The Origin of the Hubble Sequence for Spiral Galaxies

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ABSTRACT
We suggest that the bulge-to-disc ratios of spiral galaxies are primarily determined by the angular momenta of their host haloes predicted in current hierarchical clustering models for structure formation. Gas with low specific angular momentum becomes self-gravitating and presumably forms stars before it can settle into a rotationally supported disc. We assume this part of the gas in a dark halo to form a bulge, while the rest is assumed to settle into a rotationally supported disc. With these assumptions the predicted bulge-to-disc ratios in mass and in size, and other correlations between the bulge and disc components can match current observational results. This model predicts the existence of a population of low-surface-brightness galaxies which are bulgeless. The model also predicts that the bulge component has many properties in common with the disc component, because both form through similar processes. In particular, many bulges should be supported (at least partially) by rotation.

Key words: galaxies: formation - galaxies: structure - galaxies: spiral - cosmology: theory - dark matter

1 INTRODUCTION
One fundamental observation on galaxy structure is that spiral galaxies typically have two components, a disc and a bulge. The bulge-to-disc ratio (in luminosity) is considered to be an important factor in determining the morphological types in the Hubble sequence. An important goal of galaxy formation is therefore to understand how the bulge and disc components form and what determines the bulge-to-disc ratio. The formation of galactic discs has been studied quite extensively in the literature (e.g. Fall & Efstathiou 1980; Dalcanton, Summers & Spergel 1997; Mo, Mao & White 1998, hereafter MMW; Jimenez et al 1998). As discussed in MMW, disc formation can be understood as a result of gas settling into dark haloes predicted by current hierarchical clustering models of structure formation. In contrast, the formation of galactic bulges is still ill understood (see Wyse, Gilmore & Franx 1997 for a review). Three classes of scenarios have been suggested. The first class assumes that bulges form from early collapse of a protogalaxy (Eggen et al 1962). In this scenario, the size and mass of the bulge component of a galaxy depends on the efficiency of the first burst of star formation, while the properties of discs are determined by later infall of high angular momentum material. The second class assumes that bulges form from mergers of disc galaxies (Toomre & Toomre 1972; Kauffmann, White & Guiderdoni, 1993; Kauffmann 1996). In this scenario, the bulge-to-disc ratio is determined by the amount of gas locked into stars at the time of last major merger. Some quantitative predictions have been given in Kauffmann (1996). The third class assumes that bulges form as a result of the secular evolutions of galactic discs. In this scenario, the (inner) thin disc is transformed into a bulge by vertical heating due to, e.g. the bar instability (Combes et al 1990; Norman, Sellwood, & Hasan 1996, and references therein). Unfortunately, none of the models predicts the relative bulge-to-disc size distribution, and with the exception of the merger model (Kauffmann 1996), the theoretical models have not been carried out to the point of quantitative predictions about the relative proportion of bulge and disc and other observed correlations between the bulge and disc components.

In this paper, we suggest that the bulge-to-disc ratios of spiral galaxies are primarily determined by the angular momentum of dark haloes predicted in current hierarchical clustering models for structure formation. This model (described in Section 2) allows one to put the formation of the Hubble sequence for spiral galaxies into cosmological context. It also makes quantitative predictions for the properties of the bulge-disc systems (Section 3). The implications of our results are discussed in Section 4.

2 MODEL
In the standard hierarchical clustering models of structure formation, dissipationless dark matter particles are clustered into larger and larger clumps (dark haloes) in the passage...
of time due to gravitational instability. Gas associated with such haloes condenses and cools, eventually forming the visible galaxies. The properties of dark matter haloes are well understood since they are primarily determined by gravitation and can be readily studied with numerical simulations. We shall use these properties in our modelling. On the other hand, the behaviour of the gas component and the associated star formation are poorly understood. We attempt to model this part by making simple but plausible assumptions.

