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FIRST RESULTS FROM THE MADCASH SURVEY: A FAINT DWARF GALAXY COMPANION TO THE LOW-MASS SPIRAL GALAXY NGC 2403 AT 3.2 MPC*

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ABSTRACT

We report the discovery of the faintest known dwarf galaxy satellite of a Large Magellanic Cloud (LMC) stellar-mass host beyond the Local Group (LG), based on deep imaging with Subaru/Hyper Suprime-Cam. Magellanic Analog Dwarf Companions And Stellar Halos (MADCASH) J074238+652501-dw lies ∼35 kpc in projection from NGC 2403, a dwarf spiral galaxy at $D \approx 3.2$ Mpc. This new dwarf has $M_g = -7.4 \pm 0.4$ and a half-light radius of 168 ± 70 pc, at the calculated distance of 3.39 ± 0.41 Mpc. The color–magnitude diagram reveals no evidence of young stellar populations, suggesting that MADCASH J074238+652501-dw is an old, metal-poor dwarf similar to low-luminosity dwarfs in the LG. The lack of either detected HI gas ($M_{\rm HI}/L_V < 0.69\ M_\odot/L_\odot$, based on Green Bank Telescope observations) or *GALEX* NUV/FUV flux enhancement is consistent with a lack of young stars. This is the first result from the MADCASH survey, which is conducting a census of the stellar substructure and faint satellites in the halos of Local Volume LMC analogs via resolved stellar populations. Models predict a total of ∼4–10 satellites at least as massive as MADCASH J074238+652501-dw around a host with the mass of NGC 2403, with 2–3 within our field of view, slightly more than the one such satellite observed in our footprint.

Key words: dark matter – galaxies: dwarf – galaxies: formation – galaxies: halos

1. INTRODUCTION

The faint end of the galaxy luminosity function is an important probe of the astrophysics associated with the Λ+Cold Dark Matter (ΛCDM) model of galaxy formation. Quantitative verification of this model has been met with challenges on sub-galactic scales (e.g., the "missing satellites problem," Klypin et al. 1999; and "too big to fail," Boylan-Kolchin et al. 2012), but significant progress has been made with the latest generation of numerical simulations, which include a wide range of baryonic physics (e.g., Wetzel et al. 2016). Likewise, the recent boom of faint dwarf discoveries in the Local Group (LG; most recently, Torrealba et al. 2016 and references therein) has partially closed the gap between observations and theoretical expectations. Many more systems should be discovered going forward (e.g., Hargis et al. 2014). Intriguingly, several of the newly discovered faint dwarfs may be associated with the Large Magellanic Cloud (LMC; Bechtol et al. 2015; Koposov et al. 2015; Jethwa et al. 2016; Sales et al. 2016; among others), which is expected to have its own satellite system in the ΛCDM model (e.g., D'Onghia & Lake 2008; Sales et al. 2011).

To comprehensively compare observations with expectations for galaxy formation in a ΛCDM universe, we must also look beyond the LG to measure the abundance and properties of dwarfs around primary galaxies of different masses, morphologies, and environments. This work has already begun for several systems with masses similar to, or greater than, the Milky Way (MW; e.g., M81: Chiboucas et al. 2013; Cen A: Crnojević et al. 2014, 2016; NGC 253: Sand et al. 2014; Romanowsky et al. 2016; Toloba et al. 2016). However, little attention has been paid to less massive hosts (but see Sand et al. 2015 in NGC 3109), which may shed light on the putative dwarf galaxies of the LMC.

