How Concentrated Are The Haloes Of Low Surface Brightness Galaxies In The Cold Dark Matter Model?

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ABSTRACT

We investigate whether a correlation exists between the concentration ($\theta_00$) and spin ($\lambda$) parameters of dark matter haloes forming in $\Lambda$CDM N-body simulations. In particular, we focus on haloes with virial masses in the range $10^{11} \lesssim M_{\rm vir}/h^{-1}M_{\odot} \lesssim 2 \times 10^{12}$, characteristic of the hosts of Low Surface Brightness (LSB) and High Surface Brightness (HSB) galaxies. Our analysis demonstrates that $\theta_00$ and $\lambda$ are anti-correlated. If we assume that a galaxy disk forms in one of these haloes from baryons that approximately conserved angular momentum during their dissipation into the rotationally supported disk, then it is possible to estimate the disk’s central surface density. For an appropriate choice of mass-to-light ratio, we can place constraints on the central surface brightness of the disk and hence identify the analogues of the host haloes of LSB and HSB galaxies. We find that our LSB galaxy analogues occupy haloes that have lower concentrations than might be expected based on consideration of the $M_{\rm vir} - c_{\rm vir}$ relation for the $\Lambda$CDM cosmology. The distribution of concentrations peaks at $\theta_00 \sim 6$, in good agreement with observational data, although there are important differences between the shapes of the simulated and observationally inferred distributions. This suggests that LSB galaxies inhabit a biased subsample of the halo population, and that this bias may be an important ingredient for resolving the current debate regarding the structure of LSB galaxy dark matter haloes.

Key words: galaxies: haloes – cosmology: theory, dark matter, gravitation – methods: numerical, N-body simulation

1 INTRODUCTION

The Cold Dark Matter (CDM) model is widely accepted as the paradigm within which to understand the formation of structure in the Universe. A defining characteristic of this model on the scale of galaxies is the prediction that central densities of dark matter haloes rise as $\rho \propto r^{-\alpha}$, with $\alpha \approx -1$, over the radii which govern the inner rotation curves of galaxies. Over the last decade, numerous studies – principally numerical – have sought to quantify and understand this divergent or cuspy behaviour (e.g. Navarro, Frenk & White 1996, Moore et al. 1998, Navarro et al. 2004). In particular, the continued assertion that the rotation curves of dark matter dominated systems such as low surface brightness (LSB) galaxies require mass profiles with finite constant density cores or shallow “cusps” (e.g. Flores & Primack 1994, Moore 1994, Burkert 1995, de Blok & McGaugh 1996, McGaugh & de Blok 1998, de Blok et al. 2003) has prompted many detailed investigations into the consequences of these observations for the CDM model.

This disparity between the predicted and inferred mass profiles appears to call into question the most basic assumption of the CDM model, namely the nature of the dark matter, and constitutes a critical challenge to the paradigm. Indeed, reconciling theory and observation has come to represent a central problem in contemporary cosmology and is arguably one of its most contentious issues, as illustrated by recent analyses of the systematic effects that could affect high resolution rotation curve data of LSB galaxies and the fitting procedures used in mass modeling (de Blok et al. 2003, hereafter DB03) have argued that the signature of CDM cusps should be clear in the data and so the model’s predictions are inconsistent with observations, while Hayashi et al. (2004a,b), in some cases using overlapping data, find no compelling evidence for disagreement between cuspy CDM haloes and observed rotation curves. These studies focused on the shape of LSB galaxy rotation curves, which rise approximately linearly with radius in the manner one would expect if the mass
density profile contained only a shallow central cusp or a constant density core; if the underlying profile is strongly cuspy, it is argued, the rotation curve should rise more rapidly at small radii. However, the rate at which the rotation velocity increases with radius is sensitive to how centrally concentrated the mass distribution within the halo is. The more centrally concentrated the halo, the more rapidly its rotation curve will rise. Thus, a slowly rising rotation curve could be interpreted as indicative of a halo that is weakly centrally concentrated.