We model dark haloes as spherical objects with a radial density profile given by

\[ \rho(r) \propto \frac{1}{(r/r_c)^\alpha(1 + \alpha/r_c)^2}, \]  

where \( c \) is a parameter that describes the concentration of the halo and \( r_c \) is the virial radius of the halo. Navarro, Frenk & White (1996, 1997, hereafter NFW) found through numerical simulations that \( \alpha \approx 1 \) and \( c \sim 10 \) (for galactic-sized haloes). We take these as our canonical values, but later vary the value of \( \alpha \) to see the change in our results.

Dark haloes acquire angular momentum due to tidal forces and \( \mathcal{F} \) can also be applied to the gas within any spheres with \( r < r_c \). The mass and angular momentum within radius \( r \) are

\[ M(< r) = \int_0^r \rho(r) 4\pi r^2 dr, \quad J(< r) = \int_0^r \mathcal{J}(r) dM. \]  

The fractional mass and angular momentum within a sphere of radius \( r \) are therefore

\[ J_d(< r) = \frac{1}{\mathcal{J}} \int_{r_c}^r \mathcal{J}(r) dM, \quad m_d(< r) = \frac{M(< r)}{M}. \]  

where \( m_{\text{tot}} \) is (again) the fraction of total halo mass that settles into the centre to form the bulge-disc system. If we assume that the mass in the sphere also settles into a rotationally supported exponential profile conserving angular momentum, then using equation (3) we obtain

\[ r_{\text{cs}}(< r) = \frac{1}{\sqrt{2} m_d(< r)} \lambda r_v. \]  

In practice, we multiply the above scalelength by a factor of \( \alpha_{\text{rot}} = 1.5 \) to take into account the fact that bulges are only partially rotationally supported (e.g. Kormendy & Illingworth 1982). Our results, however, are not sensitive to the choice of \( \alpha_{\text{rot}} \).

Larson (1976), among others, argued that the bulge component is likely to have formed in rapid episodes of star formation. A minimum condition for rapid star formation is that the gas must become self-gravitating and be able to fragment. This means that its density must reach to a level of about 3 times the halo density, so that the fragmented clouds are not subject to tidal disruption. Simple condition may lead to the formation of a bar (which then desolves into a bulge according to the secular-evolution scenario), because self-gravitating discs may be subject to bar instability (e.g. Efstathiou, Lake & Negroponte 1982). If the bayron mass within an initial radius \( r_i \) settles within a final radius \( r_f \), the self-gravitating condition can be written as

\[ m_{\text{tot}} M(< r_i) \geq 3M(< r_f). \]  

Since we assume the mass settles into an exponential profile which does not have a sharp cutoff radius, we take \( r_f \) as the effective radius within which half of the mass is enclosed (for an exponential profile, \( r_f = 1.67r_{\text{cs}} \)). Correspondingly, we take the mass at the left hand side as the baryonic mass enclosed within the effective radius. The bulge mass and radius are then determined by the initial mass, \( r_{\text{max}} \), which still satisfies the inequality (3). Once \( r_{\text{max}} \) is found, the masses and scalelengths for the bulge and disc components are given by

\[ M_b = m_{\text{tot}} M(< r_{\text{max}}), \quad r_b = \frac{1}{\sqrt{2} \alpha_{\text{rot}}} \frac{J_d(< r_{\text{max}})}{m_d(< r_{\text{max}})} \lambda r_v, \]  

\[ M_d = m_{\text{tot}} M - M_b, \quad r_d = \frac{1}{\sqrt{2} \alpha_{\text{rot}}} \frac{J_d(< r_{\text{max}})}{m_d(< r_{\text{max}})} \lambda r_v, \]  

where \( J_d = m_{\text{tot}} \) because we assume that the gas which forms the bulge-disc system has the same specific angular
momentum as the dark matter halo and has its angular momentum conserved during the collapse.

