THE MILKY WAY’S CIRCULAR VELOCITY CURVE TO 60 kpc AND AN ESTIMATE OF THE DARK MATTER HALO MASS FROM THE KINEMATICS OF ~2400 SDSS BLUE HORIZONTAL-BRANCH STARS

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Received 2008 January 2; accepted 2008 April 15

ABSTRACT

We derive new constraints on the mass of the Milky Way’s dark matter halo, based on 2401 rigorously selected blue horizontal-branch halo stars from SDSS DR6. This sample enables construction of the full line-of-sight velocity distribution at different galactocentric radii. To interpret these distributions, we compare them to matched mock observations drawn from two different cosmological galaxy formation simulations designed to resemble the Milky Way. This procedure results in an estimate of the Milky Way’s circular velocity curve to ~60 kpc, which is found to be slightly falling from the adopted value of 220 km s^{-1} at the Sun’s location, and implies M(<60 kpc) = (4.0 \pm 0.7) \times 10^{11} M_{\odot}. The radial dependence of V_{gal}(r), derived in statistically independent bins, is found to be consistent with the expectations from an NFW dark matter halo with the established stellar mass components at its center. If we assume that an NFW halo profile of characteristic concentration holds, we can use the observations to estimate the virial mass of the Milky Way’s dark matter halo, M_{vir} = 1.0^{+0.3}_{-0.2} \times 10^{12} M_{\odot}, which is lower than many previous estimates. We have checked that the particulars of the cosmological simulations are unlikely to introduce systematics larger than the statistical uncertainties. This estimate implies that nearly 40% of the baryons within the virial radius of the Milky Way’s dark matter halo reside in the stellar components of our Galaxy. A value for M_{vir} of only ~1 \times 10^{12} M_{\odot} also reopens the question of whether all of the Milky Way’s satellite galaxies are on bound orbits.

Subject headings: dark matter — galaxies: individual (Milky Way) — Galaxy: halo — stars: horizontal-branch — stars: kinematics

Online material: machine-readable tables

1. INTRODUCTION

The visible parts of galaxies are, in the current paradigm for galaxy formation, concentrations of baryons at the center of much larger dark matter halos, which have assembled through hierarchical merging and gas cooling. Understanding the properties of these dark matter host halos and their viral masses, concentrations, and radial mass profiles vis-à-vis the luminous properties of the main galaxies at their centers is crucial for modeling the dynamics of the central galaxy, connecting observations of galaxies to large-scale cosmological dark matter simulations, and understanding what fraction of baryons in the halo ended up as stars in the central galaxy. In turn, the extended stellar distributions of galaxies, in particular the stellar halos of nearby galaxies, offer some of the best probes for testing generic predictions about the nature of dark matter mass profiles (Navarro et al. 1996).

The Milky Way and its surrounding halo are of particular interest, as our internal position permits the placement of unique constraints on the Galaxy’s stellar mass content, its dark matter profile at large radii, and the three-dimensional shape of its dark matter halo. Yet our location within the Galaxy also complicates some measurements, such as the extended rotation curve of gas in its disk. As a result, the dark mass profile for the Milky Way between ~10 and ~100 kpc and the halo’s virial mass have not been previously constrained to better than a factor of 2–3. In practice, it has proven useful to quantify the halo mass profile by either a circular velocity curve, V_{cir}(r), or by an escape velocity curve, V_{esc}(r).

In previous work, the most common tools used to estimate the Milky Way halo mass are the escape velocity and the velocity dispersion profile of the tracer populations (i.e., halo stars or the Milky Way’s satellite galaxies and globular clusters). The escape velocity provides constraints on the gravitational potential at the relevant position (Little & Tremaine 1987; Zaritsky et al. 1989; Kulessa & Lynden Bell 1992; Kochanek 1996). Recent work has shown that the total mass of the halo is around 2 \times 10^{12} M_{\odot}. Wilkinson & Evans (1999) used the velocities of 27 satellite galaxies and globular clusters to find a halo mass of ~1.9^{+1.6}_{-1.7} \times 10^{12} M_{\odot}, by adopting a truncated, flat rotation curve halo model. Sakamoto et al. (2003) used a sample including 11 satellite galaxies, 137 globular clusters, and 413 solar neighborhood field horizontal-branch stars, along with a flat rotation curve model, to
obtain a total halo mass of \(2.5^{+0.5}_{-1.0} \times 10^{12}\) or \(1.8^{+0.4}_{-0.7} \times 10^{12} \, M_\odot\), depending on the inclusion (or not) of Leo I. Recently, Smith et al. (2007) estimated a halo mass of \(\sim 1.42^{+0.14}_{-0.54} \times 10^{12} \, M_\odot\), based on a sample of high-velocity stars from the RAdial Velocity Experiment (RAVE) survey and two published databases and an adiabatically contracted NFW halo model. Battaglia et al. (2005, 2006) used a derived velocity dispersion profile to determine a total mass of \((0.5 - 1.5) \times 10^{12} \, M_\odot\), with some dependence on the model adopted for the halo profile (see also Dehnen et al. 2006).

In order to improve the precision of the mass estimate of the halo, the fundamental first step is to begin with high-quality data (tracers with accurate distances and radial velocities), augmented with an efficient method of analysis capable of extracting the maximum amount of information. For example, Wilkinson & Evans (1999) comment that a data set of \(\sim 200\) radial velocities of blue horizontal-branch (BHB) stars reduces the uncertainty in the mass estimate of the halo to \(\sim 20\%\). This goal has proven elusive, even with data samples twice this size (e.g., Sakamoto et al. 2003), due to the use of a relatively nearby sample of tracers. However, we also expect a large and distant data set to constrain the gravitational potential at different positions, which is ultimately a more reliable probe of the dark matter halo. The planned or already-underway kinematically unbiased surveys, such as the European Space Agency’s astrometric mission Gaia (Turon et al. 2005), the Space Interferometry Mission (SIM; Unwin & Shao 2000), RAVE (Steinmetz et al. 2006), the Sloan Digital Sky Survey (SDSS; York et al. 2000), and the Sloan Extension for Galactic Understanding and Exploration (SEGUE; Newberg et al. 2003; Beers et al. 2004), will finally make it feasible to obtain the required large sample of tracers with well-measured parameters.

BHB stars are excellent tracers of Galactic halo dynamics because they are luminous and have a nearly constant absolute magnitude within a restricted color range (see, e.g., Sirko et al. [2004] for BHB stars in SDSS). SDSS and SEGUE specifically targeted BHB stars for spectroscopy; we employ these stars (and other serendipitously discovered BHB stars with available spectra, e.g., misidentified QSOs) to derive precision constraints on the mass of the Milky Way’s dark matter halo.

