Detection of an Optical Counterpart to the ALFALFA Ultra-compact High-velocity Cloud AGC 249525

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Received 2017 January 27; revised 2017 February 20; accepted 2017 February 23; published 2017 March 7

Abstract

We report on the detection at >98% confidence of an optical counterpart to AGC 249525, an ultra-compact high-velocity cloud (UCHC) discovered by the Arecibo Legacy Fast ALFA survey blind neutral hydrogen survey. UCHVCs are compact, isolated H I clouds with properties consistent with their being nearby low-mass galaxies, but without identified counterparts in extant optical surveys. Analysis of the resolved stellar sources in deep g- and i-band imaging from the WIYN pODI camera reveals a clustering of possible red giant branch stars associated with AGC 249525 at a distance of 1.6 ± 0.45 Mpc. Matching our optical detection with the H I synthesis map of AGC 249525 from Adams et al. shows that the stellar overdensity is exactly coincident with the highest-density H I contour from that study. Combining our optical photometry and the H I properties of this object yields an absolute magnitude of −7.1 ± MV ≤ −4.5, a stellar mass between 2.2 ± 0.6 × 10⁶ M☉ and 3.6 ± 1.0 × 10⁶ M☉, and an H I to stellar mass ratio between 9 and 144. This object has stellar properties within the observed range of gas-poor ultra-faint dwarfs in the Local Group, but is gas-dominated.

Key words: galaxies: dwarf – galaxies: photometry – galaxies: stellar content

1. Introduction

The Arecibo Legacy Fast ALFA survey (ALFALFA) is a blind neutral hydrogen (H I) survey carried out with the Arecibo radio telescope that covers ~7000 square degrees of sky and has cataloged more than 30,000 sources, the majority of which have never before been observed in the 21 cm line (Giovanelli et al. 2005; Haynes et al. 2011). ALFALFA detects sources with 2 × 10¹⁰ M☉ of H I at the distance of the Virgo Cluster and <10¹⁵ M☉ within the Local Group at an angular resolution of ~3.5″ and a spectral resolution of ~5 km s⁻¹ (Giovanelli et al. 2005). Among these thousands of ALFALFA sources is a small population of objects first identified according to their common characteristics by Giovanelli et al. (2010) and dubbed ultra-compact high-velocity clouds (UCHVCs). The UCHVCs are very compact (<10⁵ diameter), isolated gas clouds that have H I properties (including narrow velocity widths) that suggest they may be nearby low-mass galaxies. The other important characteristic of UCHVCs is that they have no clear optical counterpart when their positions and redshifts are checked against optical surveys and catalogs like the Sloan Digital Sky Survey (SDSS; Eisenstein et al. 2011) and sources in the NASA Extragalactic Database (NED).

Some have argued that compact high-velocity clouds (CHVCs; with ~60″ diameters) detected in H I surveys are gas clouds in the Local Group with few or no stars, embedded within low-mass dark matter halos (Blitz et al. 1999; Braun & Burton 1999). The detection of a substantial population of such objects would have implications for the “missing satellites problem,” the discrepancy between the numbers of low-mass halos predicted by ΛCDM structure formation models compared to the numbers detected in observational surveys (Kauffmann et al. 1993; Klypin et al. 1999; Moore et al. 1999).

However, Sternberg et al. (2002) demonstrated that the structural properties of the CHVCs do not match the expected properties of the missing satellites in the ΛCDM framework: if extragalactic, they are physically too large. Giovanelli et al. (2010) brought renewed attention to this topic by showing that UCHVCs discovered in ALFALFA, if they are indeed at distances of ~1 Mpc, do have sizes and masses consistent with their being baryonic material embedded within low-mass (<10¹⁰ M☉) dark matter halos, or “minihalos,” that fit within the ΛCDM paradigm. Giovanelli et al. (2010) concluded that the UCHVCs are plausible minihalo candidates, but exactly what they represent—e.g., starless gas clouds, low-mass galaxies with stars that have been missed by past surveys, or some other poorly understood HVC phenomenon—remains unclear.

A preliminary list of 27 UCHVCs was presented in Giovanelli et al. (2010), and Adams et al. (2013) followed up with a more complete list of 59 objects chosen from the 40% ALFALFA catalog (Haynes et al. 2011). UCHVCs selected from ALFALFA have H I properties like those of Leo T (Irwin et al. 2007), which is the faintest (M_V ~ −7) Local Group dwarf galaxy with evidence of recent star formation. At a distance of 1 Mpc, the UCHVCs would have H I masses of ~10⁴–10⁶ M☉, H I diameters of ~2–3 kpc, and dynamical masses of ~10¹⁰–10¹¹ M☉.

