HIGH RESOLUTION OPTICAL VELOCITY FIELDS OF 11 LOW SURFACE BRIGHTEST GALAXIES

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ABSTRACT

We present high resolution two-dimensional velocity fields from integral field spectroscopy along with derived rotation curves for eleven low surface brightness galaxies. We fit NFW and pseudo-isothermal halo models to the new data combined with previous long-slit and H\(_i\) data. In most cases we find the pseudo-isothermal halo to better represent the data than the NFW halo, as the NFW concentrations are often lower than expected for a ΛCDM cosmology. We also compare our results to previous studies and find that including the new two-dimensional optical data does not significantly alter the halo parameters, but does decrease the uncertainties by roughly a factor of 2.

Subject headings: dark matter — galaxies: fundamental parameters — galaxies: kinematics and dynamics

1. INTRODUCTION

Determining the mass-density profiles of galactic dark matter halos has been an exciting, yet contentious, field for a number of years now. Though it is widely agreed that low surface brightness (LSB) galaxies are dark matter dominated down to small radii (de Blok & McGaugh 1996, 1997; Pickering et al. 1997, 1999; Blais-Ouellette, Amram, & Carignan 2001; Borrie & Salucci 2001; Simon et al. 2003; but see Fuchs 2003), much better fits to LSB observations are found when using the pseudo-isothermal halo model (Simon et al. 2005; de Blok, Bosma, & McGaugh 2003; de Blok & Bosma 2002) (hereafter BB02): Marchesini et al. 2002; Bolatto et al. 2002; de Blok, McGaugh, & Rubin 2001 (hereafter BMR01); de Blok et al. 2001; Blais-Ouellette, Amram, & Carignan 2001; Côté, Carignan, & Freeman 2000). These halos have a mass-density that remains at an approximately constant value toward the center, thus they are referred to as “cored” halos. Unlike the NFW profile, however, the pseudo-isothermal halo has no cosmological motivation or theoretical basis.

The disagreement arises when comparing the data to numerical simulations of cold dark matter (CDM). The most common description of CDM halo behavior is given by the analytic approximation of Navarro, Frenk, & White (1996, 1997) and is known as the NFW profile. The cosmologically motivated NFW halo is characterized by a mass-density that rises very steeply toward the center, a property which makes the halo “cuspy”. Cuspy halos that rise more steeply than the NFW halo have also been suggested (e.g. Moore et al. 1999; Reid et al. 2003; Navarro et al. 2004). Whether or not the dark matter halos of LSB galaxies can be described by cuspy NFW-like profiles has been a matter of debate.

NFW halos can fit to the observations, but the fits are usually of lower quality than fits with pseudo-isothermal halos. Moreover, the implied cosmological parameters are inconsistent with the standard ΛCDM picture. In particular, the observed concentrations of the NFW halos are too low (McGaugh, Barker, & de Blok 2003; Swaters et al. 2003). Better fits to LSB observations are found when using the pseudo-isothermal halo model (Simon et al. 2005; de Blok, Bosma, & McGaugh 2003; de Blok & Bosma 2002) (hereafter BB02): Marchesini et al. 2002; Bolatto et al. 2002; de Blok, McGaugh, & Rubin 2001 (hereafter BMR01); de Blok et al. 2001; Blais-Ouellette, Amram, & Carignan 2001; Côté, Carignan, & Freeman 2000). These halos have a mass-density that remains at an approximately constant value toward the center, thus they are referred to as “cored” halos. Unlike the NFW profile, however, the pseudo-isothermal halo has no cosmological motivation or theoretical basis.

In its favor, the CDM model has been successful on large scales in explaining structure formation in the early Universe as well as abundances of galaxy clusters (Tegmark et al. 2004). It is more appealing to have a halo model with explanations rooted in cosmology rather than a model that is simply a convenient fit to the data. It is therefore no surprise that a number of reasons have been given in an attempt to salvage the appropriateness of the NFW profile as a description of galactic dark matter halos.

The earliest observations which indicated cores in LSB galaxies were two-dimensional 21 cm H\(_i\) velocity fields (Moore 1994; Flores & Primack 1994; de Blok, McGaugh, & van der Hulst 1996) (hereafter BMH96). Low spatial resolution (i.e., beam smearing) was suggested to be a systematic effect that would erroneously indicate cores (van den Bosch et al. 2000).
Swaters, Madore, & Trewhella 2000). The question of beam smearing was addressed by long-slit Hα observations which had an order of magnitude increase in spatial resolution [see for example, McGaugh, Rubin, & de Blok 2001 (hereafter MRB01); BMR01]; cusps did not appear when the resolution was increased, showing that beam smearing had been of only minor importance in the Hα observations. Possible systematic errors in the long-slit spectroscopy (e.g., Simon et al. 2003; Rhee et al. 2004; Spekkens, Giovanelli, & Haynes 2005) have since become the focus of attention, with slit misplacement (Swaters et al. 2003a) and non-circular motions among the top concerns. If the slit misses the dynamical center of the galaxy, or if there are non-circular motions from, for instance, a bar, the circular velocity may be underestimated and lead to the false inference of a cuspy halo. de Blok, Bosma, & McGaugh 2003 conducted extensive modeling in which the rotation curves of both cuspy and cored halos were subjected to various effects and concluded that no systematic effect will entirely mask the presence of a cuspy halo for realistic observing conditions. Swaters et al. 2003a performed a similar exercise with similar results, but argued that it might still be possible to retain cuspy halos.

Clearly there are a number of issues which new observations must simultaneously address. The data must be both high resolution and two-dimensional in nature. Observations must have resolution $\lesssim 1$ kpc as that is the critical length scale at which the distinction between cusps and cores can be determined (de Blok 2003). Any non-circular motions should be readily identifiable in a two-dimensional velocity field. Additionally, slit placement is not a concern of two-dimensional velocity fields. This observational approach has also been applied by such groups as Simon et al. (2003, 2005).

In this paper we present the rotation curves derived from high resolution two-dimensional velocity fields of a sample of LSB galaxies. In § 2 we discuss the sample and observations; data reduction is discussed in § 3. The results for the individual galaxies are presented in § 4. In § 5 we discuss halo fits to the minimum disk case of the new data combined with previous long-slit and HI rotation curves and compare our results to previous studies. Non-circular motions are also briefly discussed. Our conclusions and goals for future work are stated in § 6.

2. SAMPLE AND OBSERVATIONS

Our primary targets were the galaxies in the “clean” sample of de Blok, Bosma, & McGaugh (2003). In brief, galaxies in the “clean” sample have inclinations between 30° and 85°, are likely to meet the minimum disk assumption, have long-slit rotation curves which are well resolved in the inner 1 kpc, have small errorbars and lack large asymmetries. The minimum disk assumption is considered applicable to those galaxies which require substantial amounts of dark matter at small radii even in the maximum disk model. We then expanded our sample to include other LSB galaxies that nearly made the “clean” cut. We also searched for low mass dwarf galaxies to fill out the RAs available at the telescope, giving preference to those targets with diffuse Hα emission detected by long-slit observations.

