THE STELLAR-TO-HALO MASS RELATION FOR LOCAL GROUP GALAXIES

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ABSTRACT

We contend that a single power-law halo mass distribution is appropriate for direct matching to the stellar masses of observed Local Group dwarf galaxies, allowing the determination of the slope of the stellar mass–halo mass relation for low-mass galaxies. Errors in halo masses are well defined as the Poisson noise of simulated Local Group realizations, which we determine using local volume simulations. For the stellar mass range $10^7 M_\odot < M_\star < 10^8 M_\odot$, for which we likely have a complete census of observed galaxies, we find that the stellar mass–halo mass relation follows a power law with slope of 3.1, significantly steeper than most values in the literature. This steep relation between stellar and halo masses would indicate that Local Group dwarf galaxies are hosted by dark matter halos with a small range of mass. Our methodology is robust down to the stellar mass to which the census of observed Local Group galaxies is complete, but the significant uncertainty in the currently measured slope of the stellar-to-halo mass relation will decrease dramatically if the Local Group completeness limit was $10^6 - 10^7 M_\odot$ or below, highlighting the importance of pushing such limit to lower masses and larger volumes.

Key words: dark matter – galaxies: dwarf – Local Group

Online-only material: color figures

1. INTRODUCTION

By comparing stellar masses of galaxies from large-scale surveys with masses of halos in cosmological dark matter simulations, one can use abundance matching techniques to derive the stellar-to-halo mass relation, $M_\star - M_{\text{halo}}$ (e.g., Moster et al. 2010; Guo et al. 2010). More direct measurements of $M_\star - M_{\text{halo}}$ can also be made by measuring halo masses using, for example, galaxy-galaxy lensing (e.g., Hoekstra et al. 2004; Hudson et al. 2013) or satellite dynamics (e.g., Prada et al. 2003; More et al. 2011), with the various methods giving reasonable agreement (e.g., Leauthaud et al. 2012). However, the range of masses that can be probed by abundance matching is limited by the luminosity down to which galaxy surveys are complete, and by variations in the halo mass functions of simulations. Large-scale galaxy surveys, e.g., the Sloan Digital Sky Survey and GAMMA, have provided complete stellar mass functions (Baldry et al. 2008, 2012) down to $\sim 10^6 M_\odot$ within volumes that are large enough such that the mass function within collisionless cosmological simulations have variations which are insignificant.

The details at the low-mass end, $M_\star \lesssim 10^9 M_\odot$, become less clear, as does the question as to how to extend the relation to even lower mass galaxies. For example, the stellar mass function from Baldry et al. (2008) has an upturn at the low-mass end, which translates to an upturn in the $M_\star - M_{\text{halo}}$ relation (Behroozi et al. 2013). This implies a slope of the $M_\star - M_{\text{halo}}$ relation of $\alpha = 1.6$ at the low-mass end, where $M_\star \propto M_{\text{halo}}^{1.6}$. Extrapolating this relation to lower masses would imply that low stellar mass galaxies would reside in significantly lower mass dark matter halos than predicted by extrapolating the earlier models of Moster et al. (2010) and Guo et al. (2010), which found steeper slopes (higher values of $\alpha$) for the $M_\star - M_{\text{halo}}$ relation.

However, Garrison-Kimmel et al. (2014) point out that extrapolating a slope of $\alpha = 1.6$ would significantly overestimate the number of Local Group galaxies with $M_\star \gtrsim 5 \times 10^6 M_\odot$. Using updated observational data from Baldry et al. (2012), which shows less upturn in the stellar mass function and hence a steeper $M_\star - M_{\text{halo}}$ relation, Garrison-Kimmel et al. (2014) find a slope $\alpha = 1.92$ at the low-mass end.

Regardless of these differences, there is no a priori reason to believe that the relation between stellar mass and halo mass should be extrapolated to low-mass galaxies, $M_\star < 10^8 M_\odot$. Further, the relation derived from large volume galaxy surveys may not be directly applicable to the particular environment of the Local Group.

In this study, we use constrained simulations of the local universe (CLUES6) to show that the mass function of a volume analogous to the Local Group follows a single power law. This allows us to match the masses of dark matter halos taken from the underlying power-law mass function directly to the stellar masses of observed Local Group galaxies. We thus provide the first robust measurement of the relation between the stellar mass of Local Group galaxies and the masses of the halos in which they are hosted, assuming a ΛCDM cosmology.

2. LOCAL GROUP SIMULATIONS

All simulations in this Letter are dark-matter-only. Within the CLUES project, the Hoffman–Ribak algorithm (Hoffman & Ribak 1991) is used to generate initial conditions as constrained realizations of Gaussian random fields using observational data of the local environment. A series of realizations were run in order to obtain a Local Group candidate with Milky Way and Andromeda (MW/M31) analog halos with proper masses, relative positions and with negative radial velocity.