In § 2 we describe the assembly of a particularly conservative (i.e., low-contamination) selection of BHB stars from the spectra of candidate BHBs in SDSS DR6. Two different cosmological simulations, one of a galaxy resembling the Milky Way with an \(\sim 2 \times 10^{12} \, M_\odot\) halo and one of a Milky Way–like galaxy simulation with an \(\sim 1 \times 10^{12} \, M_\odot\) halo, are presented in § 3. This section also describes the estimation of the circular velocity curve as a function of galactocentric radius, \(V_c(r)\), obtained by comparing the observed BHB radial velocities to the kinematics of the simulations. In § 4 we present the resulting estimates of the Milky Way’s halo circular velocity curve and discuss implications for the viral mass of the Milky Way’s halo. Our conclusions are summarized in § 5.

2. DATA

The SDSS is an imaging and spectroscopic survey covering more than a quarter of the sky (York et al. 2000). Although its main focus was (and is) extragalactic science, there are still large numbers of stars not only imaged but also targeted spectroscopically. In 2005 the project entered a new phase (SDSS-II), in which SEGUE, a sub survey of SDSS-II, addresses fundamental questions about the formation and evolution of our own Galaxy. In addition to further (low-latitude) imaging, SEGUE in particular provides for a more systematic and extensive acquisition of spectroscopy for stars in the Milky Way, from which stellar parameters and radial velocities can be derived from the application of a well-calibrated and well-tested set of procedures, the SEGUE Stellar Parameter Pipeline (SSPP; see Lee et al. 2008a, 2008b; Allende Prieto et al. 2008).

The SDSS uses a CCD camera (Gunn et al. 1998) on a dedicated 2.5 m telescope (Gunn et al. 2006) at Apache Point Observatory, New Mexico, to obtain images in five broad optical bands \((ugriz)\) (Fukugita et al. 1996). The survey data processing software measures the properties of each detected object in the imaging data in all five bands and determines and applies both astrometric and photometric calibrations (Lupton et al. 2001; Pier et al. 2003; Ivezić et al. 2004). Photometric calibration is provided by simultaneous observations with a 20 inch \((0.5 \, m)\) telescope at the same site (Hogg et al. 2001; Smith et al. 2002; Stoughton et al. 2002; Tucker et al. 2006). This work is based on stellar spectra that are part of the SDSS DR6 (Adelman-McCarthy et al. 2008).

The radial velocities are taken from the SSPP, which (primarily) uses matches of the observed spectra to a set of 908 ELODIE template spectra, corrected to the heliocentric standard of rest frame. Note that the SSPP automatically corrects for a systematic offset in SDSS stellar radial velocities of \(7.3 \, km \, s^{-1}\) (see Lee et al. [2008a, 2008b] for the derivation of this offset). After this correction is applied, the SDSS radial velocities exhibit negligible systematic errors and have an accuracy between \(5\) and \(20 \, km \, s^{-1}\), depending on the signal-to-noise ratio \((S/N)\) of the spectrum and the stellar spectral type.

2.1. Sample Selection

We aim to select as “pure” a set of true BHB stars as possible, where the contamination, e.g., from halo blue straggler (BS) stars, is minimized, even if this selection procedure results in a smaller sample. We have not made any effort to construct a complete sample of BHB stars. Therefore, we have not simply followed the DR6 classification procedures, but have employed a very stringent approach combining previously established color cuts with a set of Balmer line profile selection criteria. Our technique is similar to that of Sirko et al. (2004), but we use slightly different criteria in the adopted color cuts. Throughout this paper all magnitudes are corrected for Galactic extinction, and the colors are corrected for reddening, both based on the procedures of Schlegel et al. (1998).

2.1.1. Color Cuts

We start our selection of BHB stars by adopting the color cuts for identification of BHB candidates used in Yanny et al. (2000),

\[
0.8 < u - g < 1.6,
\]

\[
-0.5 < g - r < 0.0.
\]

These color cuts are shown in Figure 1; the rectangle is the region of BHB candidates. This color cut produces \(\sim 10,000\) BHB photometric candidates (see Table 1 for the full set of candidates) with existing spectra but with considerable contamination by both BS stars and warm main-sequence (MS) stars. The subsequent spectroscopic analysis for BHB candidates is aimed at eliminating, or at least greatly reducing, contamination from such stars.

2.1.2. Balmer Line Profile Cuts

In the range of effective temperature considered herein \((\text{roughly } 7000\text{–}10,000 \, K)\), BHB stars have lower surface gravities than
BS stars and higher temperatures than (old, halo population) MS stars. The Balmer line profiles of warm stars are sensitive to both gravity and temperature; their analysis provides a powerful method of selecting BHB stars with confidence. We analyze the line profiles after normalizing the continuum for all stars, as illustrated in Figure 2. Then we combine two independent methods to identify BHB stars; the stars with larger Balmer jump of A-type star. A plot of 

\[
d = D_0 - \ln \left( \frac{M_g}{M_0} \right) - 5,
\]

where \( d \) is the extinction-corrected magnitude in the \( g \) band, \( M_g \) is the absolute magnitude in the \( g \) band, \( M_0 \) is the absolute magnitude of the point on the theoretical track that is closest to the observed star in this color-color plane, \( M_0 \) is the absolute magnitude in the \( b \) band, \( d \) is the distance to the Sun, \( r \) is the distance from the Galactic center, and \( b \) and \( l \) are the Galactic latitude and longitude, respectively; we take \( M_0 \), the distance of the Sun from the Galactic center, to be 8.0 kpc.

2.3. The Spatial, Velocity, and Metallicity Distribution of the BHB Star Sample

For ease of subsequent analysis, we convert the heliocentric radial velocities to the Galactic standard of rest (GSR) frame by

\[
M = M_0 + 5 \log_{10} d - 5,
\]

where \( M \) refers to the \( H_\gamma \) line. This gap allows one to quite cleanly separate BHB stars from BS stars, according to

\[
0.75 \leq c_\gamma \leq 1.25,
\]

\[
7.5 \leq b_\gamma \leq 10 - 26.5 (c_\gamma - 1.08)^2.
\]

As the color coding of the points in Figure 5 shows, most BHB stars selected by the \( D_0,2 \) versus \( f_m \) method already lie in the appropriate region of the scale width versus shape method applied to \( H_\gamma \). The combination of these two stringent criteria indeed appears to eliminate most stars that are not bona fide BHB stars. The combination of Figures 4 and 5 suggests that the contamination is well below 10%.

Note that the two spectroscopic criteria are determined based on the spectra of bright stars (\( g \leq 18 \)). Because of the high-quality spectra available for such stars, the criteria can be easily identified by eye from Figures 4 and 5. For fainter stars (\( g > 18 \)) we adopt the same spectroscopic criteria as for the bright stars.

There are a total of 2558 stars (see Table 2 for a data file of the full set of adopted BHB stars) that survive the color cuts and both of the Balmer line profile cuts described above. This sample forms the basis of our remaining analysis.

