ABSTRACT

Using the Sloan Digital Sky Survey (SDSS), we probe the halo mass distribution by studying the velocities of satellites orbiting isolated galaxies. In a subsample that covers 2500 deg² on the sky, we detect about 3000 satellites with absolute blue magnitudes going down to \( M_B = -14 \), most of the satellites have \( M_B = -16 \) to the primary. For an \( L_s \) galaxy the rms line-of-sight velocity changes from \( \approx 120 \text{ km s}^{-1} \) at 20 kpc to \( \approx 60 \text{ km s}^{-1} \) at 350 kpc. This decline agrees remarkably well with theoretical expectations, as all modern cosmological models predict that the density of dark matter in the peripheral parts of galaxies declines as \( \rho_{DM} \propto r^{-3} \). Thus, for the first time we find direct observational evidence of the density decline predicted by cosmological models; we also note that this result contradicts alternative theories of gravity such as modified Newtonian dynamics (MOND). We also find that the velocity dispersion of satellites within 100 kpc scales with the absolute magnitude of the central galaxy as \( \sigma \propto L_0^{0.9} \); this is very close to the Tully-Fisher relation for normal spiral galaxies.

Subject headings: dark matter — galaxies: dwarf — galaxies: halos — galaxies: kinematics and dynamics — surveys

On-line material: machine-readable tables

1. INTRODUCTION

Measuring the distribution of mass around galaxies at large radii (\( \geq 100 \text{ kpc} \)) provides a critical test for cosmological models. By studying the mass distribution at these distances, we directly address one of the most intriguing questions of modern cosmology: the nature of dark matter. Specifically, we wish to determine the extent of galaxy dark matter halos and their density profile. While the inner parts of galaxy halos have density distributions that yield approximately flat rotation curves, our understanding of the profile at larger distances is much poorer. The issue is critical because the density profile that gives rise to a flat rotation curve (\( \rho \propto r^{-2} \)) is different from that predicted by cosmological models (Navarro, Frenk, & White 1997, hereafter NFW) at larger distances (\( \rho \propto r^{-3} \)).

The challenge in measuring the mass distribution at large radii arises from the difficulty in finding a visible tracer to probe the mass. Historically, neutral hydrogen (H i) has been used to study the outer parts of rotation curves (e.g., Roberts & Rots 1973; Bosma 1981; van Albada et al. 1985), since H i is detected well beyond the optical boundaries of spiral galaxies. The observations demonstrating that H i rotation velocities of field spirals are roughly constant at large galactocentric distances provide one of the primary pieces of evidence that galaxies are embedded in massive dark matter halos (e.g., Ostriker, Peebles, & Yahil 1974; Faber & Gallagher 1979; Sancisi & van Albada 1987; Sofue & Rubin 2001). However, H i emission is detected only out to 30–50 kpc. X-ray emission from the diffuse hot gas in isolated elliptical galaxies also indicates the presence of massive dark matter halos (e.g., Buote & Canizares 1994; Romanowsky & Kochanek 1998; Buote et al. 2002), but, just like H i in spiral galaxies, the X-ray emission does not extend far enough to distinguish isothermal from cosmological \( \rho \propto r^{-3} \) profiles (Buote et al. 2002). Strong gravitational lensing places an important upper limit on the amount of dark matter but only in the inner (few tens of kiloparsec) regions of galaxies (e.g., Keeton, Kochanek, & Falco 1998; Keeton 2001; Maller et al. 2000).

Weak gravitational lensing provides a more promising method of studying the outer parts of galaxies. Individual field galaxies produce a small distortion of background galaxies, and this distortion can be used to measure the galaxy-mass correlation function. Unfortunately, the existing data (e.g., Tyson et al. 1984; Brainerd, Blandford, & Smail 1996; Hoekstra, Yee, & Gladders 2002; Fischer et al. 2000; Smith et al. 2001) do not distinguish between a singular isothermal sphere (SIS; Schneider & Rix 1997) and a cosmological NFW profile: both models provide good fits to the galaxy-mass correlation function in the outer regions where the error bars are large. Moreover, the galaxy-mass
correlation function can be affected by neighbors of the lens galaxy (e.g., Smith et al. 2001; Guzik & Seljak 2002). Once the contamination from the neighboring galaxies is taken into account, as done by, for example, Fischer et al. (2000), Hoekstra et al. (2002) and McKay et al. (2001) place only a lower limit on the size of the halo.

Velocities of satellites of galaxies provide another way to probe the mass distribution at large radii. These have been used to constrain the mass of the Milky Way (Zaritsky et al. 1989; Lin, Jones, & Klemola 1995; Kochanek 1996; Evans & Wilkinson 2000) and M31 (Evans et al. 2000). However, because the number of detectable satellites around galaxies outside of the Local Group is small, one needs to study many galaxies to accumulate enough statistics to study the profiles of other galaxies. As a result, observational efforts to study the dynamics of satellites have been somewhat limited (Erickett, Gottesman, & Hunter 1987; Zaritsky et al. 1993, 1997; Zaritsky & White 1994; McKay et al. 2002).

Important early results were obtained by Zaritsky et al. (1993, 1997) and Zaritsky & White (1994), who compiled and studied a sample of about 100 satellites of nearby isolated spiral galaxies with an average of one to two satellites per primary galaxy. It was found that the line-of-sight velocity dispersion of the satellites does not decline with the projected distance to the primary galaxy. This result has been generally considered a strong argument for the presence of dark matter at large distances (∼200–400 kpc) around galaxies. Zaritsky & White (1994) also found that the satellite velocity dispersion does not correlate with the luminosity of the primary galaxy.