This Letter presents the discovery of Magellanic Analog Dwarf Companions And Stellar Halos (MADCASH) J074238+652501-dw, a low-luminosity satellite of the LMC stellar-mass analog NGC 2403 ($D \approx 3.2$ Mpc, $M_{\rm star} \sim 7 \times 10^9 M_\odot$, or ∼2× LMC stellar mass), the first result of a program to search for faint dwarfs and map the stellar halos of LMC analogs in the nearby universe. Prior to our discovery, NGC 2403 had one known satellite (DDO 44, $M_B \sim -12.1$; Karachentsev et al. 2013). In Section 2, we briefly summarize our survey

* Based in part on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

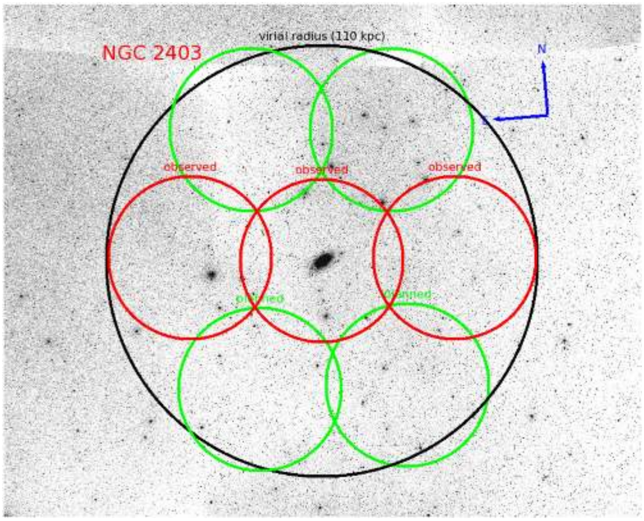

Figure 1. DSS image of NGC 2403 with the HSC field of view overlaid as green and red circles. The large black circle represents an assumed virial radius of 110 kpc. Red circles are fields already observed, encompassing ∼45% of the virial volume of NGC 2403s halo. Green fields are the four additional HSC fields planned to complete our mapping of NGC 2403.

plans and strategy to map the halos of nearby LMC-sized systems. Section 3 discusses the observations and data reduction, and Section 4 details the properties of the newly discovered dwarf galaxy. We conclude in Section 5 by placing MADCASH J074238+652501-dw in context both with respect to expectations from ΛCDM and with known systems in the Local Volume.

2. SURVEY DESCRIPTION

We designed the MADCASH survey to use resolved stars to map the virial volumes of Local Volume galaxies ($d \lesssim 4$ Mpc) with stellar masses of 1–7 × $10^9 M_\odot$ (roughly 1/3 to 3 times that of the LMC, assuming $(M/L)_K = 1$).

The Karachentsev et al. (2013) catalog includes four such galaxies—NGC 2403, NGC 247, NGC 4214, and NGC 404—that are accessible from the Subaru telescope on Mauna Kea and have $E(B - V) < 0.15$. Two additional systems (NGC 55 and NGC 300; with $D < 3$ Mpc) are in the southern sky and could be observed with the Dark Energy Camera. The virial radii of galaxies in this stellar-mass range are ∼100–130 kpc, inferred from semi-analytic galaxy catalogs generated from the Millennium-WMAP7 structure formation model of Guo et al. (2013).[15] At the time of this writing, the MADCASH team has acquired significant data (and upcoming observing time) on NGC 2403, NGC 247, and NGC 4214 (through NOAO Gemini-Subaru exchange time: PI: Willman, 2016A-0920; and Keck-Subaru: PI: Brodie, 2015B_U085HSC, 2016B_U138HSC).

The large aperture of the Subaru telescope and the 1°.5 diameter field of view of the prime focus imager Hyper Suprime-Cam (HSC; Miyazaki et al. 2012) make this project possible; the HSC field corresponds to ∼80 kpc at the distance to NGC 2403 ($D \sim 3.2$ Mpc). HSC can map the entire virial volume of an LMC-sized halo (see Figure 1) in only seven pointings. We image our fields in the g and i band to a depth that is ∼2 magnitudes below the tip of the red giant branch (TRGB). This is deep enough to identify and characterize dwarf galaxies as faint as $M_V \sim -7$.

3. OBSERVATIONS AND DATA REDUCTION

We observed three NGC 2403 fields with Subaru/HSC on 2016 February 9–10 with exposure times of 10 × 300 s in g and 10 × 120 s in i for each field. The seeing was ∼0.″5–0.″7. The fields, shown in Figure 1, extend nearly to the virial radius both to the east and west of the main body of NGC 2403 and sample ∼45% of NGC 2403's virial volume.