We observed 8 “clean” galaxies: UGC 4325, DDO 64, NGC 4395, F583-4, F583-1, DDO 185, DDO 189, and NGC 4455. These galaxies were selected from the “clean” sample because the well-resolved long-slit Hα observations show there is diffuse Hα emission for detectability in two-dimensional velocity fields and that the galaxies lack indicators of significant non-circular motions (e.g., strong bars or gross asymmetries). While not a criterion considered in the selection process, it turns out that the long-slit observations of these galaxies imply that the galaxies have either unreasonably low NFW concentrations or do not have cusps at all. These kinds of galaxies pose the biggest problem for CDM and

| Galaxy   | R.A.        | Dec.        | $\mu_0(R)$ | Dist.  | $i$ | $V_{hel}$ | $R_{max}$ | $V_{max}$ | PA | Refs. |
|----------|-------------|-------------|------------|--------|-----|-----------|-----------|-----------|----|-------|
| UGC 4325 | 08:19:20.5  | +50:00:35   | 21.6       | 10.4   | 41  | 514       | 2.3       | 86        | 52 | 2     |
| F563-V2  | 08:53:03.7  | +18:26:09   | 21.2       | 61     | 29  | 4316      | 6.7       | 104       | 328| 1     |
| F563-1   | 08:55:06.9  | +19:14:58   | 22.6       | 45     | 25  | 3482      | 5.6       | 146       | 341| 1     |
| DDO 64a  | 09:00:22.4  | +31:29:16   | -          | 6.1    | 60  | 520       | 2.1       | 51        | 97 | 2     |
| F568-3   | 10:27:20.3  | +22:14:22   | 22.2       | 77     | 40  | 5905      | 8.4       | 114       | 169| 1     |
| UGC 5750 | 10:35:45.1  | +20:59:24   | 22.6       | 56     | 64  | 4160      | 8.5       | 61        | 167| 2     |
| NGC 4395b| 12:25:48.9  | +33:32:48   | 22.2       | 3.5    | 46  | 310       | 0.8       | 33        | 327| 2     |
| F583-4   | 15:52:12.7  | +18:47:06   | 22.9c      | 49     | 55  | 3620      | 7.5       | 75        | 115| 1     |
| F583-1   | 15:57:27.5  | +20:39:58   | 23.2c      | 32     | 63  | 2256      | 4.9       | 83        | 355| 1     |
| UGC 477  | 00:46:13.1  | +19:29:24   | -          | 35     | 82  | 2635      | 10        | 112       | 347| 3     |
| UGC 1281 | 01:49:32.0  | +32:35:23   | 22.7d      | 5.5    | 85  | 145       | 1.9       | 38        | 218| 3     |

Note. — Col.(1): Galaxy name. Col.(2): Right Ascension. Col.(3): Declination. Col.(4): Central surface brightness in $R$-band (mag arcsec$^{-2}$). Col.(5): Distance (Mpc). Col.(6): inclination ($^\circ$). Col.(7): Heliocentric systemic velocity (km s$^{-1}$). Col.(8): Maximum radius of the DensePak rotation curve (kpc). Col.(9): Maximum velocity of the DensePak rotation curve (km s$^{-1}$). Col.(10): Position angle of major axis ($^\circ$); see Sec. 4.1 for details. Col.(11): References for surface brightness, distance and inclination: (1) de Blok, McGaugh, & Rubin (2001) (2) de Blok & Bosma (2002) (3) Bullock (1998).

a DDO 64 = UGC 5272.

b NGC 4395 = UGC 7524.
c Converted from $B$ band assuming $R = B - R = 0.9$.
d Taken from reference (2).
Table 2: Galaxies without Velocity Fields

| Galaxy     | UGC      | UCG      |
|------------|----------|----------|
| CamB       | 2684     | 9211/DDO |
| F756-4     | 4543     | 11583    |
| KK38 251   | 4787     | 12344    |
| UGC 891    | 5414/NGC 3104 | 12713 |
| UGC 1501/NGC 784 | 7603/NGC 4455 | 12791 |
| UGC 2455/NGC 1156 | 8837/DDO 185 |     |

Note: Galaxies which were observed with DensePak but whose detections were not good enough to construct meaningful velocity fields.

as such, provide important test cases.

We observed 4 galaxies from [MRE01] (F563-V2, F563-1, F568-3, UGC 5750) that almost made the “clean” sample. They show diffuse Hα emission, but either did not have the required number of independent points in the inner 1 kpc of the long-slit rotation curve or had an inclination outside the “clean” range.

Lastly, we observed 16 galaxies from the Nearby Galaxies Catalogue (Tully 1988). Selection criteria for these galaxies included positions satisfying 18h ≤ α ≤ 08h and +10° ≤ δ ≤ +50°, inclinations between 30° and 85°, heliocentric velocities ≤ 2500 km s⁻¹, and an estimated V_{flat} (approximated by V_{flat} ≈ 0.5W_20sin^{-1}(i)) between roughly 50 km s⁻¹ and 100 km s⁻¹.

Our sample of 28 observed galaxies is both weather and signal limited. Poor weather prevented us from observing more of the “clean” sample. Our sample is signal limited in that not all of the galaxies have enough Hα emission to construct useful velocity fields. While pre-existing long-slit observations can be used as a guide, there is no way of knowing how much Hα emission will be detected by the IFU until the experiment is done. Our sample is intentionally focused on the most dark matter dominated objects. These tend to be very low surface brightness dwarfs that are hard to observe.

The galaxies were observed during the nights of 2004 April 12-15, 2004 November 14-19 and 2005 September 1-7. Observations were made using the DensePak Integrated Field Unit on the 3.5-m WIYN telescope at the Kitt Peak National Observatory. DensePak is comprised of 3” diameter fibers arranged in a 43” × 28” rectangle. We measured the fiber separation to be 3.84”. The separation was determined by centering a bright star in a fiber and repeatedly shifting between fibers and across the array. There are 85 working fibers in this arrangement; an additional four sky fibers are arranged outside the main bundle. We used the 860 line mm⁻¹ gratings in second order, centered near Hα giving a 58 km s⁻¹ velocity resolution. The distances to the galaxies in the sample are such that a 3” fiber provides sub-kpc resolution.

