PROPERTIES OF SATELLITE GALAXIES IN THE SDSS PHOTOMETRIC SURVEY: LUMINOSITIES, COLORS, AND PROJECTED NUMBER DENSITY PROFILES

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1. INTRODUCTION

According to the currently accepted model of structure formation, galaxy systems arise as the result of hierarchical clustering (White & Frenk 1991; Bertschinger 1994; Cole et al. 1994). The details by which galaxies form and evolve in dense or moderately dense environments, where galaxy–galaxy interactions are frequent and matter distributes in a rich substructure, depend on the characteristics of those environments. The assembly of galaxy systems entails the process of matter accretion, governed by gravity, as well as astrophysical phenomena, such as the efficiency of gas cooling and collapse or the energy feedback related to the late stages of stellar evolution (Viola et al. 2008; Kang et al. 2006). Some of these details are not yet fully understood, and observational evidence is fundamental for constraining structure formation and evolution models, especially because faint galaxies are more sensitive to astrophysical processes such as supernova feedback and ram pressure stripping. In particular, statistical studies of systems of galaxies are key to understanding the transformations of galaxies due to the interactions between galaxies and their environment (Nichol et al. 2003).

Although the formation of a galaxy is believed to take place on the potential well of a dark matter halo, not all halos host a galaxy. As first pointed out by Klypin et al. (1999), the number of halos in numerical simulations was an order of magnitude greater than the observed number of satellites in the Local Group (Moore et al. 1999; Kravtsov et al. 2004; Strigari et al. 2007). This difference has been a matter of lively debate, being attributed either to a lack of observed galaxies or to an excess of formed objects in simulations. Willman et al. (2002) discussed the possibility of undercounting satellite galaxies in the Milky Way (MW) and estimated the actual number of satellites in about twice the known population at that time. The authors argued that galactic extinction and stellar foreground can lead to up to 33% of incompleteness, thus the number of MW satellites at low galactic latitude and at galactocentric distance might be underestimated. Simon & Geha (2007) found that the number of satellites in the MW system was greater than previously expected, based on an analysis of the Sloan Digital Sky Survey (SDSS) data. With these findings, the discrepancy between the number of observed and simulated satellites reduces to a factor of nearly four. Nevertheless, applying a background subtraction technique on photometric data from SDSS Data Release 7 (DR7), Liu et al. (2011) recently found that the MW galaxy has significantly more bright satellites than a typical galaxy of its luminosity.

The study of the spatial distribution of satellites around primaries and clusters has become favored by increasingly large galaxy redshift surveys. Many observational studies address the radial distribution of galaxies in spectroscopic samples (Coil et al. 2006; Lin et al. 2004; Yang et al. 2005; Collister & Lahav 2005), mostly around galaxy clusters, and on bright primary galaxies (Sales & Lambas 2005; Chen et al. 2006). Deeper
samples have also been used to compute projected density profiles, using background subtraction (Hansen et al. 2005) around MaxBCG galaxy systems. Moreover, galaxy projected density profiles were computed based on projected correlation function determinations in redshift galaxy catalogs (Li et al. 2007) and deeper photometric samples (Wang et al. 2010) around a set of spectroscopically identified galaxies.

The distribution of satellite luminosities is also key to the development of models and understanding the processes of galaxy formation (Benson et al. 2003; Benson 2010; Okamoto et al. 2010). Given the low luminosity of most satellites, however, their observation is usually onerous and hardly accessible beyond the Local Group. Mateo (1998) put forward a detailed census of dwarf galaxies from which a flat faint end of the luminosity function in the Local Group could not be discarded. Background subtraction methods have been widely used to obtain galaxy luminosity function in clusters, and results of this procedure on individual clusters have also been reported (e.g., Oemler 1974). Since it is not limited to the computation of luminosities, it can also be used to obtain the color–magnitude relation (Pimbblet 2008). Andreon et al. (2005) present a variation of the background decontamination method, avoiding the use of arbitrary binning and incorporating the background noise as part of a refined model for the description of data. Koposov et al. (2008) presented a search methodology for MW satellite galaxies in SDSS data through the computation of efficiency maps. Searches for stellar concentrations using these maps suggest a luminosity distribution that steadily rises following a power law up to $M_r \simeq 5$. From there on, a flat distribution could not be discarded (Koposov et al. 2008).

Tollerud et al. (2008) use completeness limits for the SDSS Data Release 5 to implement a correction for luminosity bias. Although a first-order correction would produce an increase in the faint end of the luminosity function, the authors put forth that this result is not constrained well enough given available data. Trentham & Tully (2002) study the faint end of the galaxy luminosity function in five different local environments from the Virgo Cluster to the NGC 1023 group. The authors derive an averaged luminosity distribution in the range $-18. < M_r < -10$ (Cousins R magnitude) and infer a faint-end slope $\alpha \sim -1.2$. In the particular case of NGC 1023, a more detailed study confirmed later that the faint end is consistent with a shallow slope (Trentham & Tully 2009). Tully & Trentham (2008) studied the NGC 5353 group and attributed a faint-end slope of $\alpha = -1.15$ to the fact that this group is at an intermediate evolutionary age.

Determining the membership of individual galaxies through spectroscopic measurements is inefficient in terms of observing time, given the large fraction of background objects that have to be rejected. This results in few systems with derived luminosity function that is complete down to faint magnitudes. For this reason, a background subtraction technique is an efficient method for studying properties of the population of companion objects on a statistical basis. Using deep mock catalogs constructed from a numerical simulation, Valotto et al. (2001) analyze systematic effects in the determination of the galaxy luminosity function in clusters. Their results indicate a strong tendency to derive a rising faint end when clusters are selected without redshift information. This is due to projection effects, since many of the clusters selected in two dimensions have no significant counterpart in three dimensions. Muñoz et al. (2009) use mock catalogs constructed using a GALFORM (Baugh 2006) semianalytic model of galaxy formation to study the reliability of the statistical background subtraction method to recover the underlying observer-frame luminosity function of high-redshift ($z \simeq 1$) cluster galaxies in the $K_r$ band. These authors find that the optimal response of the method for recovering the underlying galaxy luminosity function occurs when background corrected counts of faint galaxies are complemented with photometric redshifts of bright galaxies. They also show that the increase in the number of galaxy clusters that contribute to the computations dramatically reduces stochastic errors. Christlein (2000) studied luminosity functions for galaxies in loose groups and suggested that the ratio of dwarf to giant galaxies is continuously increasing from low- to high-mass groups. This is based on data from the Las Campanas Redshift Survey, where environment is estimated using the line-of-sight velocity dispersion of the host groups. Background subtraction has been applied to single clusters (Andreon et al. 2005; Barkhouse et al. 2007) and to ensembles of clusters (González et al. 2006).

