A dearth of atomic hydrogen in NGC1052-DF2

Aditya Chowdhury\textsuperscript{1}*

\textsuperscript{1}National Centre for Radio Astrophysics, Tata Institute of Fundamental Research (NCRA-TIFR), Pune 411007, India.

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ABSTRACT

The recently claimed discovery of an ultra-diffuse galaxy lacking dark matter has important implications for alternate theories to dark matter as well as models of galaxy formation in the lambda cold dark matter context. In this letter, we present a deep Giant Metrewave Radio Telescope search for atomic hydrogen in this ultra-diffuse galaxy, NGC1052-DF2. We report a non-detection of the H\textsc{i} 21cm transition from the galaxy and place a stringent upper limit on the H\textsc{i} mass of the galaxy - M\textsubscript{H\textsc{i}} < 3.15 \times 10^{8} (\textit{AV}/20 \text{ km}/\text{s})^{1/2} M_{\odot} (3\sigma). This makes NGC1052-DF2 an extremely gas-poor galaxy with an atomic gas to stellar mass fraction of M\textsubscript{H\textsc{i}}/M_{*} < 0.016 (\textit{AV}/20 \text{ km}/\text{s})^{1/2} (3\sigma). Such low gas fractions are typical of dwarf ellipticals in dense environments and would be consistent with NGC1052-DF2 having undergone a tidal stripping event which can also explain its apparent lack of dark matter.

Key words: galaxies: dwarf – galaxies: formation – galaxies: peculiar

1 INTRODUCTION

Ultra Diffuse Galaxies (UDGs) are a class of low surface brightness galaxies with masses comparable to those found in dwarfs (M_{\text{vir}} \sim 10^{8} M_{\odot}) but sizes of typical \textit{L}_{\text{vir}} galaxies like the Milky Way (R_{\text{vir}} \sim 1.5 – 5 \text{ kpc}) (van Dokkum et al. 2015). The initial discovery of such galaxies in cluster and group environments (e.g Koda et al. 2015; Martínez-Delgado et al. 2016; Merritt et al. 2016; van der Burg et al. 2016; Yagi et al. 2016) was seen as evidence for UDGs being failed \textit{L}_{*} galaxies, residing in large dark matter halos with early quenching of star formation (for example van Dokkum et al. 2016, found evidence for a UDG to reside in a milky way sized dark matter halo). The quenching of these galaxies are attributed to gas stripping in high-density environment (e.g Burkert 2017; Baushev 2018). On the other hand, there have been observational evidences to suggest that contrary to the failed \textit{L}_{*} galaxy picture, most UDGs reside in dwarf-sized halos (e.g Beasley & Trujillo 2016; Amorisco et al. 2018). Di Cintio et al. (2017) used high-resolution N-body simulations to suggest that UDGs form in dwarf halos as a consequence of episodes of gas outflows driven by stellar feedback. The other possible formation scenario, suggested by Amorisco & Loeb (2016), is that UDGs are dwarf galaxies that reside in halos at the high end of the spin distribution leading to an extended disk. The discovery of ~ 100 isolated UDGs from a HI selected sample by Leisman et al. (2017) provided important clues to their formation. The authors found that UDGs do reside in dwarf-like halos as well as have a higher spin.

A recent analysis of the UDG NGC1052-DF2, a satellite of the elliptical galaxy NGC1052, by van Dokkum et al. (2018b) (hereafter vD18) found evidence for anomalous kinematics which were interpreted as the galaxy containing very little dark matter. The discovery, if confirmed, may have far-reaching implications for alternate theories of dark matter such as MOND and emergent gravity which predict that signatures of "dark matter" will always be detected in galaxies. Famaey et al. (2018); Kroupa et al. (2018) investigate the dynamics of NGC1052-DF2 in the MOND paradigm and conclude that the current data are insufficient to rule out a MOND-based interpretation. On the other hand, the discovery is also interesting in the light of galaxy formation in the standard \textit{Lambda} CDM cosmology; for example, Ogiya (2018) found that tidal stripping of NGC1052-DF2’s progenitor in the gravitational field of the elliptical, NGC1052, can produce a galaxy with properties similar to those observed.

The conclusions of vD18 depend primarily on two observational quantities - (i) The distance to NGC1052-DF2, and (ii) The velocity dispersion of the galaxy. Trujillo et al. (2018) found a distance to NGC1052-DF2 of 13 Mpc , placing the galaxy significantly closer compared to the 20 Mpc distance found by vD18. This revised distance estimate lead to a significantly reduced stellar mass and hence enough room for dark matter in the galaxy. Subsequently, van Dokkum et al. (2018a) refuted this claim as a misidentification of the galaxy’s Tip of the Red Giant Branch. Recently, Blakeslee & Cantiello (2018) presented an independent analysis of the distance to NGC1052-DF2 supporting the original findings of vD18.