The images were processed using the HSC pipeline (hscPipe 4.0.1; http://hsca.ipmu.jp; http://hsc.mtk.nao.ac.jp/pipedoc_e/index.html), which is based on an earlier version of the LSST pipeline (Axelrod et al. 2010). Images are bias-subtracted, flat-fielded with dome flats, corrected for the brighter-fatter effect (W. Coulton et al. 2016, in preparation), and astrometrically and photometrically calibrated against Pan-STARRS1 Processing Version 2 (Schlafly et al. 2012; Tonry et al. 2012; Magnier et al. 2013). The images are transformed to a common reference frame and coadded with conservative clipping to remove artifacts that appear on a single visit. Coadded images are used for all the photometric and astrometric measurements reported below. We create a merged source list from deblended catalogs in each band and apply the same centroid and aperture or model (generally derived from the i-band image) to measure each object's flux in both bands. Point sources are separated from extended sources by removing objects for which the model and PSF fluxes differ by more than three times the flux error for that object. All stellar magnitudes presented in this work are derived from PSF photometry. We then match our catalogs to SDSS DR9 (Ahn et al. 2012) and transform to $g_{\rm SDSS}$ and $i_{\rm SDSS}$ magnitudes with an offset and color term. The transformed magnitudes have ∼0.03 mag scatter about the SDSS values. All magnitudes presented henceforth are on the SDSS photometric system, corrected for extinction using the Schlegel et al. (1998) maps with coefficients from Schlafly & Finkbeiner (2011). The average color excess for stars in this region of the sky is $E(B - V) \sim 0.048$.

To estimate the photometric completeness of our catalogs, we match our Subaru/HSC data to three *Hubble Space Telescope* (*HST*)/Advanced Camera for Surveys (ACS) fields in the halo of NGC 2403 from the GHOSTS program (Radburn-Smith et al. 2011).[16] The GHOSTS fields were observed with the F606W and F814W filters. Artificial star tests showed that the ACS data are >90% complete to the magnitude limit of our HSC photometry (Radburn-Smith et al. 2011). Using a matching radius of 1″, we recover half of the *HST*/ACS stellar sources (i.e., we are 50% complete) at a magnitude of F814W ≈ 26.0, which corresponds to $i \approx 26.4$ in our HSC data.

4. A NEW DWARF GALAXY COMPANION

We visually identified a candidate dwarf galaxy ∼35 kpc to the east of NGC 2403 in projection (Figure 2), which we dub MADCASH J074238+652501-dw. At this radius, MADCASH J074238+652501-dw is just beyond the field of view of previous work on the halo of NGC 2403 (Barker et al. 2012). This dwarf shows no sign of a nuclear star cluster

[15] Searchable at http://gavo.mpa-garching.mpg.de/MyMillennium/.

[16] Data products available at https://archive.stsci.edu/pub/hlsp/ghosts/index.html.