3 MODEL PREDICTIONS

In our model, there are two parameters, \( \alpha \) and \( \beta \), that describe the runs of mass and specific angular momentum with radius. Once \( \alpha \) and \( \beta \) are given, the predicted bulge-to-disc scalelength ratio, \( r_b/r_d \), and bulge-to-total mass ratio, \( M_b/M_{tot}(M_{tot} \equiv M_b + M_d) \), depend only on the spin parameter \( \lambda \). In this section, we present our model predictions and compare them with the recent observations of de Jong (1996a,b). De Jong’s sample contains 86 nearby late-type galaxies that are chosen from the UGC catalogue. For each galaxy, various decompositions of the observed light into a disc component and a bulge component have been carried out. It appears that the observed galaxies are best described by an exponential disc and an exponential bulge (see also Courteau, De Jong & Broeils 1996). The bulge-to-disc ratios in both scalelength and light are given for each galaxy in many bands, which makes it possible for us to compare model predictions directly with observations. We use the I-band data but the results are similar for other bands.

Figure 1 shows the predicted values of \( r_b/r_d \) (bottom panel) and \( M_b/M_{tot} \) (top panel) as functions of \( \lambda \) for different combinations of \( \alpha \) and \( \beta \). These two ratios vary with \( \lambda \) in very similar manner. The solid lines show the cases with \( \beta = 1.3 \) for three values of \( \alpha \): 0.7, 1 and 1.3. For all combinations of \( \alpha \) and \( \beta \), the predicted bulge-to-disc ratio decreases with increasing \( \alpha \). This dependence can be understood as follows. A larger value of \( \alpha \) implies a more concentrated distribution of dark matter and therefore requires the gas to contract more to become self-gravitating. The two dashed curves show the effect of changing \( \beta \). For a given \( \lambda \), the disc-to-bulge ratio increases with \( \beta \), because a larger value of \( \beta \) implies that there is more material with low angular momentum in the central part to form a bulge.

To have more direct comparisons with the observational results, we convolve the predicted bulge-to-disc ratios with the \( \lambda \)-distribution found in numerical simulations. This is done by Monte Carlo simulations in which the value of \( \lambda \) is randomly drawn from its probability distribution. We fix the values of \( \alpha \) and \( \beta \) to be 1 and 1.3 respectively. We also assume that the stellar mass-to-light ratio is similar for the disc and bulge components in a galaxy (see Fig. 1 in de Jong 1996c), so that the predicted bulge-to-disc ratio in mass can be compared directly with the observed bulge-to-disc ratio in luminosity.

The predicted distributions of \( r_b/r_d \) and \( M_b/M_{tot} \) are shown as the thick solid histograms. Compared with the observational data of de Jong (1996, shaded histograms), it is clear that the median values of the two distributions predicted by our model are similar to those observed. However, the model predicts more systems at both the low and high ends of \( r_b/r_d \) and \( M_b/M_{tot} \). It is not surprising that the predicted abundance of systems with large bulge-to-disc ratios is higher than that given by the observation, because the de Jong sample is biased against early-type galaxies which have larger bulge-to-disc ratios. The predicted tails of small bulges are produced mainly by systems with \( \lambda > 0.08 \). Such systems may form low surface brightness systems (cf. MMW for a discussion) which are probably also missed in the de Jong sample. In fact, the low surface brightness galaxies in O’Neil et al. (1997) sample have remarkably small central bulges. The discrepancy between the model prediction and the observational results may just be due to the selection bias in the sample.

The galaxies in the de Jong sample also show a well-defined correlation between the bulge and disc luminosities (cf. Fig. 19 in de Jong 1996b). To see whether our model can reproduce such a trend, we construct a ‘galaxy sample’ in which each galaxy is given a magnitude randomly drawn from the CfA luminosity function (Marzke et al 1994). Our results remain the same for any other luminosity function. The top panel of Figure 3 shows the predicted trend for \( \alpha = 1 \) and \( \beta = 1.3 \). The two solid lines bracket the observed scatter (\( \sim 4 \) mag). It is interesting to see that virtually all the systems with \( \lambda < 0.08 \) (filled dots) are bracketed within the observed range. The systems with \( \lambda > 0.08 \) should have smaller bulge-to-disc ratios. These systems have systematically lower surface brightness since their discs are more spread-out (MMW). In reality, there should be scatters in the values of \( \alpha \) and \( \beta \) for different haloes. Unfortunately it is unclear how large these scatters are. To illustrate how such scatters affect our results, we show in the bottom panel of Fig. 3 an example where \( \alpha \) is allowed to vary from 0.7 to...
1.3, and $\beta$ from 1.1 to 1.5. The scatter in the bulge-disc luminosity relation now becomes bigger; in particular some systems with small $\lambda$ can now have very small bulge-to-disc ratios.

