AGC198606: A gas-bearing dark matter minihalo?

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Abstract

We present neutral hydrogen (HI) imaging observations with the Westerbork Synthesis Radio Telescope of AGC198606, an HI cloud discovered in the ALFALFA 21cm survey. This object is of particular note as it is located 16 km s\(^{-1}\) and 1.2 from the gas-bearing ultra-faint dwarf galaxy Leo T while having a similar HI linewidth and approximately twice the flux density. The HI imaging observations reveal a smooth, undisturbed HI morphology with a full extent of 23′×16′ at the 5 × 10\(^{14}\) atoms cm\(^{-2}\) level. The velocity field of AGC198606 shows ordered motion with a gradient of ∼25 km s\(^{-1}\) across ~20′. The global velocity dispersion is 9.3 km s\(^{-1}\) with no evidence for a narrow spectral component. No optical counterpart to AGC198606 is detected. The distance to AGC198606 is unknown, and we consider several different scenarios: physical association with Leo T, a minihalo at a distance of ~150 kpc based on the models of Faerman et al. (2013) and a cloud in the Galactic halo. At a distance of 420 kpc, AGC198606 would have an HI mass of 6.2 × 10\(^5\) M\(_\odot\), an HI radius of 1.4 kpc, and a dynamical mass within the HI extent of 1.5 × 10\(^8\) M\(_\odot\).

Key words. galaxies: dwarf — galaxies: ISM — Local Group — radio lines: galaxies

1. Introduction

While ΛCDM provides an overall successful theoretical framework towards understanding the observations of galaxy clustering, properties, and evolution, large discrepancies have been noted between the predicted number of low mass dark matter (DM) halos and the abundance of observed dwarf galaxies (e.g., Klypin et al. 1999). This is generally attributed to the inability of halos to retain their baryons, which increases progressively with decreasing halo mass (Kravtsov 2010). The interesting question thus arises: what is the smallest mass halo capable of hosting an observable baryonic counterpart? The discovery of ultralight dwarf galaxies (UDFs) around the Milky Way (MW) highlights that galaxies with minimal stellar components (M\(_{\text{star}}\) ≤ 10\(^3\) M\(_\odot\)) can exist. However, it is not clear whether their small stellar populations are the result of evolution or interaction with the MW (e.g., McConnachie 2012; Muñoz et al. 2010).

Following the pattern of morphological segregation, gas-rich dwarf systems are seen prevalently in the periphery of the Local Group (Grebil 1999). This pattern continues with the UDFs; the most distant UDF (Leo T; d = 420 kpc) is the only one with detected HI (Spekkens et al. 2014). In a variation of the idea previously proposed by Blitz et al. (1999) and Braun & Burton (1999), we proposed in Giovaneli et al. (2010) that gas-rich low-mass halos may be detected in the HI 21cm line as ultra-compact high velocity clouds (UCHVCs). Using the ALFALFA survey data (Giovanelli et al. 2005), we presented a catalog of UCHVCs (Adams et al. 2013) as potential minihalo candidates, consistent with the models of Faerman et al. (2013, hereafter F13) for gas in low mass DM halos (see also Sternberg et al. 2002). The discovery of the extremely metal-poor, star forming dwarf galaxy Leo P via its HI content in the ALFALFA survey validates the idea that gas-rich galaxies within the Local Group or its immediate environs can be identified via this tracer (Giovanelli et al. 2013; Rhode et al. 2013; Skillman et al. 2013).

The ALFALFA source AGC198606 has properties quite similar to those of the Adams et al. (2013) UCHVCs, except for its radial velocity (cz = 51 km s\(^{-1}\)) being lower than the cutoff used in that work. Its similarity to the properties of the HI component of Leo T and nearby location (separated by 1.2 and 16 km s\(^{-1}\)) was noted by RG and MPH, and thus it received the nickname "friend of Leo T". In this paper we explore the possibility that AGC198606 is a system similar to Leo T and Leo P, except for having a less substantial stellar population.

2. Data

2.1. WSRT HI Data

The HI in AGC198606 was observed using two 12-hour tracks with the Westerbork Synthesis Radio Telescope (WSRT) in June 2013 and January 2014. The spectral setup was a 10 MHz bandwidth divided into 2048 channels, providing a nominal velocity resolution of 1 km s\(^{-1}\). Standard data calibration and reduction was undertaken in Miriad (Sault et al. 1995) imaging was done...
AGC198606 is a low surface brightness object, so the data were tapered to lower spatial resolution and binned in velocity to increase the signal-to-noise ratio. AGC198606 was imaged at 210'' resolution (ALFALFA spatial resolution), 105'' resolution, and 60'' resolution. At resolutions higher than 60'', the full flux of the system is no longer recovered.