In order to derive the masses and sizes of these H I sources, and thus to better understand their nature, we need to know their distances. One route for deriving distances for the UCHVCs is to detect their stellar populations, construct a color–magnitude diagram (CMD), and then measure a distance from the Tip of the Red Giant Branch (TRGB) method. Accordingly, we are carrying out a campaign to obtain deep optical imaging of UCHVCs with the WIYN
3.5 m telescope\textsuperscript{6} to look for stellar populations associated with these objects, and (if possible) derive their distances, masses, sizes, and other properties, and to study their star formation histories.

The first UCHVC we observed with WIYN resulted in the discovery of Leo P, an extremely metal-poor, gas-rich star-forming dwarf galaxy (Giovanelli et al. 2013; Rhode et al. 2013; Skillman et al. 2013). Located just outside the Local Group at 1.62 ± 0.15 Mpc (McQuinn et al. 2015), Leo P has an H I mass of 8.1 \times 10^6 \, M_\odot and an H I-to-stellar mass ratio of \sim 2. Its oxygen abundance is \sim 2% of the solar value, comparable to the abundances of I Zw 18, DDO 68, and the ALFALFA galaxy AGC 198691 (Hirschauer et al. 2016). Its total magnitude is \textit{M}_g = -9.3 ± 0.2, and its dynamical mass is 1.4 \times 10^7 \, M_\odot, making Leo P the lowest-mass galaxy known that is currently forming stars.

Since the discovery of Leo P, we have developed a systematic observing strategy and procedure for searching for stellar counterparts to the UCHVCs. Details are presented in Janesh et al. (2015), along with a tentative detection of a counterpart to the ALFALFA source AGC 198606, nicknamed Friend of Leo T (Adams et al. 2015) because it is close in position and velocity to dwarf galaxy Leo T. We detected a stellar counterpart at a distance of \sim 380 kpc, with \textit{M}_g \sim -4.7, and an H I-to-stellar mass ratio of \sim 45–110. Because our detection has only 92\% significance, additional observations are needed to show unambiguously whether or not this object is a real detection and a new Local Group member.

Other groups are also carrying out optical searches for counterparts to the ALFALFA UCHVCs (e.g., Bellazzini et al. 2015a, 2015b; Sand et al. 2015; Beccari et al. 2016). The results from these searches, as well as from the WIYN imaging obtained thus far, suggest that if nearby stellar counterparts to UCHVCs can be found, they will much less obvious than Leo P. This is not unexpected since ALFALFA sources are, as mentioned, not classified as UCHVCs unless they have no clear optical counterpart in extant surveys.

Our campaign to obtain and process WIYN imaging of UCHVCs is underway. We draw our targets from Adams et al. (2013) as well as from the 70\% ALFALFA catalog (Jones et al. 2016). In this Letter, we present the possible detection of a stellar population associated with the UCHVC AGC 249525, which is included in the 70\% catalog and was characterized as an excellent dwarf galaxy candidate by Adams et al. (2016, hereafter A16) based on its H I distribution and evidence of rotation in follow-up H I synthesis observations.

2. Observations and Analysis

A16 presented results from Westerbork Radio Synthesis Telescope observations of several UCHVCs. AGC 249525 shows a smooth H I morphology at improved (60\'', 105\'') angular resolution and ordered motion consistent with \sim 15 km s\textsuperscript{-1} rotation. AGC 249525, and the aforementioned AGC 198606, are among the highest column density objects in the UCHVC sample, with peak \textit{N}_{HI} \sim 5 \times 10^{21} \, \text{atoms} \text{ cm}^{-2} at 105\'' resolution. A16 reported a mean H I angular diameter at half-flux level of 8.5\' for AGC 249525 and an H I mass of 2.4 \times 10^6 \, M_\odot, assuming a distance of 1 Mpc. A16 showed that for a distance range of 0.4–2 Mpc, and assuming a baryonic mass consisting of only the neutral gas component, AGC 249525 falls on the Baryonic Tully–Fisher Relation (McGaugh 2012) when it is extrapolated to low galaxy masses.

We observed AGC 249525 with the partially filled One Degree Imager (pODI) on the WIYN 3.5 m telescope at Kitt Peak National Observatory on 16 March 2013. The pODI camera provided a \sim 24\' \times 24\' field of view and a pixel scale of 0\''11 per pixel. Nine 300 s exposures were obtained in \textit{g} and \textit{i} filters. The raw images were transferred to the ODI Portal, Pipeline, and Archive (ODI-PPA) at Indiana University and processed using the QuickReduce pipeline (Kotulla 2014) to remove the instrumental signature. We then illumination-corrected, scaled, and stacked the images. The FWHM of the point-spread function in the stacked images is 0\''78 in \textit{g} and 0\''73 in \textit{i}.

