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A LIMIT ON THE COSMOLOGICAL MASS DENSITY AND POWER SPECTRUM FROM THE ROTATION CURVES OF LOW SURFACE BRIGHTNESS GALAXIES

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ABSTRACT

The concentrations of the cuspy dark matter halos predicted by simulations of cold dark matter are related to the cosmology in which the halos form. Observational constraints on halo concentration therefore map into constraints on cosmological parameters. In order to explain the observed concentrations of dark matter–dominated low surface brightness galaxies, we require a cosmology with rather little power on galaxy scales. Formally, we require $\sigma_8\Gamma_{0.6} < 0.23$, where $\Gamma_{0.6}$ is a modified shape parameter appropriate to this problem. Practically, this means that either $\Omega_m < 0.2$ or $\sigma_8 < 0.8$. These limits apply as long as we insist that the cuspy halos found in simulations must describe the halos of low surface brightness galaxies. A low-density cosmology helps with the low observed concentrations, but it offers no explanation of the many cases where the shape of the density profile deviates from the predicted cuspy form. These cases must have suffered very extensive mass redistribution if the current halo formation picture is not to fail outright. It is far from clear whether any of the mass redistribution mechanisms that have been suggested (e.g., feedback) are viable.

Subject headings: cosmology: observations — dark matter

1. INTRODUCTION

There has been considerable recent interest in the inner structure of dark matter halos. Simulations of structure formation with cold dark matter (CDM) have advanced to the point where they are able to predict the density profile of dark matter halos (e.g., Navarro, Frenk, & White 1997, hereafter NFW). The predicted form of these NFW halos is fairly universal, with the central halo concentrations depending upon the density of the universe at the time of halo formation. This depends on the cosmology, so a constraint on halo concentrations translates into one on cosmological parameters.

The rotation curves of spiral galaxies provide accurate tracers of the combined potential of dark and luminous mass. As such, they should provide a measure of concentration that can be mapped to cosmology. Unfortunately, the simulations provide accurate predictions only for the dark matter. Luminous mass can be a significant fraction of the total mass at small radii in bright spirals, making it difficult to extract a measure of the dark-only mass that simulations predict.

Fortunately, there is a class of dark matter–dominated, low surface brightness (LSB) galaxies ideally suited for this experiment. The luminous mass of these objects is very diffuse, greatly reducing the impact of the stellar mass on the inferred halo parameters (e.g., de Blok & McGaugh 1997). In these systems, the luminous mass merely provides a convenient tracer of the dominant dark mass.

Useful constraints on the dark matter distribution require accurate, high-resolution data. McGaugh, Rubin, & de Blok (2001) present a large sample of rotation curves for LSB galaxies with resolution sufficient to constrain the NFW concentration parameter. We have modeled these in detail (de Blok, McGaugh, & Rubin 2001, hereafter BMR). Further, such data have been obtained by de Blok & Bosma (2002, hereafter BB). In this paper, we use the results of BMR and BB to obtain a constraint on cosmology.

BMR and BB find that cuspy NFW halos provide a poor description of the data. The most obvious interpretation is that real dark matter halos do not have the cusps. Halo models with constant-density cores are more viable.

Nonetheless, cuspy halos do seem to be the generic prediction of CDM simulations, whereas soft-core isothermal halos enjoy no such theoretical basis or cosmological context. Moreover, it is often possible to find NFW fits to the rotation curves of individual galaxies, even if they are formally worse than isothermal halo fits. There is therefore some reason to persist with NFW halos despite the substantial observational evidence against them. The purpose of this paper is to illustrate the consequences for cosmology if we insist that dark matter halos must have the cuspy NFW form.

In § 2 we review the data, its interpretation, and the applicability of the NFW form. In § 3 we discuss the relation of CDM halos to cosmological parameters and combine this with observations to place limits on cosmology. The implications of these limits are discussed in § 4, as are some possible ways out. Conclusions are given in § 5.

2. DATA

The data we use here are the NFW fits to the high-resolution hybrid Hα–H I rotation curves of LSB galaxies described by BMR and BB. These are based on recent optical data (McGaugh et al. 2001; BB) combined with H I data (van der Hulst et al. 1993; de Blok, McGaugh, & van der Hulst 1996; Swaters et al. 2002b) in order to optimize both the resolution and the radial extent of the data (see BMR). The observed rate of rise of these rotation curves is rather

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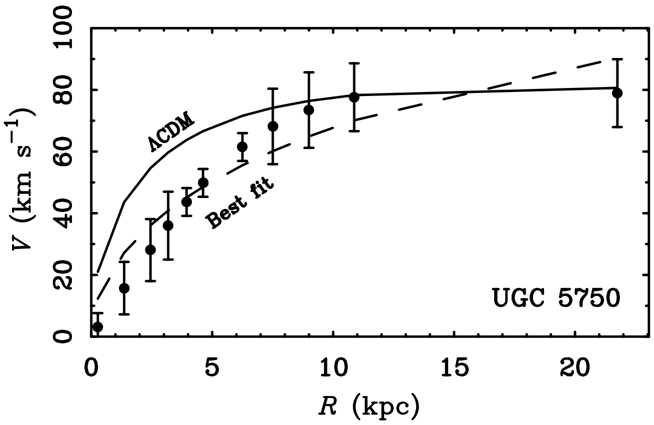

FIG. 1.—Rotation curve of the low surface brightness galaxy UGC 5750. Also shown are the best-fitting NFW halo parameters ($c = 2.6$, $V_{200} = 123$ km s^{-1}; *dashed line*) for the limiting case of a zero mass (minimum) disk and what the NFW halo should look like for a galaxy of this rotation velocity in the standard ΛCDM cosmology ($c = 10$, $V_{200} = 67$ km s^{-1}; *solid line*). The excess of the solid line over the data illustrates the cuspy halo problem. Although an NFW fit can be made (*dashed line*), it is a poor description of the data and requires a very low concentration ($c = 2.6$ does not occur in any plausible cosmology). These problems become more severe as allowance is made for stars (BMR; BB).

gradual compared to the rate of rise predicted by NFW halos for a broad range of plausible cosmologies (Fig. 1).

It was noted some time ago that the solid-body nature of the rotation curves of low-luminosity galaxies posed serious difficulties for cuspy halos (Moore 1994; Flores & Primack 1994; McGaugh & de Blok 1998a). A possible explanation offered for this was that the 21 cm data were adversely affected by beam smearing (van den Bosch et al. 2000). This might diffuse away the sharp signature of a cuspy halo, but is no guarantee that a cusp is present (van den Bosch & Swaters 2001).

The issue of beam smearing can be addressed by improving the resolution of the observations. McGaugh et al. (2001) and BB obtained Hα long-slit data with $1''$–$2''$ spatial resolution. This improves on the previous 21 cm data by more than an order of magnitude. For the most part, the high-resolution optical data confirms the gradual rate of rise of the rotation curves of LSB galaxies that had previously been indicated by the 21 cm data. Reports of the severity of beam smearing have been greatly exaggerated.

This is not to say that beam smearing was insignificant in all cases; there are certainly a few where it is apparent. However, it was not pervasive enough to hide the very distinctive signature of the cusps that are predicted for halos in the standard ΛCDM cosmology. Moreover, the objections of McGaugh & de Blok (1998a, 1998b) to the CDM explanation for rotation curves were not based on detailed NFW fits to 21 cm data but rather on the systematics of the shapes of rotation curves. These are well predicted by the light distribution, even in LSB galaxies where the luminous mass is insignificant. The cases where beam smearing was significant (e.g., F574-1; Swaters, Madore, & Trewhella 2000) had been discrepant from these relations; the improved optical data remedy this. This makes the problems with CDM discussed by McGaugh & de Blok (1998a) more severe, not less.