McKay et al. (2002) used the Sloan Digital Sky Survey (SDSS) to select and study a much larger sample of 1225 satellites. The mean number of satellites they found around each host was only two. The new analysis confirmed that the velocity dispersion of satellites does not decline with distance from the primary, as observed by Zaritsky et al. (1993, 1997) and Zaritsky & White (1994). This implies that halos of isolated galaxies extend to distances of several hundred kiloparsecs. In contradiction with the earlier results, however, McKay et al. (2002) find that the velocity dispersion of satellites, σ, increases with the luminosity, L, of the primary galaxy as σ ∝ L^{0.5} and claim that this is consistent with the predictions of the semi-analytical models of galaxy formation of Kauffmann et al. (1999) when the sample of primary galaxies in the models is defined as it is in the observational analysis.

Cosmological models made definite predictions for the mass profile of dark matter halos at large distances. Although SIS halo models with density \( \rho \propto r^{-2} \) and \( \sigma = \text{const} \) are often assumed, there is little justification for using SIS at these distances. The main motivations for using SIS are simplicity and extrapolation of flat rotation curves to much larger radii. However, during the last two decades of intensive numerical modeling of galaxy formation, not a single model has produced an SIS. Every cosmological model studied so far (and there have been plenty) has \( \rho \propto r^{-3} \) at large radii. The slope does not depend on the mean density of matter: cold dark matter (CDM) with \( \Omega_{\text{matter}} = 1 \) (Ghigna et al. 2000) and ΛCDM with \( \Omega_{\text{matter}} = 0.3 \) (Klypin et al. 2001) have the same slope. It does not depend on the nature of the dark matter: warm dark matter (Avila-Reese et al. 2001), self-interacting dark matter (Colin, Klypin, & Kravtsov 2000), and CDM all make the same prediction. The slope does not depend on the halo mass: halos ranging from cluster masses to dwarf masses all have \( \rho \propto r^{-3} \). In other words, the declining velocity dispersion of satellites is not a test for the parameters of cosmological models but rather of the hierarchical scenario itself. It is ironic that the same argument, the constant velocity dispersion of satellites, which just a few years ago provided one of the strongest cases for the existence of dark matter, is now an argument against dark matter. The only model that predicts a constant velocity dispersion is modified Newtonian dynamics (MOND; e.g., Milgrom 1984; Sanders & McGaugh 2002).

As previous authors have noted (Zaritsky 1992; Zaritsky & White 1994), a comprehensive measurement of the satellite velocity dispersion profile around isolated galaxies should ideally combine two main elements: (1) a large number of primary galaxy and satellite candidates to estimate the satellite kinematics in separate bins of primary mass (or luminosity) and projected separation, and (2) a model-independent, robust, and testable rejection of interloper galaxies—dwarfs with large physical distances from the primary galaxies but small projected and velocity differences—that are not bound to the primary. The effect of the interlopers is to make the halo mass profile difficult to measure, and that may have led to systematic effects in the few observations that suggest a constant velocity dispersion at large radii. Understanding their effect is crucial for any interpretation of the halo mass distribution. Results from weak lensing can be affected by the presence of nearby projected neighbors, leading to similar systematic problems (see Smith et al. 2001; Guzik & Seljak 2002).

In this paper, we use the vast database of SDSS to study the motion of satellites around a carefully selected sample of isolated nearby galaxies. We also develop an improved, model-independent approach for interloper rejection, which, together with state-of-the-art cosmological N-body simulations of galaxies and their satellites, allows us to measure the dark matter halo profile. In § 2, we describe the observational data and the criteria for selecting our samples of primaries and satellites. The numerical simulations are briefly described in § 3, where we also discuss the use of simulations to test prescriptions to remove interlopers. Our observational results are presented in § 4, and our conclusions are given in § 5.

2. OBSERVATIONAL DATA: SELECTION OF PRIMARIES AND SATellites

The SDSS (York et al. 2000; Stoughton et al. 2002) is a survey that images up to 10^6 deg2 of the northern Galactic cap in five bands ugriz (Fukugita et al. 1996; Pier et al. 2003; Hogg et. al. 2001; Smith et al. 2002) using a drift-scanning mosaic CCD camera (Gunn et al. 1998), down to a limiting magnitude of r' ≈ 23 (Lupton et al. 2001). Approximately 900,000 galaxies down to r' ≈ 17.7 will be targeted for spectroscopic follow-up using two fiber-fed spectrographs on the same telescope (Strauss et al. 2002; Blanton et al. 2003).

For the current analysis, we use data on galaxies for which spectra were obtained before 2002 August. We use “survey quality” redshifts derived from these spectra by D. Schlegel. The recessional velocity errors are always less than 20 km s^{-1}. Our SDSS redshift sample consists of 254,073 galaxies distributed in several strips on the sky; the total
area covered by our data is about 2500 deg$^2$. Photometric parameters were taken from the PHOTO measurement (Lupton et al. 2001) of the brightest object within 3$''$ that was loaded into the SDSS collaboration database in 2002 August (but see also discussion below); magnitudes were corrected for foreground extinction using the Schlegel, Finkbeiner, & Davis (1998) values loaded in the SDSS database. The sky coverage of the resulting SDSS imaging and spectroscopic data is shown in Figure 1.

We supplemented the SDSS data with data from the RC3 catalog (de Vaucouleurs et al. 1991) for two reasons. First, as we are identifying isolated galaxies (see below), we want to avoid choosing galaxies that have bright neighbors outside the area covered by the SDSS at the time we made our sample; the RC3 provides a catalog of galaxies over the whole sky to make this possible. While it is true that the RC3 catalog is not complete, especially at larger distances, missing companions in the SDSS data are much more likely for the nearest galaxies for which the area on the sky corresponding to our isolation criterion is large. For these, the RC3 catalog should be nearly complete. Another, possibly more important, reason for using the RC3 is that the version of PHOTO that we were using did not provide accurate photometry for large and bright galaxies owing to problems with the deblending algorithm. As a result, we used RC3 $B_T$ magnitudes (or photographic magnitudes if $B_T$ was not available), corrected for foreground reddening, for all of the SDSS galaxies for which we found a match in the RC3 catalog (within 0.5 on the sky and 100 km s$^{-1}$ in velocity); for all of the other galaxies (which are the smaller galaxies for which the SDSS photometry is accurate), we transformed the SDSS $g$ magnitude to $B$ magnitudes using the relation given by Yasuda et al. (2001).

