increases from about 3.2 ± 0.3 in B to about 4.5 ± 0.3 in H. See Figure 7.

These small departures from the expected slope probably reflect a weak dependence of $I_\circ$ and M/L on the luminosity For galaxy formation theory, the zero point of the Tully-Fisher law is also important. For example, Sakai *et al.* give the I-band Tully-Fisher law in the form

$$M_I = (-10.00 \pm 0.08)(\log W_{50} - 2.5) - 21.32$$

where W_{50} is the width of the HI profile at half peak height corrected for inclination. For the exponential disk alone, the zero point depends on $\log[I_\circ(M/L)^2]$. The M/L ratio is just a measure of the stellar population in the disk, but the central surface density $\Sigma_\circ = I_\circ M/L$ depends on the total mass M and angular momentum J of the galaxy: $\Sigma_\circ \propto M^7/J^4$. So the $J(M)$ relation for the disk is defined by the dynamics of galaxy formation and determines the zero point of the Tully-Fisher law.

5.1 The Tully-Fisher Law for Low Surface Brightness Galaxies

Now we look at the Tully-Fisher law for low surface brightness galaxies. In these galaxies, the gravitational field is believed to be dominated everywhere by the dark halo. Zwaan *et al.* (1995) showed that the Tully-Fisher law is very similar, in slope and zero point, to the law for the galaxies of high surface brightness. See Figure **??**. These LSB galaxies have low surface brightness because they have significantly longer scalelengths than the HSB at the same total luminosity.

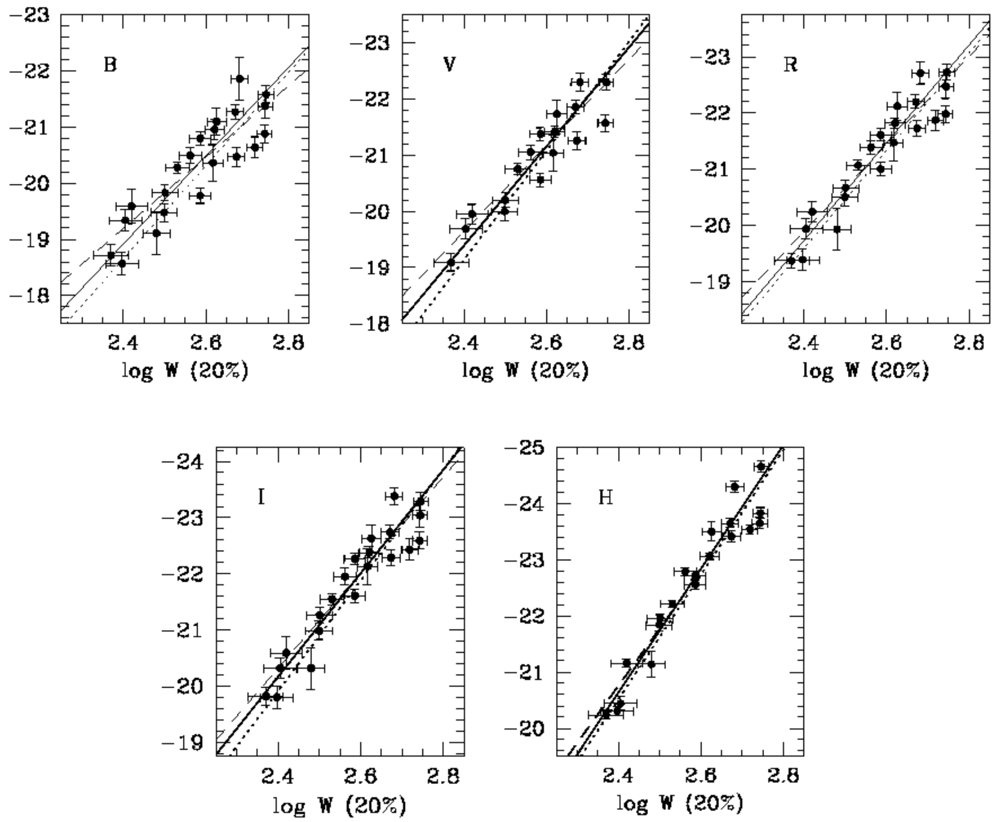

Figure 7: BVRIH Tully-Fisher relations for spiral galaxies with cepheid distances, using 20% linewidths. W is the width of the HI line profile in km s^{-1}, corrected for inclination. The solid lines show the bivariate fits (from Sakai *et al.* 1999).

