DISCOVERY AND FOLLOW-UP OF A NEARBY GALAXY FROM THE ARECIBO ZONE OF AVOIDANCE SURVEY

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ABSTRACT

The Arecibo L-Band Feed Array Zone of Avoidance (ALFA ZOA) survey has discovered a nearby galaxy, ALFA ZOA J1952+1428, at a heliocentric velocity of +279 km s⁻¹. The galaxy was discovered at low Galactic latitude by 21 cm emission from neutral hydrogen (HI). We have obtained follow-up observations with the Expanded Very Large Array and the 0.9 m Southeastern Association for Research in Astronomy optical telescope. The HI distribution overlaps an uncataloged, potential optical counterpart. The HI linear size is 1.4 kpc at our adopted distance of D = 7 Mpc, but the distance estimate is uncertain as Hubble’s law is unreliable at low recessional velocities. The optical counterpart has m_B = 16.9 mag and B − R = 0.1 mag. These characteristics, including M_HI = 10^{7.0} M_☉ and L_B = 10^{7.5} L_☉, if at 7 Mpc, indicate that this galaxy is a blue compact dwarf, but this remains uncertain until further follow-up observations are complete. Optical follow-up observations are ongoing and near-infrared follow-up observations have been scheduled.

Key words: galaxies: individual (ALFA ZOA J1952+1428) – radio lines: galaxies – surveys

Online-only material: color figures

1. INTRODUCTION

The Arecibo L-Band Feed Array Zone of Avoidance (ALFA ZOA) Survey searches for 21 cm line emission from neutral hydrogen (HI) in galaxies behind the disk of the Milky Way. The survey uses the ALFA receiver on the 305 m Arecibo Radio Telescope. This region of the sky is termed the Zone of Avoidance by extragalactic astronomers because of its low-galaxy detection rate. Extragalactic observations at visual wavelengths struggle with high extinction levels. Near- and far-infrared observations suffer confusion with Galactic stars, dust, and gas. The 21 cm line observations are sensitive to late-type galaxies in general and are not affected by extinction. As a spectral-line survey, we generally only have confusion with galaxies within approximately ±100 km s⁻¹ of the ALFA ZOA survey is sensitive to galaxies behind the Milky Way that go undetected at other wavelengths. It has been suggested by Loeb & Narayan (2008) that undiscovered mass behind the Milky Way may explain the discrepancy between the cosmic microwave background dipole and what is expected from the gravitational acceleration imparted on the Local Group by matter in the local universe (Erdogdu et al. 2006).

Two large area HI ZOA surveys have preceded ALFA ZOA; the Dwingeloo Obscured Galaxies Survey and the H I Parkees Zone of Avoidance Survey (HIZOA). The Dwingeloo survey detected 43 galaxies in the northern hemisphere within ± 5° of the Galactic plane. It was sensitive only to nearby, massive objects because of its relatively high noise level of 40 mJy beam⁻¹ (with velocity resolution of 4 km s⁻¹; Henning et al. 1998). More recently, HIZOA covered decl. = −90 to +25 at 6 mJy beam⁻¹ rms (with velocity resolution of 27 km s⁻¹), and detected about 1000 galaxies (Donley et al. 2005; Henning et al. 2000, 2005; Shafi 2008).

The ALFA ZOA survey is being conducted in two phases: a shallow and a deep phase. The shallow phase (rms = 5 mJy with velocity resolution of 10 km s⁻¹) covers 900 deg² through the inner Galaxy (30° < l < 75°, |b| < 10°) and is expected to detect 500 galaxies. Hundreds of galaxies have been detected so far, and data reduction and analysis are ongoing. This is complemented by a deep survey (30° < l < 75°, 170° < l < 215°, |b| < 5°), five times more sensitive, in which we expect to detect thousands of galaxies but for which observations are not yet complete.