Because the galaxies were too faint to be visible on the guide camera, we centered the DensePak array on a nearby star and then offset to the optical center of the galaxy. Subsequent pointings on the galaxy were made by shifting the array by small amounts from its current position. For a number of galaxies, these moves were the fine shifts required to observe the spaces between the fibers. These interstitial pointings effectively increased the resolution to ~ 2″. The fiber bundle orientation on the sky and the total number of pointings per galaxy were tailored to each galaxy so that the critical central regions were covered by the DensePak fibers. Each exposure was 1800 sec, and two exposures were taken at each pointing. A CuAr lamp was observed before and after each pointing to provide wavelength calibration.

3. DATA REDUCTION

The observations were reduced in IRAF using them as the reference wavelengths (Osterbrock et al. 1996) by which the velocities of the galactic emission lines were measured. We also tried using the CuAr calibration to measure the velocities, but the night sky lines gave cleaner results. Velocities were measured by fitting Gaussians to both the sky lines and the four galactic emission lines of interest: Hα, [N II]λ6584, [S II]λ6717 and [S II]λ6731. The average error on individual emission line velocities due to centroiding accuracy was roughly 1.5 km s⁻¹. We used the arithmetic mean of the measured emission line velocities in each fiber as the fiber velocity. The maximum difference between the measured velocities and the mean was taken to be the error on the fiber velocity. Many of these errors were less than 5 km s⁻¹, though a few were as high as ~ 20 km s⁻¹. If only Hα was observed in a fiber, the observed Hα velocity was taken as the fiber velocity and the error was set to 10 km s⁻¹.

The observed velocity fields were made by combining the individual DensePak pointings using the input shifts at the telescope. To confirm the accuracy of the off-

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2 Based on observations obtained at the WIYN Observatory. The WIYN Observatory is a joint facility of the University of Wisconsin-Madison, Indiana University, Yale University, and the National Optical Astronomy Observatory.

3 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under agreement with the National Science Foundation.
sets, an Hα flux image of the galaxy constructed from the DensePak observations was compared to an actual Hα image. Relative positions between features in the galaxy (i.e., bright HII regions) in the two images were measured and compared. The fluxes in any overlapping fibers were also compared. The accuracy of the fiber positions is ∼ 0.6′′ and we found the telescope to be capable of accurately shifting from the nearby bright offset stars (typically 1′ - 2′ shifts), as well as the smaller distances (∼ 0.7′′ shifts) required to observe the spaces between the DensePak fibers. The telescope pointing is robust and repeatable.

We used the NEMO (Teuben 1995) program ROTCUR (Begeman 1989) to derive rotation curves from our two-dimensional data. ROTCUR treats the observed velocity field as an ensemble of tilted rings and then fits for the center, systemic velocity, inclination, position angle and rotation velocity in each ring. Specifically, ROTCUR does a non-linear least squares fit to the following equation:

\[ V(x, y) = V_{sys} + V_{rot}\cos(\theta)\sin(i), \]

where

\[ \cos(\theta) = \frac{-(x - x_0)\sin(PA) + (y - y_0)\cos(PA)}{r} \]

and

\[ r^2 = (x - x_0)^2 + (y - y_0)^2/\cos^2(i). \]

The observed velocity at position \( x, y \), \( V(x, y) \), is a function of the systemic velocity \( V_{sys} \), the rotation velocity \( V_{rot} \), the inclination \( i \), the position of the center of rotation \( (x_0, y_0) \), and the position angle \( PA \) of the major axis. The position angle is defined as the angle between north and the receding side of the major axis, measured from north through east. Each point is weighted by the inverse square of the error on the fiber velocity times \( \cos(\theta) \), the angle away from the major axis.

The DensePak data cover the centers of the galaxies. We find these to be in the regime of solid-body rotation.
Consequently, neither the center nor the inclination could be determined by the observations. The center was therefore fixed to the position of the optical center and the inclination was fixed to published values (BMR01; BB02; Tully 1988). The systemic velocities were determined by ROTCUR. We also used ROTCUR to determine the position angle of the major axis, using published long-slit values as the initial guess. If the position angle could not be well-constrained by ROTCUR, then it was fixed to the long-slit value. The long-slit position angles are generally from either the HI velocity field or the surface photometry, or in some cases, are the position angles indicated in a catalog such as the UGC (Nilson 1973). Only two galaxies, UGC 477 and UGC 1281, had position angles well-constrained by ROTCUR.

Ring radii were set to the effective fiber resolution for each galaxy. The resulting rotation curve was inspected for rings with considerably higher or lower velocities than neighboring rings. These highly deviant points in the rotation curve were investigated and were usually attributable to a single fiber in the ring having an extreme velocity. These extreme fibers were removed and the rotation curve was recalculated. Lastly, we added in quadrature to the errorbars on the final rotation curve the velocity error from centroiding accuracy corrected for inclination. We do not impose a minimum error on the rotation curve points, as was the case in some previous works (e.g., 5 km s$^{-1}$ in Swaters et al. [2003a] and 4 km s$^{-1}$ in BMR01). The nature of the errors on the rotation curve points from the velocity fields is different from the errors on long-slit rotation curves. In the long-slit case, the error is on a single velocity measurement and gives the accuracy with which a Gaussian could be fitted to an emission line profile, or the error is given by the con-
Fig. 3.— Results for F563-1: (Upper left) Position of DensePak array on an Hα image of the galaxy. (Upper right) Observed DensePak velocity field. Empty fibers are those without detections. (Lower left) DensePak rotation curve. The last four points are omitted from the halo fits. (Lower right) DensePak rotation curve plotted with the raw long-slit Hα rotation curves of de Blok & Bosma (2002) and de Blok, McGaugh, & Rubin (2001) and the H\textsc{i} rotation curve of de Blok, McGaugh, & van der Hulst (1996). The triangle represents the H\textsc{i} point used in the halo fits. Figure appears in color on-line.

The observed emission lines (H\textsc{a}, [N\textsc{ii}]λ6584, [S\textsc{ii}]λ6717 and [S\textsc{ii}]λ6731). The error does not contain information about the uncertainty in the rotation velocity. Errors can become arbitrarily small in high signal-to-noise data and is the reason why minimum errors were imposed. In two-dimensional data, the rotation velocity is obtained from a tilted ring fit. The error indicates something about the spread of the velocities in a ring. In this case, a smaller error indicates that the gas in the ring has smaller non-circular motions.

4. RESULTS FOR INDIVIDUAL GALAXIES

In this section we present the DensePak fiber positions, observed velocity fields and rotation curves in Figures 1-11. A description is given for each galaxy and we compare the rotation curves to previous raw long-slit H\textsc{a} rotation curves as well as H\textsc{i} rotation curves when available.

Properties of the galaxies for which rotation curves are derived are listed in Table 1: Table 2 lists the observed galaxies for which meaningful velocity fields could not be constructed. As a result of remarkably poor weather, a number of galaxies have lopsided DensePak coverage.

