A NEW MILKY WAY SATELLITE DISCOVERED IN THE SUBARU/HYPER SUPRIME-CAM SURVEY

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ABSTRACT

We report the discovery of a new ultra-faint dwarf satellite companion of the Milky Way (MW) based on the early survey data from the Hyper Suprime-Cam Subaru Strategic Program. This new satellite, Virgo I, which is located in the constellation of Virgo, has been identified as a statistically significant (5.5σ) spatial overdensity of star-like objects with a well-defined main sequence and red giant branch in the color–magnitude diagram. The significance of this overdensity increases to 10.8σ when the relevant isochrone filter is adopted for the search. Based on the distribution of the stars around the likely main-sequence turnoff at \( r \sim 24 \) mag, the distance to Virgo I is estimated as 87 kpc, and its most likely absolute magnitude calculated from a Monte Carlo analysis is \( M_V = -0.8 \pm 0.9 \) mag. This stellar system has an extended spatial distribution with a half-light radius of 38±12 pc, which clearly distinguishes it from a globular cluster with comparable luminosity. Thus, Virgo I is one of the faintest dwarf satellites known and is located beyond the reach of the Sloan Digital Sky Survey. This demonstrates the power of this survey program to identify very faint dwarf satellites. This discovery of Virgo I is based only on about 100 square degrees of data, thus a large number of faint dwarf satellites are likely to exist in the outer halo of the MW.

Key words: galaxies: dwarf – galaxies: individual (Virgo) – Local Group

1. INTRODUCTION

Dwarf spheroidal galaxies (dSphs) associated with the Milky Way (MW) and Andromeda galaxies provide important constraints on the role of dark matter in galaxy formation and evolution. Indeed, these faint stellar systems are largely dominated by dark matter with mass-to-luminosity ratios of 10 to 1000 or even larger in fainter systems, based on their stellar dynamics (Gilmore et al. 2007; Simon & Geha 2007). Thus, the basic properties of dSphs, such as their total number and spatial distributions inside a host halo like the MW, provide useful constraints on dark matter on small scales, in particular the nature and evolution of cold dark matter (CDM) in a Λ-dominated universe.

One of the tensions between theory and observation is the missing satellite problem: the theory predicts a much larger number of subhalos in a MW-like halo than the observed number of satellite galaxies (Klypin et al. 1999; Moore et al. 1999). Solutions to this problem are to consider other types of dark matter than CDM (e.g., Maccio & Fontanot 2010) or to invoke baryonic physics (e.g., Sawala et al. 2016). Another possibility is that we have seen only a fraction of all the satellites associated with the MW due to various observational biases (Tollerud et al. 2008). Motivated by this, a systematic search for new dSphs has been made based on large survey programs, such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) and the Dark Energy Survey (DES; Abbott et al. 2016). SDSS discovered 15 ultra-faint dwarf galaxies (UFDs) with \( M_V \geq -8 \) mag (e.g., Willman et al. 2005; Belokurov et al. 2006; Sakamoto & Hasegawa 2006), and DES recently reported the discovery of many more candidate UFDs in the south (e.g., Bechtol et al. 2015; Drlica-Wagner et al. 2015; Koposov et al. 2015). These discoveries are consistent with the work by Tollerud et al. (2008), anticipating that a large number of yet unidentified dwarf satellites exist in the MW halo, especially in its outer parts.

This paper reports the discovery of a new faint dwarf satellite in the MW in the course of the Subaru Strategic Program (SSP) using Hyper Suprime-Cam (HSC). HSC is a new prime-focus camera on the Subaru telescope with a 1°5 diameter field of view (Miyazaki et al. 2012), which thus allows us to survey a large volume of the MW halo out to a large distance from the Sun, where a systematic search for new satellites has not yet been undertaken.

2. DATA AND METHOD

The HSC-SSP is an ongoing optical imaging survey, which consists of three layers with different combinations of area and depth. Our search for new MW satellites is based on its Wide layer, aiming to observe \( \sim 1400 \) deg\(^2\) in five photometric bands \((g, r, i, z, \text{ and } y)\), where the target 5σ point-source limiting magnitudes are \((g, r, i, z, y) = (26.5, 26.1, 25.9, 25.1, 24.4)\) mag. In this paper, we utilize the \((g, r)\) data in the early HSC survey obtained before 2015 November, covering \( \sim 100 \) deg\(^2\) in five fields along the celestial equator. The HSC data are
processed with hscPipe v4.0.1, a branch of the Large Synoptic Survey Telescope pipeline (Ivezic et al. 2008; Juric et al. 2015) calibrated against Pan-STARRS1 photometry and astrometry (Schlafly et al. 2012; Tonry et al. 2012; Magnier et al. 2013).