Our main galaxy list was selected from the full redshift sample by taking all galaxies with 500 km s$^{-1}$ < $cz$ < 60,000 km s$^{-1}$ and apparent magnitude $r' < 17.7$; the total number of selected galaxies is 206,352. Distances are derived assuming a smooth Hubble flow with $h = 0.7$ ($H_0 = 100$ h$^{-1}$ km s$^{-1}$ Mpc$^{-1}$); the heliocentric velocities were converted to the Local Group standard of rest before computing distances.

For the study of satellite dynamics, we define primary galaxies to be those with absolute blue magnitude brighter than $M_B = -19.0$. We put no restriction on Hubble type. We use three different isolation and selection criteria to define three different samples of isolated primaries. To be considered as isolated, a galaxy must have no other galaxies within a magnitude difference $\Delta M$, projected separation $\Delta R$, and velocity separation $\Delta V$. Satellites are defined as all objects within a projected distance $br$ and velocity difference $bv$ and being at least $dn$ magnitudes fainter than the primary. Table 1 gives the parameters used to define each sample, the number and median distance of primaries, and the number of satellites.

The first two samples have identical isolation criteria, but sample 2 is defined for primaries out to a larger distance; hence, only bright satellites can be seen for the more distant galaxies. The shallower sample has more satellites per primary, but the more distant sample has an overall larger number of total satellites. The third sample mimics conditions used by McKay et al. (2002), in which the isolation criterion is significantly relaxed. It has a very large search radius (almost 3 Mpc), but the luminosity of the neighbors

| Parameters | Sample 1 | Sample 2 | Sample 3 |
|------------|----------|----------|----------|
| Maximum depth of the sample (km s$^{-1}$) | 10000 | 60000 | 60000 |
| Constraints on bright neighbors: | | | |
| Magnitude difference, $\Delta M$ | 2.0 | 2.0 | 0.75 |
| Minimum projected distance, $\Delta R$ (h$^{-1}$ kpc) | 500 | 500 | 2000 |
| Minimum velocity separation, $\Delta V$ (km s$^{-1}$) | 1000 | 1000 | 1000 |
| Constraints on satellites: | | | |
| Minimum magnitude difference, $\Delta m$ | 2.0 | 2.0 | 1.5 |
| Maximum projected distance to primary, $br$ (h$^{-1}$ kpc) | 350 | 350 | 500 |
| Maximum velocity separation with primary, $bv$ (km s$^{-1}$) | 500 | 500 | 1000 |
| Number of isolated galaxies | 1278 | 88603 | 26807 |
| Number of satellites | 453 | 1052 | 2734 |
| Statistics of isolated galaxies with at least one satellite: | | | |
| Number | 283 | 716 | 1107 |
| Mean distance (km s$^{-1}$) | 7100 | 14700 | 23170 |
| Mean distance for $-19.5 < M_B < -20.5$ (km s$^{-1}$) | 7244 | 9785 | 11076 |
| Mean distance for $-20.5 < M_B < -21.5$ (km s$^{-1}$) | 7697 | 15917 | 20854 |
| Limiting magnitude $M_B$ | $-16.4$ | $-18.0$ | $-19.0$ |
TABLE 2
DATA FOR PRIMARY AND SATELLITE GALAXIES (SAMPLE 2)

| Host/Satellite | α (J2000.0) (deg) | δ (J2000.0) (deg) | V_{LGR} (km s⁻¹) | M_B (mag) | ΔV_R (km s⁻¹) | ΔR (kpc) |
|----------------|------------------|------------------|------------------|----------|----------------|----------|
| 0.................. | 0.05332 | 1.12020 | 7581. | -20.3 | 0.0 | 0.0 |
| 1.................. | 0.04996 | 1.12175 | 7467. | -17.7 | 114.0 | 7.0 |
| 0.................. | 0.91703 | -0.28034 | 18573. | -20.0 | 0.0 | 0.0 |
| 1.................. | 0.90817 | -0.26703 | 18477. | -17.7 | 96.0 | 66.0 |
| 0.................. | 1.52387 | 13.97885 | 22748. | -21.2 | 0.0 | 0.0 |
| 1.................. | 1.54195 | 14.01762 | 22487. | -18.9 | 262.0 | 209.0 |
| 0.................. | 2.66396 | -0.05285 | 11806. | -21.1 | 0.0 | 0.0 |
| 1.................. | 2.54570 | 0.00494 | 11804. | -18.2 | 2.0 | 359.0 |
| 2.................. | 2.63117 | -0.04288 | 11855. | -18.2 | 49.0 | 93.0 |
| 0.................. | 2.80476 | 14.28160 | 24100. | -21.6 | 0.0 | 0.0 |
| 1.................. | 2.83276 | 14.33886 | 23975. | -19.0 | 124.0 | 326.0 |

Notes.—Table 2 is published in its entirety in the electronic edition of the Astrophysical Journal.
A portion is shown here for guidance regarding its form and content.

* Here “0” indicates a host and subsequent numbers indicate satellites of that host.