BMR and BB show that flat-core, isothermal halos always provide a better description of the data than do NFW halos. There is a remarkable unanimity of results on this point. All high-resolution rotation curve data show a strong preference for soft cores (Marchesini et al. 2002; Bolatto et al. 2002; Blais-Oullette, Amran, & Carnigan 2001; Salucci 2001; Borriello & Salucci 2001; Côté, Carnigan, & Freeman 2000). So far as we are aware, there is no contradictory observational evidence that might prefer cuspy halos in galaxies that are dark matter–dominated.

There are claims (e.g., Jimenez, Verde, & Oh 2002) that cuspy halos might do as well as halos with soft cores in high surface brightness (HSB) galaxies, but these are not obviously dark matter–dominated (e.g., Palunas & Williams 2000). The role of stellar mass is a great impediment to any conclusions about cuspy halos in HSB galaxies. In cases where constraints beyond the rotation curve can be placed on stellar mass, it is very difficult to fit cuspy halos (e.g., Weiner, Sellwood, & Williams 2001). This is especially true in the Milky Way, where many lines of evidence exclude a cuspy halo (Binney & Evans 2001; Bissantz & Gerhard 2002). For LSB galaxies, Jimenez et al. (2002) confirm the results of BMR.

The preference of the data for soft cores in LSB galaxies can no longer be attributed to resolution effects as suggested by van den Bosch et al. (2000). There are now many well-resolved rotation curves for dark matter–dominated galaxies from a number of independent sources. Contrary to the expectations of beam-smearing arguments, the best-resolved rotation curves prove to be the least consistent with cuspy halos (de Blok et al. 2001). It is unlikely that any significant systematic effect afflicts the optical data as the rotation curves obtained for the same galaxies by independent observers are in good agreement (McGaugh et al. 2001; BB).

Given the strong observational evidence against cuspy halos, it is perhaps puzzling that their use persists. This is largely attributable to the convergence of many theoretical results: cuspy halos do appear to be a fundamental prediction of CDM (see below). Moreover, while NFW fits to rotation curve data are distinctly inferior to fits with isothermal halos, it is usually possible to find some combination of NFW parameters thatmore or less go through the data (Fig. 1). Given the importance of cuspy halos to the prevailing paradigm and the lack of theoretical basis for halos with soft cores, the preference of the data for the latter might not, in itself, be seen as completely disastrous.

Fortunately, it is possible to apply further tests. In CDM models the parameters of NFW halos have a direct relation to cosmology. Not only must the NFW form fit (however crudely) individual rotation curves, but the statistics of the parameters of these fits must be consistent with the cosmology that gave rise to them. The work of BMR and BB provides, for the first time, a large, homogeneous sample of precise, high spatial resolution rotation-curve data for dark matter–dominated LSB galaxies to which this test can be applied. Here we follow through on this to see what these data imply for cosmology.

3. HALO PARAMETERS AND COSMOLOGY

3.1. *Theoretical Framework: NFW Halos*

Cosmological simulations make clear predictions about the radial density distribution of CDM halos (e.g., NFW). These have a simple form that has come to be known as the NFW halo. An NFW halo is specified by two parameters:

a concentration c and a scale such as the circular velocity at the virial radius, V_{200}. The rotation curve due to an NFW halo is

$$V_c^2(x) = V_{200}^2 \frac{\ln(1+cx) - cx(1+cx)^{-1}}{x[\ln(1+c) - c(1+c)^{-1}]} , \qquad (1)$$

where $x = R/R_{200}$ and R_{200} (in kpc) $= V_{200}h^{-1}$ (in km s^{-1}). Fits of this form to rotation curves are very sensitive to the concentration parameter c, which itself depends on cosmological parameters.

The precise form of the inner density profile is critical to the result, so this warrants further examination. The profiles of halos predicted by CDM have now been studied by many groups (Dubinski 1994; Cole & Lacey 1996; NFW; Tormen, Bouchet, & White 1997; Moore et al. 1998, 1999; Tissera & Dominguez-Tenreiro 1998; Nusser & Sheth 1999; Syer & White 1998; Avila-Reese, Firmiani, & Hernandez 1998; Salvador-Śole, Solanes, & Manrique 1998; Jing 2000; Jing & Suto 2000; Kull 1999). These investigations all either concur with the NFW halo profile or find an even steeper cusp in the inner parts. If we parameterize the inner slope of the density profile by γ so that $\rho \propto r^{-\gamma}$, then the NFW result is $\gamma = 1$. Moore et al. (1998, 1999) find a steeper inner slope ($\gamma = 1.5$) from high-resolution simulations. It is unclear whether this difference in γ is significant or more a matter of the choice of fitting function. If the inner slope is very steep ($\gamma > 1$), more severe limits would result than those we derive here for the NFW case. Given this and the clear mapping between NFW halo parameters and cosmological ones, we restrict the analysis to the NFW case ($\gamma = 1$) as the conservative limit.

There are some differences between these theoretical studies, but from an observational perspective these are unimportant. The one real exception to the many studies predicting $\gamma \geq 1$ is the study of Kravtsov et al. (1998). They find[6] a shallower inner halo slope than NFW, with $\gamma \approx 0.4$. This value is significantly discrepant from other studies and was estimated perilously close to the limits of the simulations. These workers have now retracted the claim of shallow inner halo profiles (Klypin et al. 2001) and concur with other studies that the predicted slope is $\gamma \geq 1$.

If we treat γ as a free parameter, the data give a median $\gamma \approx 0.2$, with essentially all well-resolved data being consistent with $\gamma = 0$ (de Blok et al. 2001a). Although it is possible to fit NFW halos to much of the data, it is not the form favored by the data (§ 2). If CDM simulations produced a halo with a soft core, there would be little implication for cosmology. However, the vast majority of theoretical work on this subject predicts $\gamma \geq 1$, with no room to treat γ as a free parameter. If we accept this as the correct prediction of CDM, then the observed distribution of concentrations places interesting limits on cosmology.

3.2. *The Halo Concentration-Cosmology Connection*

The characteristic concentration of CDM halos depends on the density of the universe at the time of halo formation (NFW). This in turn depends on the density parameter (Ω_m), the distance scale (h), and the amplitude of the power spectrum on the relevant scales. The latter depends on both the normalization (σ_8) and shape of the power spectrum.

NFW provide a prescription that relates halo parameters to the cosmology in which they form. This is encapsulated by the program CHARDEN provided by J. F. Navarro (2000, private communication). For a specified halo mass and set of cosmological parameters, CHARDEN gives the concentration and other parameters. We use CHARDEN to make several hundred realizations of the mean concentration parameter for a variety of cosmologies. The grid of realizations samples parameters in the ranges $0.1 < \Omega_m < 0.5$, $0.45 < h < 0.85$, $0.2 < \sigma_8 < 2$, and $0.75 < n < 1.25$, where n is the scalar spectral index of the power spectrum. We consider only flat ($\Omega_m + \Omega_\Lambda = 1$) cosmologies. Open cosmologies give somewhat higher concentrations, all other things being equal. Since LSB galaxies require rather low concentrations, the constraints on an open cosmology would be tighter.