This paper presents the discovery and the results from follow-up observations of a nearby galaxy, ALFA ZOA J1952+1428. Section 2 describes the discovery and follow-up with the Arecibo Radio Telescope. Section 3 describes follow-up observations with the Expanded Very Large Array (EVLA). Section 4 describes ongoing optical follow-up with the 0.9 m Southeastern Association for Research in Astronomy (SARA) telescope. Section 5 discusses the results from these observations.

2. ARECIBO OBSERVATIONS AND RESULTS

ALFA ZOA J1952+1428 was initially detected with the shallow portion of the ALFA ZOA survey. Observations were taken with the Mock spectrometer covering 300 MHz bandwidth in two 170 MHz sub-bands of 8192 channels each, giving a Hanning-smoothed velocity resolution of 10 km s⁻¹ at z = 0. The survey uses a meridian nodding mode observation technique: the telescope slews up and down in zenith angle along

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5 Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which, when the observations were made, was operated by Cornell University under a cooperative agreement with the NSF.

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

7 The SARA-North telescope at Kitt Peak National Observatory is owned and operated by the SARA consortium.
the meridian for an effective 8 s integration time per beam giving rms = 5 mJy per beam. Observations were taken in 2008 and 2009. The angular resolution of the survey is 3′. More details of the ALFA ZOA survey techniques are presented by Henning et al. (2010).

In order to confirm this detection, it was followed up with the L-band Wide receiver on the Arecibo telescope for 180 s of integration time using a total power on–off observation. Data were taken with the Wideband Arecibo Pulsar Processor (WAPP) spectrometer with 4096 channels across a bandwidth of 25 MHz giving a velocity resolution of 1.3 km s\(^{-1}\) and rms = 2.5 mJy.

The spectrum from the follow-up observation can be seen in Figure 1. The velocity width at 50% peak flux is \(w_{50} = 28 \pm 2\) km s\(^{-1}\). The integrated flux density is \(F_{\text{HI}} = 0.94 \pm 0.07\) Jy km s\(^{-1}\). Errors were calculated as in Henning et al. (2010) following the methods of Koribalski et al. (2004). ALFA ZOA J1952+1428 has no cataloged counterparts within 7′ (two Arecibo half-power beamwidths) in the NASA Extragalactic Database (NED).

3. EVLA OBSERVATIONS, DATA REDUCTION, AND ANALYSIS

Follow-up C-configuration EVLA observations were carried out to obtain high-resolution \(\text{H}_1\) imaging of ALFA ZOA J1952+1428. The observations were scheduled dynamically for 3 \(\times\) 1 hr sessions and observed on 2010 December 3 and 4. We utilized the Wideband Interferometric Digital Architecture (WIDAR) correlator with 2 MHz bandwidth over 256 spectral channels, resulting in 7.8 kHz (1.6 km s\(^{-1}\)) channel width. The on-source integration time was two hours. The source 3C48 was used to calibrate the flux density scale and the source J1925+2106, 9° from the target source, was used to calibrate the complex gains. The editing, calibration, deconvolution, and processing of the data were carried out in AIPS. Line-free channels were extracted from the spectral-line data cube and averaged to image the continuum in the field of the \(\text{H}_1\) source and to refine the phase and amplitude calibration. The resulting phase and amplitude solutions were applied to the spectral-line data set, and a continuum-free UV data cube was constructed by subtracting the continuum emission. We then created a total intensity (Stokes I) \(\text{H}_1\) image cube that was CLEANed using natural weighting giving a synthesized beamwidth of 15′13 × 13′13 and an rms noise level of 2.6 mJy beam\(^{-1}\). Moment 0 (\(\text{H}_1\) flux density), moment 1 (velocity field), and moment 2 (velocity dispersion) maps were produced from the \(\text{H}_1\) image cube by smoothing across three velocity channels (5 km s\(^{-1}\)) and five pixels spatially (20″ at 4″ per pixel) and clipping at 2.6 mJy (the 1σ level of the unsmoothed cube). These maps can be seen in Figure 2.