TABLE 3
DATA FOR PRIMARY AND SATELLITE GALAXIES (SAMPLE 3)

| Host/Satellite | α (J2000.0) (deg) | δ (J2000.0) (deg) | V_{LGR} (km s⁻¹) | M_B (mag) | ΔV_R (km s⁻¹) | ΔR (kpc) |
|----------------|------------------|------------------|------------------|----------|----------------|----------|
| 0.................. | 0.166850 | 14.55210 | 23105. | -20.3 | 0.0 | 0.0 |
| 1.................. | 0.054980 | 14.59171 | 23708. | -20.3 | 0.0 | 0.0 |
| 2.................. | 1.52387 | 13.97885 | 22748. | -21.2 | 0.0 | 0.0 |
| 3.................. | 1.54195 | 14.01762 | 22487. | -18.9 | 262.0 | 209.0 |
| 4.................. | 2.66396 | -0.05285 | 11806. | -21.1 | 0.0 | 0.0 |
| 5.................. | 2.54570 | 0.00494 | 11804. | -18.2 | 2.0 | 359.0 |
| 6.................. | 2.63117 | -0.04288 | 11855. | -18.2 | 49.0 | 93.0 |
| 7.................. | 2.80476 | 14.28160 | 24100. | -21.6 | 0.0 | 0.0 |
| 8.................. | 2.83276 | 14.33886 | 23975. | -19.0 | 124.0 | 326.0 |

Notes.—Table 3 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.

* Here “0” indicates a host and subsequent numbers indicate satellites of that host.
The main physical properties of satellites and primaries, such as their color distribution, spectral properties, and subdivision into early- and late-type galaxies, will be discussed in M. Vitvitska et al. (2003, in preparation).

3. NUMERICAL MODELS

Cosmological simulations of galactic dark matter satellites in the hierarchical model of structure formation predict a remarkably large number of dark matter satellites orbiting around a Milky Way–size halo (Klypin et al. 1999; Moore et al. 1999). In many respects the simulations are quite realistic; we use them to develop a method for removing the effects of interlopers on the amplitude and shape of the rms velocity profile of the satellites. Note that the results of the simulations are not used in the reduction of the real astronomical data.

We use one of the simulations presented by Klypin et al. (2001). The simulation is done for the standard ΛCDM cosmological model with Ω₀ = 0.3, Ωₐ = 0.7, and h = 0.7; the spectrum normalization is σ₈ = 0.9. The adaptive-refinement-tree (ART) code (for details see Klypin et al. 2001) is used to run the simulation. The simulation box was 25 h⁻¹ Mpc. The formal force resolution was 100 h⁻¹ pc; the mass resolution is 1.2 × 10⁸ h⁻¹ M☉.

The simulation has three galaxy-size halos. All halos are relaxed and have cusps. The outer parts of the density profiles of the halos are well approximated by an NFW profile.

The distance between two of the halos is 600 kpc; we decided not to use this pair because the halos are not isolated. We selected the third halo, which does not have a massive companion within 3 Mpc radius. This halo has a virial mass of 1.5 × 10¹² h⁻¹ M☉, a virial radius of 235 h⁻¹ kpc, and a maximum circular velocity of 214 km s⁻¹. There are 200 dark matter satellites inside a 350 h⁻¹ kpc radius from the center of the halo. Most of the satellites are very small with circular velocity of 10–15 km s⁻¹ and mass 5 × 10⁷ h⁻¹ M☉.

The simulations were done in such a way that only regions around the three large halos (≥2 Mpc) have high resolution. The rest of the computational volume was simulated with significantly lower resolution. No halos outside the regions of high resolution are used in our analysis.

Figure 3 shows different velocity components of dark matter particles of the halo. The average radial velocity is very small. It is much smaller than any other velocity component. The rms velocity is close to equilibrium predicted by the Jeans equation for this density profile. This indicates that the halo is very close to the virial equilibrium. Note that there are deviations from perfect equilibrium. For example, radial velocities are well above the shot noise. These deviations are due to (sub)halos. Nevertheless, the deviations are very small and do not show any systematic infall or outflow of mass. The halo is typical for isolated galaxy-size halos. They experienced a period of fast mass accretion (and major mergers) at redshifts around 3–4. Since then their mass growth is very limited. For example, the halo in
Fig. 3.—Circular velocity $V_{\text{circ}}$, three-dimensional rms velocity $\sigma_{V}$, and radial velocity ($V_{\text{rad}}$) of dark matter in a simulated halo. The virial radius is indicated by the vertical dashed line. The dashed curve shows the rms velocity expected for a spherical halo in equilibrium for given circular velocity profile and for small velocity anisotropy measured in dark matter halos.

in our example increases its mass by only 20% since redshift 1.5, and this mass comes in the form of slow accretion.

3.1. Satellites in Cosmological Simulations: Removal of Interlopers

In any sample of isolated bright galaxies and their satellites there is a fraction of galaxies that are probably not related to the host but are included in the sample because of projection effects. We call these objects interlopers. The interlopers tend to have large velocity differences and large projected separations. The fraction of interlopers in the samples of Zaritsky & White (1994) and Zaritsky et al. (1997) was 15%. We expect a similar level of contamination in our observational samples. If the interlopers are not removed, the rms velocity of satellites and the inferred mass of the primaries will be overestimated. We use the simulations described in the last section to test prescriptions for removing the interlopers.

To understand how interlopers might affect the results, we introduce them into the simulation. We have to do this because the N-body simulation resolves only the region very close to the central halo; no interlopers are present in the simulation. To make a sample that realistically mimics the observational data, we start by making an estimate of the number of expected interlopers in the observed sample.

Using the SDSS field luminosity function (Blanton et al. 2001), we find that 0.43 galaxies between $-18 < M_B < -16$ are expected inside a volume $R < 350 \, h^{-1}$ kpc and with a velocity dispersion of $|\Delta V| < 500 \, \text{km s}^{-1}$ at a distance of $\sim 5000 \, \text{km s}^{-1}$. This is the estimated number of interlopers per primary, if galaxies are randomly distributed in space. Neglecting the large-scale correlations of galaxies appears to be a reasonable assumption at this point because our primaries are selected to avoid clusters and groups of galaxies. The latter are responsible for most galaxy clustering on a scale of a few megaparsecs. Thus, the clustering of galaxies (with the exception of true satellites) around our primaries is small and can be neglected. Using simulations, this point should be quantified in more detail in the future.