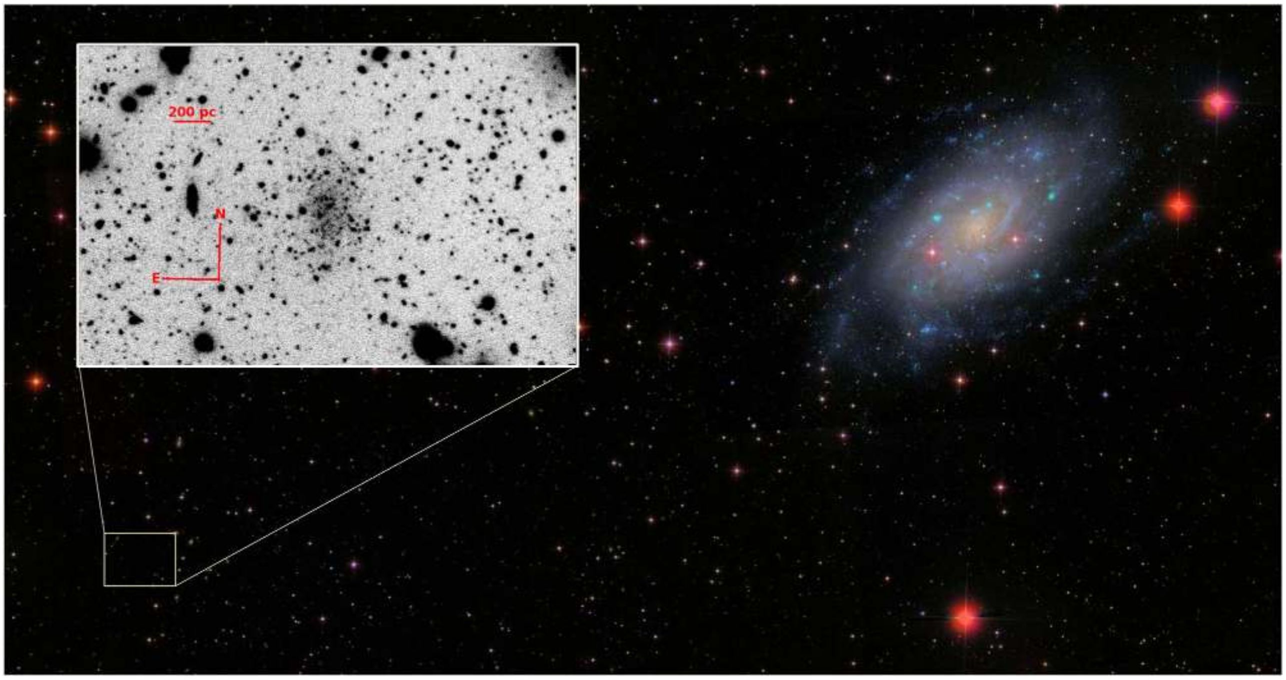

Figure 2. Inset: HSC image (in the g-band, ~2$'$.8 × 1$'$.8 in size) of the candidate dwarf galaxy MADCASH J074238+652501-dw. The center of NGC 2403 is ~38$'$ away, or ~35 kpc in projection. Background image: color composite from SDSS-III (acquired via http://wikisky.org/) of NGC 2403.