CLUES have been extensively used for other investigations (e.g., Gottl"ober et al. 2010; Libeskind et al. 2010; Ribak 1991). www.clues-project.org

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3. RESULTS

In what follows, the slope of the dark matter halo mass function, \(\alpha_{\text{dm}}\), is defined via a power-law fit to the mass function, \(N(>M_{\text{halo}}) \propto M_{\text{halo}}^{-\alpha_{\text{dm}}}\). The slope, \(\alpha\), of the \(M_\ast-M_{\text{halo}}\) is defined by assuming a power-law fit \(M_\ast \propto M_{\text{halo}}^a\). The LGF is defined as a sphere of radius 1.8 Mpc centered on the MW analog halo.

Figure 1 shows (black line) the halo mass function of the fiducial CLUES Local Group simulation within the LGV. Sub-halos, using their maximum mass values prior to stripping, are included within the total halo population. The LGV mass function follows a single power law with slope \(\alpha_{\text{dm}} = -0.89\), the same slope as the cosmological box from which the LGV is drawn, and essentially the same slope as other cosmological mass functions in the literature (e.g., Jenkins et al. 2001).

The LGV of the CLUES simulation run with WMAP3 cosmology also has a mass function slope of \(\alpha_{\text{dm}} = -0.89\), the same as the slope in the cosmological volume from which it is drawn. Further, the 10 LGVs surrounding paired MW/M31 analog halos from Garrison-Kimmel et al. (2014), follow a slope \(\alpha_{\text{dm}} = -0.9\). These results provide strong evidence that the mass function of Local Group dwarf galaxies is a single power law.

The red dots in Figure 1 are halo masses of a defined Local Group distribution which follows the mass function power law: masses are assigned to each \(N = 0.5, 1.5, 2.5\), etc., according to the inverted mass function:

\[
M_{\text{halo}}^{10^0M_{\odot}} = N_0 \times N(>M_{\text{halo}})^{-1.12},
\]

where \(N_0 = 47.9\) for our fiducial model, and \(N_0 = 38.1\) for the mean of the 12 simulated LGVs.

This distribution of masses is appropriate for direct application to the observed Local Group, with the virial masses of each halo subject only to Poisson noise around the power-law halo mass function.

We next match this power-law halo mass distribution to observed stellar masses of Local Group galaxies, assuming a one-to-one correspondence in order of mass, as shown in Figure 2. Our predicted Local Group abundance matching is shown as points with error bars, while stellar-to-halo mass relations from previous studies are shown as lines. Observed Local Group galaxy luminosities are taken from McConnachie (2012), with stellar mass-to-light (\(M_\ast/L\)) taken from Woo et al. (2008). Updated distance measurements have resulted in slight changes to the Woo et al. (2008) stellar masses (see Kirby et al. 2013).
for a table of updated stellar masses for most galaxies). We assume $M_\ast/L = 1.6$ for galaxies not listed in either Woo et al. (2008) or Kirby et al. (2013). There are 41 galaxies in our sample with $M_\ast > 10^6 M_\odot$ and within 1.8 Mpc of the MW.

Error bars for stellar masses in Figure 2 are 0.17 dex, the quoted typical error in Woo et al. (2008). Error bars for $M_{\text{halo}}$ in Figure 2 are rms errors of each simulated halo mass from the corresponding (by ordered number) power-law halo mass, $M_{\text{halo}} \propto N^{-1/\alpha}$, using our full suite of 12 simulated LGVs. These errors in halo mass are dominated by Poisson noise, with other sources of error coming from the different cosmologies and any sample variance being insignificant. The errors on the halo masses are reasonably small in the relevant region for this study, where $N(>M_{\text{halo}}) > 10$. This region is relevant because there are 10 Local Group galaxies with $M_\ast \gtrsim 10^8 M_\odot$. So the single power law in this region can be used to match galaxies with $M_\ast \lesssim 10^8 M_\odot$.

Analyzing Figure 2 we found that the $M_\ast-M_{\text{halo}}$ relation for the Local Group galaxies is well fit by $\alpha = 3.1$ in the region $10^7 < M_\ast/M_\odot \lesssim 10^8$. The catalog of Local Group galaxies within 1.8 Mpc of the MW is likely complete down to $M_\ast = 10^7 M_\odot$ and possibly down to $M_\ast = 5 \times 10^6 M_\odot$ (Koposov et al. 2008; Tollerud et al. 2008). If we do increase the assumed completeness range to $5 \times 10^6 < M_\ast/M_\odot \lesssim 10^7$, we obtain a slope of $\alpha = 3.5$.

In this context, we note the recent discovery of satellites in the vicinity of M31 that have stellar masses of several times $10^7 M_\odot$ (Martin et al. 2013a, 2013b), demonstrating that we are certainly not complete down to $M_\ast \sim 10^6 M_\odot$ in the Local Group. Even using the $M_\ast = 10^7 M_\odot$ limit, our derived slope of the $M_\ast-M_{\text{halo}}$ relation, $\alpha = 3.1$, is nevertheless significantly steeper than most values in the literature (see the Introduction and Figure 2).