2.2. The Absolute Magnitude of BHB Stars

Our basic approach is to identify BHB stars from their spectra (§ 2.1), then estimate their absolute magnitude from photometry alone. BHB stars have similar, but not identical, absolute magnitudes, as they are affected slightly by temperature and metallicity (e.g., Wilhelm et al. 1999; Sirko et al. 2004). Figure 6 shows five theoretical absolute magnitudes, \( M_g \), \( M_b \), \( M_c \), \( M_r \), and \( M_u \), in the \((u - g, g - r)\) plane taken from Sirko et al. (2004). For each BHB star in our sample we define the most probable absolute magnitude associated with its \((u - g, g - r)\) colors by simply finding the absolute magnitude of the point on the theoretical track that is closest to the observed star in this color-color space. The absolute magnitude error of a given star derived from this method is on the order of 0.2 mag (Sirko et al. 2004), corresponding to a distance accuracy of 10%; errors in the measured photometry are much smaller than this error. The distance from the Sun and the Galactic center can then be determined from

\[
M = M_g + 5 \log_{10} d - 5,
\]

\[
r^2 = (R_0 - d \cos b \cos l)^2 + d^2 \sin^2 b + d^2 \cos^2 b \sin^2 l,
\]

where \( g \) is the extinction-corrected magnitude in the \( g \) band, \( M_g \) is the absolute magnitude in the \( g \) band, \( d \) is the distance to the Sun, \( r \) is the distance from the Galactic center, and \( b \) and \( l \) are the Galactic latitude and longitude, respectively; we take \( R_0 \), the distance of the Sun from the Galactic center, to be 8.0 kpc.

The method described above could be improved upon by fitting a polynomial to the theoretical absolute magnitudes and color index \((u - g, g - r)\) and using it instead of picking the “closest” model. However, the difference between the two methods is less than the theoretical uncertainties in the derived luminosities.
| Sp. Name | Name                | R.A. (deg) | Decl. (deg) | l (deg) | b (deg) | g − r (mag) | u − g (mag) | uerr (mag) | gerr (mag) | rerr (mag) | HRV (km s⁻¹) | HRVerr (km s⁻¹) | RVgal (km s⁻¹) | $D_{0,2}$ (Å) | c (Å) | $b_{c}$ (Å) | Type |
|----------|---------------------|------------|-------------|--------|--------|-------------|-------------|------------|------------|------------|----------------|----------------|----------------|-------------|-------|--------|-------|
| 51602 0266 225        | SDSS J094218.23−002519.7 | 145.575943 | 0.422125 | 236.196579 | 36.896130 | 0.10 | 1.20 | 0.02 | 0.02 | 0.01 | 95.7 | 2.1 | 245.5 | 0.24 | 26.93 | 0.84 | 9.97 | BHB |
| 51602 0266 397        | SDSS J094138.17+001821.5 | 145.40958 | 0.305967 | 235.328827 | 37.175690 | 0.11 | 1.22 | 0.02 | 0.02 | 0.02 | 36.0 | 12.8 | 183.8 | 0.20 | 27.78 | 1.12 | 10.57 | BHB |
| 51602 0266 634        | SDSS J094840.23+002818.0 | 147.167633 | 0.471673 | 236.434402 | 38.711887 | 0.02 | 1.02 | 0.03 | 0.02 | 0.01 | 9.4 | 10.5 | 136.8 | 0.29 | 25.80 | 0.92 | 10.01 | BHB |
| 51609 0292 102        | SDSS J125223.54−003708.2 | 193.098083 | 0.618937 | 303.444397 | 62.251862 | 0.24 | 1.27 | 0.02 | 0.02 | 0.02 | 227.3 | 1.6 | 148.7 | 0.23 | 27.00 | 1.03 | 10.16 | BHB |
| 51609 0292 155        | SDSS J125050.87−000806.1 | 192.711960 | 0.135032 | 302.609894 | 62.736347 | 0.00 | 1.06 | 0.02 | 0.02 | 0.02 | 190.8 | 7.2 | 112.8 | 0.24 | 27.46 | 0.85 | 10.27 | BHB |
| 51609 0292 232        | SDSS J124759.81−000456.2 | 191.999207 | 0.082266 | 301.051117 | 62.776917 | 0.04 | 1.05 | 0.03 | 0.02 | 0.02 | 121.4 | 9.3 | 200.9 | 0.28 | 30.32 | 0.86 | 10.31 | BS |
| 51609 0292 269        | SDSS J124721.11−002931.5 | 191.837952 | 0.492089 | 300.729431 | 62.362186 | 0.19 | 1.12 | 0.05 | 0.03 | 0.02 | 232.0 | 19.5 | 151.0 | 0.30 | 32.62 | 0.93 | 10.10 | MS |
| 51609 0292 329        | SDSS J124641.66+003751.2 | 191.673569 | 0.630884 | 300.275543 | 63.478165 | 0.10 | 1.23 | 0.02 | 0.01 | 0.02 | 49.0 | 3.9 | 127.2 | 0.23 | 25.03 | 0.81 | 8.25 | BHB |
| 51609 0292 351        | SDSS J124449.35+002157.4 | 191.205612 | 0.365958 | 299.263092 | 63.190571 | 0.26 | 1.13 | 0.02 | 0.01 | 0.01 | 4.2 | 5.7 | 75.8 | 0.24 | 24.54 | 1.15 | 9.51 | BHB |
| 51609 0292 367        | SDSS J124805.12+010113.5 | 192.021347 | 1.020428 | 301.028198 | 63.879784 | 0.17 | 1.22 | 0.03 | 0.02 | 0.02 | 84.8 | 2.8 | 8.6 | 0.24 | 34.34 | 0.87 | 11.53 | BS |

**Notes.**—The first two columns give the object names, and the next four columns contain the astrometry (R.A., decl., l, b) for each object. The magnitude and color are in the next six columns, corrected for extinction. The radial velocities and errors are listed next. The next four columns contain the line width parameters from the Balmer lines. The last column gives the classification by the $D_{0,2}$ and $f_{\alpha}$ method. Table 1 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.
adopting a value of $220 \, \text{km s}^{-1}$ for the local standard of rest ($V_{\text{lsr}}$) and a solar motion of $(+10.0, +5.2, +7.2) \, \text{km s}^{-1}$ in $(U, V, W)$, which are defined in a right-handed Galactic system with $U$ pointing toward the Galactic center, $V$ in the direction of rotation, and $W$ toward the north Galactic pole (Dehnen & Binney 1998). Hereafter, $V_{\text{los}}$ is the radial velocity in the GSR frame (i.e., the radial velocity component along the star-Sun direction, corrected for Galactic rotation). If $V_{\text{helio}}$ is the heliocentric radial velocity, then

$$V_{\text{los}} = V_{\text{helio}} + 10.0 \cos l \cos b + 7.2 \sin b + (V_{\text{lsr}} + 5.2) \sin l \cos b. \tag{5}$$