The results from CHARDEN are shown in Figure 2, which plots the concentration parameter c as a function of cosmic parameters. The concentration also depends weakly on halo mass, which could be plotted as a third axis. We show the case for $V_{200} = 163$ km s^{-1} ($M = 10^{12}\ M_\odot$). This mass scale is appropriate to bright galaxies and is somewhat higher than is typical for the LSB galaxies in our sample. The correlation of c with V_{200} goes in the sense that c is higher for lower V_{200}, so adopting this mass scale for mapping between theory and observation is a conservative choice. That is, a lower mass halo more appropriate for an LSB galaxy would have a higher concentration. When required to match the low observed concentrations, a more stringent constraint on cosmology would be implied.

The top panel of Figure 2 shows the dependence of c on the shape parameter Γ, which to a first approximation is the product $\Omega_m h$. Here we use the common fitting formula

$$\Gamma = \Omega_m h e^{-\left[\Omega_b + \sqrt{2h}(\Omega_b/\Omega_m)\right]} - 0.32\left(n^{-1} - 1\right) \qquad (2)$$

(e.g., White et al. 1996). The baryon density Ω_b acts as small correction factor to the shape of the power spectrum for a given $\Omega_m h$. An increase in Ω_b depresses the relative amount of power on smaller scales, thus acting to lower halo concentrations. A similar effect can be obtained by tilting the spectrum ($n < 1$), but these are rather weak effects compared to $\Omega_m h$.

There is a clear call for a second parameter in the top panel of Figure 2. This is the normalization of the power spectrum σ_8 (*middle panel*). The combination $\sigma_8\Gamma$ seems to account for most components of the dependence of halo concentration on cosmology. There does remain some striation at low concentration and more scatter than one would like. Motivated by the fact that the relevant dependence on the mass density in many structure formation problems is $\Omega_m^{0.6}$, we define a modified shape parameter $\Gamma_{0.6}$:

$$\Gamma_{0.6} = \Omega_m^{0.6} h e^{-\left[\Omega_b + \sqrt{2h}(\Omega_b/\Omega_m)\right]} - 0.32\left(n^{-1} - 1\right) . \qquad (3)$$

This is identical to the usual shape parameter with the exception of the power of Ω_m. The result is a linear dependence of halo concentration on the product $\sigma_8\Gamma_{0.6}$ (Fig. 2, *bottom panel*).

[6] In addition to their analysis of their simulations, Kravtsov et al. (1998) examined the H I data available at the time and found that it indicated $\gamma \approx 0.2$. This same value is found in subsequent optical data (de Blok et al. 2001). The agreement between these results is another indication that systematic errors are not significant.

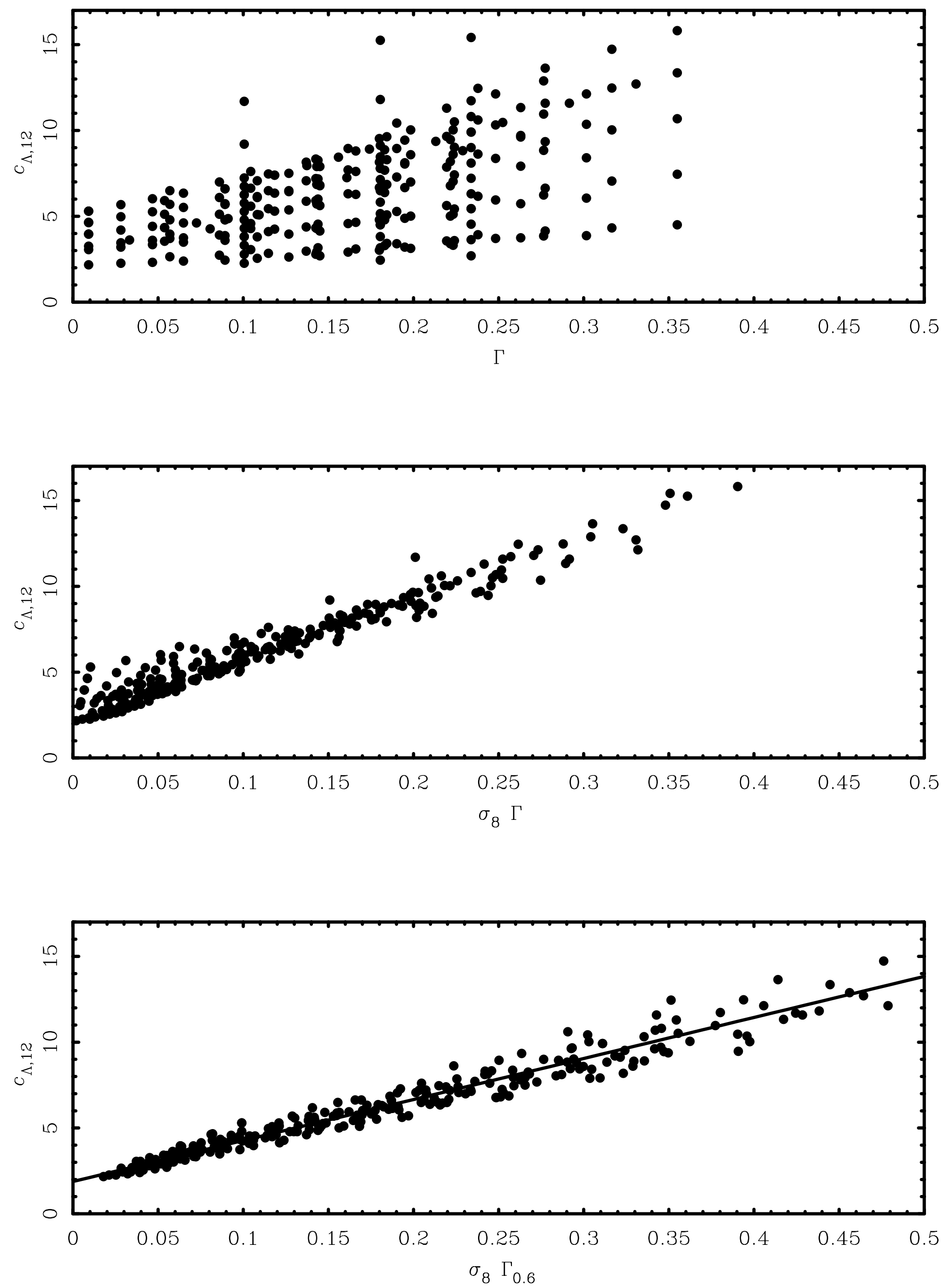

FIG. 2.—Concentration parameter $c_{\Lambda,12}$ predicted for a 10^{12} $M_\odot$ NFW halo in a flat universe as a function of cosmic parameters. In the top panel we show the concentration as a function of the shape parameter Γ, which depends on Ω_m, h, Ω_b, and n. There is a clear correlation, but the realizations are striated by their different normalizations. This is remedied by considering the product of the shape parameter and the normalization, σ_8 (*middle panel*). There is still some residual scatter, which is reduced by use of the modified shape parameter, $\Gamma_{0.6}$ (*bottom panel*). This depends on $\Omega_m^{0.6}$ rather than the linear power of Ω_m that appears in the standard shape parameter (eqs. [2] and [3]). The line in the bottom panel (eq. [4]) is a fit to these realizations, which we use to relate the observed concentrations to cosmology.

The realizations in the bottom panel of Figure 2 are well described by the relation

$$c_{\Lambda,12} = 1.88 + 23.9\sigma_8\Gamma_{0.6} \; , \qquad (4)$$

where $c_{\Lambda,12}$ is specific to 10^{12} $M_\odot$ NFW halos in flat ΛCDM cosmologies. The residual scatter about this relation is small, with a standard deviation of 0.084 in the ratio of realized to predicted concentration. This relation for the characteristic concentration produced by a given cosmology can be used to map the observed concentrations to a limit on cosmology (§ 3.4).

