A SURVEY OF SATELLITE GALAXIES AROUND NGC 4258

MEGHIN SPENCER1, SARAH LOEBMAN1,2, AND PETER YOACHIM2
1 Department of Astronomy, University of Michigan, 500 Church Street, Ann Arbor, MI 48109, USA; meghins@umich.edu
2 Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195, USA

ABSTRACT

We conduct a survey of satellite galaxies around the nearby spiral NGC 4258 by combining spectroscopic observations from the Apache Point Observatory 3.5 m telescope with Sloan Digital Sky Survey (SDSS) spectra. New spectroscopy is obtained for 15 galaxies. Of the 47 observed objects, we categorize 8 of them as probable satellites, 8 as possible satellites, and 17 as unlikely to be satellites. We do not speculate on the membership of the remaining 14 galaxies due to a lack of velocity and distance information. Radially integrating our best-fit NFW profile for NGC 4258 yields a total mass of $1.8 \times 10^{12} M_{\odot}$ within 200 kpc. We find that the angular distribution of the satellites appears to be random, and not preferentially aligned with the disk of NGC 4258. In addition, many of the probable satellite galaxies have blue $u-r$ colors and appear to be star-forming irregulars in SDSS images; this stands in contrast to the low number of blue satellites in the Milky Way and M31 systems at comparable distances.

Key words: galaxies: dwarf – galaxies: individual (NGC 4258) – galaxies: kinematics and dynamics – galaxies: spiral – galaxies: structure – techniques: spectroscopic

Online-only material: color figures

1. INTRODUCTION

The number, type, and spatial distributions of satellite systems surrounding host galaxies can serve as unique probes to theories of galaxy formation. In a ΛCDM universe, host galaxies such as the Milky Way (MW) are predicted to reside in vast, dark matter halos. In this paradigm, the main galaxy is expected to be surrounded by numerous satellite, dark matter halos that lie within a few 100 kpc of the central galaxy. It is reasonable to expect that many of these halos host luminous dwarf galaxies. Such satellite systems are potentially ideal dynamical tracers of the underlying mass distribution and can also probe the effect of environment on morphology, star formation, and quenching. Despite the theoretical utility of a well-sampled satellite system, most observations find only a handful of satellites per massive host outside of the Local Group (LG).

A limiting factor in establishing robust samples of satellites beyond the LG is the inherent faintness of these objects. To circumvent this, some have taken a statistical approach, stacking large numbers of similar systems and inspecting aggregate properties (Prada et al. 2003; Zaritsky et al. 1993). However, stacking in this manner makes it impossible to study variation between systems, and thereby restricts the inferences that can be drawn. For example, recent observations of the MW and M31 satellite systems have found them to be preferentially aligned in extended disks (Kroupa et al. 2005; Conn et al. 2013; Ibata et al. 2013). Such results are impossible to replicate in studies that stack galaxies and require detailed knowledge of particular isolated hosts with large numbers of satellites to verify the global significance.

In this light, one recent study (Kim et al. 2011, hereafter K11) focuses on the MW-like, barred spiral galaxy NGC 4258 (also known as M106) to identify a large sample of satellite galaxies. K11 use MegaCam on the Canada France Hawaii Telescope to observe a 1.7 by 2.0 degree field around NGC 4258 (roughly out to a projected radius of 130 kpc) and find 16 candidate satellite galaxies and 5 probable candidate satellite galaxies. These were selected based on the existence of literature radial velocities, resolvable stars, and/or extended and faint surface brightness structures. This catalog of 21 galaxies spans a wide range of morphologies, from dSph, dE, Sd, to Irr. Most of them have surface brightness profiles that are fit well by an exponential and have negligible color gradients. Additionally, NGC 4258 satellites follow the Schechter luminosity function with a faint-end slope of $-1.19^{+0.03}_{-0.06}$, which is steeper than the LG slope ($-1.06 \pm 0.03$) but flatter than the M81 slope ($-1.29^{+0.07}_{-0.05}$).

We revisit this work by spectroscopically observing a subset of the 16 satellite galaxies identified in the K11 sample to determine the prevalence of foreground/background galaxy contamination. We expand the K11 survey to include additional galaxies detected in the Sloan Digital Sky Survey (SDSS) that are also spatially near NGC 4258.

NGC 4258 is similar to the MW in that it has a terminal rotational velocity of 208 km s$^{-1}$ (Erickson et al. 1999), is a barred spiral galaxy, and has an average $B$-band surface brightness of 23.1 (Karachentsev et al. 2013). Due to its relatively nearby location (7.6 Mpc, Humphreys et al. 2013) and interesting inner disk morphology (resolved active galactic nucleus and warped accretion disk; Caproni et al. 2007; Martin 2008), it has been the source of a wide array of galactic studies. Significantly, NGC 4258 possesses a water maser, which tightly constrains the distance to it with an error of only ~3% (Humphreys et al. 2008). Other distance measurements made with Cepheid variables and tip of the red giant branch (TRGB) magnitudes have reasonable agreement (Humphreys et al. 2013).