Our sample of 2558 BHB stars may contain some thick-disk stars, with $1 \, \text{kpc} < |z| < 4 \, \text{kpc}$, so we impose an additional geometric constraint $|z| > 4 \, \text{kpc}$, which reduces the sample to 2401
### Table 2

| Sp. Name      | Name                          | R.A. (deg) | Decl. (deg) | l (deg) | b (deg) | u − g (mag) | r − g (mag) | Mₚ (mag) | D₀₂₅ (Å) | fₙₐ      |
|---------------|-------------------------------|------------|-------------|---------|---------|-------------|-------------|---------|---------|----------|
| 51602 0266 125 | SDSS J094317.57−011021.2      | 145.823196 | 1.172550    | 237.138931 | 36.662491 | 16.48        | 1.17        | 0.22    | 0.55    | 26.60    |
| 51602 0266 397 | SDSS J094418.17+001821.5      | 145.409058 | 0.305967    | 235.328827 | 37.175690 | 18.48        | 1.22        | 0.11    | 0.55    | 27.78    |
| 51602 0266 634 | SDSS J094840.23+002818.0      | 147.167633 | 0.471673    | 236.434402 | 38.711887 | 18.01        | 1.02        | 0.02    | 0.60    | 25.80    |
| 51609 0292 102 | SDSS J112523.54−033078.2      | 193.098083 | 0.618937    | 303.44397 | 62.251862 | 14.29        | 1.27        | 0.24    | 0.55    | 27.00    |
| 51609 0292 329 | SDSS J112441.66+003751.2      | 191.673569 | 0.630884    | 300.275543 | 63.478165 | 17.15        | 1.23        | 0.10    | 0.55    | 25.03    |
| 51609 0292 351 | SDSS J112445.39+002157.4      | 191.205612 | 0.365958    | 299.263092 | 63.190571 | 17.64        | 1.13        | 0.26    | 0.60    | 25.44    |
| 51609 0292 582 | SDSS J112525.01+002930.2      | 193.225037 | 0.484220    | 303.740709 | 63.353657 | 16.22        | 1.23        | 0.13    | 0.55    | 26.21    |
| 51609 0304 219 | SDSS J114172.88−002220.8      | 214.349503 | 0.372432    | 343.357650 | 55.602268 | 16.64        | 1.05        | 0.31    | 0.70    | 23.05    |
| 51613 0305 243 | SDSS J114208.24−002930.7      | 216.034348 | 0.491848    | 345.608093 | 54.511181 | 15.71        | 1.17        | 0.02    | 0.60    | 25.01    |
| 51613 0305 488 | SDSS J114286.28+002915.4      | 217.109497 | 0.487611    | 348.109955 | 54.617874 | 17.54        | 1.17        | 0.26    | 0.60    | 24.71    |

Notes.— The first two columns give the object names, and the next four columns contain the astrometry (R.A., decl., l, b) for each object. The magnitude and color are in the next four columns, corrected for extinction. The next four columns contain the line width parameters from the Balmer lines. The distances and positions are listed in the next five columns. The radial velocities and errors are listed next. The next three columns give the atmospheric parameters estimated by R. Wilhelm. The last column gives the classification by a combination of the D₀₂₅ vs. fₙₐ method and the scale width vs. shape method. 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.

Most of our BHB stars are metal-poor ([Fe/H] ≈ −2), as expected for a sample of halo stars. This is further testament to the quality of the SDSS spectra and the rigor of the sample selection. The observed distribution of line-of-sight velocities is well fitted by a Gaussian distribution with σlos = 105 km s⁻¹, as shown in Figure 9 (bottom). Figure 10 (top) shows the distribution of Vlos versus r for the halo BHB stars. It reveals a nearly equal number of stars with positive and negative Vlos at a given radius; the BHB population exhibits very little net rotation, so we subsequently analyze only Vlos. Figure 10 (bottom) shows the binned velocity dispersion, σlos, of the sample as a function of radius. It is well described by

\[ σ_{los}(r) = σ₀ \exp \left( \frac{−r}{r₀} \right), \]

where \( r₀ = 354.91 \pm 10 \) kpc, and \( r₀ = 354.91 \pm 10 \) kpc, which is consistent with equation (6) within 1σ. This indicates that the choice of bins has a small effect on the inferred σlos(r). We also checked that these values of σlos(r) are insensitive to small changes in the assumed Vlos.

The radial number density profile of halo stars in the Milky Way in the range ~10−60 kpc can be approximated by \( \rho \sim r^{−3.5} \) (e.g., Bell et al. 2007). Accounting for the \( r^{d} dr \) volume effect, inspection of Figures 10 and 11 reveals that the radial distribution

![Color-color (u − g vs. r − g) diagram of our BHB stars. The five black circles (right to left) represent the model colors for BHB stars of absolute magnitudes Mₚ = 0.60, 0.55, 0.65, 0.70, and 0.80.](image)
of our BHB sample falls off much more rapidly than this, especially at large distances. This is mostly attributable to the SDSS spectroscopic target selection. The chances of a candidate BHB star being targeted for spectroscopy in the course of SDSS and SEGUE is not a simple function of its apparent magnitude but depends on many (often operational) factors, which have also evolved over the course of the survey. The net result is that only under very favorable circumstances are distant (hence faint) BHBs targeted and have spectra obtained that are of sufficient S/N to pass our quality criteria. As a result, the radial distribution of our sample falls off much more steeply than the parent population of halo BHB stars. We account for these effects in the subsequent analysis, as described below.

Overall, our present sample of distant halo stars with available kinematics is nearly an order of magnitude larger than that of Battaglia et al. (2005), which has 240 stars. Because our tracers are BHB stars, their distances are also known more accurately. However, the Battaglia et al. sample does extend to larger radii, up to \( \sim 100 \) kpc.

### 3. MODELING THE BHB KINEMATICS

We now describe our approach to convert the \( v_{\text{los}}(r) \) measurements (as a function of galactocentric radius, \( r \)) for the \( \sim 2400 \) BHB stars into estimates of \( v_{\text{esc}}(r) \) of the Milky Way halo, and ultimately to estimate \( M_{\text{vir}} \) for the Milky Way’s halo. With the full line-of-sight velocity data set sampling radii of 5–60 kpc, we can both obtain the velocity dispersion, \( \sigma_{\text{los}} \), and identify a set of exceptionally high-velocity stars at various radii that might be suitable to estimate \( v_{\text{esc}}(r) \). Some previous work (e.g., Battaglia et al. 2005) considered only velocity dispersions, while others focused only on high-velocity stars in the solar neighborhood (Sakamoto et al. 2003; Smith et al. 2007). We consider the full velocity distribution; as we shall see, it is close to a Gaussian, and hence most of the pertinent information is contained in \( \sigma_{\text{los}} \).

To link the observables, \( v_{\text{los}} \) and \( r \), to \( v_{\text{esc}}(r) \), we not only must account for the particular survey volume but also need to make at least an implicit assumption about the nature of the halo star distribution function, in particular its (an)isotropy. In contrast to, e.g., Battaglia et al. (2005), we not only restrict ourselves to Jeans equation modeling but choose to account for these issues by investigating a comparison with cosmologically motivated galaxy simulations, making “mock observations” within these simulations, and then matching test results to the observations. One cannot expect the halo stars in the simulations to have exactly the same sample density profile as the actual stars in the halo of the Milky Way; we account for such differences as described below.

