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Constraints on the H I Mass for NGC 1052-DF2

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Abstract

We report deep, single-dish 21 cm observations of NGC 1052-DF2, taken with the Green Bank Telescope. NGC 1052-DF2, proposed to be lacking in dark matter, is currently classified as an ultra-diffuse galaxy in the NGC 1052 group. We do not detect the galaxy, and derive an upper limit on the H I mass. The galaxy is extremely gas poor, and we find that a 3σ $M_{\rm H\,I}$ detection at a distance of 19 Mpc and using a line width of 3.2 km s^{-1} would have an upper limit of $M_{\rm H\,I,lim} < 5.5 \times 10^5\,M_\odot$. At this mass limit, the gas fraction of neutral gas mass to stellar mass is extremely low, at $M_{\rm H\,I}/M_\star < 0.0027$. This extremely low gas fraction, comparable to Galactic dwarf spheroidals and gas-poor dwarf ellipticals, implies that either the galaxy is within the virial radius of NGC 1052, where its gas has been stripped due to its proximity to the central galaxy, or that NGC 1052-DF2 is at a distance that is large enough to inhibit detection of its gas. We also estimate the upper limit of the H I mass of NGC 1052-DF2 resided at 13 Mpc. This would give an H I mass of $M_{\rm H\,I,lim} < 2.5 \times 10^5\,M_\odot$, and an H I gas fraction if $M_{\rm H\,I}/M_\star < 0.0024$, becoming even more extreme for its environment. While the dark matter fraction would be less extreme at this distance, the neutral gas fraction would be unprecedented for an object in a low-density environment.

Key words: galaxies: evolution – galaxies: structure – galaxies: dwarf

1. Introduction

The extremely low surface brightness galaxy NGC 1052-DF2 was discovered by Karachentsev et al. (2000), who labeled it a dwarf galaxy candidate. van Dokkum et al. (2018b) measured the total mass of the galaxy by measuring the radial velocities of 10 luminous globular clusters. Using the inferred velocity dispersion, van Dokkum et al. (2018b) determined the total mass within a 7.6 kpc radius to be less than $3.4 \times 10^8\,M_\odot$. These globular clusters trace the mass profile of NGC 1052-DF2 out to radii that are nearly as large as the virial radius of the galaxy ($\sim$10 kpc). The dark matter halo mass can be estimated using the dark matter halo mass/stellar mass ratio $M_{\rm halo}/M_\star$, where the expected $M_{\rm halo}/M_\star$ ratio for low-mass galaxies like NGC 1052-DF2 is greater than 30 (Moster et al. 2010; Behroozi et al. 2013). Comparing the estimated total mass with the derived stellar mass of the galaxy, which van Dokkum et al. (2018b) determined to be $M_\star \approx 2 \times 10^8\,M_\odot$, they obtained a $M_{\rm halo}/M_\star$ of order one. Thus, they proposed that the galaxy is deficient in dark matter.

If NGC 1052-DF2 is truly a galaxy lacking dark matter, the question of how dark matter is separated from baryonic matter remains. Clowe et al. (2006) showed that dark matter can be dissociated from galaxies if dark matter is bound to baryons through nothing but gravity. However, until now, previous attempts have not been fruitful in observing a galaxy without dark matter (Romanowsky et al. 2003; Peralta de Arriba et al. 2014).

Recently, Laporte et al. (2018) suggested a lack of robustness in the method used by van Dokkum et al. (2018b) to obtain the mass to light ratio, *M/L*, by using the globular clusters in NGC 1052-DF2. They show that similar methods applied to the well-studied Fornax dwarf spheroidal (dSph) would give wildly different dark matter halo mass estimates, with large scatter in the velocity dispersion at the 95% confidence level.

Trujillo et al. (2018) proposed that many of the unusual features of NGC 1052-DF2 may be explained if the galaxy, which van Dokkum et al. (2018b) estimated to be at a distance of 19 Mpc, was brought to a distance of 13 Mpc, making it a typical low surface brightness galaxy without the anomalies described by van Dokkum et al. (2018b). van Dokkum et al. (2018a) addressed this distance concern by analyzing the color–magnitude diagram of NGC 1052-DF2 and arriving at a distance that is consistent with the 19 Mpc estimate. They provided an additional distance estimate by applying a method free of calibration uncertainties, again arriving at the same 19 Mpc distance estimate. Blakeslee & Cantiello (2018) performed an independent analysis of the distance with similar conclusions of $D = 20.4 \pm 2.0$ Mpc. In this Letter, we provide the 21 cm neutral hydrogen (H I) mass upper limit calculations using the 19 Mpc distance estimate.