Aside from assessing the significance of foreground/background contamination in a photometrically derived satellite sample, we see three primary motivations to extend the K11 study of the NGC 4258 satellite system. (1) Using a Jeans equation-based technique developed by Watkins et al. (2010), we can draw constraints on the total mass of NGC 4258. (2) We

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1 Department of Astronomy, University of Michigan, 500 Church Street, Ann Arbor, MI 48109, USA; meghins@umich.edu
2 Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195, USA

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http://www.sao.ru/lv/lvgdb/
can assess if there is a preferential orientation for the satellites surrounding NGC 4258, as has been found for the MW (Kroupa et al. 2005), M31 (Conn et al. 2013; Ibata et al. 2013), and M81 (Chiboucas et al. 2013). (3) It has long been known that the color and morphology of MW and M31 satellites vary as a function of distance from respective hosts (see, for example, Mateo 2008). However, it has yet to be established if this apparent environmental effect holds outside the LG. Given its relative isolation from other massive perturbers and numerous candidate satellites, NGC 4258 provides an ideal testbed of the significance of proximity to the host galaxy to color and morphology of satellites.

For these reasons, we build upon K11’s work to assemble and leverage the most complete list of satellite galaxies surrounding an MW-like system outside of the LG. The structure of this paper is as follows. Section 2 details our data collection/reduction process, including the target selection, observations, data processing, and velocity measurements. Section 3 provides a discussion of how we categorize the satellites and calculate the host mass. In the same section, we present a discussion of the angular distribution and color range of the satellites. Section 4 contains concluding remarks.

2. DATA COLLECTION

2.1. Target Selection

We combine the K11 catalog of 16 potential satellites with additional candidates drawn from the SDSS database to produce a list of targets for spectroscopic followup. To select potential targets from SDSS, we searched within 2 degrees (projected radius ∼250 kpc) of NGC 4258 and required that the r-band Petrosian radius be larger than 5′ and the photometric redshift be less than 0.1. Minor color cuts were applied to ensure targets had galaxy-like colors. This list was sorted by r-band brightness, and then targets were manually inspected to remove any objects that were artifacts of SDSS such as shredded galaxies or bright star halos. Satellites were then ranked based on r-band magnitude, projected distance of the satellite away from the host, and photometric redshift, using the following formula:

\[ \text{score} = \sqrt{\left(\frac{r}{r_{\text{max}}}\right)^2 + \left(\frac{d}{d_{\text{max}}}\right)^2 + \left(\frac{z}{z_{\text{max}}}\right)^2}. \]

The 30 highest scoring galaxies as well as the K11 satellites served as the basis for our observations. Due to limited observing time, we did not obtain spectra for all of these objects. See Figure 1 for galaxy distribution in right ascension and declination relative to NGC 4258 and Table 1 for relevant properties from SDSS and the NASA/IPAC Extragalactic Database (NED).\(^5\)\(^6\)

2.2. Observations and Data Reduction

We used five half-nights of observing time on the 3.5 m Apache Point Observatory (APO) telescope with the Dual Imaging Spectrograph (DIS) to observe 29 targets. The wavelength center was on 6799 Å for the red channel and 4502 Å for the blue, with each channel covering about ∼1180 Å. The high resolution 1200 line mm\(^{-1}\) grating was used with a slit width of 2″. Observations were made in February, April, and May of 2011. Exposure times ranged from 5 to 20 minutes.

Ten bias frames were averaged and subtracted from all images. Nightly quartz lamp dome flats were normalized by a ninth, tenth, or eleventh order polynomial and divided out of the science images. Arc lamp Helium–Neon–Argon spectra were taken after slewing to a new target to correct for any small distortions in the mirror and instrument while the telescope was in motion. Arc lamp frames were used to wavelength calibrate the corresponding science spectra. Standard star observations were taken at the beginning and/or end of each night. These flux standards were used to eliminate the instrument response signature in the spectra. Typical seeing was 1′, and the standards were observed at low airmass. The background was subtracted by using regions off-target, but along the slit.

Spectra were corrected to the heliocentric rest frame and were combined when repeat observations were made on the same or end of each night. These flux standards were used to eliminate the instrument response signature in the spectra. Typical seeing was 1′, and the standards were observed at low airmass. The background was subtracted by using regions off-target, but along the slit.

Objects observed with APO are listed in Table 1 along with the J2000 right ascension, declination, SDSS r-band magnitude, measured heliocentric radial velocity, and literature distances. Galaxies will hereafter be referred to by the last three (or four) digits of their SDSS DR7 object IDs. For a full SDSS ID refer to Table 1.