The goal of this work is to obtain statistical properties of satellite galaxies in the magnitude range $-18.5 < M_r < -14.5$, using SDSS photometric data. Previous studies of galaxy satellites concern mostly the MW and nearby galaxies, so this work complements a study of projected radial number density profiles, luminosity, and color distributions for a statistically large sample of primaries within $z = 0.1$. The definitions of host samples and the adopted satellite selection criteria are presented in Section 2. The details of the background subtraction procedure are given in Section 3. Then, in Section 4 we present the derived distributions of satellite properties. In order to validate the implemented method, we test it in Section 5. Finally, the main conclusions are provided in Section 6.

2. PHOTOMETRIC AND SPECTROSCOPIC DATA

We use the large database provided by the Sloan collaboration (SDSS; Stoughton et al. 2002), which provides photometric information of objects down to faint magnitudes. This survey has been carried out using a dedicated 2.5 m telescope (Gunn et al. 2006) and comprises digital photometric information of stars and galaxies in five bands (Fukugita et al. 1996; Smith et al. 2002) reduced by an automated pipeline (Lupton et al. 2001). The limiting magnitude is 22.2 in the $r$ band. A set of the brightest and more concentrated galaxies in the main galaxy sample has been selected for spectroscopic follow-up (Blanton et al. 2003a). This leads to the spectroscopic galaxy catalog, which contains galaxies with Petrosian magnitude $r < 17.77$ (Strauss et al. 2002). Both photometric and spectroscopic data are accessible through a Web interface to the public releases of the survey. The DR7 comprises nearly 18 Tb of cataloged data for objects identified as galaxies by the automated data reduction pipeline (Abazajian et al. 2009). The main galaxy sample comprises 691,055 galaxies with 95% completeness down to a limiting magnitude $r_{lim} = 17.77$ in the $r$ band. The surface brightness limits are imposed by the instrument capabilities and the automated reduction pipeline, so that these data sets allow us to retrieve information about galaxies above the surface brightness limit of the catalog, $\mu_{lim} < 24.5$ mag arsec$^{-2}$ in the Petrosian $r$ band (Strauss et al. 2002). All galaxies in this sample have redshift measurements and serve in this work as primary targets for the study of fainter galaxies, accessed from a deeper photometric sample. We obtain statistical properties of faint satellites, most of them not present in the spectroscopic survey, associated with primaries with measured redshifts in the
range 0.03–0.1. To this aim, we use the New York Value Added Galaxy Catalog (NYU-VAGC; Blanton et al. 2005) to extract photometric information of neighboring galaxies of primaries. This catalog is based on the sixth release of the SDSS and covers 9583 deg$^2$ of sky distributed into a northern cap and three southern stripes. We note that the sky coverage of the NYU-VAGC DR6 area, so that the cross-correlation between these two catalogs is suitable for the purpose of this work. We used the software HEALPix (Górski et al. 2005) to optimize the data processing of the galaxy catalogs.

### 2.1. Host Samples and Galaxy Selection Criteria

We have considered primaries brighter than $M_p = -20.5$ ($r$-band luminosities) in the redshift range 0.03–0.1, applying an isolation criterion in order to avoid high-density environments such as pairs or groups of galaxies. The density contrast around galaxies fainter than $M_p = -20.5$ is low and comparable to Poisson uncertainty. Since the method, which is detailed in Section 3, is based on the presence of a strong signal-to-background ratios, we left fainter galaxies out of consideration in defining the samples of hosts. These primaries are constrained to have no neighbors brighter than $M_p + 2$ within a projected distance of 700 kpc and a relative radial velocity difference of 700 km s$^{-1}$. These criteria are similar to those adopted in previous studies using spectroscopic samples (Sales & Lambas 2005; Chen et al. 2006; Agustsson & Brainerd 2010) and are intended to select and isolate halos where a dominating, assumed central galaxy of the satellite system is found. The total sample of primaries comprises 51,710 objects brighter than $M_p = -20.5$ in the redshift range 0.03–0.1.

Taking into account galaxy luminosities and colors, we have considered different subsamples of primaries in order to explore possible dependencies of the satellite properties on host properties. The description of the subsamples considered is given in Table 1. Subsample names are indexed on a three-character basis: a number indicating the host luminosity selection (“0” for the full sample, “1” for hosts with $-21.5 < M_r < -20.5$, and “2” for hosts with $M_r < -21.5$) and two letters indicating host and satellite colors. For simplicity, uppercase characters correspond to primary galaxy colors (A, B: All, Red, Blue), while lowercase characters indicate satellite colors (a, r, b standing for all, red, and blue, respectively). In Figure 1, we show the distributions of $r$-band absolute magnitudes, $g - r$ colors, and redshifts of hosts in the total sample. The bimodal distribution of primary galaxy colors can be clearly seen, and we use a color cut of $g - r = 0.8$ to separate subsamples according to host color.