UGC 4325: This galaxy is large on the sky and four DensePak pointings were made on the approaching side. The positions are shown on the H\textsc{a} image from van Zee (2000). The fiber velocities were the average of the H\textsc{a} and [S\textsc{ii}]λ6717 lines. H\textsc{a} is prevalent and was detected in almost every fiber. The position angle was fixed at the average of the position angles of previous long-slit observations (BB02; Swaters et al. 2003a). There is excellent agreement between the DensePak rotation curve and the long-slit H\textsc{a} rotation curve by BB02. Very similar results have also been obtained with SparsePak (Swaters et al. 2003a)
2005, private communication). The H\textsc{i} data (Swaters 1999) lie above the optical data at the inner radii. This suggests that the H\textsc{i} data have been over-corrected for beam smearing (Bosma et al. 2002). The outer H\textsc{i} points are a bit lower than the optical data, but are within 1\(\sigma\). The decline in the rotation curve at the outer radii may be a real feature (Bosma 2004).

**F563-V2:** There was one pointing for this galaxy. The DensePak fibers are shown on the H\textalpha{} image from McGaugh, Schombert, & Bothun (1995). The fiber velocities were the average of the H\textalpha{}, [S\textsc{ii}]\textlambda{}6717 and [S\textsc{ii}]\textlambda{}6731 lines. There is little H\textalpha{} emission and only roughly half of the fibers have an H\textalpha{} detection. The position angle was fixed to the value used in Swaters et al. (2003a). The DensePak rotation curve generally agrees with the H\textalpha{} rotation curve of BMH96.

**F563-1:** There was one pointing for this galaxy. The fiber positions are shown on an H\textalpha{} image (W.J.G. de Blok 2005, private communication). The fiber velocities were the average of the H\textalpha{}, [S\textsc{ii}]\textlambda{}6717 and [S\textsc{ii}]\textlambda{}6731 lines. The fibers were offset toward the receding side of the galaxy, and there was very little emission in the fibers on the approaching side. The position angle was fixed to the value in MRB01 and BB02. When compared to the long-slit H\textalpha{} rotation curves of BMR01 and BB02, there is good agreement up to 15\(''\). Beyond that, however, the long-slit curves and the H\textalpha{} curve (BMH96) turn over and flatten out, while the DensePak curve continues to rise. Additional DensePak coverage would be useful in determining where the DensePak curve turns over.

**DDO 64:** There were three pointings of the center and approaching side of this galaxy. The DensePak fiber positions are shown on a Digitized Sky Survey 4 image. Fiber

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**Fig. 4.—** Results for DDO 64: (Upper left) Position of DensePak array on a DSS image of the galaxy. (Upper right) Observed DensePak velocity field. The empty fibers are those without detections. (Lower left) DensePak rotation curve. (Lower right) DensePak rotation curve plotted with the raw long-slit H\textalpha{} rotation curve of de Blok & Bosma (2002) and the H\textsc{i} rotation curve of Stil (1999). The triangle represents the H\textsc{i} point used in the halo fits. Figure appears in color on-line.
velocities were the average of the Hα and [S II]λ6717 lines. The amount of emission in this galaxy is very high and nearly all fibers detected emission. The position angle was fixed to the BB02 value. The DensePak points rise and fall in a pattern similar to the long-slit data (BB02). The structure in the rotation curve appears to be real. That the inner two points fall below the long-slit data may suggest the presence of non-circular motions in the inner regions. The HI data [Stil 1999] lies slightly below, but within the errors of, the optical data. It should be noted, however, that over the radial range plotted in Figure 4 there are only 2 HI points.

**F568-3:** There was one pointing for this galaxy and the fiber positions are shown on an Hα image (W.J.G. de Blok 2005, private communication). The fiber velocities were the average of the Hα and the [N II]λ6584 lines. Hα emission was detected in roughly 60% of the fibers. The position angle was fixed to the MRB01 and Swaters et al. (2003a) long-slit value. The DensePak rotation curve is consistent with the long-slit Hα curve of BMR01 and the HI curve of BMH96.

**UGC 5750:** There was one pointing for this galaxy. The fiber positions are shown on an Hα image (W.J.G. de Blok 2005, private communication). The average of the Hα, [N II]λ6584, [S II]λ6717 and [S II]λ6731 lines was taken as the fiber velocity. Hα emission was sparse in this galaxy and only roughly half of the fibers had a detection. The position angle was fixed to the value listed in MRB01 and BB02. There is good agreement with the long-slit Hα rotation curves of both BB02 and BMR01.

**NGC 4395:** There were five pointings for this galaxy and the positions of the DensePak fibers are shown on an R-band image (W.J.G. de Blok 2005, private communication). The Hα line overlapped slightly with a sky
Fig. 6. — Results for UGC 5750: (Upper left) Position of DensePak array on an Hα image of the galaxy. (Upper right) Observed DensePak velocity field. Empty fibers are those without detections. (Lower left) DensePak rotation curve. (Lower right) DensePak rotation curve plotted with the raw long-slit Hα rotation curves of de Blok & Bosma (2002) and de Blok, McGaugh, & Rubin (2001). Figure appears in color on-line.

line. This was not a serious problem for this galaxy because the emission lines (particularly the Hα line) were very strong. The Hα line was measured in a fiber if the [N II]λ6584, [S II]λ6717 and [S II]λ6731 lines were visible and strong and if the Hα line was stronger than the neighboring sky lines. With these criteria, Hα was detected in nearly all the fibers. The fiber velocities were the average of the Hα and [S II]λ6717 lines. The position angle of [BB02] was used as the DensePak position angle. The DensePak rotation curve is consistent with the long-slit Hα curve of BB02 as well as the Hα and [Si II]λ6717 lines at the innermost radii. At the outer radii the Hα curve falls below the optical data at about the 2σ level.

F583-4: There were two pointings for this galaxy: a central pointing and an interstitial pointing; the fiber positions are shown on the R-band image of the galaxy from BMH96. The fiber velocities are the averages of the Hα, [S II]λ6717 and [S II]λ6731 lines, and the approaching side of the galaxy has slightly better coverage than the receding side. The position angle was fixed to the value in MRB01. The DensePak rotation curve is generally consistent with the long-slit Hα rotation curve of BMR01. Both optical rotation curves are offset to noticeably higher velocities than the Hα rotation curve of BMH96. This is one of the few galaxies where beam smearing in the Hα data turned out to be important (BMR01).

F583-1: There is one pointing for this galaxy. The DensePak fibers are shown on the R-band image of the galaxy from BMH96. The fiber velocities are the averages of the Hα, [S II]λ6717 and [S II]λ6731 lines, and more of the approaching side of the galaxy is seen than the receding side. The position angle was fixed to the value in MRB01. The DensePak rotation curve is consistent with both the long-slit Hα rotation curve of
Fig. 7.— Results for NGC 4395: (Upper left) Position of DensePak array on an R-band image of the galaxy.  (Upper right) Observed DensePak velocity field.  Empty fibers are those without detections.  (Lower left) DensePak rotation curve.  (Lower right) DensePak rotation curve plotted with the raw long-slit Hα rotation curve of de Blok & Bosma (2002) and the H i rotation curve of Swaters (1999).  The H i points used in the halo fits extend beyond the radial range of this plot.  Figure appears in color on-line.