2.3. Velocity Measures

Depending on the size of the target galaxy, we extract between 1 and 20 spectra along the spatial dimension. For each extracted spectrum, we use Penalized Pixel-Fitting (Cappellari & Emsellem 2004) and Gas AND Absorption Line Fitting (GANDALF; Sarzi et al. 2006) algorithms to fit stellar velocities

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\(^5\) http://sdss3.org

\(^6\) http://ned.ipac.caltech.edu/
Table 1
Summary of Galaxy Properties from Our Observations and the Literature

| SDSS ID (DR7) | Other ID | K11 ID | R.A. (J2000) | Decl. (J2000) | APO v (km s\(^{-1}\)) | SDSS v (km s\(^{-1}\)) | Lit v (km s\(^{-1}\)) | Dist (Mpc) | r (mag) | Status |
|---------------|----------|--------|--------------|---------------|-----------------------|------------------------|----------------------|-----------|--------|--------|
| 5888017111295918190 | SDSS J121551.55+473016.8 | 456 | 183.96482 | 47.50469 | 654 | 650 | 16.74 | Y |
| 5888017109685633092 | SDSS J121933.21+472705.2 | S8 | 184.88338 | 47.45147 | 786 | 788 | 7.06b | 17.13 | Y |
| 5888017063086342070 | SDSS J121811.04+465501.2 | S5 | 184.54613 | 46.91686 | 390 | 480 | 6.54b | 16.59 | Y |
| 5888017109685714480 | SDSS J12173195+4759420 | SDSS J121134.99+473927.1 | 184.07288 | 47.39626 | 819 | 805 | 805 | 15.82 | M |
| 5888017111833290080 | 2MASX J12173195+4759420 | S13 | 184.20767 | 47.28592 | 759 | 757 | 770 | 15.78 | M |
| 5888017111295950116 | SDSS J121933.21+473016.8 | S6 | 183.89582 | 47.65555 | 749 | 755 | 17.30 | M |
| 5888017109685633092 | SDSS J121933.21+473016.8 | S8 | 184.31344 | 45.81202 | 439 | 444 | 7.06b | 14.72 | M |
| 5888017111295918190 | SDSS J121551.55+473016.8 | S4 | 184.49338 | 46.45740 | 786 | 788 | 7.06b | 13.08 | Y |
| 5888017111295918190 | SDSS J121551.55+473016.8 | S7 | 184.78782 | 47.08978 | 136 | 136 | 7.24b | 16.09 | Y |
| 5888017109685633092 | SDSS J121933.21+473016.8 | S11 | 184.86350 | 47.31255 | 7.05c | 18.32 | M |
| 5888017111295918190 | SDSS J121551.55+473016.8 | S14 | 183.66611 | 46.35330 | 583 | 583 | 15.99 | M |
| Notes. All velocities are relative to the heliocentric radial velocity. Column 3 is the ID given by K11; entries of N/A in the APO velocity column are galaxies that we observed but could not extract a radial velocity for; entries of “>10,000” are galaxies that we observed that were high redshift; the Status column is the member categorization that we describe in Section 3.1. “Y” is a probable satellite, “M” is a possible satellite, “N” is not a satellite, “X” is a galaxy lacking velocity information, and “H” is the host galaxy.

and emission line velocities in both the red and blue spectra. For stellar templates, we use the single stellar population galaxy models from Vazdekis et al. (2010). For galaxies that were spatially extended, we fit rotation curves to the measured velocities to find the dynamical centers of the systems and systemic velocities.

The red emission lines (Hα, [S II]) are usually the brightest features. The red spectra are also better calibrated since we...
only have \( \sim 5 \) arc lines in the blue. We therefore adopt the red emission line velocity, or if it is not available, the blue stellar velocity as the systematic velocities of our galaxies.

Since many of these galaxies are spatially extended, we expect the primary source of error to be due to imperfect placement of the spectrograph slit. Given the high signal in most of our spectra, we expect velocity errors of the order of 10 km s\(^{-1}\). Formally, the errors could be smaller, but we expect that systematic errors (slit-placement, kinematic versus photometric center, etc.) will limit us as well. We assume that the maximum in the stellar continuum corresponds to the dynamical center of each galaxy.

Our velocities agree with the available SDSS values within the root mean square scatter of 10 km s\(^{-1}\) in all but three cases. Two of the galaxies (SDSS IDs 911 and 621) have bright off-center star-forming regions which were targeted by SDSS. The last galaxy (782) remains discrepant; despite being a relatively bright object, none of the measurements (ours, SDSS, or NED) agree particularly well.

Our velocity for NGC 4258 also agrees with literature values. To derive this, we carefully extracted the spectrum from a small central region, as NGC 4258 has a very sharply rising rotation curve which can skew the result if the extraction is not symmetric.

### 3. ANALYSIS

Below, we present three findings that were made with the combined SDSS and APO data. The first section describes how we categorize galaxies as probable and possible satellites versus background galaxies. The second section explains our mass calculation of NGC 4258. The third section examines the angular distribution of satellites, and the fourth section discusses the color of our satellite galaxies.