### Table 1

| Sample | Luminosity | Color | $N_p$ | Radii $R_{\text{max}}$ $<$ (kpc) | Color |
|--------|------------|-------|-------|-------------------------------|-------|
| S0-A-a | $M_r < -20.5$ | All | 51710 | <840 & $-0.4 < g - r < 1.0$ |       |
| S0-A-r | $M_r < -20.5$ | $g - r > 1.0$ | 51710 | <840 & $-0.4 < g - r < 1.0$ |       |
| S0-A-b | $M_r < -20.5$ | $g - r < 1.0$ | 51710 | <840 & $-0.4 < g - r < 1.0$ |       |
| S1-A-a | $-21.5 < M_r < -20.5$ | All | 42335 | <840 & $-0.4 < g - r < 1.0$ |       |
| S1-A-r | $-21.5 < M_r < -20.5$ | $g - r > 1.0$ | 42335 | <840 & $-0.4 < g - r < 1.0$ |       |
| S1-A-b | $-21.5 < M_r < -20.5$ | $g - r < 1.0$ | 42335 | <840 & $-0.4 < g - r < 1.0$ |       |
| S2-A-a | $M_r < -21.5$ | All | 9375 | <660 & $-0.4 < g - r < 1.0$ |       |
| S2-A-r | $M_r < -21.5$ | $g - r > 1.0$ | 9375 | <660 & $-0.4 < g - r < 1.0$ |       |
| S2-A-b | $M_r < -21.5$ | $g - r < 1.0$ | 9375 | <660 & $-0.4 < g - r < 1.0$ |       |
| S2-B-a | $M_r < -21.5$ | $g - r > 1.0$ | 4740 | <660 & $-0.4 < g - r < 1.0$ |       |
| S2-B-b | $M_r < -21.5$ | $g - r < 1.0$ | 4740 | <660 & $-0.4 < g - r < 1.0$ |       |

Notes. The number of primaries $N_p$ of each sample is also indicated. Satellite galaxies have a lower bound of $g - r = -0.4$ for samples a and b. Uppercase letters A, B, and R stand for All, Blue, and Red, respectively. Similarly, lowercase letters indicate the ranges of satellite colors.

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Figure 1. Properties of primary galaxies in the total sample. This sample comprises 51,710 galaxies brighter than $M_r = -20.5$ in the redshift range 0.03–0.1, satisfying the isolation criteria stated in Section 2.1.
3. BACKGROUND SUBTRACTION METHOD

The background subtraction method is based on the simple idea of counting the number of objects in a region where a given signal is expected to lie, superposed to an uncorrelated noise, and subtracting a statistical estimation of that noise. In this case, the signal is due to the presence of satellite galaxies in systems dominated by a central and luminous galaxy, and the noise is associated with the background and foreground galaxies not dynamically linked to the primary galaxy. This method allows us to statistically obtain properties of the faint galaxies associated with the primaries, without the need for redshift information of individual objects. This is accomplished provided that the working hypothesis of the central primary is satisfied, and convenient ranges of observed parameters are chosen, so as to minimize the contribution of background counts. Although the method does not allow us to quantify the contribution of each individual object to the signal, it is possible to obtain statistical estimates of probability density distributions describing galaxy properties. This is accomplished by restricting galaxies to a fixed bin of the variable—for instance the luminosity of the satellite or their distance to the central galaxy—and normalizing this to the number of contributing systems in that bin, after implementing the background subtraction.

Within the hierarchical clustering paradigm, the matter distribution can be roughly described by a set of halos populated with galaxies, according to certain recipes that depend on galaxy type (Cooray & Sheth 2002). This model can give insight into with galaxies, according to certain recipes that depend on galaxy distribution can be roughly described by a set of halos populated with galaxies, according to certain recipes that depend on galaxy type (Cooray & Sheth 2002). This model can give insight into galaxy interactions with the primaries, without the need for redshift information of individual objects. This is accomplished provided that the working hypothesis of the central primary is satisfied, and convenient ranges of observed parameters are chosen, so as to minimize the contribution of background counts. Although the method does not allow us to quantify the contribution of each individual object to the signal, it is possible to obtain statistical estimates of probability density distributions describing galaxy properties. This is accomplished by restricting galaxies to a fixed bin of the variable—for instance the luminosity of the satellite or their distance to the central galaxy—and normalizing this to the number of contributing systems in that bin, after implementing the background subtraction.

Figure 2 shows the observed color distributions of faint galaxies with measured redshifts in SDSS, in three different absolute magnitude intervals. Curves show spline interpolation.

3.1. Constraints Imposed by the Data

The main requirement for the success of a statistical background subtraction method relies on a significant mean overdensity around a given sample of primaries. This fact led us to consider bright galaxies, $M_r < -20.5$, since the neighborhood of fainter primaries does not show a significant density enhancement in SDSS data. The uncertainty of the background decontamination procedure is dominated by Poissonian statistics of the subtraction of large numbers. A significant increase in the signal-to-noise ratio of satellites can be achieved by eliminating those galaxies with a low probability of association with the primaries. To this end, we restrict the parameter space of galaxies in the photometric catalog so that we only use ranges of those parameters where the hypothesis assumed in the background subtraction method is best satisfied, and reliable estimations of luminosity, color, and projected radial distributions can be obtained. We impose constraints on the apparent magnitude, colors, and radial distance of photometric galaxies. Accordingly, we adopted $M_r < -14.5$, $-0.4 < g - r < 1$, and a projected radial distance in the range 100 kpc to $3 R_{\text{vir}}$, which we discuss in detail in what follows.

Along with the limiting magnitude of the photometric sample, the redshift range of primaries determines the maximum luminosity that can be studied. Given the limiting magnitude of 21.5 in the $r$ band, and a minimum redshift for the primaries of 0.03, we chose a maximum luminosity of $M_r - 5 \log(h) \sim -14$ in the $r$ band. The limiting magnitude we used was less than the limiting magnitude from SDSS in order to ensure 100% completeness (Abazajian et al. 2004).

In Figure 2 we show the observed color distributions of SDSS satellite galaxies derived from the spectroscopic sample in three different absolute magnitude bins between $-18.5$ and $-14.5$. It can be seen in this figure that a color cut in $g - r < 1$ includes most of the faint companion objects and has the advantage of removing high-redshift galaxies reddened by the $K$-correction. Therefore, in all computations we exclude objects redder than this threshold to lower the noise due to the presence of
high-redshift galaxies. A clear indication that our color cut $g - r = 1$ is a suitable threshold for removing high-redshift galaxies can be seen by an inspection of Figure 3 where we have applied background subtraction counts to sample S2-A in the range $100 \text{ kpc} < r_p < 660 \text{ kpc}$. The observed lack of excess signal beyond $g - r = 1$ shows that our method is effective in detecting companion galaxies in the color range $-0.4 < g - r < 1.0$. This is also a convenient cut according to determinations of satellite colors in semianalytic models of galaxy formation (Font et al. 2008) and galaxies in groups in SDSS Data Release 2 data (Weinmann et al. 2006). We have applied the same color cut $g - r = 1$ to galaxies in the mock catalog as described in Section 5.