The intrinsic velocity dispersion of the galaxy was determined by fitting the observed \textit{48,664.5 CaII lines} to...
the spectra of 10 globular cluster like objects in the galaxy (vD18). Based on the biweight dispersion of the globular cluster velocities, these authors reported an intrinsic velocity dispersion of $\sigma_{\text{int}} = 3.2_{-1.3}^{+5.3}$ km/s and a 90% confidence upper limit of 10.5 km/s. Martin et al. (2018) argued that the biweight dispersion may be unsuitable for measuring velocity dispersion from such a small number of globular clusters. These authors used a Monte Carlo based analysis and found a 90% confidence upper limit of 18.8 km/s on the intrinsic velocity dispersion of NGC1052-DF2. Their measurement implies a much larger dynamical mass, refuting the claim that the galaxy has little dark matter for its stellar mass. Laporte et al. (2018) also performed an independent analysis of the intrinsic dispersion of the galaxy based on the available globular cluster data and found a 95% confidence upper limit of 20.5 km/s. Further, Hayashi & Inoue (2018) found that the dynamical mass estimate depends on the assumed model of the globular cluster distribution and the low number of detected globular clusters when fitted with a Sersic profile leaves enough room for the galaxy to host a dark matter halo.

An accurate measurement of the intrinsic velocity dispersion of the NGC1052-DF2 is thus necessary to confirm vD18’s claim that the galaxy contains very little dark matter. One of the ways of doing so is by detecting the diffuse H$\alpha$ emission from the galaxy. In this letter, we present deep H$\alpha$ observations of NGC1052-DF2 with the Giant Metrewave Radio Telescope (GMRT). The observation and the analysis of data are discussed in section 2. In section 3, we discuss the results and summarize this letter.

2 OBSERVATIONS AND DATA ANALYSIS

We used the GMRT to observe NGC1052-DF2 (RA=02h41m46.8s DEC=-08°24′12″) for a total on-source time of 10 h in 2018 June. We used the GMRT Wideband Backend in its 12.5 MHz bandwidth mode around 1411.75 MHz with 4096 channels. The spectral configuration allowed us to cover the entire velocity range of the NGC1052 group with a high velocity resolution of $\simeq 0.64$ km/s. NGC1052-DF2 is centred at a velocity of $v_0 = 1802 \pm 2$ km/s (vD18), corresponding to a redshifted H$\alpha$ centreclear frequency of 1411.91 MHz. For the purpose of this letter, we analyzed 512 channels around the line centre covering 1640.37 to 1664.15 km/s. We observed 3C48 to calibrate the flux scale and 0204+170 to calibrate the amplitude, phase and bandpass.

The data were flagged for RFI using AOFlagger (Offringa et al. 2012) and all subsequent flagging and analysis were done in CASA v5.3.0 (McMullin et al. 2007). Standard data analysis procedures were followed to obtain phase, amplitude, and bandpass solutions on the phase calibrator. These amplitude solutions were scaled using the observations on 3C28 and transferred to the source. The source field is dominated by the central galaxy of the group, NGC1052, which hosts an AGN and has a NVSS reported L-band flux of 912 mJy (Condon et al. 1998). NGC1052 is 13.5 arcmin away from the pointing centre and thus lies outside the GMRT primary beam half power point at these frequencies (at 1412 MHz, the primary beam half width at half maxima is 11.5 arcmin). Such a strong continuum source beyond the half power point made deconvolution using CLEAN very difficult due to systematic effects such as anisotropy of the primary beam, varying pointing errors as a function of time, etc. As a result of these difficulties, we self-calibrated the data using the following procedure : the CASA task fixvis was used to bring NGC1052 at the phase centre and then, given that NGC1052 is at least 10 times brighter than all other sources in the field, a standard point-source phase only calibration was done using the CASA task uvcalim. An amplitude selfcal was not done to avoid introducing errors in the flux scale from the time varying intensity of NGC1052 as seen by the array due to effects such as primary beam rotation. A first-order polynomial fit was done on each continuum visibility and subtracted out using the CASA task uvccontsub. Another phase rotation was performed on these continuum-subtracted visibilities to bring the target source back at the phase centre.

NGC1052-DF2 has an effective optical radius of $R_e = 22.6$ arcsec (vD18) and thus only short baselines of the GMRT were used to ensure maximum line sensitivity. The spectral imaging was done with natural weighting and a long baseline uvcut of 4k$A$ (\approx 1km) to produce spectral cubes with a spatial resolution of 43 arcsec $\times$ 35 arcsec. This cube was further convolved to a resolution of 1 arcmin, ensuring that our measurements include most of the H$\alpha$ emission from the galaxy.