#### 3.1. Halo Star Kinematics in Simulated Galaxies

Based on prior estimates of the halo mass, we chose two smoothed particle hydrodynamics simulations corresponding to...
the formation of Milky Way–like halos from which “pseudo-observations” are constructed for comparison with the data. Both halos were picked from low-resolution cosmological dark matter simulations and were resimulated at higher resolution, including the effects of gas dynamics, star formation, and stellar feedback.

Simulation I was run using the smoothed particle hydrodynamics code GRAPESPH (Steinmetz 1996) and included a moderately efficient stellar feedback model in which the supernova energy was added to the thermal energy of the gas, as described in Abadi et al. (2003a, 2003b). This simulated halo has a present-day virial mass of about $\frac{1}{24} \times 10^{11} M_\odot$ and a virial radius of 206 kpc.

Simulation II was run using the smoothed particle hydrodynamics code GADGET-2 (Springel 2005), assuming the standard star formation prescription of Springel & Hernquist (2003), but without stellar feedback. This simulated halo has a present-day virial radius of $r_{\text{vir}} = 345$ kpc and a virial mass of $M_{\text{vir}} = 2.1 \times 10^{12} M_\odot$ (these values differ from Naab et al. [2007], as we use a different virial contrast in this paper). For further details of the simulations we refer the interested reader to Abadi et al. (2003a, 2003b; simulation I) and Naab et al. (2007; simulation II) and references therein.

For each particle in these simulations we have the three-dimensional positions and velocities; the circular velocity, $V_{\text{cir}} \equiv (r \partial \Phi / \partial r)^{1/2}$; and the escape velocity, $V_{\text{esc}}$, to the virial radius of the simulation at each given position. Because SDSS and SEGUE only observed $\approx \pi$ sr, not the entire sky (see Fig. 12), in order to compare the observations to the simulations we must select simulated star particles in the same region as the SDSS footprint.

As a first step, we specified “Galactic coordinates” in the simulation by defining the “Galactic plane” by the net angular momentum of all (stellar) particles within 10 kpc of the center. In this coordinate system one has (by definition) $L_{\text{tot}} = |L_{\text{tot}}| e_z$, and the Sun is at $(x_\odot, y_\odot, 0.0)$ kpc [$R_\odot = (x_\odot^2 + y_\odot^2)^{1/2} = 8.0$ kpc]. We can then calculate the galactocentric radial velocity as seen from the “Sun” for each simulation particle as

$$d = \sqrt{(x - x_\odot)^2 + (y - y_\odot)^2 + z^2},$$

$$v_{\text{los}} = \frac{v_x(x - x_\odot) + v_y(y - y_\odot) + v_z z}{d}. \quad (7)$$

Since the simulated “observer” is at rest in the galactocentric coordinate system, no assumptions about the LSR needs to be made in the simulations.

To create “pseudo-observations,” we first remove the satellites in the simulation and then assume 10 positions for the Sun that all have $R = 8$ and $z = 0$ kpc but different azimuthal angles $\phi$. The corresponding $l$ and $b$ in this coordinate system can then be used to select the star particles in the same region of the simulation as our observed BHB sample. The effective flux limit of the BHB sample, $g \leq 20$, implies a maximum distance from

Fig. 9.—Top: Distribution of metallicities, $[\text{Fe/H}]$, as a function of apparent magnitude, for the entire sample of halo BHB stars. Bottom: Distribution of line-of-sight velocities, corrected to the GSR, for the entire sample of BHB stars. A Gaussian of width $\sigma = 165$ km s$^{-1}$ centered on the LSR is shown for reference.

Fig. 10.—Top: Distribution of $V_{\text{los}}$ as a function of galactocentric distance, $r$, for the entire sample of halo BHB stars. Bottom: Velocity dispersion, $\sigma_{\text{los}}$, as a function of galactocentric distance. A best-fit exponentially falling relationship is plotted.
the Sun of about 76 kpc, a distance which we impose as a selection limit in the simulations. To select “halo” stars, we also require that the stars be at least 4 kpc above or below the disk plane. Finally, we average these 10 samples of simulated halo stars. Figure 12 shows the distribution of these selected simulated stars and the observed halo BHB stars in $l$ and $b$.

This procedure results in a sample of simulated halo stars (each position produces an “observational data set”) with galactocentric radial velocities, galactocentric radii, escape velocities, and circular velocities, whose distribution is shown in Figure 11. This figure makes it clear that, even in a large sample, the galactocentric radial velocity rarely approaches the escape velocity (one obvious reason being that we measure only the projected component of the space velocity).

3.2. Estimating $V_{\text{cir}}(r)$ from the Data

We analyze the implications of the observed BHB kinematics for the Milky Way halo’s mass distribution in two steps. We first estimate $V_{\text{cir}}(r)$ from the data-simulation comparison in a set of statistically independent radial bins, effectively constructing a circular velocity curve extending to 60 kpc. We then fit the circular velocity curve with NFW halo (and bulge+disk) models, resulting in estimates of $M_{\text{vir}}$. It should be noted that the Milky Way halo’s presumed virial radius extends about a factor of 4 beyond the most distant BHB stars in our observed sample of tracers.

For the data/model comparison we construct the distributions, $P(V_{\text{los}}/V_{\text{cir}})$, for the simulations and the data, respectively. For the simulations, we use the procedure described in the above section to obtain the $V_{\text{los}}$ and $V_{\text{cir}}$ at each particle position. We compare these $P_{\text{sim}}(V_{\text{los}}/V_{\text{cir}})$ distributions to analogous ones constructed from the data for a sequence of trial values $V_{\text{cir}}$. As the best observational estimate of $V_{\text{cir}}(r)$, we then take that value for which the probability that $P_{\text{obs}}(V_{\text{los}}/V_{\text{cir}})$ and $P_{\text{sim}}(V_{\text{los}}/V_{\text{cir}})$ were drawn from the same distribution is maximal. As we have no a priori functional form for these distributions, we define this best match as that which maximizes the probability in a two-sided K-S test. To define confidence limits on the $V_{\text{cir}}(r)$ estimate, we repeat this procedure with bootstrapped versions of $P_{\text{obs}}(V_{\text{los}}/V_{\text{cir}})$ and take as $\delta V_{\text{cir}}$ the variance of the resulting $V_{\text{cir}}$ distribution.

![Fig. 11.—Galactocentric radial velocity, escape velocity, and circular velocity distributions of the stars in simulation I (top) and simulation II (bottom; see § 3); the simulations are “viewed” from the position of the Sun to lie within the SDSS DR6 footprint. The solid line delineates the predicted escape velocity, while the dashed line indicates the predicted circular velocity. The dots represent the radial velocities.](image1)

![Fig. 12.—Galactic sky coverage of the observed BHB stars (red dots) and selected simulated stars (black dots), drawn from simulation I.](image2)
divide the galactocentric radius ($r$) into 10 bins and apply this method, which results in 10 (statistically) independent radial estimates of $V_{\text{circ}}(r)$. Specifically, the bins we adopted were $5 \leq r < 10$, $10 \leq r < 15$, $15 \leq r < 20$, $20 \leq r < 25$, $25 \leq r < 30$, $30 \leq r < 35$, $35 \leq r < 40$, $40 \leq r < 45$, $45 \leq r < 50$, and $50 \leq r < 60$ kpc (all distances are from the Galactic center, not from the Sun). The best-matched distributions of $P(V_{\text{los}}/V_{\text{circ}})$ are illustrated in Figures 13 and 14. In these figures, the dashed lines show $P(V_{\text{los, sim}}/V_{\text{circ}})$ and the solid lines show $P(V_{\text{los, obs}}/V_{\text{circ}})$ after finding the best-matching velocity scaling, $V_{\text{circ}}$, listed in Table 3; the best match in this context is obtained from a K-S test.

show that of the data. Overall, the velocity distributions agree well with one another.