A single channel image ($\Delta v = 46$ km s$^{-1}$) was created for each spatial resolution and used to isolate the emission; this was used as an input mask for cleaning spectral data cubes with HI column density contours overlaid. The observed total flux density is 14.8 ± 1.5 Jy km s$^{-1}$. Contours from the total intensity HI maps at 210'' and 105'' resolution are shown in the left column of Figure 1 AGC198606 is roughly circular in the inner extent with the outer envelope showing elongation in the north-south direction. At 210'' resolution, the outermost HI extent ($5 \times 10^{18}$ atoms cm$^{-2}$) is 23'x16'. The half-flux radius is 5.5 ± 0.5, and the peak column density at 60'' resolution is $6 \times 10^{19}$ atoms cm$^{-2}$.

The kinematics of AGC198606 were studied by fitting Gaussians to spectral data cubes where the signal was above the 5-$\sigma$ level. The resulting velocity fields and position-velocity slices (left and right columns of Figure 1, respectively) show a velocity gradient of ~25 km s$^{-1}$ across ~20'', aligned with the major axis of the HI emission. The turn-over in the velocity gradient at the southern edge of the 210'' velocity field is a result of diffuse emission at low velocities (including minor contamination from Galactic HI, which we estimate to contribute to the final HI flux integral at the ~1% level) affecting the fit. This is also seen as an increase in the velocity dispersion (upper middle of Figure 1).

The velocity dispersion maps show the velocity dispersion is at least 7 km s$^{-1}$ across the full extent of AGC198606. In order to search for a narrow spectral component from the presence of a cold neutral medium (CNM), the centers of the fitted Gaussians were used to shift the spectra at each pixel to the result of the Gaussian fitting. Contours show lines of constant velocity from the velocity fields (left) and are at values of [41, 43.5, 46, 48.5, 51, 53.5, 56] km s$^{-1}$. Right column: Position-velocity slice along the major axis (shown in left panels). Contours are spaced at 3-$\sigma$ for the 210'' and 105'' data $\sigma$ is 2.11 and 1.07 mJy beam$^{-1}$, respectively. The dashed line is the recessional velocity $cz = 50.9$ km s$^{-1}$, and the solid lines are offset by ±12.5 km s$^{-1}$.

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\[ M_{dyn} = 2.325 \times 10^5 \left( \frac{V_{mic}^2 + 3\sigma^2}{\text{km}^2 \text{s}^{-2}} \right) \left( \frac{r}{\text{kpc}} \right) M_\odot \] (1)

Assuming there is no rotation and that the global $W_0$ represents the dynamics of the system, we find a lower limit to the dynamical mass of $2.5 \times 10^5 d_{200} M_\odot$. The alignment of the velocity gradient with the major axis of the HI emission and the clear

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1 Common Astronomy Software Applications (CASA) is developed and maintained by the National Radio Astronomy Observatory.
structure in the position-velocity slices (seen in Figure 1), are indicative of rotation with an uncorrected amplitude of ≈12.5 km s\(^{-1}\). The inclination of AGC198606 is estimated from the HI data to be 64°; then the rotation velocity is ≈14 km s\(^{-1}\). For an intrinsic velocity dispersion of 9.3 km s\(^{-1}\), the lower limit to the dynamical mass then increases to 3.5 × 10\(^8\) \(M_\odot\). Varying the rotation velocity from [12.5 − 20] km s\(^{-1}\) results in a dynamical mass range of [3.2 − 5.1] × 10\(^8\) \(M_\odot\).

2.2. WIYN Data

Deep observations of AGC198606 were taken on 15 March 2013 with the partially-filled One Degree Imager (pODI; ∼24′×24′ field of view) on the WIYN 3.5m telescope at Kitt Peak National Observatory as part of a larger observing program aimed at characterizing the stellar populations of the UCHVCs (Janesh et al., in prep). Nine 300-second exposures were obtained in a dither pattern in both the SDSS \(g′\) and \(i′\) filters.

The WIYN pODI images were transferred to the ODI Pipeline, Portal, and Archive (ODI-PPA) at Indiana University and processed with the QuickReduce data reduction pipeline (Kotulla 2014). The reduced images were reprojected to a common pixel scale, scaled to a common flux level, and combined to create a deep stacked image in each filter. SDSS stars present in the images were used to calculate photometric calibration coefficients for converting instrumental magnitudes to calibrated values; errors on the zero points were <0.02 magnitude.

The final mean FWHM of point sources is 0.72″ in the stacked \(g′\) image and 0.78″ in the stacked \(i′\) image. The 5-σ limit on the brightness of a point source in the \(g′\)-band image is \(g′ = 25.3\). For the \(i′\) image, the corresponding 5-σ limit is \(i′ = 24.6\). We searched for an optical counterpart by first detecting all sources in the images above a modest (∼4-σ) signal-to-noise threshold, performing photometry on the detected sources, removing extended objects, applying a color-magnitude filter based on the expected stellar population for a range of distances from 0.16 to 2.5 Mpc, and implementing a smoothing algorithm to look for an overdensity of stars in the set of filtered objects. The pODI images and our search process reveal no obvious stellar counterpart for AGC198606. To estimate an upper limit for the total optical luminosity associated with AGC198606, we masked out bright foreground stars and obvious background galaxies in the combined \(i′\)-band image. We then measured the total sky-subtracted flux in an aperture of radius equal to the half-light radius of Leo T (1.4′; Irwin et al. 2007) centered on the HI centroid in Table 1. The measured \(i′\)-band flux within this aperture yields a limit to the total apparent magnitude of \(m_{i′} ≃ 16.5\). At the distance of Leo T (420 kpc), this corresponds to an absolute magnitude of \(M_{i′} ≃ −6.6\). Note that the measured apparent magnitude includes light from stars faint enough to be in a dwarf galaxy at this distance as well as light from any unmasked background galaxies. Further details of our search methods will be presented in Janesh et al. (in prep.).