In the observed samples we find on average two satellites per primary. Thus, we expect 0.215 interlopers for each true satellite. In our numerical simulation we have 200 true satellites. This means that we expect about 43 interlopers.

We randomly place 43 interlopers into a cylinder of radius $350 \, h^{-1}$ kpc and length $1000 \, \text{km s}^{-1}$. The number of interlopers is defined by the luminosity function of galaxies in the SDSS. The dashed curve gives the rms velocity in the combined sample. The solid curve shows the rms velocity of true satellites.

Figure 4 shows the resulting velocity differences for both satellites and interlopers as a function of projected distance to the parent dark matter halo, as well as the rms velocities for the true satellites and for the combined sample of the satellites and interlopers. Since the interlopers are not physically associated with the primaries, their number depends only on the volume. Therefore, their effect on the rms velocity is stronger at larger distances. Neglecting interlopers clearly leads to an apparent increase in the rms velocity with distance, while the rms velocity of the true satellites actually decreases with distance.

To reliably estimate the satellite velocity dispersion, one needs to find a way to account for the interlopers. We start by characterizing the velocity distribution of true satellites. Motivated by Figure 4, we consider a Gaussian velocity distribution but allow the width of the distribution to change with radius. Figure 5 shows the resulting distribution of normalized (to the rms velocity in different radial bins) velocities and demonstrates that the distribution is very close to Gaussian. In reality, the distribution cannot be
completely Gaussian because satellites with very high velocities will not be bound to the halo and will escape. Using simple arguments based on the virial theorem, one naively expects that satellites with velocities twice the rms velocity should not be bound. Indeed, we find an indication of this: in Figure 5 the points are systematically below the Gaussian fit for \( \Delta V > 2 \sigma \). However, it is difficult to use the simple argument because we measure only one component of the velocity and because the escape velocity changes with distance. In any case, the Gaussian fit provides a reasonably accurate approximation for the distribution of the line-of-sight velocities of true satellites.

A simple prescription for removing the interlopers was used by McKay et al. (2002). The velocity difference distribution of the entire sample of neighbors (including objects at all projected distances) was fitted by a Gaussian plus constant function. The idea is that the Gaussian describes the velocity distribution of satellites and that the constant takes into account the distribution of interlopers; the width of the Gaussian component gives a direct measurement of the rms velocity of the satellites. Our simulations show that the velocities of the true satellites are indeed well approximated by the Gaussian distribution but that the width of the distribution (i.e., the velocity dispersion) is a function of radius. We find that the McKay et al. (2002) prescription has two problems that result from making a single fit over all radii:

1. The level of interloper contamination (the constant in the fit) does not depend on the distance to the primary. This is inaccurate because of a purely geometrical factor: the volume and thus the number of interlopers are larger for larger radii. Neglecting this dependence produces a bias: the rms velocity is overestimated at large radii and underestimated at small radii.

2. There is no allowance for dependence of the velocity dispersion on projected distance. Because this dependence is in fact what we wish to study, we do not want to impose the assumption of a constant velocity dispersion on the prescription for the removal of interlopers.

In fact, if we apply the McKay et al. (2002) prescription to the simulations, we find that the recovered profile of the (interloper-removed) rms velocity is flat; the prescription fails to recover the true dispersion profile of the satellites. In this article, we apply an improved interloper prescription by making a separate "Gaussian plus constant" fit for separate radial bins. In this case the increase of the number of interlopers with the projected distance is taken into account (at least approximately). This also allows for a radially dependent velocity dispersion of true satellites. In practice we use 100 kpc radial bins (70 \( h^{-1} \) kpc in numerical simulations) and 100 km s\(^{-1}\) velocity bins. We do not include satellites with projected distance less than 20 kpc. The binned data are used to minimize the sum over all bins of normalized deviations \( \frac{(V_{\text{obs}} - V_{\text{model}})^2}{N_i} \), where \( N_i \) is the number of velocities in the \( i \)-th bin and \( V_{\text{obs}} \) and \( V_{\text{model}} \) are the observed and modeled velocities in the bin, respectively.

Figure 6 shows the accuracy of the recovery of the true rms velocity for the simulation; the short-dashed line shows the recovered velocity, while the solid line shows the true velocity distribution of the satellites. The procedure works remarkably well. It recovers the value of the velocity dispersion and the number of interlopers. In the next section we apply the same procedure to the observational samples.

The theoretical prediction for the velocity dispersion profile for an NFW profile with the same virial mass as that of the simulated dark matter halo is shown by a long-dashed line. In order to make this prediction for the rms...
line-of-sight velocity, we use the NFW profile and assume that the satellites are in equilibrium. We then use the Jeans equation to find the velocity dispersion. The velocity anisotropy \( \beta(r) \equiv 1 - \sigma_t^2 / 2 \sigma_r^2 \), which is needed for the equation, was taken from cosmological simulations (Colin et al. 2000; Vitvitska et al. 2002). (Here \( \sigma_t \) and \( \sigma_r \) are the tangential and radial rms velocities, respectively.) The velocity anisotropy changes from very small values \( \beta \approx 0 \) close to the center of a halo to \( \beta \approx 0.5-0.6 \) at the virial radius. We use this dependence of \( \beta \) on radius to make analytical estimates of the projected velocity dispersion. Specifically, we integrate the rms velocities, which we obtain from the Jeans equation, along a line of sight. The integration is truncated at 1.5 virial radii.