From this point forward, any mention of velocity refers to the velocity relative to NGC 4258. The relative velocity is defined as the line-of-sight velocity of that galaxy minus the line-of-sight velocity of NGC 4258. A histogram of all these relative velocities is shown in Figure 3 as a red line. It is immediately apparent from this figure that there are many more galaxies that are redshifted with respect to NGC 4258 than blueshifted. By symmetry, we expect a similar number of true satellite galaxies to be redshifted as blueshifted (Zaritsky 1992). In addition, there is a peak around 300 km s\(^{-1}\) indicating that there might be some other structure just beyond NGC 4258. For these reasons, we conclude that there is significant contamination from background galaxies in our sample. Before we can perform any analysis on our sample of galaxies, or on the host itself, we must discard non-members.

#### 3.1. Separating Satellites from Background Galaxies

In order for a dwarf to be considered a satellite it must be bound to the host galaxy. That is, it must have a total velocity less than the escape velocity of the system and have a distance similar to that of the host (Zaritsky et al. 1993). To determine which of our dwarf galaxies could satisfy the first requirement, we plot the line-of-sight velocity with respect to the host against the projected radius (Figure 4). For completeness, we show in Figure 5 the line-of-sight velocities of our sample as they appear on the sky.

Next, we calculate the escape velocity as a function of radius for three different mass distributions: a point mass, an NFW profile (Navarro et al. 1996), and a Burkert profile (Burkert 1995). Disk components are included for the latter two profiles.

The NFW profile is described by

\[
\rho_{\text{NFW}} = \frac{\rho_H}{x(1+x)^2},
\]

and the Burkert profile is described by

\[
\rho_{\text{Bur}} = \frac{\rho_H}{(1+x)(1+x^2)},
\]
-400 -200 0 200 400 600 800 1000

V-VNGC 4258 (km/s)

Figure 3. Histogram of the number of satellites in each 100 km s\(^{-1}\) velocity bin. The vertical black line marks the systemic velocity of NGC 4258. Notably, more galaxies are redshifted with respect to NGC 4258 than blueshifted, indicating the presence of background galaxies (Zaritsky 1992). In Section 3.1, we discuss how we narrow down the sample to probable satellites (blue filled region) and possible satellites (green filled region). The entire sample of galaxies is outlined in red. See Figure 4 for how these satellites are classified.

(A color version of this figure is available in the online journal.)

Figure 4. Projected radius vs. line-of-sight velocity with respect to NGC 4258. Potential satellite galaxies are marked and labeled with the last three or four digits of their SDSS ID and K11 ID when relevant. Filled circles are objects classified as probable satellites, open squares are possible satellites, and pluses are non-members. Blue and red lines trace the escape velocity from a disk+NFW profile and \(1 \times 10^{12} M_\odot\) point mass. Escape velocity profiles are divided by \(\sqrt{3}\) as we assume velocity isotropy in order to compare with the observed galaxy radial velocities. Objects beyond 200 kpc (vertical black dashed line) are at best listed as possible rather than probable satellites given their large projected radius (Barber et al. 2014).

(A color version of this figure is available in the online journal.)

where \(\rho_H\) is density scale, \(x = R/R_H\), and \(R_H\) is the core radius for an NFW profile, which is of the order of 10 kpc. We iterate on \(\rho_H\) and \(R_H\) in our analysis. The disk surface density that we employ is

\[
\sigma_D = \frac{M_D}{2\pi R_D^2} e^{-r/R_D}
\]

where the mass of the disk, \(M_D\), is \(6 \times 10^{10} M_\odot\) and the scale radius of the disk, \(R_D\), is 2.6 kpc. Importantly, since we only know one-dimensional velocities (radial velocities) of our galaxies, we assume they obey velocity isotropy.\(^7\) In this limit, we can compare our line-of-sight velocities with the escape velocities predicted for each profile by dividing the profiles by \(\sqrt{3}\). We have over-plotted \(\pm (V_{esc}/\sqrt{3})\) for two of these profiles in Figure 4.

\(^7\) That is, \(V_x = V_y = V_z\); it then follows that the three-dimensional velocity of a satellite is \(|V_{tot}| = \sqrt{3}V_x^2\).
The literature contains distance measurements for 13 of our 47 objects; these can help us refine our individual classifications. However, distance estimates to an “X” for excluded. They are not included in our subsequent catalog. Galaxies that fall within the total escape velocity profile are background galaxies (classified as “N”); triangles are galaxies that lack velocity information (classified as “X”). The asterisks mark galaxies with TRGB distances; the two circles with asterisks are the galaxies used to select NFW parameters.