Most recently, Chowdhury (2019) found upper limits on the H I mass to be $M_{\rm H\,I,lim} < 3.15 \times 10^6\,M_\odot$ with 20 km s^{-1} resolution. Our observation with a single dish allowed us to go deeper, probing the extreme nature of this source, obtaining a more constrained upper limit.

This Letter proceeds as follows. In Section 2 we describe the parameters of our observations using the Green Bank Telescope (GBT). In Section 3 we present our results, calculate the upper limits, and describe our analysis of the data. In Section 4 we conclude with a discussion of the significance of these results for NGC 1052-DF2.

2. Observations

We searched for 21 cm (1.42 GHz) H I line emission from NGC 1052-DF2 using the Robert C. Byrd GBT in 2018

August (project GBT18A-508). We used the *L*-band (1.15–1.73 GHz) receiver with the VErsatile GBT Astronomical Spectrometer backend in spectral line mode. At these frequencies, the FWHM beamwidth is 9.′1.

Using globular clusters in NGC 1052-DF2, van Dokkum et al. (2018b) showed that the intrinsic velocity dispersion measured was $\sigma_v = 3.2^{+5.5}_{-3.2}$ km s^{-1}. Thus, we would expect the rotational velocity of NGC 1052-DF2 to be of the same order of magnitude. This requires a velocity resolution that is smaller than σ_v in order to measure an accurate H I line profile. As a result, we aimed for a velocity resolution of $\Delta v < 1$ km s^{-1} in the source rest frame.

To achieve a 1σ sensitivity of $\sigma_{\rm rms} < 1$ mJy with the observing setup described above, we tracked NGC 1052-DF2 for a total observing time of 4 hr and 15 minutes with the GBT. We observed over a bandwidth of 100 MHz and 131,072 channels, resulting in the native resolution of 0.76 kHz, or 0.16 km s^{-1}. We searched over the bandwidth for H I emission at a wide range of velocities (0–11,000 km s^{-1}) with a focus on the range around 1803 km s^{-1}, corresponding to an optical redshift of $z \sim 0.006$. We reduced the data using *getfs* in GBTIDL and averaged and baselined each spectrum that we obtained. We followed this procedure by smoothing the averaged data to multiple velocity resolutions. These are displayed in Figure 1, where there is no obvious signal detected.

We performed a search with the NASA/IPAC Extragalactic Database (NED[4]) using a 9′ search radius around NGC 1052-DF2, revealing no other likely sources of contamination at redshifts we can detect within the beam radius.

3. Results

We calculated our H I flux upper limit using

$$S_{\rm H\,I,lim} = 3\,\sigma_{\rm rms}\sqrt{W\,dv} \qquad (1)$$

where $\sigma_{\rm rms}$ is the measured noise in Jy/beam, W is the expected line width in km s^{-1}, and dv is the velocity resolution in km s^{-1}. The flux upper limit is in units of Jy km s^{-1}.

The H I mass of a source can be calculated using

$$M_{\rm H\,I} = 2.36 \times 10^5 D^2 \int_0^\infty S(v)dv\; M_\odot, \qquad (2)$$

where D is the distance to the source in Mpc and $\int_0^\infty S(v)dv$ is the integrated H I flux over the source with units of Jy km s^{-1}.

We determined the upper limit of detectable H I with the requirement of a 3σ detection using

$$M_{\rm H\,I,lim} = 2.36 \times 10^5\, D^2\, S_{\rm H\,I,lim}\, M_\odot. \qquad (3)$$

We chose to use a line width W, consistent with that of the line widths from kinematic measurements of the globular cluster system within NGC 1052-DF2 in van Dokkum et al. (2018b) ($W = \sigma_v = 3.2^{+5.5}_{-3.2}$ km s^{-1}), and smoothed our 0.16 km s^{-1} native resolution data to $\Delta v = 1$, 3.2, 5, and 8.7 km s^{-1} (Figure 2), all within the range of errors in σ_v. Mass calculations in this Letter are made using the 3.2 km s^{-1} resolution data, with the intent to increase our signal-to-noise ratio. We also present mass upper limits using line widths of 10.5 km s^{-1} and 20 km s^{-1} given in Fensch et al. (2018) and Chowdhury (2019), respectively. Using the line width of 10.5 km s^{-1}, our calculated that the upper limit would become $M_{\rm H\,I,lim} < 9.9 \times 10^5\, M_\odot$. A direct comparison to the limit found by Chowdhury (2019) would give us a limit of $M_{\rm H\,I,lim} < 1.6 \times 10^6\, M_\odot$, a factor of >2 better. We searched throughout our 100 MHz bandwidth at each smoothed resolution and did not detect a signal at any velocity. The noise in each spectra goes down as expected, by $\sim\sqrt{N}$, where N is the number of channels being smoothed.