For the LSB galaxies, the dark halo determines the W_{50} value, almost independent of the dynamics of the baryons, and the baryonic matter determines the luminosity as before. Although the baryons can be regarded as a tracer population which hardly affects the potential, we see that the baryon mass is related to the dynamics of the dark halo. It is not clear why this should be so. One possibility is that the formation process for dark halos produces a Faber-Jackson relation between halo mass and halo velocity dispersion of the form $M_{dark} \propto \sigma^4$. Indeed, Navarro *et al.* (1997) find tight power law relationships between M and maximum circular velocity for their simulated halos; the power law slopes depend on the cosmology and range from about 3.3 to > 5. Their power law relationship reflects the higher characteristic density of the lower-mass halos, which form at higher redshift. If the ratio of baryonic to dark mass is similar from galaxy to galaxy, then this would lead directly to a Tully-Fisher relation between baryonic mass and rotational velocity.

Although most disk galaxies do lie on the Tully-Fisher relation, within the usual scatter of about 0.2 to 0.3 mag, some very gas-rich galaxies are found to be significantly under-luminous for their HI line width. Figure 8 adapted from Meurer *et al.* (1996), shows the Tully-Fisher relation for a sample of normal disk galaxies, and the two dwarf galaxies NGC 2915 and DDO 154. These two galaxies are unusually gas-rich, with gas masses that are an order of magnitude larger than their stellar masses. They lie 2 to 3 magnitudes below the Tully-Fisher relation. This appears to be due to the large fraction of their baryons that have not formed into stars. If the gas of these two galaxies is notionally converted into stars with an M/L ratio of 1, then they rise to the usual Tully-Fisher relation, as shown by the vertical bars in Figure 8. Again, this is an indication that the TF law is about the relationship of total baryon content of disk galaxies to the circular velocity of their dark halos.

6 Bars

The morphological classification of galaxies recognizes two parallel sequences, normal (SA) and barred (SB). Some galaxies are transition systems with weak central bars and are classified SAB. It turns out that many of the galaxies that appear normal in optical images do show bars in their near-IR images which are less affected by dust and star-forming regions. About 72% of spirals appear barred in the H-band, and the fraction of bars does not vary much from Sa to Sd (Eskridge *et al.* 1999).

The origin of bars is still not well understood. Stellar disks can be unstable to bar-forming modes, and the bars that form in this way thicken through vertical instabilities and appear like boxy or peanut-shaped bulges when seen edge-on (we will discuss bulges in more detail later). Sellwood (1999) has recently cast doubt