3. The Nature of AGC198606

In this section we discuss two possible scenarios for AGC198606: that it is a gas-bearing minihalo or part of the population of HI clouds in the Galactic halo.

3.1. Gas-bearing minihalo

At the distance of Leo T (420 kpc), AGC198606 would have an HI mass of 6.2 × 10\(^5\) \(M_\odot\), an HI radius at the 2×10\(^5\) atoms cm\(^{-2}\) level of 600 pc, a full HI extent of 2.8×2.0 kpc, and a dynamical mass within the full HI extent of 1.5×10\(^6\) \(M_\odot\). Leo T has a stellar mass of 1.2 × 10\(^5\) \(M_\odot\), an HI mass of 2.8 × 10\(^5\) \(M_\odot\), an HI radius of 300 pc (at the 2×10\(^5\) atoms cm\(^{-2}\) level), and an indicative dynamical mass (based on Eqn [1]) of ≃1×10\(^5\) \(M_\odot\). (Ryan-Weber et al. 2008). AGC198606 would have about twice the HI mass and size as Leo T, but its peak HI column density is significantly lower, potentially explaining the apparent lack of a stellar counterpart. In this scenario, the two systems would have a projected separation of 8.4 kpc and could be a bound pair of satellites similar to Leo IV and Leo V (de Jong et al. 2010). The ALFALFA data do not reveal HI emission connecting AGC198606 to Leo T; low level emission connecting the two cannot be ruled out as Leo T lies at the same velocity as strong foreground Galactic HI emission.

Applying the models from [3] for a flux density of 14.8 Jy km s\(^{-1}\), a half-flux radius of 5.5, and a peak column density of 6×10\(^19\) atoms cm\(^{-2}\) gives a distance estimate of 120−180 kpc for a typical flat-cored halo. At a distance of 150 kpc, AGC198606 would have an HI mass of 7.9 × 10\(^5\) \(M_\odot\), an HI half-flux radius of 240 pc, a full HI extent of 1.0 × 0.70 kpc, and a dynamical mass of 5.3 × 10\(^5\) \(M_\odot\). These HI properties are similar to those of Leo T, and the HI kinematics are similar to Leo P. HI imaging observations of Leo P reveal a rotational velocity of 15 km s\(^{-1}\) at an HI radius of 500 pc (Bernstein-Cooper et al. 2014). With less HI than Leo T and no CNM (seen in both Leo T and Leo P), the lack of a clear stellar component is understandable. However,
at this close distance, the question arises of how a small object could retain its HI gas in the presence of the MW’s hot corona.

The baryonic Tully-Fisher relation (BTFR) relates baryonic mass to rotational velocity over 5 orders of magnitude (McGaugh 2012). Figure 2 shows the BTFR from McGaugh (2012) with AGC198606 overplotted based on its total atomic gas mass to rotational velocity over 5 orders of magnitude (McGaugh 2012). AGC198606 is shown at 420 kpc (cyan star) and 150 kpc (magenta star).

4. Summary

AGC198606 is a compact HI cloud identified within the ALFALFA HI survey. It is of particular interest as it is near the gas-bearing UFD Leo T spatially and kinematically, and it has similar HI properties as measured by the single-dish ALFALFA survey. This makes it an excellent candidate to test a (nearby) starless gas-bearing DM halo. Imaging observations with WSRT show that AGC198606 has an HI mass of $3.5 \times 10^5 M_\odot$, an HI radius of 3.3 $d_{200}$ kpc, and an ordered velocity gradient of $\sim 25$ km s$^{-1}$ along the HI major axis. Deep optical imaging with the WIYN 3.5m telescope reveal no obvious stellar counterpart; future work will quantify the stellar population that could be detected in these images (Janesh et al. in prep). Without the direct identification of a stellar counterpart to constrain the distance to AGC198606, its true nature remains uncertain, and we discuss several plausible distances for AGC198606. If physically associated with Leo T, AGC198606 would have about twice the HI mass and size. Alternatively, it could be at a closer distance of 150 kpc suggested by the models in FT13. The HI morphology of AGC198606 is different from observations of clouds in the Galactic halo with no evidence for cores, although they could exist at scales smaller than 60′. HI imaging observations of other UCHVCs will offer further context for the UCHVCs and help determine if the HI structure of AGC198606 is different from that of Galactic halo clouds.

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