For comparison, we include ratios of the H I mass upper limit by the stellar mass $M_\star$, the total V-band luminosity L_V, and the dynamical mass $M_{\rm dyn}$ in Table 1. We calculated the neutral gas fraction at 13 Mpc using the $M_\star$ given in Singh et al. (2018).

4. Discussion and Conclusions

We have included a figure of our $M_{\rm H\,I}^{\rm lim}$ as a function of distance (Figure 3), encompassing the three proposed distances mentioned in this Letter (Blakeslee & Cantiello 2018; Trujillo et al. 2018; van Dokkum et al. 2018b). All prove to be very gas-poor, with a factor of ∼2 difference in H I mass between the three distance estimates.

We calculate the upper limit on the $M_{\rm H\,I}$ for the distance of 19 Mpc (as proposed by van Dokkum et al. 2018b). We also calculate our integrated flux limit $S_{\rm H\,I,lim}$ using a 3σ detection limit, the H I gas fraction, $M_{\rm H\,I}/M_\star$, the H I mass to V-band luminosity $M_{\rm H\,I}^{\rm lim}/L_V$, and the H I mass to dynamical mass ratio $M_{\rm H\,I}^{\rm lim}/M_{\rm dyn}$, where values for $M_\star \approx 2 \times 10^8\, M_\odot$, $L_V = 1.1 \times 10^8\, L_\odot$, and $M_{\rm dyn} < 3.4 \times 10^8\, M_\odot$ are all taken from van Dokkum et al. (2018b). All of these ratios are below 1%, demonstrating the insignificance of the amount of neutral, atomic hydrogen in this galaxy. This new upper limit would bring the gas fraction ($M_{\rm H\,I}^{\rm lim}/M_\star < 0.0027$) down to that of the population of gas-poor dwarf ellipticals (Hallenbeck et al. 2012), as can be seen in Figure 1. This limit demonstrates the highly gas-deficient nature of this galaxy.

Previous efforts have been made to detect neutral hydrogen in very-low-mass galaxies around the Milky Way using the GBT. These Galactic dSphs have 5σ upper limits of $M_{\rm H\,I} < 10^4\, M_\odot$ (Spekkens et al. 2014), while neutral hydrogen detections have been made in other dSphs at comparable distances with the Parkes radio telescope (Tarchi et al. 2005). Our H I mass to light ratio $M_{\rm H\,I}^{\rm lim}/L_V$ is of a similar value to that of the dSph galaxies associated with the Milky Way and the Local Group (Spekkens et al. 2014). However, our H I mass to dynamical mass ratio $M_{\rm H\,I}^{\rm lim}/M_{\rm dyn}$ is higher than that of those same Galactic dSphs by ∼2 orders of magnitude, but is on par with the Local Volume dwarfs, with a distinction between these two groups being within (Galactic dSphs) or beyond (Local Volume dwarfs) the virial radius of the Milky Way.

The amount of gas found in a galaxy is greatly connected to its environment. An ultra-diffuse galaxy (UDG) in isolation should have a neutral gas mass of $10^7 < M_{\rm H\,I} < 10^9\, M_\odot$ (Bellazzini et al. 2017; Papastergis et al. 2017). In groups, similar amounts of H I mass have been found in UDGs (Trujillo et al. 2017; Spekkens & Karunakaran 2018). There is an extreme lack of neutral gas in NGC 1052-DF2 as compared to other UDGs with H I measurements.

We have considered the possibility that this source is an old tidal dwarf galaxy (TDG), collisional debris from a previous merger. These old TDGs should show both a lack of dark matter,