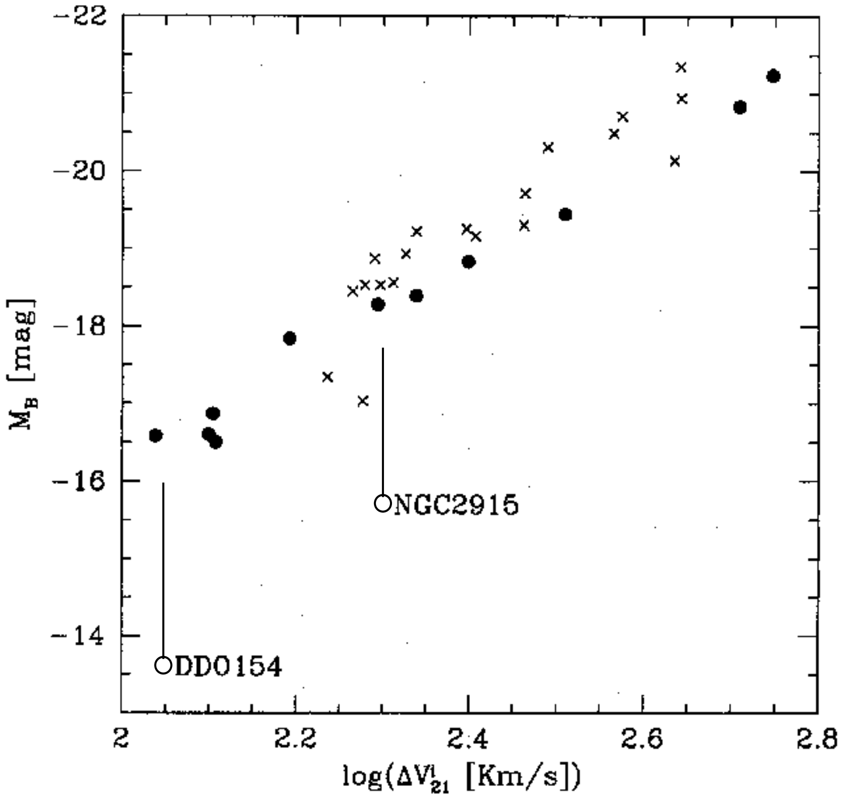

Figure 8: The Tully-Fisher relationship for a sample of nearby disk galaxies compared with the two very gas-rich galaxies NGC 2915 and DDO 154 (open circles). The upper ends of the vertical bars show where they would lie if their gas were turned into stars with $M/L = 1$ (adapted from Meurer *et al.* 1996).

on disk instability as the main mechanism that leads to bar formation. He points out that the high central densities of most disk galaxies should have inhibited bar-forming instabilities.

Another interesting argument against bar formation by instability comes from observations of disk galaxies at intermediate redshift. If bars do form through the instability of stellar disks, then they should form early in a galaxy's life. But this does not appear to be so: Abraham *et al.* (1999) studied the incidence of bars among galaxies in the Hubble Deep Field North & South, and found that bars are relatively rare for redshifts $z > 0.7$. This suggests that bars form long after the disks of these galaxies have assembled. Early disks are apparently stable against bar-forming instabilities, so some kind of secular bar-forming mechanism may be involved. This observation by Abraham *et al.* seems important for understanding disk formation and stability, but I don't believe we fully understand the implications yet.

7 Bulges

We have already seen that some disk galaxies have very substantial bulges and others do not have bulges at all (see Figure 2 for examples). Bulges show a wide variety of form, from the dominant bulge of the Sombrero galaxy at one extreme to the small bulges like the bulge of the Milky Way at the other. The goal of the following subsections is to discuss the possible origin of the different kinds of bulges. At this time, it seems likely that the small bulges and large bulges are formed through different processes.

7.1 Large Bulges

Large bulges, as in M31 and M104 (the Sombrero galaxy), follow the $r^{1/4}$ surface brightness distribution ($\log I \propto -r^{1/4}$). For example, the light distribution in the bulge of M31 follows the $r^{1/4}$ law from a radius of 200 pc out to 20 kpc (Pritchet & van den Bergh 1994). An $r^{1/4}$ light distribution is usually associated with the dynamical relaxation from a fairly violent merger or aggregation history (*e.g.* van Albada & van Gorkom 1977; Barnes 1988). Chemically, the bulges of spirals show an Mg/Fe *vs.* absolute magnitude relation in the same sense as for ellipticals: the brighter bulges show a more marked overabundance of Mg relative to Fe (Jablonka *et al.* 1996). The usual interpretation of this effect is that, after the first major burst of star formation, supernova-driven winds in the more luminous systems remove the remaining gas quickly, and so reduce the subsequent Fe-enrichment by the slower type I SNe.

For the bulge of M31, photometric studies of fields in the outer bulge show that the bulge stars have a wide range of chemical abundance, from about [Fe/H] $= -2$ to -0.2, with little or no abundance gradient out to a radius of 40 kpc (*e.g.* Durrell *et al.* 1994; Couture *et al.* 1995; Rich *et al.* 1996; Holland *et al.* 1996). All of this indicates that the formation of large bulges occurred early and quickly, with a high degree of dynamical mixing and relaxation, much as for giant ellipticals. The present view about the formation of ellipticals through mergers would then suggest that large bulges form through major or minor mergers of gas-rich galaxies; the gas is needed for the subsequent formation of the disk of the merged system.

There are differences between giant ellipticals and large bulges, most notably in their rotational behaviour. Bulges lie close to the oblate isotropic rotator curve in the $(V/\sigma - \epsilon)$ plane while, from the kinematics of their *inner* regions ($r \lesssim r_e$, where r_e is the half-light radius), the giant ellipticals mostly lie well below the oblate curve. It is not yet clear why the inner regions of large bulges rotate more rapidly than for large ellipticals. Naab *et al.* (1999) have shown that mergers of equal mass disks produce boxy merger products with slow rotation and flattened by anisotropic velocity dispersion, while the mergers of disks with a 3:1 mass ratio produce disky systems that are rotationally supported. This suggests that the rotationally supported large bulges may be preferentially the products of unequal mass mergers. (This may also be true for the lower luminosity elliptical galaxies, which are mostly rotationally supported and disky systems: see for example Rix *et al.* 1999.)