In Figure 4, we show the projected density profile of galaxies in the selected color range $-0.4 < g - r < 1.0$ around primaries of sample S2-A. For comparison, we also show the corresponding galaxies with $g - r > 1.0$. As can be seen, a significant excess of $-0.4 < g - r < 1.0$ galaxies is observed beyond $100 \text{ kpc}$, while red galaxies $g - r > 1.0$ (mainly consisting of strongly redshifted background galaxies) show a null flat profile consistent with a uniform radial distribution (shaded region in Figure 4), which also gives support to our choice for the color range of satellites. However, as can be seen in the inset of Figure 4, we note that the projected density profile of red galaxies is not uniform in the innermost region around the luminous primary galaxies. This shows that the hypothesis of a uniform background fails within $100 \text{ kpc}$ for this data set. Hence, in the computation of the statistical distributions, namely luminosity and colors, galaxies are restricted to a projected radial distance of at least $100 \text{ kpc}$. This radial distance is consistent with previous findings that indicate the presence of an extended stellar halo associated with luminous galaxies. This issue could lead to a failure of the SDSS automated pipeline to detect low surface brightness galaxies (either satellites or foreground/background galaxies). Nierenberg et al. (2011) study the spatial distribution of faint satellites at intermediate redshifts ($0.1 < z < 0.8$) using high-resolution Hubble Space Telescope images of early-type galaxies taken from GOODS fields. The authors model the light profile of host galaxies in order to study the population of faint satellites. This model gives the spatial distribution of satellites near the primaries as a combination of a satellite population with a power-law radial profile superimposed to an isotropic and homogeneous background population. The method proposed by the authors requires an analysis of the images of all hosts, which is beyond the scope of this work. This stellar halo component extends up to approximately $100 \text{ kpc}$, according to statistical determinations in SDSS (Zibetti et al. 2004; Bergvall et al. 2010; Tal & van Dokkum 2011).

An additional problem is related to fluctuations in the luminosity density of the extended images of luminous galaxies—for example, in the external parts of large, late-type galaxies at low redshift. Since SDSS images are analyzed to identify galaxies by automatic algorithms, luminosity concentrations (which are part of the primary) are often confused and classified as many faint fake galaxies. This problem is hard to address and is part of the proposed SDSS “research challenges.” The deblending process resulting from the current SDSS-DR7 pipeline appears to induce an artificial neighbor excess, which strongly affects the treatment of data in regions close to the primary (see, e.g., Tollerud et al. 2011), especially in late-type galaxies where rich luminosity patterns are present on the disk. We also show in the inset of Figure 4 the mean value of the $R_{90}$ distribution of primaries in sample S2, which is indicated with an arrow. Also, Brainerd (2005) argues that satellites show a strong preference for being aligned with the host major axis on scales below $100 \text{ kpc}$, while on larger scales ($250 \lesssim r_p/\text{kpc} \lesssim 500$) the satellite distribution is consistent with an isotropic distribution. Due to this anisotropy, satellites close to and near to the major axis of the primary could be confused as luminosity enhancements.

1 http://cas.sdss.org/dr7/en/proj/challenges/hii/default.asp
of the disk of the primary when using photometric data. Both fake galaxies and depleted background are likely to coexist and cannot be directly disentangled. This might also be complicated by other effects such as dust obscuration by the primary disk, alignment of satellites with disks, and segregation of satellite properties with radial distance (Chen 2008; Ann et al. 2008).

The chosen minimum distance of 100 kpc corresponds roughly to 0.5–0.6 $R_{\text{vir}}$. Tollerud et al. (2011) find that 12% of MW-like galaxies host a Large Magellanic Cloud (LMC) like satellite within a projected distance of 75 kpc while 42% lie within 250 kpc. In the sample with the lower mean virial radius (S1) this means that, for a typical primary galaxy and an assumed power-law profile of the satellite distribution outside 20 kpc ($\gamma = 2$, see Table 2), only about 20% of satellites within 100 kpc are not included in the analysis of sample S0 and ~14% are not included in sample S2.

The projected density profile shows an excess of galaxy counts per unit area, with respect to the local background, which decreases beyond $R_p \approx 500$ kpc, but depends on the sample of primaries and satellites considered. Sales & Lembas (2005) analyze simulations and find that the turnaround radius of satellite galaxies is of order 3 $R_{\text{vir}}$. These findings are also consistent with the approximate location of the turnaround radius according to the simple secondary infall model (Bertschinger 1985). Then, in the computation of the statistical distributions, galaxies are also restricted to be at a projected radial distance from the primary of up to three times the mean virial radius in each sample. Using the masses of dark matter halos hosting primary galaxies in a mock catalog (described in Section 5), we find a variation in the distributions of virial radius of primary galaxies corresponding to samples S0, S1, and S2. While the median virial radius ($R_{\text{vir}}$) for sample S0 is 160 kpc, it changes to 157 kpc for sample S1 and to 220 kpc for sample S2. We adopt a maximum radius for each sample (S0, S1, and S2) $R_{\text{max}} = 3 (R_{\text{vir}})$, i.e., $R_{\text{max}} = 480$ kpc for sample S0, $R_{\text{max}} = 470$ kpc for sample S1, and $R_{\text{max}} = 660$ kpc for sample S2. These values are also consistent with the results of Chen et al. (2006) and Liu et al. (2011), who find that the fraction of interlopers remains low within a projected distance of 500 kpc. In Section 5, we use a mock catalog to test the background subtraction method and confirm that the choice of this maximum radius is convenient for maintaining a low level of contamination by foreground and background galaxies.