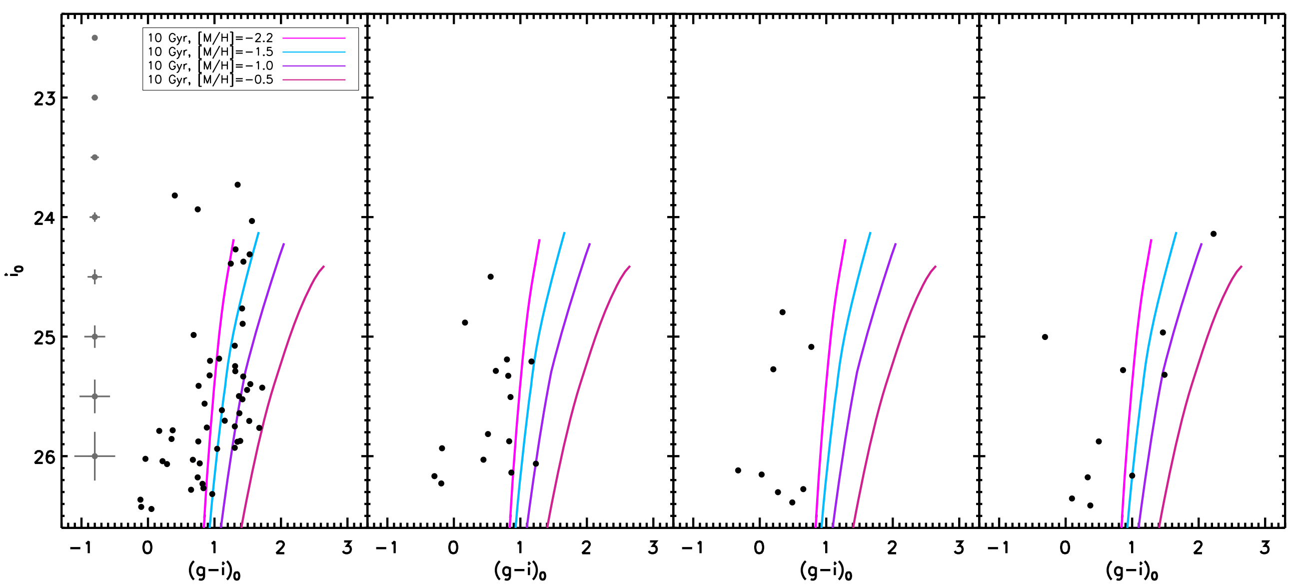

Figure 3. Left panel: color–magnitude diagram of point sources within 20$''$ of MADCASH J074238+652501-dw. Typical photometric errors as a function of magnitude are shown at the left side of this panel. The other three panels show CMDs of nearby "blank-sky" regions of the same size. In each panel, we show Padova isochrones of old (10 Gyr) populations with metallicities of [M/H] = −2.2, −1.5, −1.0, and −0.5, at D = 3.39 Mpc (the distance to MADCASH J074238+652501-dw; see Section 4.1). There is an overdensity of resolved sources at the position of the dwarf, consistent with an old, metal-poor RGB, extending ~2 mag below the RGB tip.

or disturbed morphology. NGC 2403 has one other known dwarf companion, the bright dSph/dE galaxy DDO 44 ($M_B = -12.1$; Karachentsev et al. 2013) roughly 1°.3 (~73 kpc in projection) to the north.

The left panel of Figure 3 shows a color–magnitude diagram of point sources within 20$''$ of the center of MADCASH J074238+652501-dw. For comparison, other panels show CMDs in randomly selected nearby background fields (also with 20$''$ radius). Each panel contains PARSEC isochrones (Bressan et al. 2012) for old (10 Gyr) populations at our derived distance to MADCASH J074238+652501-dw (3.39 Mpc; see Section 4.1) and metallicities ([M/H]) of −2.2, −1.5, −1.0, and −0.5 (assuming a solar metallicity of $Z_{\odot} = 0.0152$). The most metal-poor isochrones follow the red giant branch (RGB) of MADCASH J074238+652501-dw closely, with little evidence of younger populations blueward of the RGB or more metal-rich RGB stars following the reddest of the isochrones. Two conclusions can be drawn from Figure 3—first, that there is an obvious stellar excess relative to neighboring regions, and second that the excess stars

Table 1
Properties of MADCASH J074238+652501-dw

Parameter	Value
R.A. (hh:mm:ss)	07:42:38.887 ± 2″6
Decl. (dd:mm:ss)	+65:25:01.89 ± 3″2
$m - M$ (mag)	27.65 ± 0.26
D (Mpc)	3.39 ± 0.41
M_g (mag)	−7.4 ± 0.4
M_V (mag)	−7.7 ± 0.7
r_h (arcsec)	10.2 ± 3.0
r_h (pc)	168 ± 70
ϵ	<0.42 (68% CL)
θ (deg.)	29° (unconstrained)
μ_0 (mag arcsec^{-2})	25.9 ± 0.7
M_{star} ($M_\odot$)	∼1 × 10^5
M_{HI}/L_V ($M_\odot/L_\odot$)	<0.69
M_{HI} ($M_\odot$)	<7.1 × 10^4
SFR ($M_\odot$ yr^{-1})	⩽4.4 × 10^{-6}

predominantly cluster around the old, metal-poor ([M/H] < −1.0) locus of the isochrones we have overlaid. Assuming that the stars in MADCASH J074238+652501-dw mostly cluster around [Fe/H] = −2, then we conclude that the galaxy does not host populations significantly younger than 10 Gyr.

We estimate the mean metallicity of MADCASH J074238+652501-dw by comparing the CMD positions of stars with PARSEC isochrones. In order to eliminate contamination by non-members, we select the 13 stars in the left panel of Figure 3 with $i_0 < 25$ and $(g - i)_0 > 1.0$. We linearly interpolate 10 and 14 Gyr isochrones shifted to the distance modulus listed in Table 1 and assign each star the metallicity of the interpolated isochrone that passes through its color and magnitude. The mean metallicity of the 13 stars is [Fe/H] = −1.6(−1.7) for the 10 (14) Gyr isochrones, with standard deviation of 0.4 dex.