To estimate the statistical uncertainties on these values, we use bootstrap resampling on our BHB sample (typically 100 times), repeat the above procedure, and indicate the resulting 68% (1 $\sigma$) confidence region as error bars.

In a given gravitational potential, more centrally concentrated kinematic tracer populations will exhibit smaller velocity
dispersions than more extended ones. In the simple case of a spherical potential, with tracers of $r/C_2^6$ and an isotropic velocity dispersion that varies only slowly with radius, the Jeans equation, for a given $V_{\text{cir}}(r)$, yields the relative velocity dispersions of the two populations, $\sigma_1/\sigma_2 = (\gamma_2/\gamma_1)^{1/2}$, where the indices refer to two different hypothetical tracer populations.

In the radial range of 10–60 kpc, the density profile of halo stars in simulation II is approximately $\rho \sim r^{-3.5}$, while that of simulation I is $\rho \sim r^{-3.7}$. This, however, should not be compared to the radial distribution of the stars for which we actually have velocities but to the radial profile of the halo stars from which they were drawn (see §2.3). This requires the reasonable assumption that the measured velocities are uncorrelated with the spectral targeting; even a more complete sampling of BHB stars at a given radius would have yielded the same velocity distribution. As an estimate of the actual density profile of the Milky Way’s stellar halo at 10–60 kpc, we take the estimates (for MS turnoff stars) of $\rho \sim r^{-3.5}$ (Bell et al. 2007), based on SDSS. Using the above

Fig. 14.—Comparison of the galactocentric line-of-sight velocity distribution, $P(V_{\text{los}}/V_{\text{cir}})$, between the halo star particles in simulation II and the observations, shown here for all bins. The dashed lines show $P(V_{\text{los,sim}}/V_{\text{cir}})$, and the solid lines show $P(V_{\text{los,obs}}/V_{\text{cir}})$ after finding the best-matching velocity scaling, $V_{\text{cir}}$, listed in Table 3; the best match in this context is obtained from a K-S test.
correction based on the Jeans equation, we must subsequently revise the derived velocity scales for the Milky Way halo upward by (3.5/2.9)^{1/2} = 1.1 for simulation II and downward by (3.5/3.7)^{1/2} = 0.97 for simulation I.

Matching $P[V_{los}/V_{cir}(r)]$ and applying the above correction, we obtain the estimates summarized in Figure 15 and Table 3. The circles in this figure reflect the $V_{cir}(r)$ estimates based on simulation I, while the squares stand for the $V_{cir}(r)$ estimates based on simulation II. As mentioned before, the error bars are from bootstrapping.

We have explored whether the derived estimates of $V_{cir}(r)$ depend on our adopted value for the distance of the Sun from the Galactic center, $R_{gc}$, or on the adopted local rotation velocity, $V_{los}$. If we vary the $R_{gc}$ adopted in the observation and simulations (see eqs. [4] and [7]) from 7.5 to 8.5 kpc, the $V_{cir}(r)$ changes by only about 1%. Our results for the derived $V_{cir}(r)$ are also insensitive to the choice of the $V_{los}$ adopted in the observation (see eq. [5]). Taking $V_{los}$ as 200 or 240 km s^{-1} changes the estimated $V_{cir}(r)$ by only 3%.

For reference, we show how these estimates of $V_{cir}(r)$ compare to those derived from the Jeans equation and the fit to $\sigma_{los}(r)$ shown in Figure 10. From the Jeans equation, $V_{cir}(r)$ can be estimated from the velocity dispersion, $\sigma_r$ (Binney & Tremaine 1987), as follows:

$$- \frac{r}{\rho} \frac{d(\sigma_r^2 \rho)}{dr} - 2\beta \sigma_r^2 = V_{cir}^2(r),$$

with

$$\beta = 1 - \frac{\sigma_t^2}{\sigma_r^2},$$

where $\sigma_r(r)$ and $\sigma_t(r)$ are the radial and tangential velocity dispersions, respectively, in spherical coordinates and $\rho(r)$ is the stellar density.

The distribution of the halo stars in the simulations is anisotropic, with $\beta = 0.37$, and the simulations exhibit $\sigma_{los}(r) \approx \sigma_r(r)$ for this particular survey volume. Taking from Figure 10 the fit to $\sigma_{los}(r)$ of the BHB stars (eq. [6]), and assuming $\sigma_{los}(r) \approx \sigma_r(r)$ for BHB stars, we can derive two circular velocity curves, for $\beta = 0.37$ (anisotropic) and $\beta = 0$ (isotropic), by adopting $\rho(r) \sim r^{-3.5}$ (see Fig. 15). They both agree well with the simulation-based estimates and are no longer used in the following analysis.

4. RESULTS

Figures 16 and 17 present the main result of our analysis, $V_{cir}(r)$, an estimate of the circular velocity curve from ~10–60 kpc. This represents the first time that the circular curve for the Galaxy has been estimated to such large distances at this accuracy. Note that at small radii this estimate, although derived from halo stars, agrees well (within ~10%) with established determinations at the solar radius (~220 km s^{-1}). Beyond the solar radius, the circular velocity curve appears to be gently falling to 175 km s^{-1} at ~60 kpc. Also note that the circular velocity curve is a conceptually more robust estimate than $V_{los}$, which depends more sensitively on $V_{los}$ on $\Phi(r)$ at radii beyond the measurements.