Sources were identified with the IRAF task \texttt{DAOFIND} and the source lists in \textit{g} and \textit{i} were matched. We performed photometry and calculated final, calibrated \textit{g}_0 and \textit{i}_0 magnitudes for all point sources in the matched list. Photometric calibration coefficients were calculated based on SDSS DR13 (SDSS Collaboration et al. 2016) standard stars in the images, and Galactic extinction corrections were calculated using the relations in Schlafly & Finkbeiner (2011). The 5\sigma detection limit is 25.5 in \textit{g} and 24.5 in \textit{i}.

The full details of our analysis methods are given in Janesh et al. (2015). Briefly, we constructed a CMD from the \textit{g}_0 and \textit{i}_0 photometry and then applied a color–magnitude filter derived from Girardi et al. (2004) isochrones to the data, sampling a set of distances between 0.3 and 2.5 Mpc. The CMD filter is intended to select red giant branch (RGB) stars and horizontal branch (HB) stars from old, metal-poor stellar populations. We then smoothed the spatial distribution of the filtered stars by binning the positions into a two-dimensional grid with \sim 8\'' \times 8\'' bin sizes and convolving the grid with a Gaussian distribution with a 3\'' smoothing radius. Overdensities are regions in the grid that exceed the mean grid value by some number of standard deviations (\sigma). To quantify the significance of the overdensities, we created 25,000 samples with the same number of points as were found in the CMD filter, but with a uniform random distribution. We measured the peak \sigma value for each of these samples. The distribution is well-fitted by a lognormal probability distribution function. To identify significant overdensities, we calculated the percentage of the cumulative distribution function (CDF) of peak \sigma values below that of the overdensity detected in the real data. We consider an overdensity significant if it has a peak \sigma value higher than 95\% or more of the values in the simulated CDF.

3. A Possible Optical Counterpart to AGC 249525

Based on the analysis described above, we found significant stellar overdensities in the AGC 249525 images at a range of distances between 1.35 Mpc and 2.08 Mpc. In Figure 1, we show the results of the CMD filtering and smoothing process for the highest-significance detection at 1.64 Mpc (\textit{m} – \textit{M} = 26.07 ± 0.51). We adopt the distance corresponding to this detection as our assumed distance to the object. We estimate an uncertainty of \pm 0.45 Mpc, based on the observed range of significant (\geq 95\%) overdensities that show up at that location. In Figure 2, we show the results of the significance testing for the detection at 1.64 Mpc. At this distance, 98.4\% of peak overdensities in the random

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\textsuperscript{6} The WIYN Observatory is a joint facility of the University of Wisconsin–Madison, Indiana University, the University of Missouri, and the National Optical Astronomy Observatory.
realizations are weaker than the peak overdensity in the data, indicating that the overdensity is unlikely to be a random clustering of sources.

Figure 3 shows the $i$ image overlaid with the H1 contours from the WSRT data presented in A16. The location of the stellar overdensity, marked by a magenta circle, is coincident with the highest H1 contour level, providing further evidence that the stellar overdensity is associated with the UCHVC.

Another check on the validity of the overdensity of RGB stars in the center of the AGC 249525 field is shown in Figure 4. We divided the image into regions $4'4 \times 4'4$ in size and plotted the CMD for each portion of the image. The central region shows an increased number of stars at $(g - i)_0 \approx 1$, consistent with the colors of RGB stars in our CMD filter. When visualized in this way, the overdensity of potential RGB stars in the center of the image is readily apparent. We note that a modest overdensity appears in the northwest corner of the image (top right of Figure 4). The peak $\sigma$ value for this overdensity is greater than the peak value in only 2% of the random realizations, so it is not significant.

3.1. Estimated H1 and Optical Properties

We can use the 1.64 Mpc distance to calculate the H1 properties of AGC 249525. Combining the values presented in A16 with our distance yields an H1 mass of $3.2 \pm 0.9 \times 10^6$
M_\odot$, an H I radius\(^7\) of 1.8 \pm 0.5 kpc, and a dynamical mass of 1.6 \pm 0.5 \times 10^8 \ M_\odot$.