4.1. Distance

We estimate the distance to MADCASH J074238+652501-dw using the TRGB method (Lee et al. 1993). The TRGB absolute magnitude is estimated by averaging the magnitudes of the brightest metal-poor ([M/H] = −2.2, −1.5, and − 1.0), old (10 Gyr) stars in the PARSEC isochrones; we adopt a TRGB magnitude of $M_i^{TRGB} = -3.47 \pm 0.05$. We locate the TRGB of MADCASH J074238+652501-dw using stars within 20″ of the dwarf center, keeping only stars with $0.8 < (g - i)_0 < 2.1$ (the color range of the metal-poor RGB; see Figure 3). We bin these in magnitude to create a luminosity function, then use a zero-sum Sobel edge-detection filter to locate the transition in stellar density corresponding to the RGB tip. We repeat this for bins of different widths (from 0.15 to 0.2 mag in steps of 0.01) and then adopt the mean value; the standard deviation is taken as the uncertainty.[17] We measure $i_{0,TRGB} = 24.18 \pm 0.20$ for MADCASH J074238+652501-dw (in agreement with the distance to NGC 2403 from previous work; e.g., Bellazzini 2008), corresponding to $m - M = 27.65 \pm 0.26$ ($D = 3.39 \pm 0.41$ Mpc) for the new dwarf galaxy. For comparison, we also perform the TRGB analysis on stars near the main body of NGC 2403 and find $i_{0,TRGB} = 23.92 \pm 0.11$ for NGC 2403, or a distance modulus of $m - M = 27.39 \pm 0.16$ ($D = 3.01 \pm 0.23$ Mpc). This agrees with typical measurements of the distance to NGC 2403 within the uncertainties (e.g., Radburn-Smith et al. 2011: $m - M$ =27.51 ± 0.07).

4.2. Structural Parameters

To derive structural parameters of MADCASH J074238+652501-dw, we select RGB candidates centered on the three most metal-poor isochrones in Figure 3, with magnitudes $23.7 < i_0 < 26.2$, within a 5′ × 5′ box centered on the dwarf. This catalog was passed to a maximum-likelihood estimator of the dwarf structural parameters using the Sand et al. (2012) implementation of the Martin et al. (2008) method. The resulting structural parameters for MADCASH J074238+652501-dw are given in Table 1, with uncertainties determined via 1000 bootstrap resamplings of the data.

The central position of MADCASH J074238+652501-dw is well constrained, but the additional parameters are poorly measured due to the small number of resolved stars in the dwarf. We derive a half-light radius of $r_h = 10''.2 \pm 3''.0$, corresponding to 168 pc at a distance of 3.39 Mpc. For the ellipticity, we derive only an upper limit of $\epsilon < 0.42$ (within 68% confidence limits). Because the ellipticity is poorly constrained, we cannot reliably measure the dwarf's position angle; the value of $\theta = 29°$ corresponds to the likelihood maximum, but is unconstrained.

4.3. Luminosity and Stellar Populations

We estimate the luminosity of MADCASH J074238+652501-dw by measuring the integrated flux in a circular aperture of radius $r_h = 10''.2$ and central position as measured in Section 4.2 (see, e.g., Sand et al. 2014, 2015). After subtracting the average background from 100 equal-area apertures in random positions throughout the same CCD frame and multiplying the flux by two to account for our half-light radius aperture, we find integrated luminosities of $M_g = -7.4 \pm 0.4$ and $M_i = -8.1 \pm 0.6$. This translates to $M_V = -7.7 \pm 0.7$ using the filter transformations of Jordi et al. (2006).

The measured luminosity and half-light radius place MADCASH J074238+652501-dw upon the observed relationship for LG dwarfs (Figure 4). This suggests that even though MADCASH J074238+652501-dw has evolved in a different environment than MW/M31 dwarfs, the physical processes that determine its properties are similar to those in more massive hosts' halos. If MADCASH J074238+652501-dw also follows other scaling relations for LG dwarf galaxies (e.g., McConnachie 2012), then this dwarf with $M_V = -7.7$ should have a dynamical mass-to-light ratio of ∼100, dynamical mass of $M_{dyn}(<r_h) \sim 5 \times 10^6\ M_\odot$, and a mean metallicity of [Fe/H] ∼ −2.0. This metallicity is consistent with our inference of an overall metal-poor population in MADCASH J074238+652501-dw.