Figure 5. Line-of-sight velocity for each satellite as it appears in the sky. Red indicates that the satellite is redshifted with respect to the host and blue indicates that the satellite is blueshifted with respect to the host. The green ellipse marks the size, location, and inclination of NGC 4258. Circles are probable satellites (classified as “Y”); squares are possible satellites (classified as “M”); pluses are background galaxies (classified as “N”); triangles are galaxies that lack velocity information (classified as “X”). The asterisks mark galaxies with TRGB distances; the two circles with asterisks are the galaxies we used to select NFW parameters.

We determine the best-fit parameters to these profiles. As a first guess, we use the parameters for the MW as defined by Nesti & Salucci (2013). Because the NFW and Burkert models yield nearly identical results, we opt to use the NFW profile for further analysis rather than both models. To further refine the density models, we need to know additional information about the system. If there was a selection of galaxies with reliable distance measurements that match NGC 4258 and have velocities within a reasonable range, we can conclude that such galaxies must be bound to the system and leverage them to constrain the halo parameters. This is the case for two of our 47 galaxies (996 and 207), which have TRGB distances within the errors of the distance to NGC 4258 (Munshi & Macri 2007; Karachentsev et al. 2013). More importantly, they are located near the edge of the NFW escape velocity profile and can be used to create lower limit boundaries for the profile. We increase $\rho_H$ and $R_H$ so that these two satellites fall within the NFW escape velocity profile. Thus we assume density and radius values for the NFW model of $\rho_H = 1.4 \times 10^7 \text{M}_\odot/\text{kpc}^3$ and $R_H = 16 \text{kpc}$.

We now use our best-fit lower limit NFW profile to determine further satellite membership. Any galaxy that has a line-of-sight velocity that falls within the NFW $\pm (V_{esc}/\sqrt{3})$ lines in Figure 4 is a strong candidate for being a satellite galaxy (but see Barber et al. 2014, for possible confusion at large projected radii). Eight galaxies fall within the $\pm (V_{esc}/\sqrt{3})$ boundaries and have projected radii of less than 200 kpc; they are deemed the most probable satellites and are tagged with a “Y” for yes in our catalog. Galaxies that fall within the $\pm (V_{esc}/\sqrt{3})$ boundaries but have projected radii of greater than 200 kpc, are tagged with an “M” for maybe.

Next, we relax our initial assumption about velocity isotropy and consider the case when most of the total velocity is along the line of sight; a system is bound in this scenario if the line-of-sight velocity is simply less than the total escape velocity. This is a possible, but not a probable, scenario. Hence, we categorize galaxies with a line-of-sight velocity greater than $\pm (V_{esc}/\sqrt{3})$ but less than $\pm V_{esc}$ as possible satellites and tag them with an “M” for maybe as well.

There are 17 galaxies that fall beyond the total escape velocity profile. We categorize them as non-members and tag them in our catalog with an “N” for No. The remaining 14 galaxies lack velocity information. At this time, we draw no conclusion about their membership. These galaxies are indicated in Table 1 with an “X” for excluded. They are not included in our subsequent analysis but would be strong candidates for further follow-up.

We consider the steps outlined above to be a good first pass at determining membership. However, distance estimates to these objects can help us refine our individual classifications. The literature contains distance measurements for 13 of our 47 galaxies. Here, we amend a few of our previous $Y/M/N/X$ categorizations on the basis of these values, as outlined below.

Recall NGC 4258 is 7.6 Mpc away. Galaxy 850 was initially classified as “M”; however, its average distance in NED is 15.7 Mpc from Tully Fisher and surface brightness fluctuation measurements; due to the large separation in distance, it is reclassified as an “N” for background galaxy. Galaxies 909, 042, and 206 have average Tully Fisher distances in NED of 17.9, 14.4, and 21.05 Mpc respectively; again, they are reclassified as “N.” Another galaxy we reclassify is 782, which has a single Tully Fisher distance in NED of 21.2 Mpc; we demoted from “Y” to “N.” Finally, galaxy 911 has a TRGB distance of 5.63 Mpc in NED. It was originally a “Y” but is demoted to “N” as it is a foreground galaxy. Any galaxies unmentioned retain the same membership classifications as before. These final classifications are listed in Table 1.

We add one additional galaxy to our list from the archival Hubble Space Telescope data analyzed by L. Macri and F. Munshi (see, Munshi & Macri 2007). They present the TRGB distance to galaxy 358. We categorize it as an “M” galaxy since the distance is similar to the host galaxy, but refrain from a higher ranking because we do not have a velocity measurement. Additionally, Macri and Munshi also provide a TRGB distance for 207 that is consistent with NGC 4258.

It should be noted that seven of the galaxies we considered (067, 207, 4639, 422, 970, 678, and 012) are listed with distances of 7.8 Mpc in Karachentsev et al. (2013) based upon K11’s photometric work. 7.8 Mpc is the distance to NGC 4258 found from Cepheid measurements of Newman et al. (2001). We do not list these distances in Table 1 because, as we demonstrate here, membership based on photometry alone is uncertain.