UGC 477: There were three interstitial pointings along the length of this galaxy and spatial coverage of the galaxy was optimal.  The DensePak fibers are shown on the R-band image obtained at the KPNO 2m telescope.  Fiber velocities were the average of the Hα, [N ii]λ6584, [S ii]λ6717 and [S ii]λ6731 lines.  The amount of emission was very high in this galaxy and almost every fiber had a detection.  The position angle was well-constrained by the data.

UGC 1281: There were five interstitial pointings for this galaxy.  The amount of emission was sparse as less than 50% of the fibers had a detection.  The DensePak fibers are shown on the R-band image obtained at the KPNO 2m telescope.  Fiber velocities were the average of the Hα, [S ii]λ6717 and [S ii]λ6731 lines.  The position angle was well-constrained by the data and the DensePak rotation curve is consistent with the long-slit Hα rotation curve of BB02.  UGC 1281 is a nearly edge-on galaxy.  At high inclination, line-of-sight integration effects become important and may cause an intrinsically steeply rising rotation curve to appear slowly rising.  The shape of the emission line profiles can be used to constrain the shape of the rotation curve.  If instrumental resolution is high enough and there is no line-of-sight obscuration, then symmetric line profiles indicate a solid-body rotation curve and skewed line profiles indicate a curved, NFW-like rotation curve (Kregel, van der Kruit, & Freeman 2004).  The line profiles in the DensePak fibers are symmetric.  UGC 1281 is unlikely to be so optically thick that the observations are hampered by obscuration (de Naray, McGaugh, & de Blok 2004).  Our instrumental resolution, however, is probably not high enough to resolve any skewing which may be present.  We will present the minimum disk case analysis for this galaxy in § 5.2 but exclude it from further modeling.

Obtaining high-quality velocity fields is not trivial.  LSB galaxies are difficult to observe.  The Hα emission is faint.  Additionally, the emission may not be spread out enough to be detected across the entire DensePak fiber...
array. Though we tried to select galaxies with promising Hα emission, the remaining 17 galaxies of our sample (listed in Table 2) were observed, but unfortunately the detections were not good enough to construct meaningful velocity fields.

For the eleven galaxies for which we have constructed velocity fields, there is good overall agreement between the new DensePak rotation curves and the previous data sets. In all cases, the data are broadly consistent with previous long-slit rotation curves. In only two cases, F563-1 and F583-4, do these independent data seem to differ, and then only over a very limited range in radius. In cases where H i data are available, five are in good overall agreement. In two cases, DDO 64 and F583-4, the H i data are somewhat lower than the optical data. In one case, UGC 4325, the H i data are too high. It is tempting to blame these cases on beam smearing, or in the case of UGC 4325, over-correction for beam smearing, though other factors such as the intrinsic H i distribution are also relevant. On the whole, we are encouraged by the extent to which various independent data sets agree given the difficult observational challenge posed by LSB galaxies.

5. PRELIMINARY ANALYSIS AND DISCUSSION

In this section we wish to give an impression of how well the data are described by various halo models. We limit this discussion to the minimum disk case in which we ignore the contribution of the stars and gas and attribute all rotation to dark matter. This puts an upper limit on the slope and/or concentration of the halo density profile. More detailed analysis including mass modeling will be presented in a future paper.

5.1. Halo Models

Two of the most prominent competing dark matter halo density profiles are the pseudo-isothermal halo and the NFW profile. We provide a brief description of each below.

5.1.1. Pseudo-Isothermal Halo
The density profile of the pseudo-isothermal halo is

$$\rho_{\text{iso}}(R) = \rho_0 \left[ 1 + \left( \frac{R}{R_C} \right)^2 \right]^{-1},$$

with $\rho_0$ being the central density of the halo and $R_C$ representing the core radius of the halo. The rotation curve corresponding to this density profile is

$$V(R) = \sqrt{4\pi G \rho_0 R_C^2 \left[ 1 - \frac{R_C}{R} \arctan \left( \frac{R}{R_C} \right) \right]}.$$  

This form has traditionally been used in rotation curve fitting because it works well. By construction it produces flat rotation curves at large radii. This halo form is empirically motivated, predating those stemming from simulations.

5.1.2. NFW Profile

Numerical simulations produce the NFW profile and its variants. It predicts the same functional behavior for CDM halos of galaxy clusters as for the CDM halo of a single galaxy. The NFW mass-density distribution is described as

$$\rho_{\text{NFW}}(R) = \frac{\rho_\Lambda}{(R/R_s)(1 + R/R_s)^2},$$

in which $\rho_\Lambda$ is related to the density of the universe at the time of halo collapse, and $R_s$ is the characteristic radius of the halo. The NFW rotation curve is given by

$$V(R) = V_{200} \sqrt{\frac{\ln(1 + cx) - cx/(1 + cx)}{x \ln(1 + c) - c/(1 + c)}},$$

with $x = R/R_{200}$. The rotation curve is parameterized by a radius $R_{200}$ and a concentration parameter $c = R_{200}/R_s$, both of which are directly related to $R_s$. 

Fig. 9.— Results for F583-1: (Upper left) Position of DensePak array on a $R$-band image of the galaxy. (Upper right) Observed DensePak velocity field. Empty fibers are those without detections. (Lower left) DensePak rotation curve. (Lower right) DensePak rotation curve plotted with the raw long-slit Hα rotation curve of de Blok, McGaugh, & Rubin (2001) and the H\textsc{i} rotation curve of de Blok, McGaugh, & van der Hulst (1996). The triangle represents the H\textsc{i} point used in the halo fit. Figure appears in color online.
and \( \rho_i \), \( R_{200} \) is the radius at which the density contrast exceeds 200, roughly the virial radius. \( V_{200} \) is the circular velocity at \( R_{200} \) (Navarro, Frenk, & White 1996). As previously mentioned, there are other cuspy halo models with slopes steeper than the NFW profile (e.g. Moore et al. 1999; Reed et al. 2003; Navarro et al. 2004; Diemand et al. 2005). The NFW profile thus serves as a lower limit to the slope of cuspy density profiles and as such, gives the cuspy halo the best possible chance to fit the data. From an observational perspective, there is very little to distinguish the various flavors of cuspy halos.