3.3. *Scatter in Concentrations*

Equation (4) gives the characteristic concentration of NFW halos for a given set of cosmological parameters. Of course, not all halos of a given mass are identical—some scatter is expected about the nominal concentration. This issue has been investigated in detail by Jing (2000) and Bullock et al. (2001). Both groups find a lognormal distribution of concentration parameters with $\sigma_c = 0.18$. This apparent consistency is marred by the fact that Jing (2000) uses the natural logarithm and Bullock et al. (2001) use the base

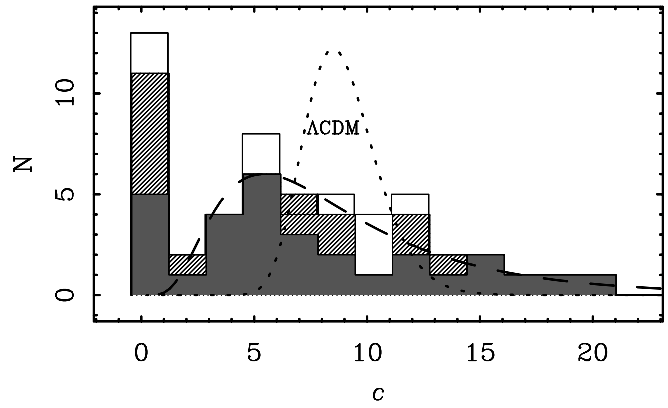

FIG. 3.—Histogram of the observed concentrations from the data of BMR and BB for the case of minimum disk. Several histograms are shown for different subsets of the data. The open histogram shows all data from BMR and BB. The hatched histogram includes only those objects for which the NFW fits have $\chi^2 < 2$. The shaded histogram includes only those with $\chi^2 < 1$. The shape of the observed distribution is robust to these changes. The characteristic concentration is low ($c \approx 6$) and the peak of extremely low concentrations ($c < 2$) never disappears. The data look nothing like the prediction of ΛCDM (*dotted line*; Jing 2000). A crude fit of the lognormal form advocated by Jing (2000) and Bullock et al. (2001) can be made (*dashed line*) if (1) cosmological parameters are adjusted in accordance with the observed low median concentration, (2) the amount of scatter is allowed to be much larger than found in simulations, and (3) the galaxies with $c < 2$ are ignored.

10 logarithm so that the same value of σ_c actually corresponds to a broader distribution in the latter case. Nevertheless, there does seem to be broad agreement about the form the distribution should take even if the value of σ_c is not uniquely fixed by simulations.

The histogram of observed concentrations is shown in Figure 3. These data are taken from BMR and BB for the case of minimum disk. This choice is made to maximize the number of galaxies that can be included in the analysis and to be conservative in the sense that minimum disk fits allow larger concentrations than do fits that include stars. There are other sources of data that we do not include here in order to maintain a consistent analysis: the mass models of BMR and BB have been constructed in an identical fashion. Other data for dark matter–dominated galaxies are limited in number so far, so their inclusion or exclusion makes little difference to the histogram in Figure 3. As discussed in § 2, the independent analyses that do exist are entirely consistent with the findings of BMR and BB.

The distribution in Figure 3 is broad: there are many galaxies with low ($c < 6$) concentrations, and some with rather high concentrations ($c > 15$). Although these are outside the nominal range that one would expect for ΛCDM, there is a well-defined central peak. There is, therefore, some hope that the anticipated lognormal distribution can be fitted to the data if the relevant cosmological parameters are allowed to vary, and an explanation can be found for the outliers.

The observed distribution of concentrations is robust. Figure 3 shows three different selections of the data: (1) all of the data of BMR and BB (54 galaxies), (2) only those galaxies (45) with tolerable NFW fits ($\chi^2 < 2$), and (3) only those (31) with good fits ($\chi^2 < 1$). While there are of course some detailed differences between these, the overall shape of the distribution is unaffected. The central peak is unmoved; its width varies little. The large peak of galaxies with very low concentrations ($c < 2$) never disappears. One might have hoped that by including only the best fits, a sensible distribution would emerge and the galaxies with unacceptably low concentrations would disappear. Unfortunately, simply having a good NFW fit is no guarantee that the halo parameters correspond to any sensible cosmology: no cosmology ever produces halos with $c < 2$.

The failure of the data in Figure 3 to conform to the predictions of ΛCDM is not a data quality issue (McGaugh et al. 2001; BMR; BB). Many of the galaxies with $\chi^2 < 1$ have $\chi^2 \ll 1$, implying that the error bars have, if anything, been overestimated. This makes the many objects with $\chi^2 > 1$ more problematic. These are generally the better data. NFW fits with $\chi^2 < 1$ are usually obtained when the uncertainties[7] are large, not because the data look like cuspy halos. In addition to making cuts by χ^2, we have also made cuts by inclination and by subjective judgement of the data quality (de Blok, Bosma, & McGaugh 2002). The results are indistinguishable from those presented here.

There are many galaxies with concentrations that are either too small or too large for ΛCDM. There may be astrophysical explanations for these outliers. An obvious explanation for the galaxies whose concentrations are too high for ΛCDM would be that they are not entirely dark matter–dominated. An appropriately massive stellar disk, when subtracted off, might leave the right amount of dark matter. One has to be careful with such a procedure, as a heavy disk implies some compression of the original (cosmological) halo, which might end up with too low a concentration if one merely aims to get the " right " concentration currently. Moreover, it might be possible to choose a stellar mass-to-light ratio that simply gives a desired result. It is for this reason that a large sample of dark matter–dominated galaxies is best for this experiment.

That said, it is not obvious that plausible stellar mass-to-light ratios will reduce the implied concentrations of the high-c outliers. In the cases where adequate photometry is available, BMR and BB present mass models with $M_*/L_R = 1.4\ M_\odot/L_\odot$. In none of the cases of high concentration does the inclusion of stars of this mass-to-light ratio significantly reduce c. Implausibly large mass-to-light ratios would be required to have an impact. The excess number of high-c galaxies may therefore pose a genuine problem.

A more severe (and certainly genuine) problem is posed by the low-c outliers. This cannot be solved by allowing stars to have mass, as this makes matters worse. Indeed, contrary to the case of high-c galaxies, attributing even a small mass to the stars can have a significant downward impact on c if it is already low in the minimum-disk case. More generally, these extremely low concentration galaxies embody the soft-core problem for which many explanations have been hypothesized. We therefore postpone discussion of this problem until § 4.4.

3.4. *A Limit on Cosmology*

In this section we derive a limit on cosmology by requiring that the peak of the distribution of observed concentrations c_p follow from cosmology in the manner prescribed by NFW. Extracting the optimal value of c_p from the data is at once both straightforward and challenging—straightforward because the peak position in Figure 3 is well defined,

[7] $\Delta\chi^2$ generally favors soft cores (BMR; BB).