In Figure 5, we show the resulting profiles for different ranges in satellite luminosities, where it can be seen that fainter satellites are more strongly concentrated. This maximum projected radius 3($R_{\text{vir}}$) is suitable for studying satellite properties in the range $-18.5 < M_r < -14.5$, although the brightest satellites can be detected beyond this value. Agustsson & Brainerd (2006) analyze simulations in a lambda cold dark matter framework to work the locations of satellite galaxies. The authors define their samples of satellites as all galaxies around luminous central galaxies that have a difference in projected distance less than 500 kpc and a difference in radial velocity below 500–1000 km s$^{-1}$, according to the selected sample. Primary galaxies have a median host halo virial radius of 275 kpc. Ann et al. (2008) analyze satellite galaxies in SDSS Data Release 5 in order to study the dependence of radial distribution and the environment of galaxy morphology. These works show agreement on the extension of the satellite populations up to ~500 kpc.

In order to account for large-scale angular fluctuations in the distribution of faint galaxies, we have used a local background in all samples. The density profile is approximately constant beyond 1.5 Mpc (see Figure 6); therefore, we chose the density in the projected radius interval 2000–3000 kpc as the reference level of background galaxy counts. Although a global background could be used instead, we argue that a mean number density of galaxies obtained locally is better suited to account for possible irregularities in the number density of background galaxies. We use the redshift of each host to compute the absolute magnitudes corresponding to

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**Table 2**

| Sample  | $\langle N_s \rangle$ | $\gamma$ |
|---------|----------------------|----------|
| S0-A-a  | 1.5 ± 0.4            | $-2.0 \pm 0.2$ |
| S0-A-r  | 0.7 ± 0.4            | $-2.1 \pm 0.5$ |
| S0-A-b  | 0.9 ± 0.2            | $-1.8 \pm 0.4$ |
| S1-A-a  | 0.9 ± 0.5            | $-2.4 \pm 0.3$ |
| S1-A-r  | 0.2 ± 0.5            | $-2.0 \pm 2.0$ |
| S1-A-b  | 0.7 ± 0.2            | $-1.9 \pm 0.5$ |
| S2-A-a  | 6.1 ± 1.4            | $-1.5 \pm 0.4$ |
| S2-A-r  | 3.4 ± 1.3            | $-1.5 \pm 0.7$ |
| S2-A-b  | 2.7 ± 0.6            | $-1.6 \pm 0.3$ |
| S2-R-a  | 7.8 ± 2.2            | $-1.1 \pm 0.6$ |
| S2-R-r  | 4.2 ± 2.0            | $-0.8 \pm 0.7$ |
| S2-R-b  | 3.7 ± 0.9            | $-1.8 \pm 0.2$ |
| S2-B-a  | 4.7 ± 1.8            | $-1.9 \pm 0.5$ |
| S2-B-r  | 2.5 ± 1.6            | $-2.1 \pm 0.7$ |
| S2-B-b  | 2.1 ± 1.0            | $-1.5 \pm 0.6$ |

Notes. The mean number of satellites per host ($N_s$) was calculated in the $r$ band. Errors are calculated as described in Section 3. In all cases, primary redshifts lie in the range $0.03 < z < 0.10$ and the indicated number of satellites includes objects in the magnitude range $-18.5 < M < -14.5$, with the $g - r$ color index limited to the range $-0.4 < g - r < 1.0$, and at a projected distance between 100 kpc and $R_{\text{max}}$ (see Table 1).
the excess galaxy counts in different apparent magnitudes, assuming that these true companion galaxies are at the same redshift as the primary. We compute a composite luminosity distribution by averaging over a sample of primaries with a given set of properties. The number counts per magnitude bin for the resulting composite luminosity distribution estimates are normalized according to the appropriate limits of magnitudes in order to assure completeness:

\[ N_i = \sum_j N_{ij} F_j C_j, \]

where \( N_i \) is the number of galaxies within the \( i \)th magnitude bin for the total ensemble and \( N_{ij} \) is the number of galaxies in that magnitude bin for the \( j \)th primary. The normalization for each magnitude bin is given by the fraction of fields contributing within the completeness limits, \( C_j \), and by the fractional area, \( F_j \), determined by the mask.

3.2. Detailed Masks

Since we expect a relatively small number of satellites compared to the total background number counts, several primaries should be used in order to add up the signal over the background noise. Since the number of satellites grows approximately linearly with the number of hosts and Poisson errors scale as the square root of the number of galaxies, a large number of fields are required in order to override the satellite population number over the background counts. In Table 1, it can be seen that all samples comprise thousands of primaries, and in particular, the smallest sample (S2-B) contains nearly 5000 host galaxies. Fields of galaxies are extracted from the NYU-VAGC around the primary galaxies. However, the survey area from which the data are drawn does not have a simple geometry, and the detailed structure of holes and borders is an additional problem for the method used in this work. While the external borders are relatively simple, the survey has small disconnected holes of a variety of shapes. The origin of these holes relies on the presence of several bright objects that blanket the background galaxies, in particular the faint ones. The most important ones are stars in our Galaxy, but we can also mention the trails of solar system objects or artificial satellites, cosmic rays, etc. Moreover, in certain cases, there is a regular pattern of holes, sometimes associated with an incomplete structure of stripes. Therefore, a mask must be built for each of the fields in order to correctly account for the effective areas used in the method. As an example in Figure 7(a) we show a typical field where a hole in the projected distribution of galaxies can be seen. The construction of the mask is based on the ansatz that, in a coarse resolution, faint galaxies provide a dense, nearly uniform background so that the holes can be directly associated with the absence of faint objects in a patch of the sky. In order to identify regions without faint galaxies we use a Monte Carlo method. The method consists of determining distances from the faint galaxies in the photometric sample to a large number of uniformly distributed random points within the area considered. Those random points that are separated from the nearest neighbor galaxy by at least a percolation radius \( r_0 \) are used to characterize the holes, i.e., holes are detected as concentrations of random points percolated by using this criterion. We have adopted a percolation radius \( r_0 \) equal to a fraction \( f \) of the mean angular galaxy separation \( \langle D \rangle \) of each field. The value of \( f \) was obtained by diluting several realizations of complete and dense fields of galaxies, and retrieving in each case the ideal limiting value for the percolation radius. We calibrated the value of this fraction and found a mean value of \( f = 0.17 \), with a slight variation as a function of the projected galaxy density in each field (Lares 2009). Given the complicated shapes of identified holes, we simply eliminate angular sectors that contain the random points inside holes, as can be seen in Figure 7(a). In this figure we show the locations of galaxies used in the background subtraction procedure with gray points and the locations of galaxies in the same angular sector as the mask hole that were not considered in this analysis with dark gray points. We computed the distribution of the fractions of angular areas finally used in the analysis presented in the following sections. We show this distribution in Figure 7(b) where we have indicated the location of the fraction of the used area of the field shown in Figure 7(a). The high level of completeness of the data can be seen from Figure 7(b), with 90% of the fields losing less than 5% of their areas by the application of the masks. Furthermore, there is a negligible amount of fields with less than 90% angular completeness and these fields are excluded from the analysis. Note that this method is able to identify detailed small-scale features in the angular distribution of photometric galaxies. Given the resolution required to account for small holes, a mask constructed by using standard methods (e.g., Hamilton & Tegmark 2004; Górski et al. 2005; Swanson et al. 2008) would be computationally expensive for reaching the same accuracy used in the methodology. Besides, this procedure allows us to adapt the percolation radius for each field instead of using a fixed resolution on a pixelization scheme and makes the computation of areas straightforward by using angular bins.