Using the functional form for $V_{cir}(r)$ expected for an NFW halo and the stellar component (see below) as a means to interpolate the individual circular velocity curve estimates, one obtains $V_{cir}(60$ kpc) = 170 ± 15 km s^{-1}, or $M(< 60$ kpc) = (4.0 ± 0.7) $\times 10^{11} M_\odot$. This is the largest radius for which the data directly constrain $V_{cir}(r)$ or $M(< r)$. Yet this radius is only one-fourth of the expected virial radius of the Milky Way’s halo. We therefore proceed with a separate step, to use these $V_{cir}(r)$ estimates to constrain parameterized models for the overall dark matter halo. We assume that the Galactic potential is represented by three components: a spherical Hernquist (1990) bulge, an exponential disk, and a dark matter halo, and we describe the halo using an NFW profile (Navarro et al. 1996). The total potential can then be simply expressed as

$$\Phi_{tot}(r) = \Phi_{disk}(r) + \Phi_{bulge}(r) + \Phi_{NFW}(r),$$

with an assumed potential, presumed to be spherically symmetric, for the disk and bulge of

$$\Phi_{disk}(r) = - \frac{GM_{disk}(1 - e^{-r/b})}{r},$$

$$\Phi_{bulge}(r) = - \frac{GM_{bulge}}{r + c_0},$$
where $M_{\text{bulge}} = 1.5 \times 10^{10} M_{\odot}$, $c_0 = 0.6$ kpc, $M_{\text{disk}} = 5 \times 10^{10} M_{\odot}$, and $b = 4$ kpc (similar to Smith et al. 2007). The radial potential for a spherical NFW density profile can be expressed as

$$\Phi_{\text{NFW}}(r) = -\frac{4\pi G \rho_{\text{crit}} r_{\text{vir}}^3}{c^3 r} \ln \left( 1 + \frac{c r}{r_{\text{vir}}} \right),$$

where $c$ is a concentration parameter, defined as the ratio of the virial radius to the scale radius. For standard $\Lambda$CDM cosmogonies we do not attempt to constrain halo flattening. The parameter $\rho_{\text{crit}}$ is a characteristic density given by

$$\rho_{\text{crit}} = \frac{3 H^2}{8 \pi G},$$

and

$$\Omega_m = \frac{\rho_m c^3}{3 \ln (1 + c) - c/(1 + c)},$$

where $\rho_m = 3H^2/8\pi G$ is the critical density of the universe, $\Omega_m$ is the contribution of matter to the critical density, and $\delta_{\text{th}}$ is the critical overdensity at virialization. The virial mass can then be determined from the virial radius using

$$M_{\text{vir}} = \frac{4\pi}{3} \rho_{\text{crit}} \Omega_m \delta_{\text{th}} r_{\text{vir}}^3.$$  \hspace{1cm} (15)

For our analysis we adopt $\Omega_m = 0.3$, $\delta_{\text{th}} = 340$, and $H_0 = 65$ km $s^{-1}$ Mpc$^{-1}$. Given recent discussions (and doubts raised) regarding whether the baryons modify the dark matter profile, as expected from “adiabatic contraction” (Dutton et al. 2007), we consider both an unaltered and an adiabatically contracted NFW profile in the fit of $\Phi_{\text{tot}}$. By fitting the observed $V_{\text{cir}}(r)$ with $(rd\Phi/dr)^{1/2}$ from $\Phi_{\text{tot}}(r)$, shown as equation (10), we can constrain the halo mass of the Milky Way. In this fit, we simply adopt an unaltered NFW profile and a present-day relation between the mean value of $c$ and $M_{\text{vir}}$,

$$\log_{10} c = 1.075 - 0.12(\log_{10} M_{\text{vir}} - 12).$$  \hspace{1cm} (16)

This relation is accurate over the range $11 \leq \log M_{\text{vir}} \leq 13$ and is based on the model of Macciò et al. (2007) with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, $\sigma_8 = 0.9$, and $n_s = 1.0$. Therefore, the $M_{\text{vir}}$ is derived
as a one-parameter fit [fit only \( M_{\text{vir}} \), presuming \( c(M_{\text{vir}}) \)]. The results are summarized in Figure 16.

Specifically, for the circular velocity estimates resulting from simulation I we find

\[
M_{\text{vir}} = 0.91^{+0.27}_{-0.18} \times 10^{12} M_\odot,
\]

with \( r_{\text{vir}} = 267^{+12}_{-11} \) kpc and \( c = 12.0 \pm 0.3 \).

For the circular velocity estimates based on simulation II we find

\[
M_{\text{vir}} = 0.83^{+0.21}_{-0.18} \times 10^{12} M_\odot,
\]

with \( r_{\text{vir}} = 258^{+20}_{-13} \) kpc and \( c = 12.2^{+0.3}_{-0.4} \).

Note that the error bars of \( M_{\text{vir}} \), \( r_{\text{vir}} \), and \( c \) are determined from 1 \( \sigma \) confidence intervals in a \( \chi^2 \) test. For the two cases above we have adopted an unaltered NFW profile and an average relation between \( c \) and \( M_{\text{vir}} \). If we fit an adiabatically contracted NFW profile (using the prescription of Blumenthal et al. 1986 and Mo et al. 1998) and the same disk and bulge as in equations (11) and (12), taking the concentration parameter \( c \) and virial mass \( (M_{\text{vir}}) \) of the NFW profile as independent parameters (i.e., we do not require that they follow the relationship in eq. [16]), the \( M_{\text{vir}} \) can be derived as a two-parameter fit \((M_{\text{vir}} \text{ and } c)\), as shown in Figure 17.

For the circular velocity estimates resulting from simulation I,

\[
M_{\text{vir}} = 1.6^{+0.3}_{-0.2} \times 10^{12} M_\odot,
\]

with \( r_{\text{vir}} = 275^{+23}_{-20} \) kpc and \( c = 6.6^{+1.8}_{-1.5} \).

The virial mass calculated by the circular velocity estimates based on simulation II is

\[
M_{\text{vir}} = 1.21^{+0.40}_{-0.30} \times 10^{12} M_\odot,
\]

with \( r_{\text{vir}} = 293^{+31}_{-24} \) kpc and \( c = 4.8^{+1.3}_{-0.9} \).

The error bars on \( M_{\text{vir}} \) and \( r_{\text{vir}} \) are determined for 1 \( \sigma \) confidence intervals in a \( \chi^2 \) test, fixing the best-fit value of \( c \), while the error bars on \( c \) are determined for 1 \( \sigma \) confidence intervals in a \( \chi^2 \) test, fixing the best-fit value of \( M_{\text{vir}} \).

Note that although contracted and uncontracted halo fits differ quite strongly in their (initial) concentration, reassuringly, the \( M_{\text{vir}} \) estimates remain relatively unaffected. The lower concentrations for the contracted halo fits are still reasonably consistent with the concentration scatter expected from cosmological simulations (e.g., Navarro et al. 1996).

The results here show that the Milky Way’s circular velocity curve must be gently falling to distances of 60 kpc from its value of \(~220 \text{ km s}^{-1}\) at the solar radius; the null hypothesis that \( V_{\text{cir}}(r) \) has a constant value of \( 220 \text{ km s}^{-1} \) is rejected by our fits with very high statistical significance (at a level of 0.01).

A direct comparison with earlier work, at the data or \( \sigma_{\text{los}} \) level, is not straightforward, as each sample has distinct selection effects, such as differing radial distributions. Our estimate of \( M_{\text{vir}} \), taken to be the average of the four estimates derived in this section, \( 1.0^{+0.3}_{-0.2} \times 10^{12} M_\odot \), falls well within the (considerably larger) range of values estimated by Battaglia et al. (2005, 2006): \( (0.5–1.5) \times 10^{12} M_\odot \). This value is also reasonably consistent with the recent estimate by Li & White (2008), based on Local Group dynamics. In general, however, the new mass estimate presented here lies at the lower limit of most previous estimates.