The seminal work of Navarro, Frenk & White (1996, hereafter NFW) formalised this concept of concentration. Based on a comprehensive suite of simulations, they established their universal mass profile that could describe the structure of an average dark matter halo in dynamical equilibrium, independent of its mass or the choice of cosmological parameters and initial density perturbation spectrum. The circular velocity of a NFW halo can be expressed as

$$V_c(x) = \sqrt{\frac{1}{x} \ln(1 + \frac{c_{\text{vir}} x}{1 + c_{\text{vir}}}) - \frac{c_{\text{vir}} x}{1 + c_{\text{vir}}}},$$

where $x = r/r_{\text{vir}}$ is the radius $r$ normalised by the virial radius $r_{\text{vir}} = v_{\text{vir}}/c_{\text{vir}}$ is the concentration parameter where $r_s$ is the scale radius, and $V_{\text{vir}} = \sqrt{GM_{\text{vir}}/r_{\text{vir}}}$ is the virial velocity of the halo. From Equation 1, we observe that the circular velocity rises as $r^{1/2}$ at small radii, and the larger $c_{\text{vir}}$, the greater $V_c(x)/V_{\text{vir}}$.

NFW found that, on average, concentration decreased with increasing virial mass, and they understood that this reflected the mean density of the Universe at the time of the halo’s formation; more massive systems collapse at later times when the mean density of the Universe is lower. Bullock et al. (2001, hereafter B01) and Eke et al. (2001, hereafter ENS) formulated prescriptions that allow the concentration of a given halo of a given mass in a given cosmology to be predicted. Within the B01 or ENS formulations, we expect a typical galaxy mass halo (2 × 10^{12} M_☉) forming in the ΛCDM cosmology to have a concentration parameter $c_{\text{vir}} \sim 10$.

If LSB galaxies occupy dark matter haloes of the kind that form in the ΛCDM model, then we might expect typical concentrations of $c_{\text{vir}} \sim 10$. Both McGaugh et al. (2003) and DB03 have considered the distribution of concentrations obtained from fits to their LSB galaxy rotation curve data, and as illustrated in Figure 3 of McGaugh et al. (2003) and Figure 1 of DB03, the distribution shows two well defined peaks, one at $c_{\text{vir}} \sim 5$, the other at $c_{\text{vir}} = 0$. The preference for the data to favour such a low value of concentration appears troubling for the CDM model. The mass-concentration relation, predicts that $c_{\text{vir}} \sim 5$ is typical of low mass clusters with $M_{\text{vir}} \sim 10^{14} M_☉$, rather than low mass galaxies, and the $1 - \sigma$ scatter in concentration at a given mass is expected to be 50% at most.

Implicit in this comparison is the unstated assumption that the haloes of LSB galaxies are typical for their mass. LSB galaxies are considered ideal for probing the structure of dark matter haloes because the baryons contribute minimally to the rotation curve, greatly facilitating the process of decomposing the rotation curve into baryonic and halo contributions. However, if the haloes of LSB galaxies are biased with respect to the general halo population, then this is a biased comparison. Indeed, it has been noted observationally that detailed mass models of LSB galaxies reveal dark matter haloes that are less dense and more extended than those of high surface brightness (HSB) counterparts of similar masses (see the review of Bothun et al. 1997), suggesting lower concentrations than might be expected. Furthermore, there are theoretical grounds to expect that LSB galaxies inhabit a special class of haloes. The low surface brightness of LSB galaxies is a consequence of their low central density. If we make the reasonable assumption that specific angular momentum of the baryons is approximately conserved during their dissipation into a rotationally supported disk, then the scale length of the resulting disk is related to the angular momentum of the dark matter halo, and we anticipate that LSB galaxies will occupy dark matter haloes with larger spin parameters (a measure of the degree to which the halo is supported by angular momentum; see §2) than their HSB counterparts. These considerations suggest that LSB galaxies occupy dark matter haloes with low concentrations and high spin parameters, echoing the conclusions of previous studies (e.g. Dalcanton et al. 1997, Jimenez et al. 1998, Mo, Mao & White 1998).