The sparse CMD precludes a precise quantification of the SFH beyond our previous statement that the galaxy does not host stars significantly younger than 10 Gyr.

[17] We attempted to apply the maximum-likelihood method of Makarov et al. (2006), but it failed to converge due to the small number of resolved stars near the TRGB of the dwarf.

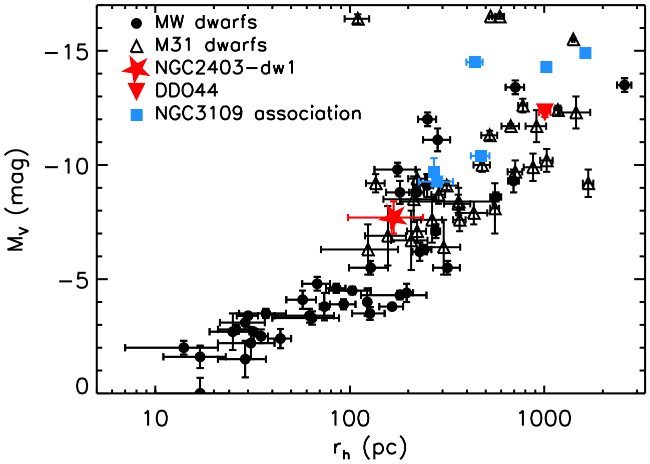

Figure 4. Absolute V-band magnitude (M_V) and half-light radius (r_h) of MADCASH J074238+652501-dw (large red star) placed in context with other known systems. Black points and triangles are data for MW and M31 dwarf galaxies (e.g., McConnachie 2012), and blue squares are members of the NGC 3109 association, including Antlia and Antlia B (Sand et al. 2015). The small, red, downward-pointing triangle represents DDO 44, another known satellite of NGC 2403 (Karachentsev et al. 1999).

4.4. GALEX UV

We discern no FUV or NUV flux enhancement in available *GALEX* imaging at the position of MADCASH J074238+652501-dw. The nearest source in the MAST/*GALEX* GR6 catalog, at $\sim 0\rlap{.}'86$ from the center of the dwarf, is faint in the FUV, with no NUV detection. This source has no obvious counterpart in our HSC images.

Using tiles from the *GALEX* All-Sky Imaging Survey, we measure the FUV flux of MADCASH J074238+652501-dw, using the same aperture and background-subtraction technique used in estimating the optical luminosity in Section 4.3. This flux was converted into a luminosity using our adopted TRGB distance modulus of 27.65, adopting an extinction coefficient $A_{\rm FUV} = 7.9\,E(B-V)$ (Lee et al. 2009). We convert this to a star formation rate (SFR) using the relation between SFR and UV continuum from McQuinn et al. (2015): $\mathrm{SFR}(M_\odot\ \mathrm{yr}^{-1}) = 2.04 \times 10^{-28}\ L_\nu(\mathrm{erg\ s^{-1}\ Hz^{-1}})$, and find an upper limit on the SFR in MADCASH J074238+652501-dw of $4.4 \times 10^{-6}\,M_\odot\ \mathrm{yr}^{-1}$. The same relation using the *GALEX* FUV aperture magnitude for MW dwarf Leo T from Lee et al. (2011) yields $\mathrm{SFR_{LeoT}} \approx 5.6 \times 10^{-6}\,M_\odot\ \mathrm{yr}^{-1}$, suggesting that MADCASH J074238+652501-dw is at most forming stars at a similar rate as Leo T.