The normalization of the mass function coming from the total mass of the Local Group will not affect such derived value of $\alpha$; instead, the effect will be to shift all points in Figure 2 left or right. In the region $10^7 < M_\ast/M_\odot \lesssim 10^8$, the $M_\ast-M_{\text{halo}}$ relation is fit by

$$M_\ast = \left(\frac{M_{\text{halo}}}{M_0 \times 10^6}\right)^{3.1},$$

where $M_0 = 79.6$ in our fiducial run. $M_0 = 63.1$ when using the mean power-law mass function for the 12 LGVs. Similarly, systematic errors in observed stellar mass determinations, such as assuming a different initial mass function, will shift all points up or down.

In Figure 3, we plot the stellar mass function of observed Local Group galaxies, shown as the black line. Fixing the halo mass function slope at $\alpha_{\text{dm}} = -0.89$ along with various assumed slopes for a power-law $M_\ast-M_{\text{halo}}$ relation, $\alpha = 2, 2.5, 3, 3.5$ are plotted as dashed, dot–dashed, triple-dot–dashed, and long-dashed lines, respectively, in Figure 3. Normalization ensures 10 galaxies with $M_\ast > 10^8 M_\odot$, i.e., the observed number, in each case.

The stellar mass functions for low values of $\alpha$ diverge from the observed function as we go to lower stellar masses. Down to a completeness limit of $M_\ast \sim 10^7 M_\odot$, values of $\alpha$ are hard to distinguish, with just a few galaxies separating $\alpha = 2$ from $\alpha = 3.5$. However, assuming that the completeness limit for Local Group is closer to $5 \times 10^6 M_\odot$, a slope of $\alpha \gtrsim 3$ is clearly favored. As the catalog of observed Local Group galaxies becomes complete to lower stellar masses, the stellar mass–halo mass relation will become increasingly well defined.

In Figure 3, no assumption of a one-to-one correspondence between halo mass and stellar mass is made, as it is in Figure 2. The slope of the stellar mass function, $\alpha_\ast$, is simply derived from the relation, $1+\alpha_\ast = (1+\alpha_{\text{dm}})/\alpha$. Any scatter around the $M_\ast-M_{\text{halo}}$ relation, which may be large for low-mass galaxies (e.g., Behroozi et al. 2013), will not affect our result for the preferred slope, $\alpha \gtrsim 3$.

4. CONCLUSIONS

Supported by evidence from constrained Local Group simulations, we argue that a power-law mass function for halos is appropriate to be directly applied to Local Group galaxies. Poisson noise of simulated realizations provide well-defined errors in halo masses. By matching such power-law mass function to stellar masses of observed Local Group galaxies, we determine a slope of the $M_\ast-M_{\text{halo}}$ relation of $\alpha = 3.1$ for galaxies with stellar mass $M_\ast \lesssim 10^8 M_\odot$. This determination of the relation for Local Group galaxies down to $M_\ast = 10^7 M_\odot$ is significantly steeper than most values in the literature, which have generally been extrapolations of the abundance matching relation from higher masses.

Our value of $\alpha$ is consistent with the extrapolation of the Guo et al. (2010) relation to small stellar masses, yet the upturn in the relation at masses above $M_\ast = 10^8 M_\odot$ (Behroozi et al. 2013; Garrison-Kimmel et al. 2014) indicates that the extended relation is likely to be more complex than a single power law for masses $M_\ast < 10^9 M_\odot$.

The key insight of our Letter comes from the fact that the halo mass function of the Local Group analog simulation in a volume with radius 1.8 Mpc follows a single power-law slope to large enough masses to host all the Local Group galaxies with $M_\ast \lesssim 10^8 M_\odot$. Because the census of observed Local Group galaxies is well known down to $M \sim 10^7 M_\odot$ (or a
little lower) within such a volume, we can match Local Group dwarf galaxies to dark matter halos drawn from a population that follows a power law in a region where Poisson noise, which determines the uncertainties in the halo masses, is low.

On the other hand, smaller volumes, such as sub-halo mass functions of MW analog halos, are not constrained in this manner. On average, such populations will also follow a single power law (e.g., Boylan-Kolchin et al. 2010), but their individual mass functions are dominated by Poisson noise. Therefore, the Local Group is unique, with a volume that is large enough to have a single, well-defined power-law mass function, yet small enough to find faint galaxies.

Scatter in the \( M_\star - M_{\text{halo}} \) relation appears evident in the Local Group. For example, Fornax is 100 times more luminous than Draco, but seems to have a smaller halo mass (Peñarrubia et al. 2008). However, such scatter will not flatten the slope of the stellar-to-halo mass relation that we derived, as is evident in Figure 3 where only slopes are considered, with no assumption made regarding how stellar masses and halo masses are matched. Nevertheless, scatter in the \( M_\star - M_{\text{halo}} \) relation will result in some relatively high stellar mass galaxies being hosted by relatively low-mass halos, but this is only achieved in conjunction with relatively low stellar mass galaxies being hosted by high-mass halos.

As we show in Figure 3, surveys of Local Group galaxies that extend the completeness limit to lower luminosities, such as SKYMAPPER (Keller et al. 2007) and LSST (LSST Science Collaboration et al. 2009) will provide increasingly strong constraints on the \( M_\star - M_{\text{halo}} \) relation, and particularly on the slope of such relation at small masses, simply by matching observed data to a power-law mass function for dark matter halos.

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