[4] http://ned.ipac.caltech.edu/

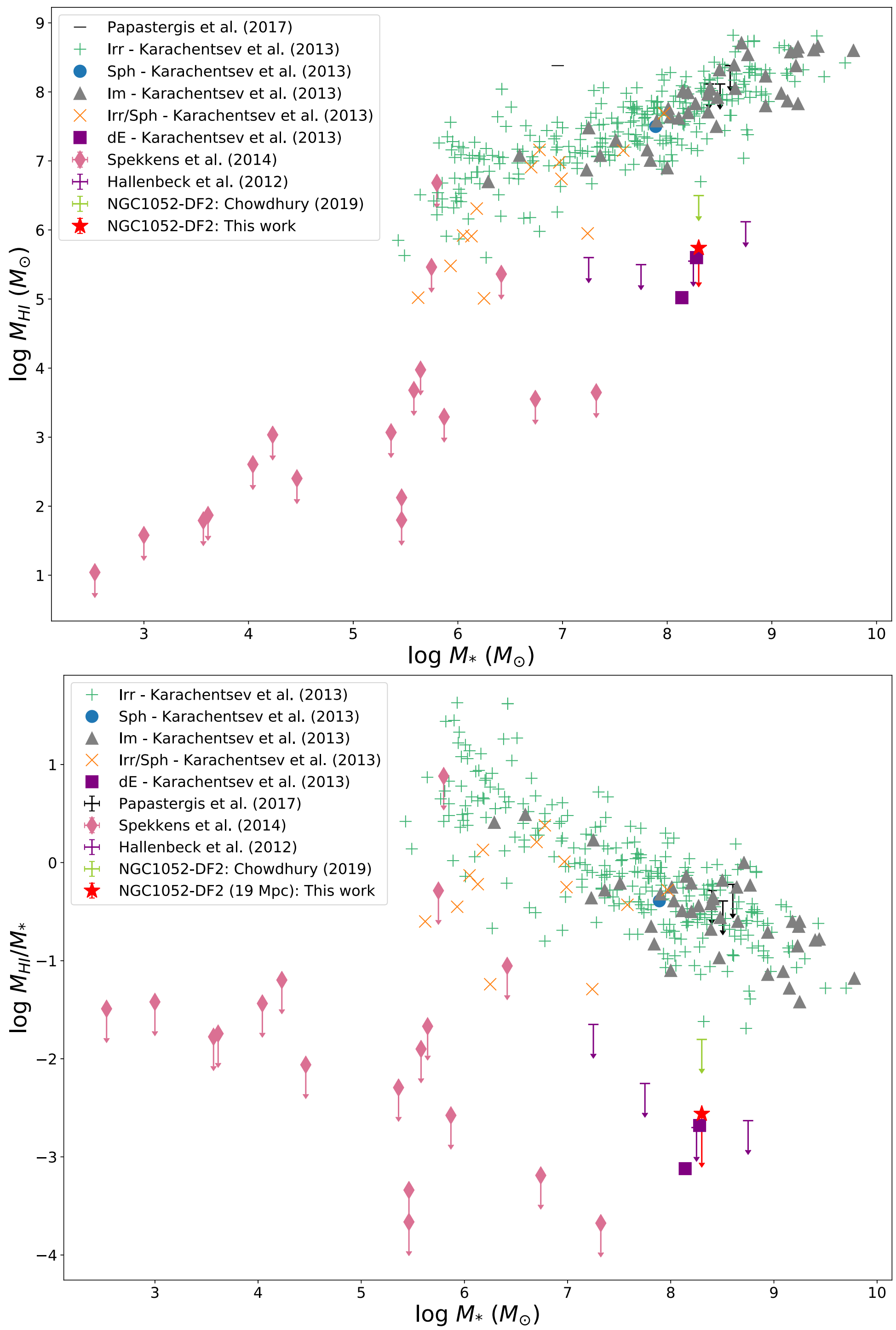

Figure 1. Top: stellar mass–H I mass relation for dwarf galaxies. The black upper limits from Papastergis et al. (2017) represent isolated ultra-diffuse galaxies (UDGs) at 40–80 Mpc. The pink diamonds represent the upper limits for Galactic dSphs and Local Group dSphs from Spekkens et al. (2014; nearly all are <1 Mpc). Crosses, circles, triangles, Xs, and squares represent the various morphologies of dwarf galaxies within 11 Mpc (Karachentsev et al. 2013). Purple upper limits from Hallenbeck et al. (2012) represent the dwarf ellipticals and dwarf lenticulars (dE, dS0) in the Virgo cluster ($D \sim 17$ Mpc). The previous upper limit on the H I mass of NGC 1052-DF2 by Chowdhury (2019) is shown in yellow–green. An updated H I mass upper limit for NGC 1052-DF2 from this Letter is shown for the distance of 19 Mpc in red. Bottom: relationship between the stellar mass and the H I gas fraction for the sample in the figure above. Symbols remain the same. Apart from the extremely nearby (<1 Mpc) dSphs from Spekkens et al. (2014), the extreme nature of the gas fraction of NGC 1052-DF2 becomes clear, as it is a galaxy in a low-density environment with a comparable neutral gas fraction to those in a high-density cluster environment.

and an unusually high metallicity for their mass, with large gas depletion timescales (Hunter et al. 2000; Braine et al. 2001; Duc et al. 2007; Sweet et al. 2014). Given the less-than-solar metallicity (Fensch et al. 2018) and gas-deficient nature of NGC 1052-DF2, we do not consider this to be a likely origin.