In this paper, we investigate whether the correlation between concentration and spin, as envisaged by e.g. Dalcanton et al. (1997), Jimenez et al. (1998), and Mo, Mao & White (1998), is sufficient to explain the distribution of concentrations observed by McGaugh et al. (2003) and DB03 for their sample of LSB galaxies. For this purpose, we have analysed a statistical sample of haloes, with masses in the range 10^{11} < M_{\text{vir}}/h^{-1} M_☉ < 2 × 10^{12}, forming in a high resolution cosmological ΛCDM N-body simulation, and observe a trend for a halo’s spin parameter to increase with decreasing concentration. Using the analytic prescription presented in Mo, Mao & White (1998), we use the halo spins to estimate disk scale lengths and surface densities for our hypothetical sample of galactic disks, and hence construct the distribution of concentrations we might expect for the host haloes of LSB galaxies. Although there are important differences between the distribution we recover and those presented in McGaugh et al. (2003) and DB03, we observe that the peak at $c_{\text{vir}} \sim 5$ is reproduced in our distribution. We present the results of our analysis in the next section (§5) and discuss their significance in §6.

2 RESULTS

Our results are based on analysis of the z=0 output of a 512^3 particle cosmological N-body simulation of a periodic volume, 50 h^{-1} Mpc on a side, that was run assuming the ΛCDM cosmology (Ω_0 = 0.3, Ω_Λ = 0.7, Ω_b = 0.045, h = 0.7, σ_8 = 0.9) using the GADGET2 code (Springel et al., in preparation). A (comoving) gravitational softening length of 5h^{-1}kpc (approximately 1/20th the mean interparticle separation) was adopted, and the chosen parameters imply
a particle mass of $7.75 \times 10^7 h^{-1} M_\odot$. The mass resolution of the simulation is sufficient to resolve a $2 \times 10^{12} h^{-1} M_\odot$ halo with $\sim 26,000$ particles. Haloes are identified using a friends-of-friends (FOF; e.g. Davis et al. 1985) algorithm with a linking length of $b = 0.2$ times the mean interparticle separation. We note that this simulation formed the basis of recent studies by Bailin & Steinmetz (2004a,b).

In order to facilitate comparison to observations, we define the concentration with respect to the radius that encloses a spherical overdensity of 200 times the critical density (as in the original NFW papers), rather than the cosmology dependent $\Delta \simeq 100$. This has the effect of lowering the measured concentration of the halo by $\sim 30\%$ (approximately independent of concentration) relative to that predicted by either the B01 or ENS prescriptions, reflecting the smaller measured virial radius relative to a fixed scale radius. Concentrations are determined by identifying best fitting parameters $(c_{200}, c_{200})$ for the enclosed mass at $(0.06, 0.12, 0.25, 0.4, 0.6, 1.00) r_{\text{vir}}$; we find that this method is efficient and it produces accurate and robust estimates of $c_{200}$.

The standard definition of the spin parameter,

$$\lambda = \frac{J|E|^{1/2}}{GM^{3/2}},$$

where $M$, $J$ and $E$ are the mass, total angular momentum and energy of the halo respectively, depends on binding energy, which is both a slow operation ($\sim N^2$) and ill defined in the context of a cosmological simulation. Instead, we have chosen to compute the Bullock et al. (2001b) measure,

$$\lambda' = \frac{J}{\sqrt{2MVR}},$$

where $V$ is the circular velocity at radius $R$; this can be corrected by a factor $\lambda = \lambda' f(c_{200})^{1/2}$,

$$f(c_{200}) = 2/3 + (c_{200}/21.5)^{0.7} \quad \text{(3)}$$

(Mo, Mao & White 1998; Bullock et al. 2001b).