3 DISCUSSION

We searched for H$\alpha$ emission from NGC1052-DF2 in the spectral cube at a wide range of velocity resolutions from 1.25 km/s to 30 km/s. These resolutions cover the wide range of reported uncertainties in the velocity dispersion of NGC1052-DF2(vD18,Martin et al. (2018)). We did not detect the H$\alpha$ line from the galaxy in any of the velocity resolutions. The spectra at each resolution was tested for gaussianity using the Anderson-Darling test and was found
to be consistent with random sampling from a normal distribution. Figure 1 shows the spectra at a velocity resolution of 20 km/s resolutions. This velocity resolution is at the lower end of typical line widths of UDGs in Leisman et al. (2017)’s sample and is comparable to the 18.5 km/s 90 % upper limit to the intrinsic dispersion by Martin et al. (2018).

The rms flux density of the spectra shown in Fig. 1 is 0.56 mJy. This flux density rms can be converted to a corresponding 3σ upper limit via the standard relation between the Hi21cm line flux (S) and the Hi mass of the galaxy (M_Hi) : M_Hi/M_⊙ = 2.35 x 10^6 (D/Mpc)^2/ S dV / Jy km/s), where D is the distance to the galaxy. With an assumed distance of 20 Mpc to NGC1052-DF2 (Blakeslee & Cantiello 2018; van Dokkum et al. 2018b,a), we derive a 3σ upper limit to the Hi mass of NGC1052-DF2 of 3.15 x 10^9 (ΔV/20 km/s)^1/2 M_⊙. For the stellar mass, M_ * = 2 x 10^9 M_⊙ (vD18), we find a stringent upper limit on the atomic gas fraction of M_HI/M_ * < 0.016 (ΔV/20 km/s)^1/2 (3σ). We note that this upper limit on the gas fraction is independent of the assumed distance to NGC1052-DF2 because both the stellar as well as the Hi mass has the same D^2 dependence.

Figure 2 compares the atomic gas fraction of NGC1052-DF2 to other galaxies. We note that all reported detections of Hi from UDGs are in low-density environments (e.g. Papastergis et al. 2017; Spekkens & Karunakaran 2018). For optically selected studies of UDGs, Spekkens & Karunakaran (2018) found blue UDGs around the Hickson Compact Groups to be broadly gas rich. On the other hand, Papastergis et al. (2017) found a mix population with three out of the four isolated UDGs targeted for Hi studies remaining undetected down to a gas fraction ~ 0.5. These authors suggest that there is a dichotomy in the UDG population with the formation mechanism of gas-poor UDGs being poorly understood. Leisman et al. (2017) found a high mean gas fraction, M_HI/M_ * = 35, in their sample of isolated UDGs but their sample is Hi selected and thus is biased towards detecting galaxies with high Hi content. Overall, compared to most UDGs detected in low-density environments, we find NGC1052-DF2 to be extremely gas-poor. The gas fraction upper limit is comparable to what is found for gas-poor dwarf ellipticals in cluster environments. For example, Hallenbeck et al. (2012) found an upper limit of M_HI < 10^5.5 M_⊙/5σ in a sample of dwarf ellipticals in the Virgo cluster. The lack of atomic gas in NGC1052-DF2 suggests that either (a) UDGs in clusters and groups form via a different evolutionary path than their low-density counterparts (see Carleton et al. 2018, for a formation mechanism of UDGs in clusters via tidal stripping and heating) (b) NGC1052-DF2 is a special case of a UDG that underwent tidal stripping leaving the galaxy with little dark matter as well as gas (Ogiya 2018).

In summary, we describe a sensitive Hi21cm observation towards NGC1052-DF2 with the GMRT. We report a non-detection of atomic gas in the galaxy with M_HI < 3.15 x 10^9 (ΔV/20 km/s)^1/2 M_⊙ (3σ) corresponding to very low gas fraction limit of M_HI/M_ * < 0.016 (ΔV/20 km/s)^1/2 (3σ). The non-detection does not lead to a resolution of the debate around NGC1052-DF2 containing little dark matter but suggests that the galaxy is similar to extremely gas-poor dwarf ellipticals; thus it is unlikely that a deep observation to detect the Hi21cm from this galaxy can be done using realistic telescope times. This study also suggests that a broad survey of atomic gas in UDGs residing in dense environments will be important to study their formation mechanism and evolutionary path viz. their lower density counterparts.

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