The velocity anisotropy enters these calculations twice: through the Jeans equation and during the integration along the line of sight. For a fixed mass profile \( M(r) \) the effects of the velocity anisotropy are rather mild. The line-of-sight rms velocity in the realistic nonisotropic halo declines with distance slightly more rapidly as compared with the isotropic case \( (\beta = 0) \).

4. RESULTS

4.1. Radial Dependence of Satellite Velocity Dispersion

Figure 7 shows the relative line-of-sight velocities for a subset of sample 2; only companions of galaxies with \(-19.5 < M_B < -20.5 \) are shown. Figure 8 shows a comparable plot for sample 3, but only for the brighter primaries, since the statistics are poor for the fainter primaries. The raw rms velocity is shown by the dashed curve. Both figures show that the rms velocity of the raw (uncorrected) data either does not change or slightly increases with the distance from the primary. A few years ago this would have been a strong argument in favor of dark matter in the outer parts of galaxies, but as discussed in the introduction, a flat rms velocity curve extending to 300 kpc strongly contradicts any existing dark matter model. Taken at face value, the raw rms velocities presented in Figures 7 and 8 contradict the dark matter scenario and actually favor MOND.

However, if we remove interlopers using the Gaussian plus constant technique discussed in the previous section, as shown by the solid lines with error bars in Figures 8 and 9, we find that the velocity dispersion of satellites declines with distance. We note that the results for sample 1, which extends to fainter primaries, are similar to those shown here for the other two samples. Using Monte Carlo simulations, we reject a hypothesis that the rms velocity is constant at the 97\% level corresponding approximately to the 3 \( \sigma \) level for Gaussian statistics. For the simulations we combine samples 2 and 3, which provide independent measurements. We assume that deviations of the rms velocities are Gaussian in each of four bins for each sample. The average value of the rms velocity is defined by four random points. The probability of having \( \chi^2 \) larger than the observed \( \chi^2 \) and declining curves in two independent realizations is \( 2.9 \times 10^{-2} \), based on 10,000 realizations. Most of the constraints come from sample 2, where the first and the last points deviate from the average by 1.5 and 1.8 \( \sigma \), respectively. Sample 3 alone is consistent with the constant rms velocity. Still, even in this case the velocity declines. When we combine both samples, the constant rms velocity becomes very improbable.
The number of estimated interlopers is quite modest. For sample 1, which has 132 satellites for primaries in the range $-19.5 < M_B < -20.5$, we estimate that 23 are interlopers, 17% of the sample. The numbers are similar for the other samples: 19% in sample 2 and 20% in sample 3. As expected from geometrical arguments, the number of interlopers increases with the radius. For example, in sample 3 the number of estimated interlopers is 16.7 for radii in the range 100–200 kpc and 54 for 200–360 kpc, which is roughly consistent with a constant number of interlopers per unit volume.

The observed decline in velocity dispersion with radius closely matches that predicted by an NFW dark matter density profile. Figures 8 and 9 give the predicted NFW velocities for halos of mass $6 \times 10^{12} M_\odot$ (for primaries with $-20.5 < M_B < -21.5$) and $M_{vir} = 1.5 \times 10^{12} M_\odot$ (for primaries with $-19.5 < M_B < -20.5$).

If we remove interlopers using the method of McKay et al. (2002), the mean velocity dispersion for each magnitude bin is smaller than the raw value, but we do not get a declining velocity curve. This explains the difference between our conclusions and those of McKay et al. (2002), who do not find a radial dependence on velocity dispersion; as discussed above, we feel that our procedure of allowing for the radial dependence of interloper contamination is better motivated physically.

In Figure 10 we plot the normalized velocity distribution of satellites in our SDSS sample 2 for primaries in the range $-19.5 < M_B < -20.5$. The distribution was obtained in the same way as we did for the N-body simulations (§ 3.1; see Fig. 5) by finding the rms velocities for individual bins and then combining the normalized velocities. Following the same arguments discussed in § 3.1, one can expect that objects with velocities $\Delta V > 2 \sigma$ should be interlopers, as shown by the constant velocity component.

4.2. Relation of Satellite Velocity Dispersion with Host Luminosity

A comparison of Figures 8 and 9 clearly indicates that the mass of the host depends on the luminosity of the primary. This contradicts the earlier results of Zaritsky et al. (1997). Because the NFW profile provides an accurate fit to the observed velocity dispersion profile, we can use it to estimate the virial mass of each group of galaxies. For galaxies with $-19.5 < M_B < -20.5$ we find

$$M_{vir} = 1.5 \times 10^{12} M_\odot.$$

For the brighter magnitudes, $-20.5 < M_B < -21.5$, the virial mass is

$$M_{vir} = 6 \times 10^{12} M_\odot.$$

These values give us virial mass–to–light ratios $M/L = 100$ and 150 for the dimmer and brighter galaxies, respectively. Thus, the $M/L$ ratio increases with the luminosity roughly as $M/L \approx L^{0.5}$. We believe that this change in $M/L$ with luminosity is real and does not reflect a change in the stellar populations for both magnitude bins. A reason for this is that we did not see a dependence of the fraction of E-S0 with luminosity for the primaries in sample 1, at least from $-19$ to $-22$ blue absolute magnitudes. A similar increase of $M/L$ with luminosity ($M/L \propto L^{0.4\pm0.2}$) has been seen from weak lensing studies by Guzik & Seljak (2002). See, however, McKay et al. (2001), who, also from weak lensing, found no dependence of the $M/L$ on luminosity.