7.2 Small Bulges

A large fraction of the small bulges seen in later-type disk galaxies have a boxy or peanut-like structure when seen edge-on. Their photometric structure is usually exponential rather than $r^{1/4}$ (Courteau *et al.* 1996). What is the origin of these smaller bulges ? N-body simulations of self-gravitating disks strongly suggest that most of the small boxy/peanut bulges, like the bulge of the Milky Way, are bars arising from planar and vertical instabilities of disks (*e.g.* Combes *et al.* 1990; Pfenniger & Friedli 1991). Some of these structures may themselves be triggered by interactions (*e.g.* Noguchi 1987).

Until recently, observational verification of the bar-like nature of boxy bulges has been difficult, because boxy bulges are seen most clearly in edge-on spirals, and then it is not so clear whether they are barred. Kuijken & Merrifield (1995) devised a kinematical test of the bar-like nature of near-edge-on boxy/peanut bulges. This test, which depends on the properties of the two principal orbit families in the gravitational field of a rotating bar, is particularly effective and direct for galaxies with extended emission lines in the region of the bulge. An example of this test (from Bureau & Freeman 1999) is shown in Figure 9 for the boxy/peanut bulge of NGC 5746. The upper panel shows an image of the galaxy, and the lower panel shows the [NII] and Hα emission lines from a long slit placed along the major axis of the galaxy. The spatial scales of the image and the spectrum are the same, so position along the emission lines corresponds to position along the major axis of the image. The striking figure-of-eight shape of the emission lines arises from the orbit properties in a bar: it is an excellent diagnostic of the presence of the multiple orbit families within a bar, and hence of the presence of a bar.

Bureau & Freeman (1999) applied the Kuijken-Merrifield test to 15 edge-on boxy/peanut bulges with extended emission lines, and a non-boxy control sample. Of these 15, 11 show the effect clearly, 3 are very dusty so the effect may be masked, and one galaxy is disturbed by interaction. None of the 7 galaxies in the non-boxy control sample shows the effect. One can conclude from this work that most boxy/peanut bulges are indeed bar-like. We can infer from these observations that a large fraction of the small bulges seen in later-type edge-on disk galaxies are in fact bars, which probably arose from instabilities of the disk before or after the disk reached equilibrium.