4. RESULTS: STATISTICAL PROPERTIES OF SATELLITE GALAXIES

4.1. Determination of Projected Radial Distributions

Although it would be desirable to consider satellites as close as possible to the primary galaxies, there are systematic detection biases that strongly limit this possibility. We have also
by inspection of Figure 6 that the two profiles have a similar spatial extent and radial density profiles. We also computed the density profiles for red (M_r < -20.5) and blue (M_r < -18.0) fields. It can be appreciated that close to primaries, the detection of faint objects can be strongly biased due to several facts such as obscuration, confusion, etc. Galaxies behind bright galaxy disks could also be covered by intrinsic absorption, producing significant changes in the observed magnitudes. Taking these issues into account, we have adopted a minimum distance of 100 kpc to primaries for our analysis. We considered galaxies in projected radial distance bins from the corresponding primaries to compute the averaged density profile for the different samples. The radial bins are chosen so that all the resulting rings have the same area. This partition allows to explore the inner region with more detail. In Figure 6, we show the density profile of samples S1-A-a and S2-A-a corresponding to all primaries with -21.5 < M_r < -20.5 and -22.0 < M_r < -21.5, respectively, without restrictions in the colors of primaries nor satellites. It can be appreciated the smoothly declining mean density profiles, although the extent of the overdense region is larger for the brightest hosts. We have also computed the density profiles for red (0.4 < g - r < 1.0) and blue (g - r < 0.4) companion galaxies of bright primaries with M_r < -21.5 (samples S2-A-r and S2-A-b). It can be seen by inspection of Figure 6 that the two profiles have a similar spatial extent and radial density profiles.

We have fitted power-law functions to the radial density profiles \( \rho(r_p) = A r_p^{-\gamma} \). The resulting values of the profile slope \( \gamma \) are given in Table 2 where it can be seen that in general the companion galaxies of primaries show a concentrated distribution. Agustsson & Brainerd (2010) investigated the locations of the satellites of relatively isolated host galaxies in the SDSS and the Millennium Run simulation. These authors found that the distribution of the satellites within 500 kpc of red, high-mass hosts with low star formation differs from the distribution of satellites of blue, low-mass hosts with low star formation.

4.2. Mean Number of Satellites and Luminosity Distributions

We compute the mean number of satellites beyond \( R_{\text{min}} = 100 \) kpc and up to a projected radial distance equivalent to \( R_{\text{max}} = 3 R_{\text{vir}} \) for each sample, no extremely red galaxies (g - r > 1) were included since both restrictions were applied in the computations as previously explained (Section 3.1). The mean number of satellites (as shown in Table 2) \( \langle N_s \rangle \) in the magnitude range \( M_r < -14.5 \) is estimated for all primary samples as

\[
\langle N_s \rangle = \frac{1}{N_p} \sum_{j=1}^{n} \frac{N_{in}^j}{A} - \frac{1}{A} N_{out}^j,
\]

where \( N_p \) is the number of primaries in the sample, \( N_{in}^j \) is the number of galaxies inside the inner ring of the \( j \)th field, and \( N_{out}^j \) is the number of galaxies inside the chosen outer ring. The area of the background, corrected by the mask, is \( A \) times the area enclosed between the chosen radius of the signal inner region. The isolation condition ensures that bright galaxies chosen as centers are somewhat separated from other luminous galaxies, and is intended for selecting a given group of galaxies with similar properties, but does not affect the calculation of the luminosity function, given that it includes satellites at most as bright as \( M_r = M_p + 2 \). The faintest possible satellite in sample S0 has an absolute magnitude \( M_p = -20.5 \), so that no satellites with \( M_r < -18.5 \) are expected to be found in the spectroscopic sample. If galaxies brighter than this limit are considered, the sample of satellites would not be complete, so we limit the study of satellites to the range \(-18.5 < r < -14.5\). We assign uncertainty estimates to the mean number of satellites using Poisson errors resulting from the number counts of galaxies within \( R_{\text{max}} \) from the primaries and the expected number of
We find that the number of satellites depends on primary luminosity. As can be seen in Table 2, sample S1 has typically one satellite within the range of color and magnitude adopted. This number increases to nearly six satellites on average for sample S2, equally distributed between red and blue satellites. This result is consistent with that of Macciò et al. (2010), who study numerical simulations of MW-sized halos as predicted by cold-dark-matter-based models of galaxy formation and find that the number of satellite galaxies increases with halo mass. On the other hand, the number of companion objects of primaries on the same luminosity interval does not have a clear dependence on satellite g − r color index. In all samples of primaries, the numbers of blue and red satellites are comparable. We note that this is valid for the ranges of projected radii and magnitudes used in this study (Table 1).

In the computation of the luminosity distribution, a convenient normalization is set for each magnitude bin, so that the mean number of satellites per magnitude interval per primary is obtained. This was achieved by dividing the number counts of excess galaxies by the number of contributing primaries in each magnitude bin. We performed Schechter fits (Schechter 1976) to the differential histograms of magnitude distributions and computed the faint-end slopes as given in Table 2. For samples S0-A-a, S1-A-a, and S2-A-a, the luminosity distributions are consistent with a Schechter function with a faint-end slope of $-1.3 \pm 0.2$, adopting a universal $M_\star$ value of $-20.44$ (Blanton et al. 2003b).