To calculate the observed properties of the optical counterpart, we masked all objects in the images that are obvious background galaxies or foreground stars. We then measured the magnitude in the masked images within a circular aperture of radius 75" centered on the location of the highest-density peak in Figure 1. The 75" radius was chosen to minimize contributions from sky background fluctuations while maximizing the number of stars that fell within the CMD filter. This process yielded apparent magnitudes of \(g_0 = 19.61 \pm 0.10\) and \(i_0 = 18.20 \pm 0.07\) and a \((g - i)_0\) color of 1.41 \pm 0.12. At a distance of 1.64 Mpc, this corresponds to an absolute magnitude of \(M_V = -7.1\). Because these values include all unmasked light inside the 75" radius aperture, including fluctuations in the sky background, they should be considered upper limits.

We also compute lower limit magnitudes by summing the flux from only those sources selected by the CMD filter that are inside the 75"-radius circle around the stellar overdensity peak. In this case, we find apparent magnitudes of \(g_0 = 22.10 \pm 0.02\) and \(i_0 = 20.93 \pm 0.02\), with a \((g - i)_0\) color of 1.18 \pm 0.02. At a distance of 1.64 Mpc, the “minimum” absolute magnitude of AGC 249525 is \(M_V = -4.5\). Although extremely faint compared to most dwarf galaxies, these absolute magnitudes are consistent with the range of values for ultra-faint dwarfs (UFDs) in the Local Group and its environs (McConnachie 2012).

We can use the distance to compute an H I-to-stellar mass ratio for this object. We begin by estimating the stellar mass-to-light ratio using the relations from Bell et al. (2003), finding for the redder, brighter magnitude limit a value of \((M/L)_h = 3.79\), and for the bluer, fainter magnitude limit a value of \((M/L)_i = 2.87\). Using these mass-to-light ratios we calculate a stellar luminosity of \(L_\ast = 9.6 \pm 2.6 \times 10^4 \ L_\odot\) and a stellar mass of \(M_\ast = 3.6 \pm 1.0 \times 10^5 \ M_\odot\) for the bright limit, and a luminosity of \(L_\ast = 7.7 \pm 2.1 \times 10^3 \ L_\odot\) and mass of \(M_\ast = 2.2 \pm 0.6 \times 10^4 \ M_\odot\) for the faint limit. Using an H I mass of \(3.2 \times 10^6 \ M_\odot\), we find H I-to-stellar mass ratios of \(M_{HI}/M_\ast \sim 9\) for the bright limit and \(M_{HI}/M_\ast \sim 144\) for the faint limit. The H I and optical properties are listed in Table 1.

A16 discuss the potential close neighbors of AGC 249525: Bootes I, Bootes II, and UGC 9128. Bootes I and Bootes II are both located within 60 kpc of the Sun, and so are not in close spatial proximity to AGC 249525. At the distance we have estimated here, the most likely neighbor is the galaxy UGC 9128 at 2.27 Mpc (Tully et al. 2013). UGC 9128 has a \(cz = 152\) km s\(^{-1}\) (McConnachie 2012) and is less than 10° away from AGC 249525, which has a \(cz = 48\) km s\(^{-1}\).

4. AGC 249525: A Gas-rich Ultra-faint Dwarf Galaxy?

The possible detection of an optical counterpart for the UCHVC AGC 249525 has interesting implications. Along with AGC198606 (Janesh et al. 2015), it would represent one of the most extreme galaxies in or near the Local Group, with its sparse stellar population and large \(M_{HI}/M_\ast\) ratio. While galaxies like these are difficult to detect, models have predicted that they should exist. High-resolution hydrodynamic cosmological simulations from Oñorbe et al. (2015) indicate that

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\(^7\) Measured at the \(1 \times 10^{19}\) atoms cm\(^{-2}\) level.

Figure 3. WIYN pODI i-band image (~22' \times 22'; north is up, east is left) of AGC 249525 with H I contours from A16 overlaid at [9, 15, 20, 30, 40] \times 10^{19}\ atoms cm\(^{-2}\) (solid black lines). The WSRT beam is shown in the bottom left corner. Also marked are stars selected by the CMD filter (red circles) and a 3″-radius circle at the location of the overdensity from Figure 1 (magenta). A 75″-radius circle (blue) shows the aperture used to estimate optical properties in Section 3.1. The center of the stellar overdensity identified by the CMD filtering process coincides with the highest column density H I contour.
isolated, low-mass dark matter halos result in galaxies with stellar masses between $10^4 \sim 10^6 M_{\odot}$ and large $M_{\text{gas}}/M_*$ ratios and stellar masses between $10^4 \sim 10^6 M_{\odot}$, consistent with the range of possible values for AGC 249525. Additionally, the N-body and semi-analytic models of Bovill & Ricotti (2011) predict that isolated UFDs should exist in significant numbers in the Local Volume, with optical properties similar to known UFDs, though most of these predicted UFDs have lost their gas via stripping or stellar feedback effects.