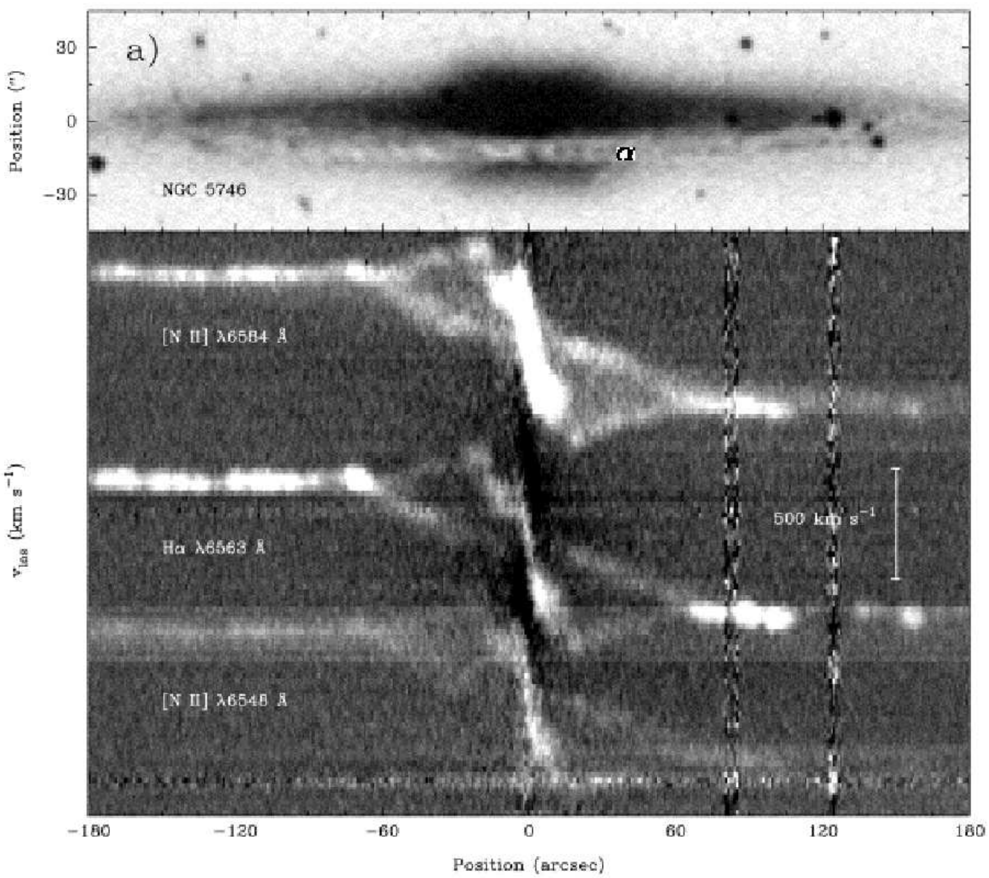

Figure 9: The upper panel is an image of the nearly edge-on galaxy NGC 5746, showing its boxy bulge. The lower panel shows the emission lines of [NII] and Hα, from a long slit located along the major axis of the galaxy. The spatial scales of the upper and lower panels are the same. The figure-of-eight structure seen in the emission lines from the region of the boxy bulge is believed to result from the orbit properties in the gravitational field of a rotating bar (from Bureau & Freeman 1999).

Why do some disk galaxies appear to have no bulge ? If the above discussion is correct, we would infer that these pure disk galaxies have managed to avoid the bar-forming events that lead to small bulges (and the mergers that lead to large bulges). These pure disk galaxies include systems like M33, and are mostly of lower luminosity. Recent work shows that these fainter galaxies have denser dark halos (e.g. Kormendy & Freeman 2002), and it may be that the dark halos of these pure disk systems are more effective in suppressing the bar-forming instabilities that would lead to the emergence of a small bulge. For example, compare two disks, one with $M_B = -22.5$ and the other with $M_B = -18.5$, corresponding to a massive spiral and to a galaxy like M33 respectively. Assume that each has the same baryonic disk surface density and disk velocity dispersion, and that the dark halos follow the observed scaling relations which we will discuss later. Then we would expect the Toomre $Q-$parameter to be about twice as large for the disk of the fainter galaxy. Similarly the stability index of Efstathiou *et al.* (1982) would indicate that the fainter disk is more stable against bar forming modes.

At this stage, the indications are that there is more than one way to form bulges. Small exponential bulges apparently form from their parent disks, while the large $r^{1/4}$ bulges probably form via mergers of gas-rich systems of unequal mass. If this is correct, then the early merger history of individual disk galaxies and the stabilising effects of their dark halos are very influential in determining their bulge-to-disk ratios and their present-day morphologies.

8 Pure Disk Galaxies

These systems (like the example of IC 5249 in Figure 2) lie late in the Hubble sequence and are mostly systems of relatively low mass and luminosity. Many authors have discussed the fragility of disks and have shown how the existence of a thin disk limits the amount of mass such galaxies can have accreted after the stars of the disk had formed. This limit is only a few percent of the mass of the stellar disk (*e.g.* Toth & Ostriker 1992). So the thinness of the disks of these pure disk galaxies indicates a relatively undisturbed history.

Some galaxies that appear to have a pure disk structure show a weak underlying stellar halo or thick disk from very deep surface photometry (see Figure 10). NGC 5907 is an example (Morrison *et al.* 1994; Sackett *et al.* 1994; Lequeux *et al.* 1998). This galaxy is unusually luminous for an Sc system ($M_B \simeq -20.5$), and its faint extended structure may well be the result of a very minor merger or interaction at some point in the galaxy's history. The apparently metal-rich nature of this halo or thick disk (from its relatively red color) argues against the possibility that it came from a weak episode of star formation before the disk had settled.