When taking into consideration the available velocities and distances, we conclude that four of the objects classified by K11 are probable satellites (072, 207, 277, and 996), two are possible satellites (593 and 634), three are not satellites (782, 850, and 909), and seven are still uncertain (012, 067, 422, 678, 828, 970, and 4639). We note that 072, also known as NGC 4248, has long been considered a satellite galaxy (van Albada 1977). See Table 1 for mapping between K11 ID and SDSS ID, as well as Figure 1.

We conclude that eight of the galaxies we consider have the highest probability of being satellites. This represents 17% of our sample. A dwarf galaxy survey done by Carrasco et al. (2006) found only 78 out of their 409 target galaxies within four clusters were actually members, equating to a 19% yield. Since the surface density of galaxy clusters is much larger than

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8 In this case, $|V_{vel}| \sim V_c$. 
that of field galaxies, we consider the results of the Carrasco et al. (2006) survey as an upper limit for how well we expect to be able to select system members. However, we caution that without knowing both velocities and distances, it is impossible to state with absolute certainty whether a galaxy is a satellite, and it is still quite possible that some of our most probable samples are in fact non-members.

To summarize, we adopt the following classification scheme.

1. Probable Satellites (“Y”): galaxies with distance measurements consistent with NGC 4258 or no known distances; line-of-sight velocity within \( \pm (V_{\text{esc}}/\sqrt{3}) \) and have projected radii less than 200 kpc.
2. Possible Satellites (“M”): galaxies with distance measurements consistent with NGC 4258 or with no known distances; line-of-sight velocity greater than \( \pm (V_{\text{esc}}/\sqrt{3}) \) but smaller than \( \pm V_{\text{esc}} \), or line-of-sight velocity within \( \pm (V_{\text{esc}}/\sqrt{3}) \), but with projected radii greater than or equal to 200 kpc, but less than 300 kpc.
3. Unknown if Satellites (“X”): galaxies with distance measurements consistent with NGC 4258 or no known distances; galaxies with no known line-of-sight velocities; projected radii less than 300 kpc.
4. Not Satellites (“N”): galaxies with distance measurements inconsistent with NGC 4258 or velocities outside \( \pm V_{\text{esc}} \).

Based on these criteria, we categorize 8 objects as probable satellite galaxies, 8 as possible satellite galaxies, and 17 as non-members; for 14 galaxies we draw no conclusion.

### 3.2. Halo Mass

With this collection of probable satellite galaxies, we next aim to estimate the dynamical mass of NGC 4258. Watkins et al. (2010) publish a set of robust mass estimators for cases where only the projected radius and line-of-sight velocity of each target are known (as opposed to true radii and peculiar velocities). They assume the population of satellites is spherically symmetric. The relevant equations are

\[
M = \frac{C}{G} < v^2_{\text{los}} R^2 >, \quad C = \frac{(\alpha + \gamma - 2\beta)}{I_{\alpha,\beta}} r^{1-\alpha}
\]

\[
I_{\alpha,\beta} = \frac{\pi^{1/2} \Gamma \left( \frac{\alpha + 1}{2} \right)}{4 \Gamma \left( \frac{\alpha}{2} + \frac{1}{2} \right)} [\alpha + 3 - \beta(\alpha + 2)]
\]

where \( M \) is the galaxy mass, \( G \) is the gravitational constant, \( \alpha \) is a fiducial radius at which the power-law approximation for the relative potential is valid, \( \beta \) is the Binney anisotropy parameter that depends on the tangential and radial velocity dispersions, \( \gamma \) is the power-law index of the radial density distribution of satellites, \( v_{\text{los}} \) is the upper limit of a gravitational field that is scale-free, and \( \Gamma(x) \) is the gamma function, where \( \Gamma(x) = (x - 1)! \). We use \( \alpha = 0 \) (satellites move in a large-scale mass distribution with a flat rotation curve), \( \beta = 0 \) (isotropic satellite orbits), and \( \gamma = 2 \) (the satellite density falls off as \( r^{-2} \)).

Incorporating our eight probable satellite galaxies into the mass calculation, we find the mass of the host to be \( 3.1 \pm 0.7 \times 10^{12} M_{\odot} \) out to a radius of 200 kpc. Including the eight probable satellites plus the three possible satellites that fall within \( \pm (V_{\text{esc}}/\sqrt{3}) \) but have projected radii greater than 200 kpc, we find the mass of the host to be \( 3.7 \pm 1.0 \times 10^{12} M_{\odot} \) out to 240 kpc. Current estimates for the MW range between 0.6 to \( 10^{12} M_{\odot} \) and 3.1 to \( 10^{12} M_{\odot} \) within the virial radius (McMillan 2011; Boylan-Kolchin et al. 2013; Barber et al. 2014).