TABLE 1
Peak Location Estimates

Sample	Median	Biweight	Lognormal
All...........	6.0	6.4	5.4
$\chi^2 < 2$.......	5.7	6.3	5.4
$\chi^2 < 1$.......	5.7	6.2	5.3

and challenging because the data do not agree with the NFW form. Properly, we would use the $\chi^2(c, V_{200})$ of the fits from BMR and BB to compute the likelihood distribution and hence the optimal c. In practice, there is essentially zero likelihood because the NFW form provides such a poor description of so much of the data. In order to do this exercise at all, we overlook this small failing of the NFW model and work directly with the raw histogram of concentrations (Fig. 3). This is a generous thing to do, as it gives credit to fits that do not really fit, and the net result remains robust because the location of c_p is the same regardless of how the data are subdivided.

In Table 1 we give several estimations of c_p. These include eyeball fits of the lognormal distribution and the robust statistical estimators the median and the biweight location. Formal fits with the lognormal function are ill-defined for the same reason that the likelihood cannot be used directly. Nonetheless, the eyeball fits do nicely describe much of the data: allowing the lognormal form to have a large scatter[8] ($\sigma_c \approx 0.6$) provides a plausible explanation for the high-c outliers (while offering no explanation for the low-c galaxies). The skew of the distribution tends to make c_p from the lognormal fits a bit lower than the median and biweight location. The latter are useful statistics because they are robust against outliers, although even their interpretation is open to question since the many outliers may simply be another indication that the underlying model is inappropriate.

We can now place a limit on cosmology by equating c_p derived from the observations with $c_{\Lambda,12}$ from equation (4). In doing so, we are making the approximation that the observed concentrations apply to $10^{12}\,M_\odot$ halos rather than the particular mass scale appropriate to each individual fit. In practice this is a very good approximation because the predicted c-V_{200} relation is very flat (NFW), so the correction to c when projected to the V_{200} appropriate for a given galaxy is usually smaller than the uncertainty in c. Moreover, most LSB galaxy halos should be less massive than $10^{12}\,M_\odot$, so c_p should, if anything, be compared to the higher concentrations predicted for lower mass halos.

Evaluating equation (4) with the lognormal $c_p = 5.4$ yields $\sigma_8\Gamma_{0.6} = 0.15$. For comparison, standard ΛCDM, with $\Omega_m = 0.33$, $h = 0.66$, $n = 1.03$ (Netterfield et al. 2002), $\Omega_b h^2 = 0.02$ (O'Meara et al. 2001), and $\sigma_8 = 0.96$ (Pierpaoli, Scott, & White 2001) gives[9] $\sigma_8\Gamma_{0.6} = 0.28$. This is nearly twice the value derived here and predicts substantially higher concentrations: $c_{\Lambda,12} = 8.5$ (Fig. 3). Such concentrated halos have a very distinctive dynamical signature and would be *easily* recognized by current observations (de Blok et al. 2002).

If dark matter halos were well described by cuspy halos, the peak of the distribution of concentration parameters would provide a useful measurement of $\sigma_8\Gamma_{0.6}$. However, the NFW form, upon which this analysis is based, does not provide a good description of the data (BMR; BB). Instead, halos with lower density cores are preferred. Even persisting with NFW halos as we have done here, the observations demand rather low concentrations. Not only is c_p lower than expected, but there is also the substantial population of galaxies with $c < 2$ that have no explanation in the cuspy halo picture. The data are telling us that dark matter halos cannot be as concentrated as nominally expected. Rather than attempt to use this method to measure cosmic parameters, we ask: what cosmology could produce tolerable concentrations? This leads to an upper limit on $\sigma_8\Gamma_{0.6}$ that is quite firm as long as the NFW picture of halo formation holds.

In order to limit cosmology to parameters that might produce suitably low concentrations, we note that 95% of our realizations have $c/c_{\Lambda,12} < 1.15$. A given c_p cannot originate from a cosmology that produces halos more concentrated than this. The largest estimate of the peak concentration from Table 1 is $c_p = 6.4$. Multiplying this by 1.15 to allow for the residual scatter about equation (4) leads to the limit

$$c_p < 7.4 \; . \tag{5}$$

The corresponding limit on cosmology is

$$\sigma_8\Gamma_{0.6} < 0.23 \; . \tag{6}$$

This is a very hard limit, as we have adopted the largest estimate of the peak location from Table 1 and hedged upward from there. The data certainly do not indicate such a large c_p, and the true vale of $\sigma_8\Gamma_{0.6}$ must be much less if there has been no radical redistribution of mass subsequent to halo formation.

4. DISCUSSION

In this section, we discuss possible interpretations of the concentration limit on cosmology. These come in several basic flavors:

1. CDM halos must have cusps, so the stated limits hold and provide new constraints on cosmological parameters.
2. Something (e.g., feedback, modification of the nature of dark matter) eliminates cusps and thus the constraints on cosmology.
3. The picture of halo formation suggested by CDM simulations is wrong.

The bulk of the dynamical data may well prefer the last of these interpretations, potentially with drastic consequences for CDM (McGaugh & de Blok 1998a, 1998b; de Blok & McGaugh 1998; Sanders & Verheijen 1998; Sanders 1996; Sanders & McGaugh 2002). We focus the discussion here on items (1) and (2), which have a variety of subflavors.

4.1. *Assumptions*

As in any study of cosmological parameters, a number of assumptions must be made. Before trying to sort out possible interpretations, it is worth examining the validity of the

[8] The scatter is much larger than anticipated. A large scatter in c should have a severe impact on the scatter in the Tully-Fisher relation. That it apparently does not leads to fine-tuning problems (McGaugh & de Blok 1998a; Bullock et al. 2001).

[9] For these parameters, the ordinary shape parameter is $\Gamma = 0.18$, slightly less than used by Pierpaoli et al. (2001): $\Gamma = 0.23$.

assumptions underlying our analysis. Everything we do here is confined to the context of the currently standard ΛCDM cosmology. In order to map the rotation curve results to cosmological parameters, we have made a number of operative assumptions:

1. The NFW halo is the correct prediction of CDM.
2. The concentration parameter maps to cosmology via the NFW prescription.
3. NFW halos provide an adequate description of the data.
4. LSB galaxies reside in typical halos.

Assumption 1 has already been discussed in § 3.1 and appears certainly to be true modulo only the remaining debate over the precise slope of the inner cusp. Since $\gamma = 1$ is at the lower limit of predicted cusp slopes, this assumption is both valid and conservative. Steeper cusps would result in more stringent limits on cosmology. If we accept assumption 1, then assumption 2 follows.

Assumption 3, that NFW halos provide an adequate description of the rotation curve data, is the most dubious (§ 2). The most obvious interpretation of these data is that dark matter halos do not have cusps (de Blok et al. 2001) or do not exist at all (Sanders & McGaugh 2002). However, the point of this paper is to explore the consequences if we insist on retaining cuspy halos.

Assumption 4 is important because we treat the concentrations determined from LSB galaxy rotation curves as a measure of that produced by cosmology. If for some reason halo concentration is correlated with surface brightness, then the cosmological measure will be biased. There is little reason to suspect such a bias in theory, and none empirically.

In most modern theories of galaxy formation (e.g., Dalcanton, Spergel, & Summers 1997; Mo, Mao, & White 1998; McGaugh & de Blok 1998a; van den Bosch & Dalcanton 2000), it is the spin of the halo and not its concentration that dictates the surface brightness. Concentration may be correlated with formation epoch, and scatter in the latter may well be the dominant cause of scatter in the former (Wechsler et al. 2002). It is not unreasonable to suppose that LSB galaxies form late (McGaugh & Bothun 1994), but this does not happen in theories where spin is the dominant factor determining surface brightness. Moreover, the range of formation times discussed by Wechsler et al. (2002) is far too small to explain the range of observed concentrations.