We use the extendedness parameter from the pipeline to select point sources. This parameter is computed from the ratio between point-spread function (PSF) and cmodel fluxes, which are measured by fitting PSF models and two-component PSF-convolved galaxy models to the source profile, respectively (Abazajian et al. 2004). When the ratio between these fluxes is larger than 0.985, a source is classified as a point source. We use the parameter measured in the $i$ band, in which the seeing is typically the best of our five filters with a median of about 0.6". In particular, the $i$-band seeing for the region around our newfound satellite is about 0.5". In order to characterize the completeness and contamination of our star/galaxy classification, we stack the COSMOS data (COSMOS is one of our UltraDeep fields, where we have many exposures) to the depth of the Wide survey and compare our classification against the HST/ACS data from Leauthaud et al. (2007). We find that the completeness, defined here as the fraction of objects that are classified as stars by ACS, and correctly classified as stars by HSC, is above 90% at $i < 22.5$, and drops to ~50% at $i = 24.5$. On the other hand, contamination, which is defined as the fraction of HSC-classified stars that are classified as galaxies by ACS, is close to zero at $i < 23$, but increases to ~50% at $i = 24.5$. Based on this test, we choose to use the extendedness parameter down to $i = 24.5$ to select stars in this work. We further apply a $g - r < 1.0$ cut to eliminate numerous M-type disk stars.

In order to search for the signature of new satellites, we count stars in $0\degree.05 \times 0\degree.05$ bins in right ascension and declination, with an overlap of $0\degree.025$ in each direction, where $0\degree.05$ corresponds to a typical half-light diameter (~80 pc) of a UFD at a distance of 90 kpc. We then calculate the mean density and its dispersion over all cells for each of the Wide layer fields to search for any spatial overdensities of stars (e.g., Koposov et al. 2008; Walsh et al. 2009). The deviation from the mean density has close to a Gaussian distribution. We have found one stellar overdensity with 5.5σ in one of the Wide layer fields. The standard deviation is estimated separately for each survey field (covering typically 20–30 deg²); each field is at different Galactic coordinates. This overdensity is centered at $(\alpha, \delta) = (180.04, -0.68)$. As Figure 1 shows, there is no corresponding overdensity in extended objects (galaxies).

In Figure 2(a), we plot the spatial distribution of the stars around this overdensity, which shows a localized concentration of stars within a circle of radius 2'. To get further insights into this overdensity, in Figure 2(c), we plot the $(g - r)$ color–magnitude diagram (CMD) of stars within the 2' radius circle shown in Figure 2(a). This CMD shows signatures of main-sequence (MS) stars near its turnoff (MSTO) as well as stars on the red giant branch (RGB), whereas these features disappear when we plot stars at $6' < r < 6.33$ with the same solid angle, i.e., likely field stars outside the overdensity, as shown in Figure 2(e). To investigate the distribution of the overdensity in the CMD further, we adopt a fiducial locus of stars in a typical UFD galaxy based on a PARSEC isochrone (Bressan et al. 2012), in which we assume an age of 13 Gyr and metallicity of $z = 0.0001 ([\mathrm{M}/\mathrm{H}] = -2.2)$. We first derive this isochrone in the SDSS filter system and then convert to the HSC filter system using the following formula calibrated from both filter curves and spectral atlas of stars (Gunn & Stryker 1983),

$$g = g_{\text{SDSS}} - a(g_{\text{SDSS}} - r_{\text{SDSS}}) - b$$

and

$$r = r_{\text{SDSS}} - c(r_{\text{SDSS}} - i_{\text{SDSS}}) - d,$$

where $(a, b, c, d) = (0.074, 0.011, 0.004, 0.001)$ and the subscript SDSS.

Another high-sigma overdensity (6.8σ) of the sources with extendedness = 0 has been identified in the survey region, but this appears to be an artifact related to scattered light from a nearby bright star.

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10 Another method for star/galaxy classification by combining the colors of the sources (J. A. Garmilla et al., in preparation) has also been applied and we have confirmed that the main results of this work remain unchanged. The full description for the analysis of the data based on this alternative scheme will be presented in a future paper.

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denotes the SDSS system. This isochrone, at the assumed distance modulus of $(m - M)_0 = 19.7$ mag as determined below, is shown in Figure 2(d), which does a good job of tracing the distributions of MSTO and RGB stars. To test the statistical significance of the overdensity along this isochrone, we set the selection filter defined by the CMD envelope (shaded region in Figure 2(d)), which consists of the above isochrone, $1\sigma (g - r)$ color measurement error as a function of $r$-band magnitude, and a typical color dispersion of about $\pm 0.05$ mag at the location of the RGB arising from a metallicity dispersion of $\pm 0.7$ dex for dSph stars. By passing this filter over the stars in the relevant region, we derive an overdensity that peaks at a distance modulus of 19.7 mag at a statistical significance of 10.8$\sigma$, much higher than without the filter.