We begin by considering the distribution of halo concentrations $c_{200}$ relative to their spin parameters $\lambda$ for all FOF groups with masses between $10^{11}$ and $2 \times 10^{12} h^{-1} M_\odot$, as shown in Figure 1. Although there is large variation in $\lambda$ at a given $c_{200}$, we note a discernible trend for $\lambda$ to increase with decreasing $c_{200}$; the median increases from $\lambda_{\text{med}} \simeq 0.03$ at $c_{200} = 10$ to $\lambda_{\text{med}} \simeq 0.05$ at $c_{200} = 5$. This precisely the behaviour we would expect the host haloes of LSB galaxies to display, in agreement with previous work (e.g. Dalcanton et al. 1997; Jimenez et al. 1998).

Having established a correlation between $\lambda$ and $c_{200}$, we wish to derive the quantity that characterises a LSB galaxy, namely its central surface brightness $\mu_0$; our particular treatment follows that of Mo, Mao & White (1998). If we assume that the angular momentum of the baryons is approximately conserved during their dissipation into a rotationally supported disk, we can estimate the angular momentum of the disk $J_d$ and hence its extent for a given mass $M_d$. We assume that the disk’s mass and angular momentum are fixed fractions of those of the host halo’s mass and angular momentum, and choose $j_d = m_d = 0.05$ such that $M_d = m_d M$ and $J_d = j_d J$. Accordingly, the central surface density $\Sigma_0$ is given by

$$\Sigma_0 = \frac{M_d}{2\pi r_d^2}, \quad \text{(5)}$$

where $r_d$ is the scale length of the disk,

$$r_d = \frac{r_{200}}{\sqrt{2}} \left( \frac{j_d}{m_d} \right) \lambda f(c_{200})^{-1/2} J \left( \lambda, c_{200}, m_d, j_d \right), \quad \text{(6)}$$

and we use the fitting formula of Mo, Mao & White (1998) (see their equation (32)). The central surface brightness $\mu_0$ can be estimated by assuming a particular choice of local mass-to-light $(M/L)_\odot$ ratio, which is a combination of the gas $(M/L)_{\text{HI}}$ and star $(M/L)_*$ ratios. De Blok et al. (1997) indicates a local $(M/L)_{\text{HI}} \sim 1$, and de Blok (2004, private communication) suggests $(M/L)_* \sim 1$; in what follows, we adopt $(M/L)_{\text{tot}} = 2$.

By definition, a LSB galaxy is one whose central surface brightness satisfies $\mu_0 \geq 23$ mag arcsec $^{-2}$; typical B-band values lie in the range $23 \leq \mu_0 \leq 24$ mag arcsec $^{-2}$ for LSB galaxies, compared with $21 \leq \mu_0 \leq 22$ mag arcsec $^{-2}$ for HSB galaxies. Converting to central surface densities, we select LSB and HSB galaxies by applying cuts of $1.5 \leq \log \Sigma_0 \leq 1.9$ and $2.3 \leq \log \Sigma_0 \leq 2.7$ respectively, where $\Sigma_0$ is expressed in units of $M_\odot$ pc$^{-2}$.

In Figure 2 we demonstrate how central surface density $\Sigma_0$ correlates with concentration $c_{200}$, where $\Sigma_0$ is evaluated using equations (5) and (6). As expected, there is a clear trend for haloes with lower concentrations to host disks that have lower central surface densities; the median increases from $\Sigma_{0,\text{med}} \simeq 10^2 M_\odot$ pc$^{-2}$ at $c_{200} = 5$ to $\Sigma_{0,\text{med}} \simeq 10^3 M_\odot$ pc$^{-2}$ at $c_{200} = 10$. We can quantify this trend by computing the mean value of $c_{200}$ in bins of width 0.5 in $\log \Sigma_0$ and performing a linear regression over the range $1 \leq \log \Sigma_0 \leq 3.5$ to obtain the relation,

$$c_{200} = 3.4 + 2.1 \log \Sigma_0.$$

Concentrations of LSB Galaxy Haloes
shown by the solid curve in Figure 2; outside of this range, $c_{200} \sim 5$ for $\log \Sigma_0 \leq 1$ and $c_{200} \sim 10$ for $\log \Sigma_0 \geq 3.5$. This correlation is due in equal parts to the direct dependence of $u_d$ on $c_{200}$ and on the indirect dependence via the spin parameter $\lambda$. For a fixed $\Sigma_0$, we find the distribution of $c_{200}$ has a width of $\sim 2.5 - 3$, essentially independent of the precise value of $\Sigma_0$.