Instead of trying to estimate masses of the galaxies (which is bound to be model dependent), we can study the more direct dependence of the rms velocity on the luminosity of the primary galaxy. This can be viewed as an analog of the Tully-Fisher relation. Figure 11 presents the dependence of the satellite rms velocity, computed within 120 kpc as a function of galaxy luminosity. We calculate the rms velocity relatively close to the primary galaxy because within this...
distance the velocity dispersion depends only weakly on the distance to the primary for all primaries considered here. Hence, we can meaningfully compare results from galaxies that might have different sizes. The estimated value of the velocity dispersion for an $L_*$ galaxy from weak lensing studies (Hoeskstra et al. 2002; McKay et al. 2001) is also shown; the results of lensing studies are very close to those derived from the SDSS satellite data.

The results are consistent with a slope of $\sigma \propto L^{0.3}$. We can write this dependence using a form analogous to the Tully-Fisher relation:

$$M_B = 0.02 - 8.7 \log(2 \sigma).$$

(1)

This relation is shown in Figure 11. The slope of this relation is the same as for spiral galaxies (Verheijen 2001), which is shown as a long-dashed line in the figure. The zero point for the spiral relation was shifted down by a factor of 1.6 to match the SDSS data points; this factor is close to the naively expected $\sqrt{3}$ correction from rotational velocity to one-dimensional line-of-sight velocity. The remaining difference of 8% is difficult to assign to any particular effect; there are several effects that could produce the small difference (e.g., projection effects, nonisotropic orbits).

However, when we compute the rms velocity within a larger radius of 350 kpc, we find $\sigma \propto L^{0.5}$. The reason for the steeper slope is a combination of the very large radius and declining $\sigma(r)$, which will occur if the density profiles of halos at different mass are not homologous, e.g., if the concentration of the halo decreases with increasing mass. This is consistent with theoretical prediction.

It is rather straightforward to find the $\sigma$–virial mass relation for the NFW halos. Using the model described in § 3.1 (equilibrium NFW with slightly anisotropic velocities), we find the line-of-sight rms velocity averaged for radii 20–100 kpc and the line-of-sight velocity for projected distance 350 kpc. The results are shown in Figure 12. For the range of masses considered here, the $\sigma$-$M$ relations are power laws. Just as the observed slope of the $\sigma$-$L$ relation, the slope of the $\sigma$-$M_{\text{vir}}$ relation increases with the radius within which the rms velocity is calculated. For the 350 kpc radius the slope 0.5 is the same as the slope of the $\sigma$-$L$ relation for the same radius. This would imply a constant mass-to-light ratio. This result, being formally correct, is a bit misleading. Measured in terms of a more physically motivated quantity, the virial radius, the $M/L$ ratio increases with luminosity.

Comparison with theoretical predictions of the luminosities is more complicated and will be deferred to another paper. We use only the virial $M/L$ for two magnitudes $M_B = -20$ and $-21$. In a recent paper, Yang, Mo, & van den Bosch (2003) ask which model parameters are required for the cosmological models to explain the observed luminosity function and the Tully-Fisher relation. The main uncertainty is the $M/L$ ratio. Yang et al. (2003) predict an $M/L(L)$ that is needed to account for observations. We compare our two $M/L$ ratios with the Yang et al. (2003) predictions and find them remarkably close. However, this comparison actually required numerous corrections, including a correction for overdensity of 180 to the virial overdensity, correction for galactic absorption, correction for different bands, and scaling with the Hubble constant. The corrections were provided by R. Somerville. Preliminary comparison with semianalytical models (R. Somerville 2002, private communication) indicates a problem: observed galaxies are $\approx 0.75$ mag too bright as compared to theoretical predictions.
5. CONCLUSIONS

We construct samples of isolated galaxies and associated satellites using data from the SDSS. We detect about 3000 satellites with absolute blue magnitudes going down to $M_B = -14$. Analysis of the satellite velocities clearly indicates that galaxies are embedded in large halos extending to distances up to 350 kpc. Our measured velocity dispersion for $\sim L^*$ galaxies is in agreement with measurements from weak lensing studies.

Our analysis of galaxies selected from the SDSS database clearly indicates that the line-of-sight rms velocity of satellites declines with the distance to the primary galaxy. Similar results were found for each of our three samples, suggesting that it is robust to statistical effects and the exact definition of an isolated galaxy. This decline agrees remarkably well with $\rho \propto r^{-3}$ predicted by all cosmological models. Both the isothermal and MOND profiles contradict the observational results. Observations of weak lensing from the SDSS combined with the Tully-Fisher and fundamental plane relations (Seljak 2002) also find that the galactic halo profiles have to be steeper than isothermal at large radii.

Interlopers play an important role. We believe that the decline in satellite velocity was not seen previously (Zaritsky & White 1994; Zaritsky et al. 1997; McKay et al. 2002), mainly because of either lack of statistics or insufficient removal of interlopers. We use numerical simulations to test prescriptions for correcting the effects of interlopers and isolation criteria. Both effects, interlopers and isolation criteria, have a tendency to overestimate the mass of the dark matter halo and imply a velocity profile that is too flat.

We find that the satellite velocity dispersion inside a projected 100 kpc radius and the absolute blue magnitude of the galaxy are related as $M = 0.02 - 8.7 \log(2\sigma)$ ($\sigma \propto L^{0.5}$). This dependence is in agreement with the slope and the zero point of the Tully-Fisher relation for spiral disks. If we calculate the rms velocity within a radius of 350 kpc, the slope of the velocity-luminosity relation is visibly steeper: $\sigma \propto L^{0.5}$. The likely explanation for the difference in the slopes is an interplay between the shape of the velocity dispersion and the virial radius of galaxies.

The mass-to-light ratio increases with luminosity as $M/L \propto L^{0.3}$. For $M_B = -20\pm21)$ we find that $M/L = 100$ (150).

Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the National Science Foundation, the US Department of Energy, the Japanese Monbukagakusho, and the Max-Planck Society. The SDSS Web site is http://www.sdss.org. The SDSS is managed by the Astrophysical Research Consortium (ARC) for the participating institutions. The participating institutions are the University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, University of Pittsburgh, Princeton University, the United States Naval Observatory, and the University of Washington. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. F. P. acknowledges the hospitality of the NMSU Astronomy Department, where part of this work was done, and is grateful to Anatoly Klypin for financial support during this visit. M. V. acknowledges the hospitality and financial support of the MPIA, where the work was started. M. V. was supported by the Los Alamos National Laboratory. J. H. acknowledges the hospitality of the Instituto de Astrofísica de Andalucía, where some of this work was completed.

REFERENCES

Avila-Reese, V., Colin, P., Valenzuela, O., D’Onghia, E., & Firmani, C. 2001, ApJ, 559, 516
Blanton, M. R., Lin, H., Lupton, R. H., Maley, F. M., Young, N., Zehavi, I., & Loveday, J. 2003, AJ, 125, 2276
Blanton, M. R., et al. 2001, AJ, 121, 2358
 Bosma, A. 1981, AJ, 86, 1825
Brainerd, T. G., Blandford, R. D., & Smail, I. 1996, ApJ, 466, 623
Buote, D. A., & Canizares, C. R. 1994, ApJ, 427, 86
Buote, D. A., Jeltema, T. E., Canizares, C. R., & Garmire, G. P. 2002, ApJ, 577, 183
Colin, P., Klypin, A. A., & Kravtsov, A. V. 2000, ApJ, 559, 516
de Vaucouleurs, G., et al. 1991, Third Reference Catalogue of Bright Galaxies (Austin: Texas Univ. Press)
Erickson, L. K., Gottesman, S. T., & Hunter, J. H. 1987, Nature, 325, 779
Evans, N. W., & Wilkinson, M. I. 2000, MNRAS, 316, 929
Evans, N. W., Wilkinson, M. I., Guhathakurta, P., Grebel, E. K., & Vogt, S. S. 2000, ApJ, 540, L9
Faber, S. M., & Gallagher, J. S. 1979, ARA&A, 17, 135
Fischer, P., et al. 2000, AJ, 120, 1198
Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., & Schneider, D. P. 1996, AJ, 111, 1748
Ghigna, S., Moore, B., Governato, F., Lake, G., Quinn, T., & Stadel, J. 2000, ApJ, 544, 616
Grebel, E. K. 2000, in Proc. 33d ESLAB Symp., Star Formation from the Small to the Large Scale, ed. F. Favata, A. Kaas, & A. Wilson (ESA SP 577), 67
Hogg, D. W., Schlegel, D. J., Finkbeiner, D. P., & Gunn, J. E. 2001, AJ, 122, 2129
Hogan, D. N. C., Jones, B. F., & Klemola, A. R. 1995, ApJ, 439, 652
Lupton, R. R., Gunn, J. E., Ivezić, Z., Knapp, G. R., Kent, S., & Yasuda, N. 2001, in ASP Conf. Ser. 238, Astronomical Data Analysis Software and Systems X, ed. F. R. Harnden Jr., F. A. Primini, & H. E. Payne (San Francisco: ASP), 269
McKay, T. A., et al. 2001, ApJ, submitted (astro-ph/0108013)
Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J., & Tozzi, P. 1999, ApJ, 524, L19
Nakamura, O., et al. 2003, AJ, 125, 1682
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493 (NFW)
Ostriker, J. P., Peebles, P. J. E., & Yahil, A. 1974, ApJ, 193, L1
Prieto, J. M., Munn, J. A., Hindsley, R. B., Kent, S. M., Lupton, R. H., & Ivezic, Z. 2003, AJ, 125, 1559
Pritchet, C. J., & van den Bergh, S. 1999, AJ, 118, 883
Roberts, M. S., & Rot, A. H. 1973, A&A, 26, 483
Romanowsky, A. J., & Kochanek, C. S. 1998, ApJ, 493, 641
Sanders, R. H., & van Albada, T. S. 1987, in IAU Symp. 117, Dark Matter in the Universe (Dordrecht: Kluwer), 67
Sanders, R. H., & McGaugh, S. S. 2002, ARA&A, 40, 263
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Seljak, U. 2002, MNRAS, 334, 797
Smith, D. R., Bernstein, G. M., Fischer, P., & Jarvis, M. 2001, ApJ, 551, 643
Smith, J. A., et al. 2002, AJ, 123, 2121
Sofue, Y., & Rubin, V. 2001, ARA&A, 39, 137
Stoughton, C., et al. 2002, AJ, 123, 485
Strauss, M. A., et al. 2002, AJ, 124, 1810
Tyson, J. A., Valdes, F., Jarvis, J. F., & Mills, A. P. 1984, ApJ, 281, L59
van Albada, T. S.,Bahcall, J. N.,Begeman, K.,& Sancisi, R. 1985, ApJ, 295, 305
Verheijen, M. A. W. 2001, ApJ, 563, 694
Vitvitska, M., Klypin, A., Kravtsov, A. V., Wechsler, R. H., Primack, J. R., & Bullock, J. S. 2002, ApJ, 581, 799
Yang, X., Mo, H. J., & van den Bosch, F. C. 2003, MNRAS, 339, 1057
Yasuda, N., et al. 2001, AJ, 122, 1104
York, D. G., et al. 2000, AJ, 120, 1579
Zaritsky, D. 1992, ApJ, 400, 74
Zaritsky, D., Olszewski, E. W., Schommer, R. A., Peterson, R. C., & Aaronson, M. 1989, ApJ, 345, 759
———. 1999, ApJ, 480, 759
Zaritsky, D., Smith, R., Frenk, C., & White, S. D. M. 1993, ApJ, 405, 464
———. 1997, ApJ, 478, 39
Zaritsky, D., & White, S. D. M. 1994, ApJ, 435, 599