Figure 2(b) shows the distribution of the stars that pass this filter, revealing a higher overdensity contrast than Figure 2(a). This suggests that the overdensity we have found here is indeed an old stellar system, either a globular cluster or dwarf galaxy. Hereafter we refer to this system as Virgo I.\(^{12}\) The stars selected by this isochrone filter lie along a clear stellar sequence even in a two-color ($g - r$, $r - i$) diagram. We note that the statistical significance of this overdensity before (after) passing this isochrone filter remains basically unchanged when we adopt different magnitude limits for the sample: $5.6\sigma$ ($10.3\sigma$) for $i < 24$ mag and $4.8\sigma$ ($9.6\sigma$) for $i < 25$ mag.

\(^{12}\) This is not to be confused with the so-called Virgo overdensity, which is closer at $\sim 6–20$ kpc and covers a much larger volume (Juric et al. 2008).
3. PROPERTIES OF STELLAR POPULATION

We estimate the basic structural properties of Virgo I. For this purpose, we adopt six parameters \((\alpha_0, \delta_0, \theta, \epsilon, r_h, N_\text{ap})\), \((\alpha_0, \delta_0)\) for the celestial coordinates of the centroid of the overdensity, \(\theta\) for its position angle from north to east, \(\epsilon\) for the ellipticity, \(r_h\) for the half-light radius, and \(N_\text{ap}\) for the number of stars belonging to the overdensity. The maximum likelihood method of Martin et al. (2008) is applied to the stars within a circle of radius 20′ passing the isochrone filter; the results are summarized in Table 1.

Figure 3 shows the radial profile of the stars passing the isochrone filter (Figure 2(b)) by computing the average density within elliptical annuli. The overplotted line corresponds to the best-fit exponential profile with a half-light radius of \(r_h = 1.5\) or 38 pc. This spatial size is larger than the typical size of MW globular clusters but is consistent with the scale of dwarf satellites as examined below.

The total absolute magnitude of Virgo I, \(M_V\), is estimated by summing the luminosities of the stars within the half-light radius, \(r_h\), and then doubling the summed luminosity (e.g., Sakamoto & Hasegawa 2006). For the transformation from \((g, r)\) to \(V\), we adopt the formula in Jordi et al. (2006) calibrated for metal-poor Population II stars, which is appropriate for stars in UFD galaxies. Assuming that the distance to this stellar system is 87 kpc or \((m - M)_0 = 19.7\) mag, we obtain \(M_V = -0.17\) mag for \(r_h = 1.5\). This value varies when we adopt different half-light radii or different distance moduli within their 1σ uncertainties. We find \(M_V = +0.08\) mag if we adopt \(r_h = 1.1\) and \((m - M)_0 = 19.5\) mag and \(M_V = -1.87\) mag for \(r_h = 1.9\) and and \((m - M)_0 = 20.0\) mag. The latter case yields a much brighter \(M_V\) due to the inclusion of a bright RGB star inside the aperture.

Shot noise due to the small number of stars in Virgo I is a significant additional source of uncertainty in \(M_V\). We quantify this and other sources of error using a Monte Carlo method similar to that described in Martin et al. (2008) to determine the most likely value of \(M_V\) and its uncertainty. As summarized in Table 1 for Virgo I, we have derived \(N_\text{ap} = 19 \pm 5\) at \(i < 24.5\) mag, the distance modulus of \((m - M)_0 = 19.7^{+0.3}_{-0.1}\) mag, and we use a stellar population model with an age of 13 Gyr and metallicity of \(\text{[M/H]} = -2.2\). Based on this information, we generate 10⁴ realizations of CMDs for three different initial mass functions (IMFs): Salpeter, Kroupa, and Chabrier (lognormal) (Salpeter 1955; Chabrier 2001; Kroupa 2002). We then derive the luminosity of the stars for each CMD at \(i < 24.5\) mag, taking into account the completeness of the observed stars with HSC. Based on this Monte Carlo simulation, we obtain the expected values of \(M_V\) as \(M_V = -0.82 \pm 0.95\), \(M_V = -0.81 \pm 0.91\), and \(M_V = -0.83 \pm 0.92\), for Salpeter, Kroupa, and Chabrier IMFs, respectively. Thus, the values of \(M_V\) for these different IMF models are consistent each other, summarized as \(M_V = -0.8 \pm 0.9\) mag, and are within the 1σ uncertainty of \(M_V\) determined above by directly counting the observed member stars.

Note: Integrated magnitudes are corrected for the mean Galactic foreground extinction, \(A_V\) (Schlafly & Finkbeiner 2011).