One could of course construct a theory that imposes a correlation between concentration and surface brightness. The motivation to do this is not independent of the problems discussed here, and it faces a host of other problems (discussed in detail by McGaugh & de Blok 1998a). Most importantly, such an approach runs contrary to the remarkable empirical normalcy of LSB galaxies.

In terms of their physical properties (metallicity, gas content, etc.), LSB galaxies are quite normal for their part of the luminosity function. They adhere to the same Tully-Fisher relation as do brighter galaxies (Sprayberry et al. 1995; Zwaan et al. 1995; Tully & Verheijen 1997) and to the same baryonic Tully-Fisher relation (McGaugh et al. 2000; Bell & de Jong 2001; Verheijen 2001). This is usually interpreted to mean that LSB galaxies inhabit halos that are similar to those of HSB galaxies of the same mass. Invoking a correlation between concentration and surface brightness predicts a shift in the Tully-Fisher relation between HSB and LSB galaxies, which is not observed.

The empirical normalcy of LSB galaxies includes not just the normalization of their asymptotic rotation velocities (the Tully-Fisher relation), but extends also to the *shapes* of their rotation curves. These are quite predictable given knowledge of their luminosity distribution (e.g., Persic & Salucci 1991; de Blok & McGaugh 1998; Sanders & McGaugh 2002). This obedience[10] to scaling relations established for HSB galaxies is a strong indication that LSB galaxies are dynamically normal. There is, therefore, no reason to suspect that assumption 4 is invalid.

4.2. *How Firm a Limit?*

Proceeding with the above assumptions, we next examine the firmness of the concentration limit on cosmology. So long as we insist on having cuspy halos, this limit is valid. Indeed, we have been quite conservative in placing it. On every occasion where there has been any room to hedge, we have done so in the direction that maximized the allowed concentration. Hedges that act in this way include the following:

1. The adoption of minimal disks.
2. Ignoring adiabatic contraction.
3. Ignoring the angular momentum catastrophe.
4. The use of heavy halos to predict $c_{\Lambda,12}$.
5. Ignoring the low-c spike in the distribution.
6. Adopting the largest estimate of c_p.
7. Making a generous allowance for scatter in the $c_{\Lambda,12}$-$\sigma_8\Gamma_{0.6}$ relation.

These combine to make the limit $\sigma_8\Gamma_{0.6} < 0.23$ both conservative and hard. Taking the best-guess value of any of these effects would lead to a lower value, in some cases by a large factor.

Item 1 is very generous. Stars do have mass, but we have pretended they do not. Consequently, the concentrations we use do not refer to the primordial dark matter halo as they should, but rather to the present dark matter halo plus the stars. Subtracting off the stars lowers c, even in LSB galaxies where dark matter domination minimizes this effect but does not entirely eliminate it.

Items 2 and 3 depend on the galaxy formation process. The natural expectation is that whatever baryons collapse to form the disk will drag along some of the dark matter. This will make the present-day halo more concentrated than the primordial halo that CHARDEN computes. This effect is probably modest in LSB galaxies, but should act some—in the wrong direction. Item 3 is hard to quantify (Steinmetz & Navarro 2002) but could be quite severe, and again it acts in the wrong direction.

The remaining items on the above list have been discussed as they arose in the analysis, and we will not repeat this here. The point is that there are many turns where we have adopted concentrations that are, if anything, too high. The fact that fiducial ΛCDM cosmologies predict still higher concentrations emphasizes the severity of this problem.

[10] The adherence of LSB galaxies to the scaling relation for rotation curve shape is also another indication that the data do not suffer from systematic errors.

4.3. *Implications for Cosmology*

Having reviewed our assumptions and the validity of the concentration limit, we turn now to the first flavor of possible interpretations. If we insist that galaxy halos must have cusps, the limit imposed on cosmology is unavoidable. Here we consider the implications of this limit in the context of other cosmological constraints. In a subsequent section we will address the possibility of dodging these constraints by invoking processes that might alter cusps (e.g., feedback; warm or self-interacting dark matter).

The concentration limit $\sigma_8\Gamma_{0.6} < 0.23$ excludes a significant fraction cosmological parameter space, including that occupied by our fiducial ΛCDM parameters (§ 3.4). In order to satisfy this limit, we need to reduce the density of the universe at the time of halo collapse. This can be accomplished by lowering the matter density directly or by delaying halo formation by suppressing the power spectrum on galaxy scales. We examine these possibilities in turn.

4.3.1. *Matter Density*

For a standard power spectrum and baryon density, the concentration limit excludes $\Omega_m^{0.6}h > 0.28$ (Fig. 4). This limit is fairly restrictive, excluding some parameter combinations that are otherwise viable: $\Omega_m = 1$ is right out, and even $\Omega_m \approx 0.3$ cannot be sustained. Cuspy halos and "standard" ΛCDM are mutually exclusive.

It may be possible to salvage the ΛCDM picture with cuspy halos if the density is low. For $h = 0.7$, the concentration limit requires $\Omega_m < 0.22$. While this is lower than usually quoted for ΛCDM, it is actually in keeping with a number of recent determinations. Bahcall et al. (2000) give $\Omega_m = 0.16 \pm 0.05$. A similar number is also given by Rines et al. (2001)—$\Omega_m = 0.17 \pm 0.05$—and by Hoekstra et al. (2001)—$\Omega_m = 0.13 \pm 0.07$—for a flat universe. These independent determinations are consistent with the findings presented here and may be an indication of a rather small density parameter that is acceptable to many independent data sets (Peebles 1999). However, it may be hard to simultaneously reconcile such a low matter density with the requirement for both flatness $\Omega_m + \Omega_\Lambda \approx 1$ (de Bernardis et al. 2000) and the limit on the cosmological constant from gravitational lensing, $\Omega_\Lambda < 0.7$ (Kochanek 1996; Cooray, Quashnock, & Miller 1999).

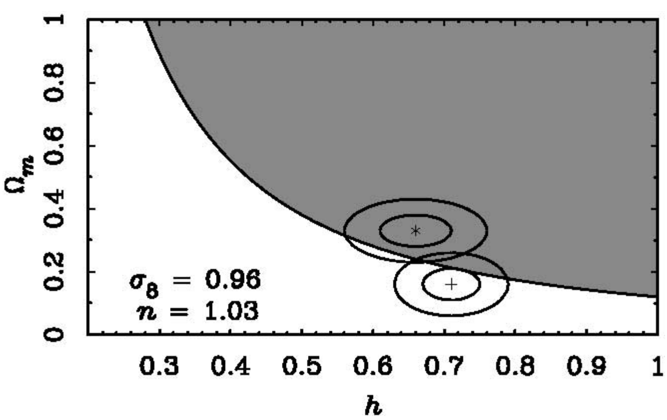

FIG. 4.—Region of the Ω_m-h plane excluded by the concentration limit on $\sigma_8\Gamma_{0.6}$, assuming $\Omega_b h^2 = 0.02$. The entire region $\Omega_m^{0.6}h > 0.28$ is excluded if we require NFW halos to fit observed rotation curves in the standard ΛCDM cosmology. For comparison, we also show 1 and 2 σ error ellipses around independent determinations of Ω_m and h. The asterisk at the point (0.66, 0.33) illustrates the standard ΛCDM value as fitted by Netterfield et al. (2002). Such a "high"-density universe and cuspy halos are mutually exclusive. The cross at the point (0.71, 0.16) takes for the Hubble constant the results of the *Hubble Space Telescope* Key Project on the extragalactic distance scale (Sakai et al. 2000). For the mass density, we take the value estimated by Bahcall et al. (2000): $\Omega_m = 0.16 \pm 0.05$. It is possible to consider NFW halos for many galaxies in such a very low density universe, although a plausible explanation for those with $c < 2$ remains wanting.