4.5. GBT HI Observations

Using the Robert C. Byrd Green Bank Telescope,[18] we obtained position-switched HI observations of MADCASH J074238+652501-dw through Director's Discretionary Time (AGBT-16A-462; PI: Spekkens) on 2016 May 9 and 11. The GBT spectrum in the velocity ranges $-1000 \leqslant V_{\rm LSRK} \leqslant -50\ \mathrm{km\,s^{-1}}$ and $50 \leqslant V_{\rm LSRK} \leqslant 1000\ \mathrm{km\,s^{-1}}$ has an rms noise of $\sigma = 0.35$ mJy at a spectral resolution of $15\ \mathrm{km\,s^{-1}}$. We do not find any HI emission in these velocity ranges within the FWHM = $9\rlap{.}'1$ (8.97 kpc) GBT beam at this frequency. This non-detection combined with the measured distance and luminosity suggest that a putative HI counterpart has a 5σ, $15\ \mathrm{km\,s^{-1}}$ HI mass upper limit of $M_{\rm HI,lim} = 7.1 \times 10^4 M_\odot$ and $M_{\rm HI}/L_V = 0.69\,M_\odot/L_\odot$. The satellite is therefore gas-poor, similar to what is found for other dwarf spheroidals in the Local Volume (Grcevich & Putman 2009; Spekkens et al. 2014).

5. CONCLUSIONS

We report the discovery of a faint ($M_g = -7.4 \pm 0.4$) dwarf galaxy companion of the LMC analog NGC 2403 ($\sim 2\times$ LMC stellar mass) in imaging data from the MADCASH survey using HSC on the Subaru telescope. From resolved stars reaching ~ 2 mag below the RGB tip, we show that the new dwarf, MADCASH J074238+652501-dw, has predominantly old, metal-poor stellar populations (~ 10 Gyr, $[\mathrm{M/H}] \sim -2$) similar to those in the LG ultra-faint galaxies. Using non-detections in HI and UV observations, we place upper limits on the available gas reservoir and SFR, confirming this as a gas-poor system with old stellar populations. Our derived distance modulus of $m - M = 27.65 \pm 0.26$ places MADCASH J074238+652501-dw near NGC 2403, bolstering the case that it is a faint satellite of this Local Volume LMC analog.

Should we have expected to find only one new satellite? NGC 2403 has one previously known satellite, the dwarf galaxy DDO 44[19] ($M_V \sim -12.5$, $[\mathrm{Fe/H}] \sim -1.7$; Karachentsev et al. 1999), which is outside our current footprint. The stellar masses of this satellite and the newly discovered dwarf are $M_{\rm star,DDO\,44} \sim 6 \times 10^7\,M_\odot$ (estimated from the K-band magnitude from Karachentsev et al. 2013, assuming $M/L = 1$) and $M_{\rm star} \sim 1 \times 10^5\,M_\odot$ for MADCASH J074238+652501-dw. Based on abundance-matching relations (Moster et al. 2013; Garrison-Kimmel et al. 2014), applied to subhalo mass functions from dark-matter-only simulations (e.g., Garrison-Kimmel et al. 2014), we expect 3–11 dwarf galaxies at least as massive as MADCASH J074238+652501-dw in NGC 2403's virial volume. If satellites follow the subhalo distribution in dark-matter-only simulations (Han et al. 2016), which is nearly isothermal and consistent with the distribution of satellites at high redshift (Nierenberg et al. 2011), we should have found 2–3 satellites in our footprint with $M_{\rm star} \gtrsim 1 \times 10^5\,M_\odot$. This suggests that we should find a factor of 2–3 more in a complete survey of the remaining $\sim 55\%$ of NGC 2403's virial volume. While this simple estimate suggests that one dwarf galaxy is fewer than we expect to find in our current data, we must observe the entire virial volume of NGC 2403 to fully assess the significance of its satellite abundance. Placing definitive constraints on cosmological models will require mapping the virial halos of the ensemble of hosts, which sample a variety of environments, in our MADCASH program.

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18 The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

19 Karachentsev et al. (2002) suggested NGC 2366, Holmberg II, UGC 4483, and KDG052 may also be companions of NGC 2403. Of these, only NGC 2366 ($M_B = -16.1$) has NGC 2403 designated as its main tidal disturber by Karachentsev et al. (2014); all others are predominantly influenced by M81. For this work, we assume that these galaxies are not satellites of NGC 2403.

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