The angular extent of the \(\text{H}_1\) out to 1 \(M_\odot\) pc\(^{-2}\) is 44′′ × 40′′. The \(\text{H}_1\) flux density shows a main peak and a secondary peak 16′′ away that overlaps a region of high velocity as well as significant velocity dispersion. The velocity field shows structure but non-uniform rotation. The integrated flux from the Arecibo and the EVLA spectra are 0.94 ± 0.07 Jy km s\(^{-1}\) and 0.80 ± 0.13 Jy km s\(^{-1}\), respectively. The EVLA recovered all integrated flux to within 1σ. A comparison of the \(\text{H}_1\) profile between Arecibo and the EVLA can be seen in Figure 1.

4. OPTICAL OBSERVATIONS, DATA REDUCTION, AND ANALYSIS

Digitized Sky Survey\(^8\) (DSS) images show what looks to be a very faint, uncataloged galaxy that may be the optical counterpart of ALFA ZOA J1952+1428. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope.

\(^8\) The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166.
were processed into the present compressed digital form with the permission of these institutions.

9 This research has made use of data obtained from the SuperCOSMOS Science Archive, prepared and hosted by the Wide Field Astronomy Unit, Institute for Astronomy, University of Edinburgh, which is funded by the UK Science and Technology Facilities Council.

Figure 2. 2′ × 2′ SARA B-band image and EVLA moment maps. Top: H\textsc{i} column density map overlayed on a SARA B-band image. Contours are at 1, 2, 3, 4, 5, 6 × 10^{20} cm\(^{-2}\). The H\textsc{i} peak is offset by 8′.7 from the apparent optical counterpart. Center: velocity field of ALFA ZOA J1952+1428 showing structure but not uniform rotation with contours at 274, 279, and 284 km s\(^{-1}\). Bottom: velocity dispersion map showing with contours at 2, 6, 9, and 12 km s\(^{-1}\). (A color version of this figure is available in the online journal.)

5. DISCUSSION

5.1. Distance

ALFA ZOA J1952+1428 has a heliocentric velocity of \(v_{\text{hel}} = +279\) km s\(^{-1}\). Solving for its Local Group centered velocity using derivations of the solar motion with respect to the Local Group by Courteau & van den Bergh (1999) gives \(v_{\text{LG}} = 491\) km s\(^{-1}\). Using Hubble’s Law with \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\) puts this source at a distance of 7 Mpc. However, Hubble’s Law is not a reliable distance indicator here because the dispersion of peculiar velocities in the local universe (\(v_{\text{hel}} < 10,000\) km s\(^{-1}\)) is \(\sigma = 298 \pm 34\) km s\(^{-1}\) (Masters 2008). The galaxy is probably not closer than 3 Mpc as the H\textsc{i} linear size at this distance would be smaller than most compact galaxies containing H\textsc{i} (Huchtmeier et al. 2007). For the following analysis, we take the distance to be 7 Mpc, although future observations may well revise this number.

5.2. Classification

As can be seen in the EVLA and SARA images, the H\textsc{i} peak is slightly offset (\(\Delta\theta = 8′.7\)) from the optical emission, indicating either a false counterpart or a disturbed H\textsc{i} distribution. The offset is \(\sim 300\) pc at 7 Mpc, which is not uncommon even for isolated galaxies (cf. ~400 pc offset in VV 124, Bellazzini et al. 2011). This could conceivably be a pair of low surface brightness dwarf galaxies (cf. HIZSS 3 with separation of ~900 pc; Begum et al. 2005), but there is no evidence for a second peak in the high signal-to-noise H\textsc{i} spectrum shown in Figure 1. Further, ALFA ZOA J1952+1428 has half the velocity width that the H\textsc{i} peak is offset by 8′.7 from the apparent optical counterpart.
pair in HIZSS 3 appeared to have; $W_{50} = 55$ km s$^{-1}$ for HIZSS 3 (Henning et al. 2000) compared to $W_{50} = 28$ km s$^{-1}$ here. Any second galaxy would have to be much closer both spatially and in velocity than the pair in HIZSS 3 in order to escape detection. Deeper interferometric observations would be needed to be entirely conclusive.