Abe *et al.* (1999) made deep surface photometry of the our less luminous edge-

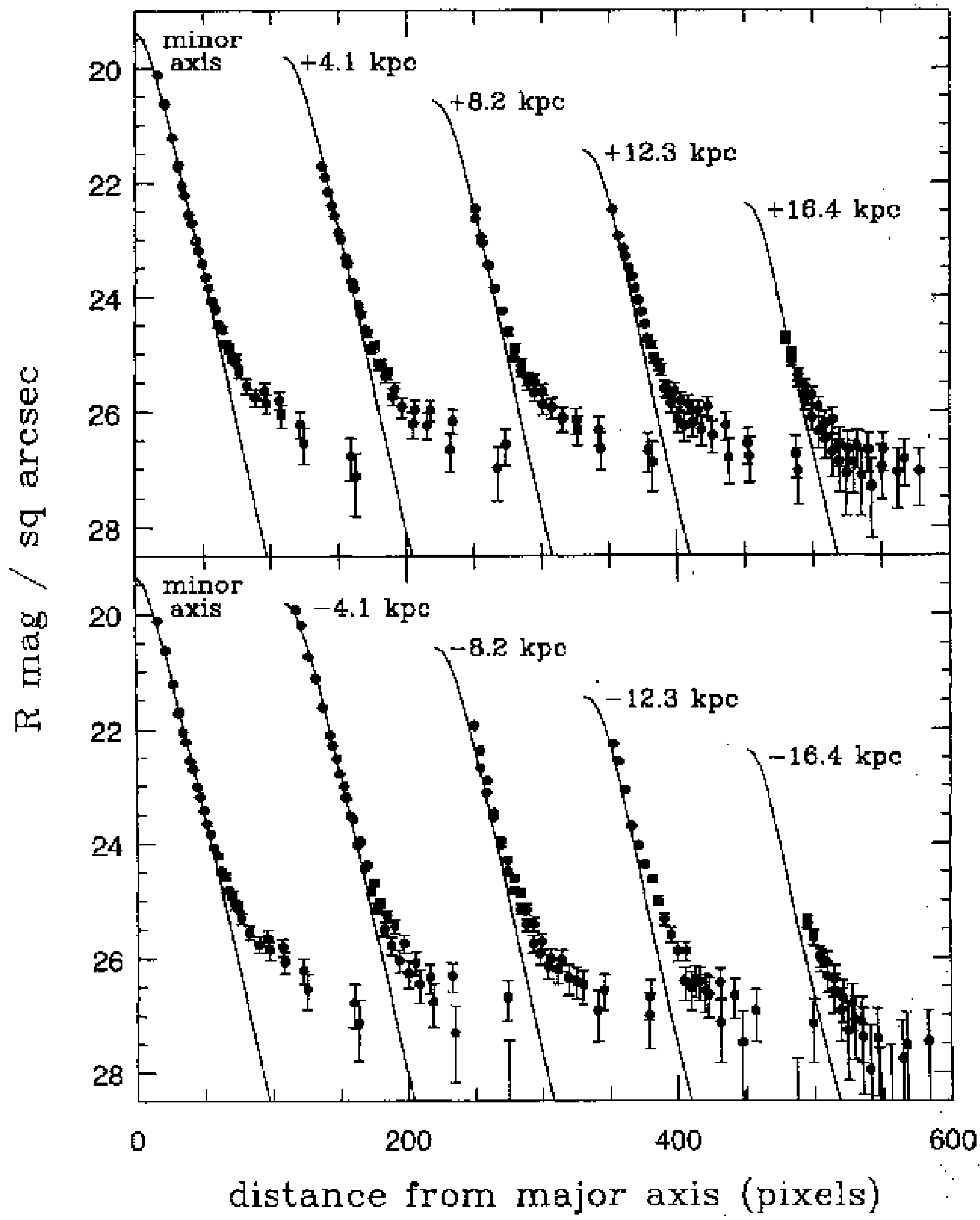

Figure 10: R-band surface brightness profiles parallel to the minor axis of NGC 5907. The distance from the minor axis is shown for each profile. The curves show the expected surface brightness distribution for a pure disk that is exponential in radius and height above the plane, with scaleheight 430 pc and scalelength 4.8 kpc. The faint excess light associated with the stellar halo or thick disk is evident below a surface brightness of about 25 mag arcsec^{-2}. (From Morrison *et al.* 1994)

on galaxy IC 5249 (see Figure 2) and again find evidence for a very faint thick disk in this system. But not all pure disk galaxies show a stellar halo or thick disk. Very deep surface photometry of the edge-on galaxy NGC 4244 by Fry *et al.* (1999) shows no evidence for a halo or thick disk. This galaxy is relatively faint ($M_B \simeq -18.4$) and its surface brightness distribution shows only a single exponential disk with a radial cutoff at about 5 radial scalelengths. NGC 4244 appears to be a true undisturbed pure disk system. The existence of such systems is interesting and very important, because it demonstrates that in at least some of the late-type disk galaxies

- star formation did not begin until the gas of the disk had settled to the plane, and
- since the onset of star formation in the disk, the galaxy has suffered no significant dynamical disturbance from internal or external sources, *i.e.* no mergers or accretion of small satellites or dark matter lumps, and no growth of a bar/bulge by disk instabilities.