5.2. Halo Fits to Combined Data

In this section we combine the DensePak data with the previous smoothed long-slit H\( \alpha \) and HI rotation curves when available. For the ten galaxies with long-slit and/or HI data, we supplement the DensePak data with the entire long-slit rotation curve, and include only those HI points which extend beyond the radial range of both the DensePak and long-slit data. Using only the outer HI points where the rotation curves have usually begun to flatten lessens possible resolution effects. As discussed below, there are three galaxies, F563-1, F583-4 and UGC 4325, for which we exclude some of the DensePak and/or HI data.

We find the best-fit isothermal halo and NFW halo. This NFW halo fit is referred to as \( NFW_{\text{free}} \). The \( NFW_{\text{free}} \) halo fits do not necessarily have parameters that are realistic or consistent with \( \Lambda \)CDM. There is a tendency for the fits to drive towards very low \( c \) and very high \( V_{200} \). There is also a \( c-V_{200} \) degeneracy which allows halos of different \( c,V_{200} \) to look the same over a finite range of radius. It is common for the \( NFW_{\text{free}} \) halos to overshoot the data at small radii, then undershoot the data and then overshoot the data again and provide a poor description of the data at large radii. To address this, we also make a fit which we refer to as \( NFW_{\text{constrained}} \). This halo was required to match the velocities at the outer radii of each galaxy while constraining the concentration to agree with cosmology. We chose a value of \( V_{200} \) which
forced the NFW velocities to match as many of the data points in the turn-over region as closely as possible, with a minimum requirement of falling within the errorbars. This is a reasonable constraint because dark matter must explain the high velocities at large radii where the contribution of the baryons has fallen off. Equation 7 of de Blok, Bosma, & McGaugh (2003), which gives the concentration as a function of $V_{200}$ (Navarro, Frenk, & White 1997), was then used to calculate the concentration. We adjusted this concentration to agree with the cosmology of Tegmark et al. (2004) by subtracting 0.011 dex (McGaugh, Barker, & de Blok 2003).

We did not include the last four DensePak points of F563-1 or the last three DensePak points of F583-4 in the halo fits. The F563-1 points were excluded because they are based on few fibers and because of the significant inconsistency with the long-slit and HI rotation curves as discussed in § 4.1. The outer DensePak points of F583-4 spike to higher velocities than the long-slit data at the equivalent radii. Neither the isothermal nor NFW halo model will be able to fit this feature in the DensePak rotation curve. These DensePak points also have little influence on the halo fits; there is essentially no change in the values of the isothermal or NFW halo parameters, only much improved $\chi^2$, when the three DensePak points are removed. There are 2 and 3 HI points beyond the optical data for UGC 4325 and F583-4, respectively, which were also not used. Though the rise then sudden decline suggested by the combined optical and HI data for UGC 4325 may well be real, no simple, smooth model can fit it. Since we are interested in the inner halo structure as probed by the new data, we exclude the 2 HI points. For a thorough comparison of many more independent data for this galaxy see Bosma (2004). The situation is similar for the HI points of F583-4.

In Figure 12 we plot the halo fits over the data and list the parameters in Table 3. We plot $\log(V)$ against $\log(r)$ to emphasize the fits to the data at small radii. The $NFW_{constrained}$ halos have already been required to match the data at large radii, and although the best-fit $NFW_{free}$ halos do not necessarily match the velocities at

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**Fig. 11.—** Results for UGC 1281: (Upper left) Position of DensePak array on a R-band image of the galaxy. (Upper right) Observed DensePak velocity field. Empty fibers are those without detections. (Lower left) DensePak rotation curve. (Lower right) DensePak rotation curve plotted with the raw long-slit Hα rotation curve of de Blok & Bosma (2002). Figure appears in color online.
large radii, the magnitude of the discrepancy is generally smaller than it is at small radii.

No NFW$_{\text{free}}$ fit could be made to four of the galaxies: UGC 4325, DDO 64, F568-3, UGC 1281. Three galaxies, UGC 5750, F583-4 and F583-1, have concentrations too low to be consistent with ΛCDM. Specifically, the concentrations are farther from the concentrations of the NFW$_{\text{constrained}}$ halos than the expected log scatter in $c$ of 0.18 (Bullock et al. 2001). Only the concentrations from the NFW$_{\text{free}}$ fits of the remaining four galaxies, NGC 4395, UGC 477, F563-V2 and F563-1, are consistent with ΛCDM.

One should bear in mind that these fits are taken in the limit of minimum disk. Baryons do matter some in LSB galaxies. This will drive the concentrations even lower in proper mass models.

The four galaxies for which no NFW$_{\text{free}}$ fits could be made are fit significantly better by isothermal halos than NFW$_{\text{constrained}}$ halos. The case of F568-3 is typical: the NFW$_{\text{constrained}}$ halos overpredict the velocity at all radii interior to where they were forced to match the observed velocity. Of the galaxies with NFW$_{\text{free}}$ fits, UGC 5750 is a good example of the over-under-over fitting trend of the NFW halo. This fitting trend has been observed before (e.g. BMRO1; Gentile et al. 2004) and is what is being referred to when it is said that the NFW rotation curve has the wrong shape. Of the galaxies with NFW$_{\text{free}}$ fits, UGC 5750, F583-1 and F563-1 are best fit by isothermal halos in terms of $\chi^2$. UGC 5750 is the strongest case, as the value of its best-fit concentration, 0.5, is far too low according to current ideas from cosmological simulations. NGC 4395 has a reasonable NFW concentration and a $\chi^2$ favoring the NFW halo. There are signs of a possible bar or oval structure at the center of this galaxy. Mass modeling beyond the minimum disk case may help to determine the central structure of the galaxy and whether or not the NFW halo remains a good description of the data. F583-4 and F563-V2 also have $\chi^2$ in favor of the NFW halo; however, the best-fit concentration for F583-4 is bordering on the low side of expected values, and F563-V2 has too few data points to really distinguish between halo types. It is worth noting that when the small uncertainty in the first DensePak point of F563-V2 is increased to 5 km s$^{-1}$, neither the isothermal nor NFW fit is significantly changed. Finally, UGC 477 is equally fit by both isothermal and NFW halos.

In total, seven galaxies are well-described by the isothermal halo, one is consistent with NFW, and three are indistinguishable. For the majority of the galaxies, NFW halos could either not be fit to the data, or the halos had concentrations too low to be consistent with ΛCDM. As shown by NGC 4395, velocities consistent with cuspy halos can be detected in the two-dimensional data.

### 5.3. Comparison to Literature

Ten of the eleven galaxies have published pseudo-isothermal and NFW halo fits to the long-slit and/or HI data. In Figure 13 we plot the DensePak halo parameters for each galaxy ($R_c$ and $\rho_0$ for isothermal, $c$ and $V_{200}$ for NFW) against the minimum disk literature values. There is gross agreement between the DensePak and literature halo parameters, showing that the addition of the new two-dimensional optical data has not substantially altered the fits. The addition of the DensePak data does, however, bring down the errors on the halo parameters by roughly a factor of 2. The DensePak parameters are listed in Table 3; the numbers mentioned in the text below are from the cited references.