For given set of $\alpha$ and $\beta$, the bulge-to-total ratio depends only on the spin parameter (cf. Fig. 1), our model therefore predicts a deterministic relation (without any scatter) between the bulge-to-total mass ratio and disk size (because $r_d \propto \lambda$, see MMW). To see the scatter induced by the scatter in $\alpha$ and $\beta$, we plot, in Fig. 4, the bulge-to-total mass ratio as a function of $r_d/L^{1/3}$, where $L$ is the total luminosity. According to the disk model we are considering here, the quantity $r_d/L^{1/3}$ is expected to be approximately proportional to the spin parameter (see Mao, Mo & White 1998 for a detailed discussion). The scatter plot is obtained from the same Monte Carlo simulation as shown in the bottom panel of Fig. 3. As one can see, there is a broad trend of $M_b/M_{tot}$ with $r_d/L^{1/3}$ in the model prediction, although the scatter in the relation is very large. For comparison, we plot (as the solid dots) the observational data from the de Jong’s sample. The model prediction is generally consistent with the observational result, but there are noticeable differences. There are more predicted systems at both the low and high ends of $M_b/M_{tot}$, for the reasons we discussed before. There are also several observed galaxies which have large $M_b/M_{tot}$ and large $r_d/L^{1/3}$. Some of these galaxies seem to have low-surface-brightness disks. Their disks may appear fainter for their mass (and show up at the upper right part of the diagram) because they have systematically higher mass-to-light ratio (McGaugh & de Block 1997). Alternatively, these systems could form via other mechanisms such as galaxy merging or their halos have extreme density and angular momentum profiles. Clearly to make more detailed comparison, it is important to obtain more observational data and also to understand the real distributions of $\alpha$ and $\beta$ from future numerical simulations.

4 DISCUSSION

We have examined a scenario in which the bulge-to-disc ratios of spiral galaxies are primarily determined by the angular momenta of their host dark haloes in the framework of hierarchical structure formation models. The low angular momentum gas in a dark halo falls into the centre and, if it becomes self-gravitating before settling into a rotationally supported disc, forms a bulge. The predicted bulge-to-disc ratios in both size and luminosity are consistent with observational results. In this model, the bulge and disc components in a galaxy have similar properties, because both form in a similar manner. This is consistent with the observations of Courteau et al (1996) who showed that the colours and other photometric properties of the bulge and disc components are similar. This is also consistent with the fact that many galactic bulges are supported (at least partially) by rotation rather than by random motion (Kormendy & Illingworth, 1982; Wyse et al 1997 and references therein). Our model also predicts that low surface brightness galax-

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**Figure 2.** Histograms (thick solid) for the predicted bulge-to-total mass ratio (lower panel) and the bulge-to-disc ratio in scale-length (upper panel). The model assumes $\alpha = 1$ and $\beta = 1.3$. The shaded histograms are the data from de Jong (1996a). Note that the model predicts more systems at both the small and large bulge-to-disc ratio ends (see text).

**Figure 3.** Predicted correlation between the bulge magnitude vs. disc magnitude. The top panel is for Monte Carlo simulations with $\alpha = 1, \beta = 1.3$ while the bottom one shows the results where $\alpha$ is allowed to vary uniformly between 0.7 to 1.3 and $\beta$ between 1.1 and 1.5. The filled and open dots are for systems with spin parameter $\lambda < 0.08$ and $\lambda > 0.08$, respectively. The two solid lines roughly indicate the four magnitude scatter in observations.
Figure 4. Monte Carlo results for the bulge-to-total mass ratio vs. $r_d/L^{1/3}$, which is an approximate measure for the spin parameter. We have allowed $\alpha$ to vary uniformly between 0.7 to 1.3 and $\beta$ between 1.1 and 1.5. The open circles are for the Monte Carlo results while the filled dots are for the de Jong sample.