It is possible that ALFA ZOA J1952+1428 is a high-speed cloud (HVC) co-incident with an optical source (cf. HIPASS J1328–30; Grossi et al. 2007), though this is unlikely as there is strong evidence that ALFA ZOA J1952+1428 is not an HVC. Its recessional velocity does not lie near HVCs in this part of the sky (cf. Figure 3(a) in Morris et al. 2000). The nearest population of HVCs is the Smith Cloud which lies 10° and 170 km s$^{-1}$ away (Lockman et al. 2008) at its nearest point. If ALFA ZOA J1952+1428 were an HVC, it would be a remarkable outlier. Furthermore, the velocity field of ALFA ZOA J1952+1428 shows a gradient 10 times larger than those of HVCs (Begum et al. 2010).

ALFA ZOA J1952+1428 appears to be a dwarf galaxy judging from its Gaussian H$\text{i}$ profile and low H$\text{i}$ mass. At a distance of 7 Mpc, $M_{H\text{i}} = 10^{5.9} M_{\odot}$, which is significantly lower than the gaseous content of spiral-type galaxies (Roberts & Haynes 1994). Also, its low luminosity ($L_B = 10^{7.5} L_{\odot}$ at 7 Mpc), H$\text{i}$ content, and blue colors are strong evidence that it is not an early-type galaxy.

There is no possible counterpart visible in Two Micron All Sky Survey (2MASS) archive images or listed within 8' in the 2MASS Extended Source Catalog (Jarrett et al. 2000). We plan follow-up NIR observations later this year with the 1.4 m Infrared Survey Facility in Sutherland, South Africa. We will use observations by its main instrument, SIRIUS, which has three detectors that operate simultaneously ($J$, $H$, and $K_s$) with a field of view of $7.8 \times 7.8$ arcmin.

Table 1 summarizes the observational data and derived quantities. Columns 1 and 2 give equatorial coordinates (J2000) for the H$\text{i}$ peak. Columns 3 and 4 give the Galactic coordinates. Column 5 gives the heliocentric velocity from the midpoint of the velocity width at 50% peak flux. Column 6 gives the velocity width at 50% peak flux. Column 7 gives the integrated flux. Column 8 gives the $M_{H\text{i}}/L_B$ ratio using the $m_B$ calculated from the SARA telescope. The error on $L_B$ is dominated by the unknown uncertainty in $A_B$, thus we do not quote an error on $M_{H\text{i}}/L_B$. Column 9 gives the angular size of the H$\text{i}$ out to the 1 $M_{\odot}$ pc$^{-2}$ level. The last two columns give values as a function of the distance to the galaxy in Mpc. Column 10 gives the linear size of the H$\text{i}$ at its largest extent. Column 11 gives total H$\text{i}$ mass.

### 5.3. Morphological Type

Compared to other dwarf galaxies (Roberts & Haynes 1994; O’Neil et al. 2000), ALFA ZOA J1952+1428 is not particularly gas rich, $M_{H\text{i}}/L_B = 0.3 M_{\odot}/L_{\odot}$, but it is very small and blue with an H$\text{i}$ linear size of 1.4 x 1.3 kpc at 7 Mpc and $B - R = 0.1$ mag. The H$\text{i}$ mass, $M_{H\text{i}}/L_B$ ratio, blue optical colors, and linear size of ALFA ZOA J1952+1428 are similar to those of blue compact dwarf (BCD) galaxies (Huchtmeier et al. 2007). BCDs are small, blue, irregular dwarf galaxies, which have low surface brightness features, ongoing star formation, and higher metallicities than typical dwarf galaxies. The velocity field of ALFA ZOA J1952+1428 shows structure, but non-uniform rotation which is common in BCD galaxies (Ramya et al. 2011). The velocity dispersion map shown in Figure 2 shows a significant amount of dispersion around the stellar looking object on the left side of the galaxy. This could be an ionized hydrogen region. He observations with the SARA telescope will examine this and quantify the star formation in this system. Deep $B$-, $V$-, and $R$-band observations with the SARA telescope will reveal whether there are low surface brightness features in ALFA ZOA J1952+1428.