**UGC 4325:** The DensePak isothermal halo parameters agree well with the results of BB02 ($R_c = 2.7 \pm 0.1$, $\rho_0 = 100.1 \pm 2.1$), and the agreement between those two datasets is better than the agreement of either set with the parameters of Swaters et al. (2003a) ($R_c = 0.94$, $\rho_0 = 263$). No NFW$_{\text{free}}$ fit could be made to the DensePak data, and the BB02 data preferred a concentration less than 0.1 ($c = 0.1$, $V_{200} = 3331.6$). Many of the BB02 galaxies have NFW fits with unphysical (very small or negative) values of the concentration. In these cases, the concentration was set to 0.1. The NFW fits by both Swaters et al. (2003a) and van den Bosch & Swaters (2001) required very high concentration values ($c = 14.8$, $V_{200} = 83$; $c = 30.9$, $V_{200} = 53.5$, respectively). The Swaters et al. (2003a) NFW fit shows the over-under-over fitting trend and is not a good representation of the data. For this galaxy, all of the listed concentrations are far beyond the reasonable range of expected values. The DensePak, BB02 and Swaters et al. (2003a) results all favor the isothermal halo as the best fit.

**F563-V2:** For both the isothermal and NFW halo parameters, there is excellent agreement between the DensePak values and the results of the BMRO1 analysis of the Swaters, Madore, & Trewella (2000) data ($R_c = 1.69 \pm 0.17$, $\rho_0 = 131.2 \pm 19.4$). The error on each parameter has also been reduced by the DensePak data. The agreement is not as good with the isothermal parameters of Swaters et al. (2003a) ($R_c = 1.13$, $\rho_0 = 231$). Their NFW concentration ($c = 14.4$) is again much higher than the DensePak value, and $V_{200}$ much lower ($V_{200} = 92$). As previously discussed, there are few points in the DensePak data, making a clear distinction between halo fits difficult. Certainly there is nothing to contradict the conclusions of both previous studies that found the data to prefer the isothermal halo.

**F563-1:** The DensePak results agree extremely well with both the isothermal ($R_c = 2.0 \pm 0.2$, $\rho_0 = 70.4 \pm 13.1$) and NFW ($c = 7.8 \pm 1.4$, $V_{200} = 106.8 \pm 10.3$) fits of BMRO1. The new data shrink the formal uncertainties on the isothermal halo parameters by a considerable amount. The level of agreement with the BMRO1 results ($R_c = 1.72 \pm 0.23$, $\rho_0 = 91.9 \pm 21.6$; $c = 10.7 \pm 1.2$, $V_{200} = 93.1 \pm 4.3$) is only slightly less. The isothermal halo is preferred by all three studies.

**DDO 64:** There is a difference between the isothermal halo parameters determined by the DensePak data and the results of BB02 ($R_c = 1.2 \pm 0.2$, $\rho_0 = 72.7 \pm 11.9$), but both studies prefer the isothermal halo to the NFW halo. The NFW results, however, are similar: no NFW$_{\text{free}}$ fit could be made to the DensePak data, and the BB02 data favored a concentration less than 0.1 ($c = 0.1$, $V_{200} = 11823$). While the two isothermal fits are distinguishable, they are not too different. This galaxy seems to have real structure which is reflected in the rotation curve. The independent long-slit and DensePak data both show non-monotonic features (“bumps and wiggles”) that cannot be fit by any simple, smooth halo.
TABLE 3

| Galaxy       | ISO     | NFWfree | NFWconstrained |
|--------------|---------|---------|----------------|
|              | $R_c$   | $\rho_0$| $\chi^2$      | $c$ | $V_{200}$| $\chi^2$|
| UGC 4325     | 3.3±0.2 | 91±4    | 3.8            | ... | ...     | ...     |
| F563-V2      | 1.5±0.1 | 119±6   | 0.71           | 7.7±2.0 | 128±32 | 0.40 |
| F563-1       | 2.1±0.1 | 67±2    | 0.43           | 7.8±1.3 | 106±10 | 0.88 |
| DDO 64       | 4.4±0.9 | 38±3    | 5.5            | ... | ...     | ...     |
| F568-3       | 3.8±0.2 | 27±1    | 1.2            | ... | ...     | ...     |
| UGC 5750     | 5.7±0.4 | 71±0.3  | 0.83           | 0.5±0.1 | 320±43 | 1.7   |
| NGC 4395     | 0.7±0.1 | 258±9   | 2.9            | 10.1±0.6 | 77±4 | 9.1   |
| F583-4       | 1.3±0.1 | 67±2    | 0.67           | 5.5±2.2 | 92±32 | 0.41 |
| F583-1       | 2.7±0.1 | 35±2    | 5.4            | 4.7±0.7 | 133±21 | 8.7   |
| UGC 477      | 2.2±0.1 | 57±2    | 4.6            | 6.9±0.6 | 120±9 | 4.6   |
| UGC 1281     | 2.6±0.1 | 23±1    | 3.8            | ... | ...     | ...     |

Note. — Best-fit halo parameters for the combined DensePak, long-slit and HI rotation curves. $R_c$ is the core radius in kpc, $\rho_0$ is the central density in $10^{-3}$ $M_\odot$ pc$^{-3}$, and $V_{200}$ is in km s$^{-1}$.

F568-3: The isothermal halo of the BMR01 analysis of the Swaters, Madore, & Trewella (2000) data ($R_c = 3.93±0.75$, $\rho_0 = 30.2±5.6$) are in very good agreement with the DensePak results. Again, the DensePak parameters have lower errors. There is also moderate agreement between the DensePak parameters and isothermal halo parameters of BMR01 ($R_c = 2.92±0.36$, $\rho_0 = 36.6±5.4$) and Swaters et al. (2003a) ($R_c = 3.23$, $\rho_0 = 35.3$). No NFW$_{free}$ fit could be made to the DensePak data, and all three other datasets require halos with low concentrations [BMR01] analysis of Swaters, Madore, & Trewella (2000): $c = 1.2$, $V_{200} = 591.1$, BMR01: $c = 3.2±3.7$, $V_{200} = 214.6±233.9$; Swaters et al. (2003a): $c = 1.0$, $V_{200} = 637$). In all datasets, the isothermal halo is a better fit.

UGC 5750: There is agreement with the DensePak isothermal halo parameters and the results of both BBR02 ($R_c = 5.0±0.9$, $\rho_0 = 7.9±1.6$) and BMR01 ($R_c = 4.25±0.39$, $\rho_0 = 10.6±1.0$). The errors are lower on the DensePak-derived parameters. All three datasets require a very low NFW concentration [BBR02]: $c = 1.9±2.1$, $V_{200} = 145.7±122.9$, BMR01: $c = 2.6±1.5$, $V_{200} = 123.1±58.8$). The NFW halo is not a good description of the data. Though the formal fit parameters differ for the NFW halo, the degeneracy between halo parameters is such that there is little to distinguish the resulting halo rotation curve.