Finally, in Figure 3, we show distributions of concentrations corresponding to the host haloes of LSB (red histogram; hereafter the LSB distribution) and HSB (blue histogram; hereafter the HSB distribution) galaxies by applying the observationally motivated cuts in central surface density ($1.5 \leq \log \Sigma_0 \leq 1.9$, $2.3 \leq \log \Sigma_0 \leq 2.7$ for LSB and HSB disks respectively) discussed above. For comparison, we show also the distribution derived from fits to high resolution LSB galaxy rotation curves presented in Figure 1 of DB03 (hereafter the DB03 distribution).

There are two main points worthy of note in this figure. Firstly, we find that the LSB and HSB distributions peak at different values of $c_{200}$; the peak value of the HSB distribution occurs at $c_{200} \sim 8.5$, compared with $c_{200} \sim 6$ for the LSB distribution. Secondly, the values of $c_{200}$ at which the LSB and DB03 distributions peak are in remarkably good agreement -- $c_{200} \sim 6$ -- although we note that the overall shapes of the respective distributions differ; the DB03 distribution has an additional well defined peak at $c_{200} = 0$ and a tail extending to $c_{200} = 20$. However, the peak at $c_{200} = 0$ in the DB03 distribution is an artifact of the fitting procedure; when the NFW fits were clearly unphysical, such as when they preferred negative values of $c_{200}$, the value of $c_{200}$ was arbitrarily set to 0.1 (de Blok & Bosma 2002). Therefore, these haloes should be characterized as haloes which cannot be fit by the NFW form, rather than haloes with a well-defined concentration of 0.1. We also note that the $M_{\text{vir}}/c_{200}$ relation implies that very high concentration haloes are exclusively very low mass systems. In particular, the observed halo with $c_{200} \sim 19$ is likely a dwarf galaxy whose mass falls well below our low mass cutoff of $10^{11} h^{-1} M_{\odot}$ (Power 2003).

We can estimate the likelihood that the DB03, LSB and HSB samples are drawn from the same distribution by applying the K-S test. If we include the entire DB03 sample, we find that it is inconsistent with both the LSB ($P_{\text{KS}} = 0.04$) and HSB ($2 \times 10^{-6}$) samples; ignoring the peak at $c_{200} = 0$, we find reasonable agreement with the LSB sample (0.11) but not the HSB sample (0.002); and finally, ignoring both the peak at $c_{200} = 0$ as well as the high-$c_{200}$ tail, we find improved agreement with the LSB sample (0.15) but similarly poor agreement with the HSB sample (0.001).

3 DISCUSSION

The status of LSB galaxies as dark matter dominated systems is a well established observational result (e.g. Bothun et al. 1997) and their rotation curves can provide, in principle, clean probes of the distribution of dark matter within their host haloes. However, as the divergent conclusions reached by the recent studies of DB03 and Havashi et al. (2004a) demonstrate, the question of whether the shape of LSB galaxy rotation curves can be used to place strong constraints on the nature of the dark matter and hence the validity of the ΛCDM model on small scales continues to be a matter of heated debate. We have not attempted to address this particular issue in our study -- the mass resolution of our simulation is insufficient to reliably recover halo density profiles on the scales that are of most interest for comparison with observations (Power et al. 2003) -- but it is unlikely that their structure will differ significantly from that predicted by NFW and more recent studies (e.g. Navarro et al. 2004). Instead we have focused on the related topic of the degree to which haloes of the kind predicted to host LSB galaxies in the ΛCDM cosmology are centrally concentrated.