An alternative way of calculating the mass is by integrating the NFW density profile over an appropriate range of radius. Utilizing the NFW profile derived in Section 3.1, we determine that the total mass out to 200 kpc is \( 1.8 \times 10^{12} M_{\odot} \). Any uncertainty here is due to the fact that we have one-dimensional velocities and projected radii.

### 3.3. Satellite Distribution

Several studies of the MW, M31, and M81 have found that satellites exist in a plane centered around the host (Kroupa et al. 2005; Conn et al. 2013; Ibata et al. 2013; Chiboucas et al. 2013). K11 find that their sample of 16 satellites are preferentially aligned along the disk of NGC 4258. We reassess these findings based on our revised satellite list.

A rigorous evaluation would consider both a satellite’s angle and projected distance away from the disk before drawing conclusions about the angular dependence. However, the disk of NGC 4258 is highly inclined relative to our line of sight; this minimizes the impact of projection effects, which could cause a satellite elevated above the disk to appear aligned with the disk instead. Because of this, we only consider the angular separation between a satellite and the disk plane. We use a position angle of \( 150^\circ \) (de Vaucouleurs et al. 1991).

Figure 6 displays the cumulative angular distribution of three subsets of satellites. The blue solid line traces the probable satellites; the dashed green line traces the probable plus possible satellites; and the red dash-dotted line traces the original K11 satellites. Data has been folded from \( 360^\circ \) to \( 90^\circ \) to allow for better statistical sampling. An angle of \( 0^\circ \) indicates that a satellite galaxy is perfectly aligned with the disk of the host (i.e., major axis alignment); an angle of 90 indicates that a galaxy is not at all aligned with the disk and might instead be aligned with the minor axis of the host.

In Figure 6, a black dash-dotted line marks the case where there is no angular dependence, that is, there are just as many satellites at low angles as high angles. Distributions that grow faster than this line are said to be preferentially aligned with the disk; distributions that grow slower than this line are not aligned with the disk.

Overplotted on Figure 6 are the one sigma envelopes for random distributions drawn from samples of 8 and 16 satellites, shown in blue and red, respectively. Our probable sample has 8 satellites; the probable plus possible sample and the K11 sample both have 16 satellites. All three distributions grow faster than the random distribution; however, both the probable and probable plus possible samples fall (marginally) within the envelopes of what is allowed by a random distribution.

For completeness, we have used the IDL routine ksone to run a one-sample Komolgorov–Smirnov (KS) test on the data to quantitatively assess if the angular distributions of probable satellites, possible plus probable satellites, and K11 satellites are drawn from a random distribution. However, we caution that the KS test requires a relatively large number of data points to properly reject the null hypothesis (that the sample is drawn from a random uniform distribution).

The KS statistic \( (D) \) specifies the maximum deviation between the data and a supplied distribution; \( D \) varies between 0 and 1. Larger \( D \) values indicate that the data and supplied distribution are significantly different. The significance level \( (p \text{ value}) \) of the KS statistic is also considered; the \( p \) value is the probability of drawing from a random distribution and obtaining results as extreme or more extreme than the data. \( P \) values vary from 0 to 1; a large \( p \) value indicates that it is highly likely that one will generate samples like the data.
Ever since Holmberg initially found that satellite galaxies found in this study, the dashed green line indicates the eight probable plus eight possible satellite galaxies ("Y" + "M"), and the dash-dotted red line indicates the 16 satellite galaxies from K11. The blue and red shaded regions are the one sigma envelopes for random distributions drawn from samples of 8 or 16 satellites, respectively. The blue and green samples of satellites are consistent with there being no angular dependence around the disk of NGC 4258, shown as a straight black dash-dotted line along the center of the shaded region.

We make two comparisons to a flat distribution, where a satellite is equally likely to be at any angular position: we consider our catalogs of probable satellites and probable plus possible satellites. The KS statistics for these are \( D = 0.24 \) and 0.18 with significance levels of \( p = 0.66 \) and 0.63, respectively. Since the \( D \) numbers are small and \( p \) values are large, this means that with a high confidence level, our samples of probable and probable plus possible satellites are drawn from a flat distribution.

Ever since Holmberg initially found that satellite galaxies are preferentially aligned along the minor axis of their host (Holmberg 1969), there has been a steady stream of conflicting results regarding satellite galaxy alignments (see Bailin et al. 2008 and references therein). Besides numerous observational disagreements, there is also no broad theoretical agreement on whether satellites should be aligned at all or found on randomly oriented orbits (Zentner et al. 2005; Kroupa et al. 2005). There are two standard interpretations of satellites existing in a disk; either they recently merged as an infalling group, or they tend to fall along cold dark matter filaments (Hartwick 2000). On the other hand, a lack of any orientation could imply that the host galaxy has not accreted any new dwarfs in recent cosmic times. While our findings very loosely support the latter hypothesis, we feel that we have too few satellites to draw definitive conclusions. There may even be an alternative interpretation when taking satellite colors into consideration (see Section 3.4).