NGC 4395: There is agreement between the DensePak isothermal halo parameters and the values of the parameters found by BBR02 ($R_c = 0.9±0.1$, $\rho_0 = 175.6±18.9$). The NFW$_{free}$ concentration determined by the DensePak data is between the values listed in BBR02 ($c = 12.1±0.9$, $V_{200} = 69.7±3.8$) and van den Bosch & Swaters (2001) ($c = 8.5$, $V_{200} = 71.9$). As with UGC 5750, though the formal NFW fit parameters differ, the degeneracy between halo parameters is such that there is little to distinguish the resulting halo rotation curve. BBR02 find the isothermal halo to be a slightly better fit to the data than the NFW halo, whereas the DensePak data have a slight preference for the NFW halo. The NFW halo certainly cannot be excluded as it has a reasonable concentration in all three fits. The misalignment of the minor axis in the DensePak velocity field (see also Garrido et al. 2002; Noordermeer, Sparke, & Levine 2001) and effects from star formation [BBR02] need to be considered. The presence of a bar may create strong enough non-circular motions that the true potential is underestimated. Correcting for this would cause the halo profile to become more NFW-like. However, bars are disk dynamical features and imply that the disk has mass (which has so far been ignored in the minimum disk case) and would cause the halo profile to become more core-like.

TABLE 4

| Galaxy     | Vel.Disp. km s$^{-1}$ |
|------------|----------------------|
| UGC 4325   | 7.8                  |
| F563-V2    | 8.2                  |
| F563-1     | 8.1                  |
| DDO 64     | 6.2                  |
| F568-3     | 8.7                  |
| UGC 5750   | 8.7                  |
| NGC 4395   | 9.7                  |
| F583-4     | 9.5                  |
| F583-1     | 7.5                  |
| UGC 477    | 8.1                  |
| UGC 1281   | 6.9                  |

Note. — Velocity dispersion in the DensePak data for each galaxy. Values are between 6 and 10 km s$^{-1}$ and are consistent with the typical dispersions for the gas components of galaxies.
(\(R_c = 2.44 \pm 0.06, \ \rho_0 = 33.0 \pm 1.1\)) and NFW (\(c = 5.1 \pm 1.0, \ V_{200} = 106.6 \pm 17.0\)) halo parameters of BMR01 with the DensePak parameters. Both datasets find the isothermal halo to be the better description of the data.

**UGC 1281:** There is moderate agreement between the isothermal halo parameters of the DensePak data and the results of BB02 (\(R_c = 2.2 \pm 0.1, \ \rho_0 = 28.0 \pm 1.7\)). No NFW\(_{\text{free}}\) halo could be fit to the DensePak data. The BB02 data required a very low concentration (\(c = 0.1, \ V_{200} = 785\)).

**5.4. A Word about Non-Circular Motions**

The presence of non-circular motions may cause the circular velocity to be underestimated or sometimes overestimated (Swaters et al. 2003a). This effect has been suggested as a reason why cored halos appear to be preferred to those with cusps (e.g., Swaters et al. 2003a; van den Bosch & Swaters 2001). The presence of non-
Fig. 13.— Comparison of DensePak halo parameters to previously published values. $R_c$ and $\rho_0$ are displayed for the isothermal halo and $c$ and $V_{200}$ are shown for the NFW halo. Stars represent the data from BB02, squares the data from BM01, circles the data from van den Bosch & Swaters (2000), triangles the data from Swaters et al. (2003a), and hexagons the BM01 analysis of the Swaters, Madore, & Trewhella (2000) data. The addition of the DensePak does not significantly alter the previous halo fits, but does reduce the errors on the halo parameters.

circular motions and the magnitude of the effect on the system can be qualitatively ascertained by looking at the velocity field. For instance, the alignment of the major and minor axes will begin to deviate from perpendicular (a mild example being NGC 4395). Or, the isovelocity contours will become noticeably more kinked, wiggly or twisted as non-circular motions increase. There are indications of non-circular motions in some of our sample of galaxies, but how significant are they?

One way of measuring this is to look at the velocity dispersion about the mean difference of the individual fiber velocities from the circular velocity. The velocity dispersions measured in this fashion for each galaxy are listed in Table 4. The velocity dispersions are all in the range of 6 - 10 km s$^{-1}$. These values are totally consistent with the typical dispersions for the gas component of galaxies, and suggest that we are not seeing signs of extreme non-circular motions. If added in quadrature to the rotation velocity, dispersions of this magnitude affect only the innermost points where the rotation velocity and velocity dispersion are comparable. We tried this exercise assuming an isotropic dispersion ($v_{\text{circ}}^2 = v_{\text{rot}}^2 + 3\sigma^2$) for the UGC 5750 DensePak data. We chose UGC 5750 because, of the galaxies with NFW fits, it is the least consistent with the NFW halo and because it has the largest differences between the halo fits at low radii. With the exception of only the first data point, all corrected velocities remain within the errors of the uncorrected velocities. The first data point increases by $\sim 8$ km s$^{-1}$, but this does not improve the $NFW_{\text{free}}$ fit; the concentration remains virtually unchanged ($c = 0.4 \pm 0.1$). A more in-depth analysis of non-circular mo-
tions will be discussed in a future paper, but this simple analysis already suggests that the magnitude of realistic non-circular motions is not likely to be sufficient to recover the high concentration cuspy halos expected from $\Lambda$CDM structure formation simulations.

6. CONCLUSIONS AND FUTURE WORK

We have presented the two-dimensional velocity fields and rotation curves of a sample of LSB galaxies that have been observed with DensePak. The majority of these new data have been shown to be consistent with the rotation curves of previous long-slit Hα and HI observations. In a preliminary analysis, we have combined these data and have fit the minimum disk case for three halo models: the best-fit isothermal halo, the $NFW_{\text{free}}$ halo with no constraints on the parameters, and the $NFW_{\text{constrained}}$ halo which was constructed to agree with $\Lambda$CDM cosmology. We found seven galaxies to prefer the isothermal halo, one to prefer the $NFW$ halo and three to show no clear preference. When $NFW_{\text{free}}$ fits could be made, the concentrations were often too low compared to the expected values for $\Lambda$CDM.

We have compared our DensePak halo fits to the results of previous studies. The DensePak halo parameters change little, but do have improved uncertainties. Future work will include a detailed assessment of non-circular motions, slit placement and mass-modeling to determine the distribution of dark matter in more realistic cases than the minimum disk scenario.

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