ACKNOWLEDGMENTS

We thank Roelef de Jong for making his data available to us in electronic form. We are grateful to Simon White for helpful comments on the paper. This project is partly supported by the “Sonderforschungsbereich 375-95 für Astro-Teilchenphysik” der Deutschen Forschungsgemeinschaft.

REFERENCES

Cole S., Lacey C., 1996, MNRAS, 281, 716
Combes F., Debbasch F., Friedli D., Pfenniger D., 1990, A&A, 233, 82
Courteau S., de Jong R. S., Broeils A. H., 1996, ApJ, 457, L73
Dalcanton J.J., Spergel D.N., Summers, F.J., 1997, ApJ, 482, 659
de Jong R.S., 1996a, A&AS, 118, 557
de Jong R.S., 1996b, A&A, 313, 45
de Jong R.S., 1996c, A&A, 313, 377
Eggen O., Lynden-Bell D., Sandage A., 1962, ApJ, 136, 748
Fall S.M., Efstaithiou G., 1980, MNRAS, 193, 189
Kauffmann G., White S.D.M., Guiderdoni B., 1993, MNRAS, 264, 201
Kauffmann G., 1996, MNRAS, 281, 487
Kormendy J., Illingworth G., 1982, ApJ, 256, 460
Jimenez R., Padovan P., Matteucci F., Heavens A., 1998, preprint [astro-ph/9801237]
Larson R.B., 1976, MNRAS, 176, 31
Lemson G., Kauffmann G., 1998, preprint [astro-ph/9710122]
Mao S., Mo H.J., White S.D.M., 1998, preprint [astro-ph/9801237]
Marzke R. O., Geller M.J., Huchra J.P. Corwin H. G. Jr., 1994, AJ, 108, 437
McGaugh S.S., de Blok W.J.G., 1997, ApJ, 481, 689
Mo H.J., Mao S., White S.D.M., 1998, MNRAS, 295, 319 (MMW)
Navarro J.F., Frenk, C. S., White, S.D.M., 1996, ApJ, 462, 563
Navarro J.F., Frenk, C. S., White, S.D.M., 1997, ApJ, 490, 49 (NFW)
Norman, C. A., Sellwood J.A., Hasan, H., 1996, ApJ, 462, 114
O’Neil K., Bothun G. D., Cornell M. E., 1997, AJ, 113, 1212
Schechter P., Dressler A. 1987, AJ, 94, 563
Toomre A., Toomre J., 1972, ApJ, 178, 623
Tormen G., Mo H.J., Mao S., 1998, in preparation
Warren M.S., Quinn P.J., Salmon J.K., Zurek W.H., 1992, ApJ, 399, 405
White S.D.M., Frenk C.S., 1991, ApJ, 379, 52
White S.D.M., Rees M.J., 1978, MNRAS, 183, 341
Wyse, R.F.G., Gilmore G., Franx M., 1997, ARA&A, 35, 637

pies have systematically small bulges, in agreement with the observations of O’Neil et al (1997) that many such galaxies lack bright central bulges. Since the $\lambda$ distribution has only a weak dependence on halo mass (Lemson & Kauffmann 1998), our model does not predict a correlation between the bulge-to-disc ratios and galaxy luminosities. However, there is some weak observational evidence that brighter galaxies have systematically larger bulge-to-disc ratios (Schechter & Dressler 1987). Such a correlation can be produced by environmental effects: systems with higher mass may be biased towards higher density regions where discs can be truncated by tidal interaction or gas stripping. Another possibility is that bulges are easier to form in higher mass systems because their dark haloes are less concentrated.

We emphasize that the scenario explored here is unlikely to be the only channel for bulge formation. All the processes discussed in the introduction may be relevant to some degree for the formation of bulges. In particular, there is evidence that merging must have played some role in the formation of some massive bulges. The question is, of course, which processes are relevant for the formation of the main population of bulges. The merits of our model are: (1) it is built in the generally successful framework of hierarchical clustering, so that our assumptions can be tested by future numerical simulations; (2) it makes quantitative predictions for the properties of the bulge-disc systems, so that it can be falsified by future observations.

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