9 S0 Galaxies

The S0 galaxies are disk systems without significant spiral structure. Figure 11 shows an example.

What is their origin ? Are they simply spirals that have used up most of their interstellar gas through star formation ? S0 galaxies are found predominantly in denser galactic environments, and opinion at this time is that S0 galaxies have lost their gas through interaction with other galaxies or with their environment. For example, Bekki (1998) suggests that S0 galaxies form through unequal-mass mergers; the enhanced star formation rate exhausts the interstellar medium, leaving a single gas poor remnant S0. Jones *et al.* (1999) studied the stellar content of E and S0 galaxies in several clusters at intermediate redshift and find no significant difference between the luminosity-weighted ages of the E and S0 galaxies in these clusters. They conclude that the progenitors of S0 galaxies in rich clusters are mostly early-type galaxies which have had their star formation truncated through interaction with the cluster environment. The fate of later-type lower-surface-brightness spirals in clusters is different: Moore *et al.* (1998) showed that these less dense systems are likely to end up as dwarf spheroidal or dwarf elliptical galaxies through the effects of the cluster harassment process. Ram pressure stripping in clusters is also likely to be a significant (though not on its own sufficient) element in the production of S0 galaxies (Abadi *et al.* (1999).

Some S0 galaxies do have a significant interstellar medium and a low level of ongoing massive star formation (*e.g.* Pogge & Eskridge 1998). A nearby example is the S0 galaxy NGC 5102 in the Centaurus A group: this galaxy has a substantial

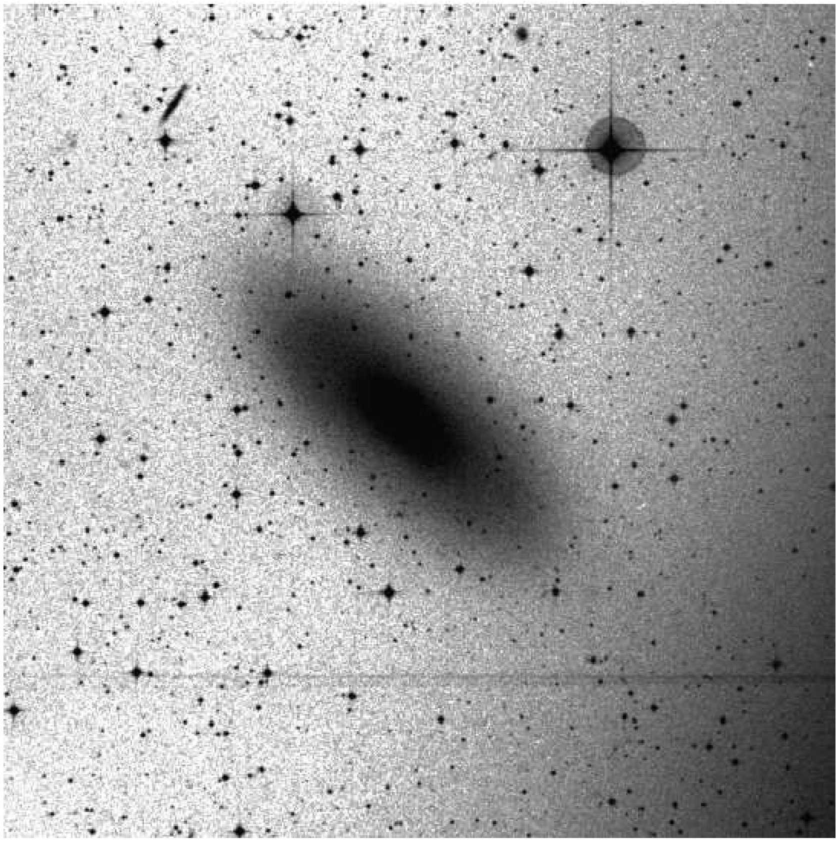

Figure 11: NGC 5102: an S0 galaxies in the nearby Centaurus A group. Note the relatively structureless disk. Image from the DSS.

HI content (van Woerden *et al.* 1993) and shows a sprinkling of OB stars and small HII region over part of its disk (Pritchet 1979).

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