The method to estimate \( V_{\text{esc}}(r) \) can also be used to derive the escape velocity curve \( V_{\text{esc}}(r) \). We have carried out a procedure analogous to that described in § 3.2, using \( P(V_{\text{los}}/V_{\text{esc}}) \), and found lower limits on \( M_{\text{vir}} > 0.5 \times 10^{12} M_\odot \) which do not appear to be as stringent as the \( V_{\text{esc}}(r) \) estimates.

5. SUMMARY AND CONCLUSION

We have constrained the mass distribution of the Milky Way’s dark matter halo by analyzing the kinematics of nearly 2400 BHB stars drawn from SDSS DR6 that reach to galactocentric distances of \(~60 \text{ kpc}\). To obtain a clean sample of BHB stars, we have reanalyzed all candidate BHB spectra following the prescription by Sirko et al. (2004), which should result in a contamination fraction (mostly by BS stars) of well below 10%. The metallicity distribution, centered on [Fe/H] \(~-2 \text{ dex}\), confirms that most sample members must be halo stars. The distances to the BHB stars are known to \(~10\%\).

To account for the complex survey geometry and plausible orbital distributions of our sample of BHB stars, we have compared the observed radial velocities to analogous quantities drawn from the “star particles” in galaxy formation simulations that resemble the Milky Way. In particular, we have placed a virtual “observer” at 8.0 kpc from the simulation centers, looking in the actual SDSS directions and sampling radial velocities for stars that are more than 4 kpc above and below the disk plane. We then explore to what mass scale, or \( V_{\text{cir}}(r) \), the simulations need to be scaled in order to match the observed line-of-sight velocity distribution in a set of radial bins. In this analysis, we adjust this scaling using the Jeans equation, to account for the slight difference in the radial profile of observed halo stars (\( \rho \sim r^{-3.5} \)) and simulated halo stars (\( \rho \sim r^{-2.9} \)) over this radial range.

This procedure results in direct estimates of \( V_{\text{cir}}(r) \) from \(~10 \text{ to } ~60 \text{ kpc}\), the best such estimates to date over this range. The circular velocity estimate varies slightly with radius, dropping from \( ~220 \text{ km s}^{-1} \) at 10 kpc to \(~170 \text{ km s}^{-1} \) in the most distant two bins. Applying this procedure to two independent cosmological simulations (simulation I and simulation II) results in consistent estimates of \( V_{\text{cir}}(r) \). The mass enclosed within 60 kpc, constrained quite directly by the data, is found to be \( (4.0 \pm 0.7) \times 10^{11} M_\odot \). As a result of the much more extensive data set provided by SDSS, the uncertainties on this estimate are substantially lower than those obtained by previous comparable work. A simple, Jeans equation–based modeling approach, assuming (an)isotropies of either \( \beta = 0.37 \) or \( \beta = 0 \) (as found for the halo stars in the cosmological simulations), yields results that are consistent with these values.

Although each of the \( V_{\text{cir}}(r) \) points were estimated independently, the implied overall profile is consistent with both the mass profile in the simulations and a parameterized mass model that combines a fixed disk and bulge model with an NFW dark matter halo, whose concentration \( c \) corresponds to the expected mean value for its virial mass. We have also explored halo fits with the concentration \( c \) as a free parameter, as well as halo profiles that have been modified by adiabatic contraction. We find that our data cannot discriminate well whether or not adiabatic contraction occurs; an uncontracted halo of higher than average concentration and a contracted halo of (initially) low concentration fit comparably well. The resulting virial masses, \( M_{\text{vir}} = 1.0^{+0.3}_{-0.2} \times 10^{12} M_\odot \), are consistent for both fitting approaches. We have also checked that these results are quite robust with respect to distance errors, modest sample contamination (\( \leq 10\% \)), and the choice of a different, independent galaxy formation simulation.

The estimate of \( M_{\text{vir}} \), which does imply an extrapolation from \( r_{\text{max}} = 60 \text{ kpc} \) to the virial radius of \(~250 \text{ kpc}\), is consistent with a recent estimate from a much smaller sample of halo stars (Battaglia et al. 2006), but it is lower than previous estimates that also rely on the kinematics of satellite galaxies (e.g., Kochanek
We thank Xianzhong Zheng and Jianrong Shi for useful discussions and assistance. This work was made possible by the support of the Chinese Academy of Sciences and the Max Planck Institute for Astronomy and is supported by the National Natural Science Foundation of China under grant Nos. 10433010 and 10521001. T. C. B. and Y. S. L. acknowledge partial support from the US National Science Foundation under grants AST 06-0715 and AST 07-07776, as well as from grant PHY 02-15783, Physics Frontier Center/Joint Institute for Nuclear Astrophysics (JINA).

P. R. F. acknowledges partial support through the Marie Curie Research Training Network ELSA (European Leadership in Space Astrometry) under contract MRTN-CT-2006-033481.

Funding for the Sloan Digital Sky Survey (SDSS) and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. 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 American Museum of Natural History, the Astrophysical Institute Potsdam, the University of Basel, the University of Cambridge, Case Western Reserve University, the University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, the Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max Planck Institute for Astronomy (MPIA), the Max Planck Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, the University of Pittsburgh, the University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

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1996). However, recent results on the LMC (Kallivayalil et al. 2006; Besla et al. 2007) indicate that not even the Magellanic Clouds may have been bound to the Milky Way for long, posing a potential conceptual problem for the use of satellite dynamics. It should be interesting to explore how our new constraint modifies the Local Group timing argument and its implication for M31’s halo mass (Li & White 2008).

The estimate of $M_{\text{vir}} \sim 10^{12} M_\odot$, together with an estimated total cold baryonic mass of $6.5 \times 10^{10} M_\odot$, and a global baryonic mass fraction of 0.17, implies that nearly 40% of all baryons within the virial radius have cooled to form the Milky Way’s stars and (cold) gas, consistent with recent estimates for galaxies of that mass scale, based on statistical arguments (van den Bosch et al. 2007; Gnedin et al. 2007).

We note that parts of our analysis have been performed under the assumption that the stellar halo of the Galaxy is considered as a single relaxed population, or one that matches the simulations. Our data on the overall dynamics are consistent with that hypothesis. Recent evidence from Carollo et al. (2007) and Miceli et al. (2008) suggest that the halo may well be more complex and comprise two distinct populations of inner and outer halo stars, with (slightly) different net rotational velocities and spatial profiles. We defer all analysis of kinematic and spatial substructure in this particular sample to a future paper.

SDSS and SEGUE have shown in this context that they can provide unparalleled sets of kinematic tracers for the Milky Way, enabling a direct “circular velocity curve” estimate of the Milky Way extending to 60 kpc. Once the full set of spectroscopy from SEGUE is available, a much larger set of stars for such an analysis should be available. The proposed extension of SDSS, known as SDSS-III (using a more sensitive, 1000 fiber spectrograph), will provide the opportunity to obtain higher quality spectra for fainter, more distant BHB stars, thus extending the reach of our analysis to over 100 kpc.
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