The results shown in Table 2 show a better signal-to-noise ratio as more primaries comprise the subsamples. Bright primaries ($M_r < -21.5$) host on average seven satellites while low-luminosity primaries ($-21.5 < M_r < -20.5$) host a mean of only one satellite galaxy per primary. In Figure 8, we show the r-band luminosity distribution of satellites around bright primaries ($M_r < -21.5$) and primaries with intermediate luminosities ($-21.5 < M_r < -20.5$, sample S1). We also show in this figure Schechter function fits computed using the universal value of $M_\star$, with a faint-end slope parameter $\alpha = -1.3 \pm 0.2$, obtained using a maximum likelihood method. These luminosity functions indicate a lack of a dominant population of faint satellites, which would be reflected in much larger negative values of the $\alpha$ parameter. These results contrast with those obtained for groups/clusters of galaxies (Popesso et al. 2005; González et al. 2006), where the faint component contribution $M_r > -18$, to a double Schechter fitting gives slope values as steep as $\alpha \sim -2$.

We have also analyzed the dependence of the results on primary color index. As mentioned in Section 2.1, we have used the threshold $g - r = 0.8$ to divide the samples of primaries. Similarly, we find a larger population of satellites associated with red hosts, with a slightly steeper luminosity distribution at the faint end (Figure 9). We have studied the radial density profiles of red and blue satellites around the different samples of primaries, finding that the system of blue satellites is in all cases more extended than that of the red ones by approximately 30%. Luminosity distributions of red and blue satellites are shown for the brightest hosts in Figure 10.

We also computed a color–magnitude diagram for the satellites obtained by means of applying the background subtraction method simultaneously to these two variables. The results are shown in Figure 11 for sample S2-A-a, where the smooth extension of the spectroscopic data onto fainter objects obtained by our statistical approach is shown.

5. TESTING THE METHOD WITH NUMERICAL SIMULATIONS

The success of a background subtraction method relies on the signal-to-background strength from satellites around bright
galaxies, providing the overdensity enhancement obtained in the stacking procedure. However, the superposition of large-scale structures projected onto the sky could affect the uniformity of the background. In order to estimate the ability of the method to correctly reproduce the actual distributions of satellite galaxies in SDSS-DR7 data, we have tested it on a mock catalog derived from a numerical simulation using conditions similar to those applied to the observations. We constructed the mock catalog within a $\pi/2$ steradian light cone, based on a semianalytic model of galaxy formation (Croton et al. 2006) at redshift zero in the Millennium simulation (Springel et al. 2005), which is publicly available from the German Virtual Observatory.2 This solid angle corresponds to approximately half the area covered by the spectroscopic DR7 catalog of galaxies and the $z = 0$ snapshot was replicated eight times along the axes to achieve a suitable depth.

Since the output of the semianalytic model includes magnitudes in the ugriz photometric system, the mock spectroscopic catalog is obtained directly by selecting galaxies brighter than the limiting apparent magnitude of the Sloan spectroscopic galaxy catalog, $r = 17.77$. From the mock spectroscopic catalog, we extract a sample of mock primaries using criteria similar to those in Section 2 which will be used as centers in the following analysis. For each galaxy, a redshift was assigned by placing a fiducial observer at one corner and determining the comoving distance to the observer and the peculiar velocity of the galaxy. The evolution corrected $r$-band magnitude is

$$M_r = -2.5 \log(L) + E - 5 \log(h),$$

where $E$ is given by Blanton et al. (2003b).

For the adopted $r$-band limiting magnitude 21.5 of the photometric sample, the maximum redshift of the mock should be 1.2, corresponding approximately to the distance at which an intrinsically luminous galaxy is observable within the absolute magnitude range explored, $-18.5 < M_r < -14.5$. Although the lack of evolution in both galaxies and structure is a drawback of the mock catalog, it serves as a strong test of the method given that in this case there is a larger clustering amplitude of high-redshift structures (i.e., more structures along the line of sight) compared to a mock catalog with consistent evolution of clustering.

Since we adopted a color cut $g - r < 1$ in SDSS data to reduce background noise, we performed an appropriate noise reduction in the mock catalog using a Monte Carlo procedure in order to reproduce the conditions of the observations. We considered photometric redshifts obtained by O’Mill et al. (2011) for the SDSS-DR7 galaxy sample to derive the fraction $P(z)$ of galaxies with an observed color index $g - r < 1$ as a function of redshift. A suitable fit to this probability is given by $P(z) = 1 - 2.381 (z - 0.08)$ which rejects about half the galaxies with $g - r > 1$ at $z \sim 0.3$. We adopted this statistical procedure instead of a direct filtering of galaxies by the observed color in the photometric mock catalog given that this would be model dependent, which also requires a reliable K-correction for the semianalytic galaxies. We also checked that our results were not strongly dependent on the precise assumed $P(z)$, so that small modifications to the fit had minimal impact on the obtained radial and luminosity distributions.

We first tested if the galaxy density profile around primaries derived by the background subtraction method was able to reproduce the actual projected three-dimensional profile. To this aim, we computed the projected radial distribution of galaxies around centers reproducing sample S2-A-a in the mock catalog using the real space positions in order to test the reproducibility of the results through the background subtraction method. We show the results obtained for this sample (S2-A-a) in the mock catalog since it presents the stronger signal. The results described in this section, however, do not depend on the chosen

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2 http://www.g-vo.org

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Figure 10. Cumulative luminosity distributions of blue ($0.0 < g - r < 0.4$), red ($0.4 < g - r < 1.0$), and all ($0.0 < g - r < 1.0$) excess galaxies around bright primaries in sample S2-A.