Our analysis indicates that a correlation exists between concentration $c_{200}$ and spin $\lambda$ for haloes with masses in the range we have studied, $10^{11} \leq M_{\text{vir}}/h^{-1} M_{\odot} \leq 2 \times 10^{12}$, such that haloes with low values of $c_{200}$ tend to have high values of $\lambda$, and vice versa. By assuming that the baryons associated with these low-$c_{200}$, high-$\lambda$ haloes approximately
Conserves angular momentum during the formation of the galaxy disk, we recast this trend as one between the central surface density of the disk, $\Sigma_0$, and the concentration of its host halo, $c_{200}$, using the formalism of McConnell, Mao & White (1998). Adopting an observationally motivated local mass-to-light ratio, $(M/L)_{tot}$, we identified those halos most likely to contain LSB galaxy disks, thus allowing us to construct a distribution of concentrations that we compared with the distribution of inferred concentrations presented in DB03. Although there are important differences between the DB03 and our hypothetical LSB distributions, namely the presence of a significant number of galaxies for which $c_{200} = 0$ and several high-$c_{200}$ systems, we recover a peak value of $c_{200} \sim 6$ that is in good agreement with observations. In addition, when we exclude the $c_{200} = 0$ systems, which are not true measurements of halo concentration but rather a failing of the entire fitting formula, and the $c_{200} \sim 19$ system, which likely has a much lower mass than our haloes, we find that the observed and predicted distributions of $c_{200}$ are consistent at the 15% level.

This is a compelling result because it establishes the relation between a halo’s concentration and its spin, and confirms the expectation that haloes with low $c_{200}$ and high $\lambda$ are the natural hosts of LSB galaxies. This is in good agreement with the observational evidence, which indicates that LSB galaxies occupy dark matter haloes that are more diffuse and more extended than those of HSB galaxies of comparable mass (e.g. Bothun et al. 1997). As noted in $\S$ 1.1, this is equivalent to stating that the host haloes of LSB galaxies are less centrally concentrated than those of their HSB counterparts. B01 observed and quantified a scatter in concentration for fixed halo mass, and found a 1-$\sigma$ variation of $\Delta \log c_{vir} \sim 0.14$ (although we note that this has been revised to $\Delta \log c_{vir} \sim 0.18$; Bullock, private communication). Thus we expect a galaxy halo with a virial mass $M_{200} = 2 \times 10^{12} h^{-1} M_\odot$ to have a concentration in the range $6 \lesssim c_{200} \lesssim 12.5$ (B01, ENS). However, previous studies failed to identify any correlation between a halo’s concentration and its spin; NFW examined the distribution of residuals in characteristic overdensity $\delta_c$ (a function of the concentration) and found no correlation with spin. Similarly, Bullock et al. (2001b) found no evidence for a correlation between the spin parameter $\lambda$ and concentration, although they noted a weak trend between their modified spin $\lambda'$ (see equation 5) and concentration $c_{vir}$, such that smaller $c_{vir}$ corresponded to larger $\lambda'$ and vice versa. We suggest that the absence of a correlation in the Bullock et al. (2001b) data reflects the relatively poor mass resolution of their simulation in comparison with ours (a factor of $\sim 10$ in mass), while we suspect that the selective nature$^2$ and poor number statistics of the NFW study will have made the correlation difficult to identify.

Although this result does not resolve the current debate surrounding the mass profiles of LSB galaxy haloes and the implications for the CDM model, it is promising that a set of reasonable assumptions and a simple correlation between concentration and spin can so elegantly lead to two halo populations that bear the characteristics of LSB and HSB galaxies. The central density profiles of the haloes must still be reconciled with the detailed density profiles of LSB rotation curves. One possibility is that an additional correlation exists, such that LSB galaxies occupy low-$c_{200}$, high-$\lambda$ and triaxial haloes, which may have observational consequences for the kind of rotation curves that we might observe; indeed, the bearing of triaxiality on measured rotation curves has been investigated by Hayashi et al. (2004). Intriguingly, a subpopulation of our LSB host haloes have particularly triaxial figures. Overall, we consider this an encouraging result for advocates of the CDM model and one worthy of further study.

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