3.4. Satellite Morphology

Figures 7 and 8 display the SDSS images of our probable and possible satellites, respectively. From these images, it is immediately apparent that the vast majority of these satellites are blue irregulars. We plot further in Figure 9 a map of the Sloan \( u-r \) colors of the satellites as they appear on the sky. Colors less than 2.2 are blue, late-type galaxies. All but two of our probable satellites have \( u-r \) colors less than 1.7. The remaining two have colors less than 2.15. In addition, all of the possible satellite galaxies have \( u-r \) colors less than 1.6. Given our technique for identifying the line-of-sight velocity of these galaxies, this is not surprising (that is, our catalog is not complete, as the method is biased against red, dim satellites). What is surprising is the sheer number of blue satellites; if this system was like the MW or M31, we would expect many fewer blue star-forming satellites at small projected radii.

To further stress this point, we replicate a color–magnitude plot from Mateo (1998) shown in Figure 10. Color transformations from Chonis & Gaskell (2008) are used to move from \( g \) and \( r \) to \( B \) and \( V \). Galaxies that fall below the black line are blue late-type galaxies; galaxies above the black line are red early-type galaxies. Many of our probable and possible galaxies that have small projected radii are found below the line.

It is conventionally thought that galaxies experience quenching as they fall inward toward the host (see, for example, Geha et al. 2012). Since our satellites are blue star-formers they most likely have not had enough time to be quenched. As mentioned in the previous section, this might imply that they have recently been accreted to the system.

Again, we are not making an argument for completeness here because we are only sensitive to the brightest satellites and therefore miss dimmer dwarf spheroidals. However, even in an incomplete sample we find a large number of blue, late-type galaxies. Our results are consistent with the photometric work of Ludwig et al. (2012) for NGC 7331.

4. DISCUSSION AND CONCLUSION

4.1. Necessity of Spectroscopy

As we have demonstrated, satellite membership is challenging to determine. It cannot be done from photometry alone, nor spectroscopy alone, but instead requires, at minimum, a combination of the two. With photometry, one can make a good first
guess as to which galaxies might be satellites based on resolvability of stars and surface brightness as was done by K11. Spectroscopy can help narrow that sample, as we have shown here. To further refine the selection, distance measurements are needed. Finally, to verify a galaxy as a satellite with absolute certainty would require orbital radius and proper motions. Without these, it is impossible to confidently declare satellite membership.

While our sample of satellites does take velocities and distances into consideration, we caution that it might still contain non-members in the foreground and background. Since small number statistics are in play for these sorts of systems, it only takes a couple non-member galaxies to produce misleading conclusions about the characteristics of the sample as a whole. This is why we choose four categorizations for our satellites: probable, possible, non-member, and unknown. We do not refer to any of the satellites as confirmed.

Despite our cautionary language, we cannot emphasize enough that our sample has much better constraints than a purely photometrically derived ground-based satellite catalog. That is, while it is not complete and perhaps suffers some minimal degree of contamination, it is certainly the most reliable catalog of NGC 4258 satellites to date.

4.2. Conclusion

We present a spectroscopic catalog of 47 dwarf galaxies surrounding NGC 4258. Fifteen of these targets did not previously have published redshifts. A histogram of line-of-sight velocities of potential satellite galaxies indicates that a substantial fraction are background galaxies; without proper motions (or, realistically, distances to the galaxies) there is no easy way to determine which are bound to NGC 4258 and which are background contaminants. Using an NFW profile to eliminate any
obvious interlopers, we classify eight of our dwarf galaxies as probable satellites and eight as possible satellites. Our selection criteria are based upon distance measurements and velocities. With this sample of satellite galaxies, we make four conclusions.

1. The mass yielded when using the eight probable satellite galaxies in a mass estimator based on the spherical Jeans equation is \(3.1 \pm 0.7 \times 10^{12} M_\odot\) out to a radius of 200 kpc. If we instead integrate our NFW profile, we find the mass to be \(1.8 \times 10^{12} M_\odot\) out to 200 kpc.

2. The orientation of the probable and possible plus probable galaxy subsets do not indicate a strong preferential alignment with the disk.

3. A large number of the probable satellites are blue irregulars, which is atypical in comparison to the MW and M31 systems.

4. Satellite membership is difficult to identify when only photometry is utilized. We conclude that velocity and distance measures are necessary to determine satellite membership with any certainty.

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GANDALF was developed by the SAURON team and is available from the SAURON Web site (www.strw.leidenuniv.nl/sauron). See also Sarzi et al. (2006) for details.

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**References**

- Bailin, J., Power, C., Norberg, P., Zaritsky, D., & Gibson, B. K. 2008, MNRAS, 390, 1133
- Barber, C., Starkenburg, E., Navarro, J., McConnachie, A., & Fattahi, A. 2014, MNRAS, 437, 959