The putative optical counterpart for AGC 249525 has an absolute magnitude that places it in the middle of the range of the faint dwarf galaxies in or near the Local Group. UFDs like Segue 1 ($M_V = -1.5$), Segue 2 ($M_V = -2.5$), and Willman 1 ($M_V = -2.7$) are at the faintest end of the range of known nearby dwarfs (McConnachie 2012). Koposov et al. (2015) recently discovered nine new UFDs in the southern hemisphere with $M_V = -2.0$ to $-6.6$. The gas-rich dwarfs Leo P ($M_V = -9.3$; Rhode et al. 2013; McQuinn et al. 2015) and Leo T ($M_V = -8.0$; Irwin et al. 2007) are significantly brighter, though they are actively forming, or have recently formed, stars. The possible optical counterpart to AGC 198606, which is gas-rich but without active star formation, is closer to the UFDs in its luminosity, with $M_V \sim -3.5$. AGC 249525, while more luminous than AGC 198606, is still substantially fainter than Leo T and Leo P.

Previous work has concluded that some UFDs could be the stellar populations left over after their progenitor dwarf

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**Table 1**

| Property         | Value                        |
|------------------|------------------------------|
| R.A. (J2000)     | $14^h 17^m 53.4^s$          |
| Decl. (J2000)    | $17^\circ 32′ 42.5^s$       |
| Distance         | $1.64 \pm 0.45$ Mpc         |
| $cz$             | $47$ km s$^{-1}$             |
| H I mass         | $3.2 \pm 0.9 \times 10^6 M_\odot$ |
| H I radius       | $1.8 \pm 0.5$ kpc           |
| Rotational velocity | $15 \pm 5$ km s$^{-1}$   |
| Dynamical mass   | $1.6 \pm 0.5 \times 10^8 M_\odot$ |

| $i_0$            | $20.9 \pm 0.02$             |
| $M_V$            | $-4.5$                      |
| $(g-i)_0$        | $1.18 \pm 0.02$             |
| $L_*$            | $7.7 \pm 2.1 \times 10^4 L_\odot$ |
| Stellar mass     | $2.2 \pm 0.6 \times 10^4 M_\odot$ |
| $M_{H_1}/M_*$    | 144                         |

**Figure 4.** CMDs for $4/4 \times 4/4$ subsets of the full image; the grid is arranged with north up, east left. The central coordinates and the number of stars are printed in the upper right corner of each box. An overabundance of stars at $(g-i)_0 \approx 1$ appears in the central box, which is coincident with the overdensity described in Section 3.
galaxies were stripped of gas and stars by the Milky Way (Willman et al. 2006; Martin et al. 2007). In Janesh et al. (2015), we speculated that, with the discovery of gas-rich galaxies with extremely sparse stellar populations like AGC 198606 and now AGC 249525, a different formation scenario for UFDs is possible. With less massive progenitors, less stripping would be necessary to reach the low stellar masses and faint total magnitudes observed in UFDs.

Further observations are needed to confirm the optical counterpart to AGC 249525. Only the upper portion of the RGB is accessible in the current WIYN pODI data, whereas a detection of HB stars would provide a more definitive distance determination. Our derived distance is similar to that of Leo P. McQuinn et al. (2015) used Hubble Space Telescope (HST) observations to measure a distance to Leo P of 1.62 ± 0.15 Mpc, based on a combination of TRGB stars, HB stars, and RR Lyrae variables. At 1.6 Mpc, HB stars would have $M_V \sim 26.5$, so a robust detection of the HB in AGC 249525 would therefore likely require very deep imaging with a large-aperture ground-based telescope or HST. Spectroscopic radial velocity measurements of the putative RGB stars in this object would also help confirm the association of stars with H1 gas, although at these magnitudes such observations would be a challenge.

We thank the anonymous referee for helpful comments. We thank the WIYN, NOAO, and ODI-PPA staff for their help at various stages of this project. W.F.J. and K.L.R. are supported by NSF grant AST-1615483. S.J. acknowledges support from the Australian Research Council’s Discovery Project funding scheme (DP150101734). E.A.K.A. is supported by TOPiEW.14.105, which is financed by the Netherlands Organisation for Scientific Research (NWO). The ALFALFA team at Cornell is supported by NSF grants AST-0607007 and AST-1107390 to R.G. and M.P.H. and by grants from the Brinson Foundation. J.M.C. is supported by NSF grant 1211683. This research made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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