Alternatively, there is evidence for the existence of blue, metal-poor, gas-rich dwarf galaxies on the margins of galaxy groups (Grossi et al. 2007). These dwarfs are old (2–10 Gyr) but have had remarkably little star formation in their history. They are thought to be galaxies in transition between dwarf irregular and dwarf spheroidal galaxies. ALFA ZOA J1952+1428 differs from the Grossi et al. galaxies because it has a lower $M_{H\text{i}}/L_B$ ratio and appears to be a field galaxy, though it may be a part of a group behind the Milky Way that has not yet been discovered.

There is a recently discovered Local Group galaxy, VV124 (Bellazzini et al. 2011), which is similar to ALFA ZOA J1952+1428 in size, H$\text{i}$ mass, and $M_{H\text{i}}/L_B$ ratio. This galaxy is isolated, as ALFA ZOA J1952+1428 appears to be. There is only one galaxy (3:8 away) with $v_{hel} < 1000$ km s$^{-1}$ within 10° of ALFA ZOA J1952+1428 in NED (though this is not unusual in the ZOA). VV124 also shows an offset between the H$\text{i}$ and the optical counterpart as well as a velocity field with structure but non-uniform rotation. VV124 is considered to be a precursor of modern dwarf spheroidal galaxies that did not undergo an interaction-driven evolutionary path. Follow-up observations will reveal whether ALFA ZOA J1952+1428 has metallicity and star formation rates similar to a VV124-type galaxy.

### 5.4. Group Membership

It is possible that ALFA ZOA J1952+1428 is a Local Group galaxy, but it appears unlikely; ALFA ZOA J1952+1428 does not follow the relationship between radial velocity and angle from the solar apex that most other Local Group members do, as can be seen in Figure 3 (Courteau & van den Bergh 1999). Further, the linear size of the H$\text{i}$ would be 210 pc at 1 Mpc, which is four times smaller than the smallest compact dwarfs (Huchtmeier et al. 2007).

There are no known galaxy groups within 60° with $v_{hel} < 1000$ km s$^{-1}$ (Fouqué et al. 1992), making ALFA ZOA J1952+1428 either a field galaxy or a member of an undiscovered nearby group. Continued analysis of the ALFA ZOA data may clarify this.

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### Table 1

Properties of ALFA ZOA J1952+1428

| R.A. (J2000.0) | Decl. (J2000.0) | $I$ (deg) | $b$ (deg) | $v_{hel}$ (km s$^{-1}$) | $W_{50}$ (km s$^{-1}$) | $F_{H\text{i}}$ (Jy km s$^{-1}$) | $M_{H\text{i}}/L_B$ ($M_{\odot}/L_{\odot}$) | $H\text{i}$ Size (arcsec) | $A_B$ (mag) | $M_{H\text{i}}$ ($M_{\odot}$) |
|----------------|----------------|-----------|-----------|-------------------------|------------------------|-----------------------------|--------------------------------|-------------------------|-----------|--------------------------|
| 19 52 11.8     | +14 28 24      | 52.82     | −6.42     | 279 ± 1                 | 28 ± 2                 | 0.94 ± 0.07                 | 0.3                           | 44 x 40                  | 0.21D     | $10^{5.3} D^2$           |
Figure 3. Heliocentric velocity versus the cosine of the angular distance from the solar apex (modified with permission from Courteau & van den Bergh 1999). The black dots are Local Group galaxies and the red, open circle is ALFA ZOA J1952+1428. The solid line represents the solar motion solution of Courteau and van den Bergh ($v = 306$ km s$^{-1}$, $l = 99^\circ$, $b = -3^\circ$). The dotted lines represent the Local Group radial velocity dispersion, $\sigma_r = 61$ km s$^{-1}$.

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

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