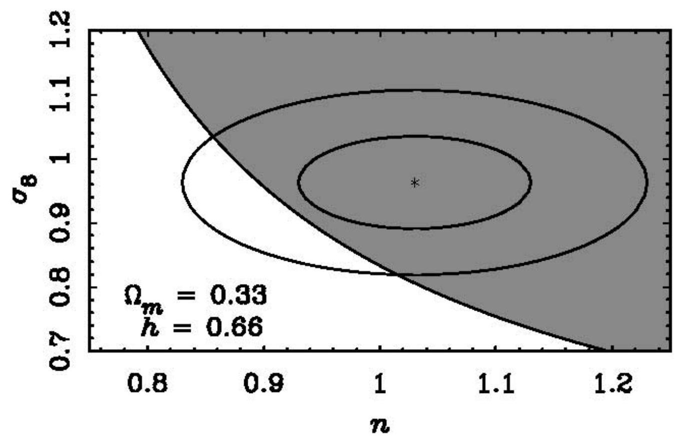

FIG. 5.—Power spectra parameters excluded by the concentration limit for nominal (Ω_m, h) of (0.33, 0.66). Also shown (*asterisk, with 1 and 2 σ error ellipses*) are the best estimates of these parameters from Netterfield et al. (2002; $n = 1.03 \pm 0.10$) and Pierpaoli et al. (2001; $\sigma_8 = 0.96 \pm 0.07$). A substantial reduction in the amplitude of the power spectrum on galaxy scales can decrease the concentration of dark matter halos to tolerable levels, although it leaves open the question of why their preferred shape is not cuspy.

4.3.2. *Power Spectrum*

If a density parameter as low as $\Omega_m < 0.22$ is not acceptable, the requirement stipulated by the concentration limit may be satisfied by a decrease in the amplitude of the power spectrum on galaxy scales. This can be achieved by either a tilt or a decrease in the normalization σ_8 or by some combination of both. For example, for $\Omega_m = 0.33$ and $h = 0.66$, we need $\sigma_8 \lesssim 0.8$ (Fig. 5). Lately there have been contradictory tugs on the value of the normalization, with a combined analysis of the 2dF and CMB data suggesting $\sigma_8 \approx 0.73$ (Lahav et al. 2002), while high-multipole Cosmic Background Imager (CBI) data suggest $\sigma_8 \sim 1$ (Bond et al. 2002).

The same effect could also be achieved by tilting the power spectrum ($n \lesssim 0.9$) or by introducing a break in the power spectrum at some appropriate scale. Such behavior is contrary to the scale-free nature of CDM but might occur with warm dark matter or an admixture of hot dark matter. This may not be necessary as a purely cosmological solution appears to be least marginally viable. A universe with a low mass density or suppressed power spectrum (or both) could satisfy the concentration limit, although it would leave open many related questions.

4.4. *Halo Modification*

This section examines the second flavor interpretation, that some mechanism alters the initially cuspy form of dark matter halos. This approach has the advantage that it might explain why galaxy observations prefer halos with soft cores to those with cusps, with little or no consequence for cosmology. It has the rather substantial disadvantage that some drastic and poorly understood effect must be invoked to alter halos, thus destroying the elegance and predictive power of the NFW paradigm.

4.4.1. *Feedback*

The mechanism most commonly invoked in this context is feedback. This is the notion that the action of star formation, most particularly winds and supernovae from massive stars, injects sufficient mechanical energy into the interstellar medium to alter the surroundings. The hope is that such feedback might mediate between the cosmological initial state of halos predicted by simulations and their current observed state.

The term "feedback" has come to be used to mean a great variety of things. We must immediately make a distinction between the relatively mild sort of feedback activity that is actually observed in galaxies and the explosive feedback required to address the problems posed by soft core halos. There is no doubt that the former does occur (e.g., Martin 1998, 1999; Rupke, Veilleux, & Sanders 2002) and probably plays an important role in enriching the intergalactic medium. However, the amount of gas involved is generally a small percentage of a galaxy's interstellar medium, which is a small fraction of its baryonic mass, which is a fraction of its dark mass. The observed examples of feedback are far too feeble to have any significant impact on the distribution of the dominant dark mass.

In the context of galaxy formation, feedback is invoked to do a variety of things that bear little relation to observed feedback. Feedback from some star formation might suppress further star formation. If this varies systematically with galaxy mass, it might translate the steep halo mass function predicted by CDM into the flat observed galaxy luminosity function. The dramatic loss of angular momentum experienced by baryons in live-halo simulations (the "angular momentum catastrophe") leads to the formation of disks that are much too small. Feedback is invoked as a possible cure for this, although sensible numerical implementations have no such effect (e.g., Navarro & Steimentz 2000). Most importantly for our purposes here, explosive feedback is invoked to drive out so much gas that it gravitationally drags some of the dark mass with it, perhaps creating a soft core where initially there had been a cusp (e.g., Navarro, Eke, & Frenk 1996).

Supposing, for the moment, that explosive feedback might be able to turn cusps into cores, there are two possible interpretations. One is that *all* galaxies are affected so that the current dark matter distribution bears no resemblance to the cosmological prediction. In this case, observations of LSB galaxies are fossil records of the mass redistribution process with no implication for cosmology. In effect, this invokes a deus ex machina to render irrelevant all rotation-curve data. A second, less extreme possibility is that cusp destroying feedback occurs only in *some* galaxies. In this case, feedback need only be invoked to explain galaxies with $c < 2$. The cuspy halo fits to the remaining galaxies hold—as do the cosmological limits derived from them. Since all of the estimators in Table 1 already ignore the low-concentration galaxies, the constraint $\sigma_8 \Gamma_{0.6} < 0.23$ is unaltered.

A separate question is whether explosive feedback really happens and can have the desired effect of converting a dark matter halo with a cusp into one with a core. McGaugh & de Blok (1998a) raised an empirical objection to this scheme. The LSB galaxies in which this is an issue are quite gas-rich (McGaugh & de Blok 1997; Schombert, McGaugh, & Eder 2001)—a curious state for galaxies that were supposed to have exploded so energetically that so much gas was swept out that the dark matter was pulled along with it. One does require the expulsion of a huge amount of mass for this mechanism to have any hope of working, as the dark matter can be dragged along with the gas only by the weak shackles of gravity. In order to arrive at the current observed state, LSB galaxies must undergo a double-whammy formation scenario. First, an intense knot of star formation must occur inside the primordial cuspy halo. Feedback from this star formation must completely detonate the baryonic component of the initial galaxy, sweeping out all gas and hopefully converting the dark matter cusp into a constant-density core. Subsequent to this mass redistribution, some gas must reaccrete to reform the galaxy into its more tenuous present state. This seems like a lot to ask, and it has the undesirable consequence of inserting an untestable intermediary step between prediction and reality.

The fundamental problem with invoking explosive feedback to redistribute mass is that it is a case of the tail wagging the dog. A small fraction of the minority baryons—those that form the first stars—must have a tremendous effect on the majority dark matter. This huge effect must be most severe where the dark mass is most strongly concentrated, and it is mediated only by the weak force of gravity.