4. DISCUSSION

To assess if Virgo I identified here is indeed a new MW dwarf satellite galaxy, we compare its size quantified by \(r_h\) with globular clusters with comparable luminosity in the range of \(M_V \sim +0.10\) to \(-1.72\) mag. In Figure 4(a), we plot the relation between \(M_V\) and \(r_h\) for the MW globular clusters (dots) taken from Harris (1996) and dwarf galaxies in the MW (filled squares) and M31 (open squares) from McConnachie (2012), the recent DES work (Bechtol et al. 2015; Drlica-Wagner et al. 2015; Koposov et al. 2015), and other recent discoveries (Laevens et al. 2014, 2015b, 2015a; Kim et al. 2015; Kim & Jerjen 2015). The red star with error bars shows Virgo I detected in this work.

As is clear from the figure, the current stellar system is systematically larger than MW globular clusters with comparable \(M_V\) and is located along the locus of the MW and M31 dwarf galaxies. This is the case even if we adopt the brighter estimate of \(M_V = -1.72\) mag by considering the 1σ uncertainty in \(M_V\). Thus, the overdensity of the stars we have found

| Parameter \(^a\) | Value |
|-----------------|-------|
| Coordinates (J2000) | \(12^h00^m09^s6, \,-0^\circ40'48''\) |
| Galactic coordinates \((l, b)\) | 276°94', 59°58' |
| Position angle | +51°14', 40 deg |
| Ellipticity | 0.44 \(+0.14, -0.17\) |
| \(A_V\) | 0.066 mag |
| \((m - M)_0\) | 19.7 \(+0.2, -0.3\) mag |
| Heliocentric distance | 87.3 \(+1.5\) kpc |
| Half-light radius, \(r_h\) | 1.5 \(+0.4\) or 38 \(+12\) pc |
| \(M_{tot, V}\) | \(-0.8 \pm 0.9\) mag |

Note. \(^a\) Integrated magnitudes are corrected for the mean Galactic foreground extinction, \(A_V\) (Schlafly & Finkbeiner 2011).
Figure 4. (a) Relation between \( M_V \) and \( r_h \) for stellar systems. Dots denote globular clusters in the MW taken from Harris (1996). Filled and open squares denote the MW and M31 dSphs, respectively, taken from McConnachie (2012), the recent DES work for new ultra-faint MW dSphs (Bechtol et al. 2015; Drlica-Wagner et al. 2015; Koposov et al. 2015), and other recent discoveries (Laevens et al. 2014, 2015b, 2015a; Kim et al. 2015; Kim & Jerjen 2015). The red star with error bars corresponds to the overdensity described in this paper. Virgo I, which lies within the locus defined by dSphs. (b) The relation between \( M_V \) and heliocentric distance for the systems shown in panel (a).

here is a candidate UFD galaxy. This is also supported from its non-zero ellipticity of \( \epsilon = 0.44 \pm 0.17 \), which is more similar to those of dwarf galaxies than globular clusters.

The heliocentric distance to Virgo I is \( D = 87^{+13}_{-8} \) kpc, where the error estimate is derived from the range of the distance yielding the 1\( \sigma \) decrease in the statistical significance of Virgo I after passing the isochrone filter (defined in Figure 2 (d)) from its peak value of 10.8\( \sigma \). This distance is beyond the reach of previous surveys for MW dwarfs with comparable luminosity. This is demonstrated in Figure 4, which shows the relation between \( M_V \) and \( D \) for the MW and M31 dwarfs as well as the MW globular clusters.

5. CONCLUSIONS

We have identified a new UFD satellite of the MW, Virgo I, in the constellation of Virgo. The satellite is located at a heliocentric distance of 87 kpc and its absolute magnitude in the \( V \) band is estimated as \( M_V = -0.8 \pm 0.9 \) mag, which is comparable to or fainter than that of the faintest dwarf satellite, Segue I. The half-light radius of Virgo I is estimated to be \( \sim 38 \) pc, significantly larger than globular clusters with the same luminosity, suggesting that it is a dwarf galaxy. To set further constraints on Virgo I, follow-up spectroscopic studies of bright RGB stars will be useful to investigate their membership and to determine the chemical and dynamical properties in this dwarf satellite.

Virgo I is located beyond the reach of the SDSS: its limiting magnitude of \( r = 22.2 \) implies that the completeness radius beyond which a faint dwarf galaxy like Virgo I will not be detected (Tollerud et al. 2008) is 28 kpc. With Subaru/HSC, this completeness radius for Virgo I is estimated as 89 kpc, if we adopt the limiting \( i \)-band magnitude of 24.5 mag combined with a typical \( r - i \) color of \( \sim 0.2 \). Thus, Virgo I with \( D = 87^{+13}_{-8} \) kpc is located just at the edge where Subaru/HSC can reach. We therefore expect the presence of yet unidentified faint satellites in the outer parts of the MW halo as the HSC survey continues. Deep imaging surveys for these faint and distant satellites are indeed important to get further insights into their true number and thus the nature of dark matter on small scales.

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