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Figure 11. Color–magnitude distribution of excess counts of $-18 < M_r < -15$ companions of bright primaries (sample S2-A) resulting from a background subtraction calculation.
subsample. The criteria to select satellites in the mock three-dimensional catalog were chosen so that a galaxy from the semianalytic output is considered a satellite if it is within $3R_{\text{vir}}$ of the host dark matter halo of the primary galaxy, in three-dimensional space. This is consistent with the criteria adopted in Section 4.2 for the selection of the region where the signal is studied in the observational samples. In Figure 12, we show good agreement of the projected three-dimensional and background-subtraction-derived profiles, indicating that the method is effective at revealing the true projected profile of companion galaxies.

The luminosity distribution of satellite galaxies was computed using the halo membership and galaxy luminosities in the mock catalog and was compared to the luminosity distribution of galaxies obtained with background subtraction in the region $100 < R_p/\text{kpc} < 660$ corresponding to this sample. The cumulative luminosity distribution obtained through the background subtraction procedure reproduces the true underlying distribution remarkably well, as can be seen in Figure 13. In the inset of this figure we also show the differential distributions, which present a general consistency. Although a small difference is present between the two samples that does not affect the shape of the luminosity distribution and the determination of the Schechter parameter, since this is due to a small difference in the first magnitude bin. The method also succeeds in reproducing the discontinuity at $M_r \approx -17.6$, due to the absolute limiting magnitude in the parent semianalytic galaxy catalog.

These tests eliminate the possibility that background structures affect the shape of the obtained luminosity distributions so that the faint-end slopes are computed on a firm statistical basis. However, we stress the fact that this procedure is reliable provided that adequate selection criteria have been imposed on the data. Since primary galaxies in our samples span a redshift range much smaller than most of galaxies contributing to background counts, the procedure used to compute radial and luminosity distributions performs in convenient conditions, as our tests in the mock catalog have shown. This result is in agreement with previous tests of the method in less favorable conditions such as the determination of cluster luminosity functions (Valotto et al. 2001; Muñoz et al. 2009).

6. DISCUSSION AND CONCLUSIONS

We have carried out different statistical analyses to infer properties of faint satellite galaxies in the projected distance range $100 < R_p/\text{kpc} < 3(R_{\text{vir}})$, associated with bright primaries taken from SDSS with redshift $z < 0.1$. To this end, we have implemented a background subtraction method on faint galaxies with photometric information that are close in projection to galaxies with measured redshifts. The innermost region of the satellite systems is not accessible using the proposed background subtraction method and data from the photometric galaxy catalog. However, assuming a power-law profile for satellites and considering objects outside of a 100 kpc radial distance from the host, we can study more than 80% of satellites. We have used a mock galaxy catalog based on a semianalytic model of galaxy formation from the Millennium simulation to test the method with conditions similar to the observational data. According to the results of the tests performed, the method is able to provide a good estimation of the true distributions of luminosities and projected radial galaxy density as a function of the distances to the host (Figures 12 and 13). In our mock catalog, we test how the projection of background structures affects our measurement in a worst case scenario. We conclude that these structures do not affect the shape of the luminosity distribution, provided that central galaxies are sufficiently bright ($M_p < -20.5$) and isolated, and a color cut $g-r < 1$ is imposed.
on satellites. We also find it important to define an adequate maximum radius, using theoretical insight and mock catalogs to calibrate the values of $R_{\text{max}}$ for each sample.

In all samples of primaries (defined in Table 1), we detect an excess of faint galaxy counts and can statistically determine the properties of companion objects associated with the central galaxy. We find that the radial density profiles of satellites are consistent with power laws of the form $\rho(r_p) = Ar_p^{-\gamma}$, with $-2.4 \lesssim \gamma \lesssim 1.1$ and that the maximum extent and amplitude of the overdensity depend on the primary luminosity and color (see Figure 6) as well as on galaxy luminosity (Figure 5). The dependence of the number of satellites with $M_r < -14.5$ on host luminosity is strong: bright primaries with $M_r < -21.5$ host on average approximately six satellites, which is reduced to $\sim 1$ satellite for S1 primaries (Table 2). Liu et al. (2011) investigate the probabilities of finding an MW-like galaxy to host satellites with luminosities similar to the Magellanic Clouds. This result is valid for the same magnitude range (Mateo 1998). This result is valid for the same magnitude range (Mateo 1998). This result is valid for the same magnitude range (Mateo 1998). This result is valid for the same magnitude range (Mateo 1998). This result is valid for the same magnitude range (Mateo 1998). This result is valid for the same magnitude range (Mateo 1998). This result is valid for the same magnitude range (Mateo 1998). This result is valid for the same magnitude range (Mateo 1998). This result is valid for the same magnitude range (Mateo 1998). This result is valid for the same magnitude range (Mateo 1998). This result is valid for the same magnitude range (Mateo 1998).

Recently, Wang et al. (2010) used a deep photometric sample around spectroscopically identified galaxies and found that projected density profiles show a similar slope to the correlation function slope, independent of galaxy luminosity. Due to the different luminosity and redshift ranges considered between the work of Wang et al. (2010) and ours, a direct comparison is difficult to perform. While this paper was being reviewed, Guo et al. (2011) presented a complementary analysis of the luminosities of satellites of SDSS primary galaxies, finding a general agreement with our results.

The redshift range of the spectroscopic sample and the apparent magnitude limit of the photometric catalog allows us to obtain luminosity distributions in the range $-19.5 < M_r < -14.5$. The derived luminosity distributions can be well described by Schechter function fits (Figure 8). Our findings indicate that faint-end slopes of the satellite luminosity functions are slightly rising ($\alpha = -1.3 \pm 0.2$). This is in agreement with the luminosity distributions of galaxies in the Local Group, in the same magnitude range (Mateo 1998). This result is valid for all samples and indicates that the population of satellites of bright isolated primaries is consistent with the nearly flat faint-end slope of the global luminosity function as derived for the SDSS data (Blanton et al. 2003b; Baldry et al. 2005; Montero-Dorta & Prada 2009). These findings contrast with the results obtained via similar methods in samples of clusters and groups where a significantly steep function was obtained ($\alpha \sim -2$ to $-1.5$; e.g., de Propris et al. 1995; Popesso et al. 2005; González et al. 2006). These results are expected, given the evidence from semianalytic models of galaxy formation which suggest that the total mass of a dark matter halo determines the normalization and shape of the luminosity function (Macciò et al. 2010).

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