Basic physics considerations make the required mass redistribution highly unlikely. Numerical simulations of feedback suggest much weaker effects. For example, MacLow & Ferrara (2000) find that feedback can be effective only in galaxies several orders of magnitude less massive than those considered here, and only in ejecting gas, not redistributing dark mass. Gnedin & Zhao (2002) put a strict limit on the possible effects of explosive feedback by examining the consequences of the instantaneous removal of all gas. They find that even this extreme fails to destroy the initial cusp. Hence, it seems unlikely that explosive feedback can have the mass redistributing effects that are required to address the cusp-core problem.

4.4.2. *Other Mass Redistribution Mechanisms*

There could be mechanisms to redistribute mass besides feedback. Weinberg & Katz (2001) suggested that bars in disks could impart enough angular momentum to halo particles to alter the halo mass distribution. However, this process can be effective only when the disk is a significant fraction of the total mass. Hence this mechanism might at best work in HSB galaxies like the Milky Way. It cannot, as Weinberg & Katz note, explain dark matter–dominated LSB galaxies unless explosive feedback is invoked first. Whether this mechanism is viable even in principle has been questioned by Sellwood (2002).

Another dynamical mechanism invokes the in-spiraling of supermassive black hole pairs (Milosavljević et al. 2002). This process might displace up to 10 times the black hole mass and could well be important in elliptical galaxies. However, the black hole mass–velocity dispersion relation (Merritt & Ferrarese 2001) predicts very small black hole masses for bulgeless, dynamically cold LSB galaxies, far too small to cause any significant redistribution of dark mass. For example, a galaxy comparable in mass to many of the

LSB galaxies discussed here is M33. The limit on the central black hole mass in M33 is less than 3000 $M_\odot$ (Merritt, Ferrarese, & Joseph 2001). Unless LSB galaxies host abnormally massive black holes, and acquired them in pairs through mergers (which these galaxies appear not to have experienced), this mechanism cannot apply to them.

4.4.3. *Dark Matter Physics*

Mass redistribution mechanisms that invoke the interaction of baryons and CDM appear either not to be viable or not to apply to LSB galaxies. One might next consider modifying the nature of dark matter in order to alter the cuspy halo prediction. Such ideas fall into two broad categories: those that prevent the formation of cusps in the first place and those that might reduce their concentration to more tolerable levels. Either would relieve or eliminate the cosmological constraints imposed here in the strict context of pure CDM.

Perhaps the first case to consider is a mixed hot plus cold dark matter cosmogony. Neutrinos do appear to have mass and so will affect structure formation at some level. Massive neutrinos have the effect of suppressing the power spectrum on small scales relative to what it would have been in their absence. This operates in the desired direction, although a fairly hefty neutrino fraction ($\Omega_\nu/\Omega_m \gtrsim 10\%$) is probably needed to have a significant impact. This would require neutrinos near the current upper bound on their mass (a few eV). This may well be possible, but it can at best reduce the concentrations of halos a bit. The halos should still have cusps, not cores. So while it may be possible in this fashion to relax somewhat the constraints on cosmology, the more basic question about the shape of the density distribution of the dark matter halo remains unaddressed.

An effect similar to a mixture of hot and cold dark matter can be obtained with warm dark matter (WDM). In this case, the mass of the particle is fine-tuned so that it is neither hot nor cold dynamically. Again, the power spectrum is reduced on small scales, and the halo profile may be affected as well (Bode, Ostriker, & Turok 2001). The latter point is controversial, as Knebe et al. (2002) find that halo cuspiness persists in WDM. Observationally, there are already serious objections to WDM. Fermionic WDM should have a characteristic phase space density, which appears to be inconsistent with galaxy and cluster data (Sellwood 2000; Marchesini et al. 2002).

The net effect of hot plus cold dark matter and WDM models are similar for this problem. Some suppression of the power spectrum on small scales makes the cosmological limits more palatable. The presence of soft cores in at least some galaxies remains a difficult issue.

More radical suggestions about the nature of dark matter have also been made to address the cusp-core problem. These include annihilating and self-interacting dark matter (SIDM: Spergel & Steinhardt 2000). Annihilating dark matter may form halos with a core (e.g., Craig & Davis 2001) but could oversuppress small-scale power. SIDM produces a cusp for small-interaction cross sections, but it can produce a core with sufficiently large cross sections (Davé et al. 2001). The cross section that works for galaxies does not work for clusters (Yoshida et al. 2000), so one must invoke a velocity-dependent cross section. This seems rather contrived, and other objections have been raised: Kochanek & White (2000) argue that the gravothermal catastrophe will cause SIDM cusps to steepen faster than they flatten.

There remains ample room to consider further modifications to the nature of dark matter. On the one hand, these seem like a more promising approach to the problem of turning cusps into cores than does explosive feedback. On the other hand, the problem is considerably more subtle than just turning a cusp into a core. It is well established observationally that the distributions of dark and luminous matter are tightly coupled (Sanders & McGaugh 2002; see also McGaugh 2000). The cusp-core problem is just one manifestation of this more fundamental issue. None of the approaches we have reviewed have made any attempt to explain the full richness of the observational phenomenology. SIDM interacts with itself, but not with baryons. It is hard to imagine how any explanation of the coupling between baryons and dark matter can be achieved by modifications of cold dark matter that explicitly ignore the baryons.

5. CONCLUSIONS

We have examined the cosmological consequences of the rotation curve data for dark matter–dominated LSB galaxies in the context of cuspy NFW halos. If we insist that dark matter halos must have the cusps suggested by current structure formation simulations, an interesting limit on cosmology follows. This concentration limit is

$$\sigma_8 \Gamma_{0.6} < 0.23 , \tag{7}$$

where $\Gamma_{0.6}$ is a suitably modified shape parameter (eq. [3]). As a practical matter, this means either a low-density universe ($\Omega_m < 0.2$) or one with a depressed power spectrum on small scales ($\sigma_8 < 0.8$).

Such a universe is marginally inconsistent with the nominal parameters of standard ΛCDM. However, it is consistent with a number of recent determinations of the density parameter and with most other constraints. It does therefore appear to be possible to tweak cosmology in order to satisfy our concentration constraint.

If dark matter halos do not have cusps, then there is no constraint on cosmology. However, cuspy halos do appear to have become a fundamental tenet of CDM structure formation. If so, the implications for cosmology are unavoidable.

Adjusting cosmological parameters can address only the problem of halo *concentration*. It does nothing to explain the *shape* of the radial mass distribution in dark matter halos, which must be cuspy in the current paradigm. In many objects with well-determined rotation curves, this appears not to be the case. Tweaking cosmology is a necessary step, but it is only a partial solution to one aspect of a broader problem.

Various mechanisms have been proposed to convert cusps into constant-density cores. These include explosive feedback and modifications of the nature of dark matter (e.g., warm or self-interacting dark matter). Some cusp altering mechanism does appear to be necessary. However, it is far from obvious that any of the ideas that have been discussed so far are viable. All suffer from serious problems, both empirical and theoretical. At this juncture, a satisfactory explanation of observed galaxy dynamics remains beyond galaxy formation theory.

Note added in manuscript.—While this paper was in submission, some related results have appeared. Zentner &

Bullock (2002) have performed a similar analysis, finding that a suppression of the power spectrum on small scales helps with the concentration problem. This appears to be in complete accord with our results. Swaters et al. (2002a) have very recently provided a new analysis of rotation curves in addition to those studies already cited. This work appears consistent with previous results insofar as χ^2 prefers halos with cores to those with cusps. There are a number of objects in common with our sample; adding the new independent cases into Figure 3 makes no difference to our result.

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