Our H I mass upper limit, however, is consistent with the upper limits for dwarf ellipticals in the Virgo cluster found by Conselice et al. (2003), who reported H I mass upper limits as low as $5 \times 10^5 M_\odot$. The gas fraction upper limit that we found is also consistent with the gas fractions from dwarf ellipticals

Table 1
Properties of NGC 1052-DF2

Δv[a] (km s^{-1})	$\sigma_{\rm rms}$[b] (mJy/beam)	$S_{\rm H\,I,lim}$[c] (Jy km s^{-1})	$M_{\rm H\,I}^{\rm lim}$ [19 Mpc] ($M_\odot$)	$M_{\rm H\,I}^{\rm lim}/M_\star$	$M_{\rm H\,I}^{\rm lim}/L_V$ ($M_\odot/L_\odot$)	$M_{\rm H\,I}^{\rm lim}/M_{\rm dyn}$
3.2	0.673	0.006	$<5.5 \times 10^5$	$<$0.0027	$<$0.005	$<$0.0016

Notes.
[a] Velocity resolution.
[b] Measured rms noise.
[c] Integrated flux limit.

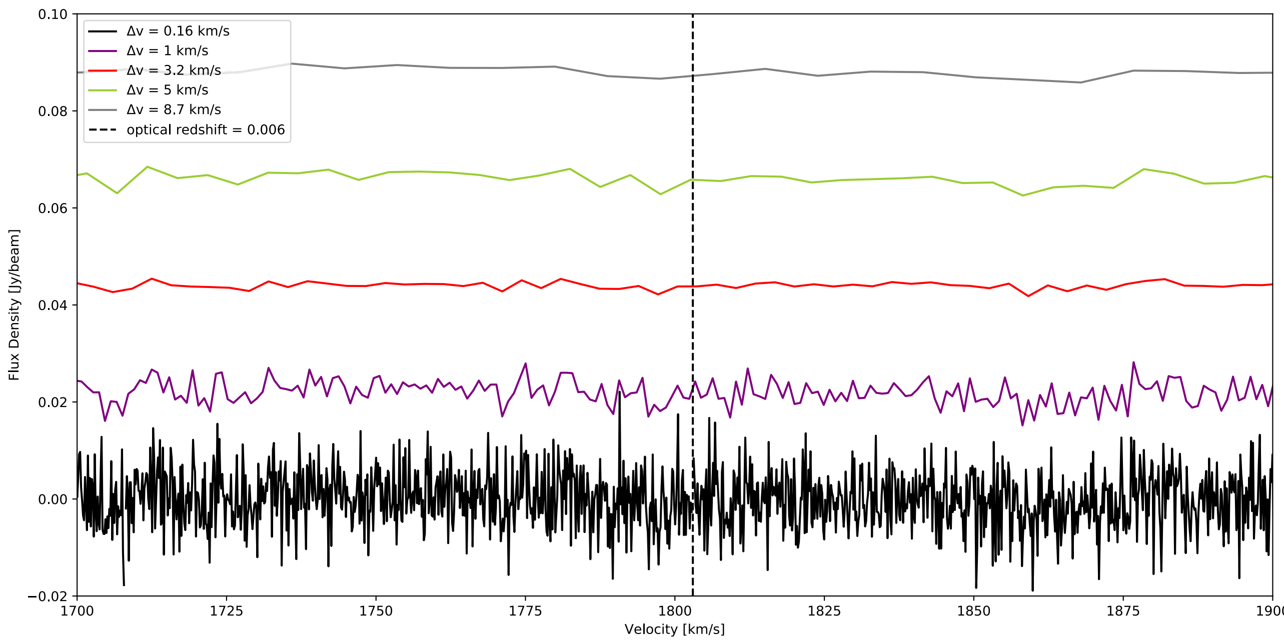

Figure 2. Averaged 4 hr data set showing 100 km s^{-1} on either side of the proposed velocity (1803 km s^{-1}) of NGC 1052-DF2. The smoothed data, each offset by 22 mJy, is shown in various colors above the native resolution data in black. Note the 3.2 km s^{-1} velocity resolution in red, the velocity resolution of the globular cluster system found in van Dokkum et al. (2018b), which we used for our calculations and should have produced the greatest signal-to-noise ratio.

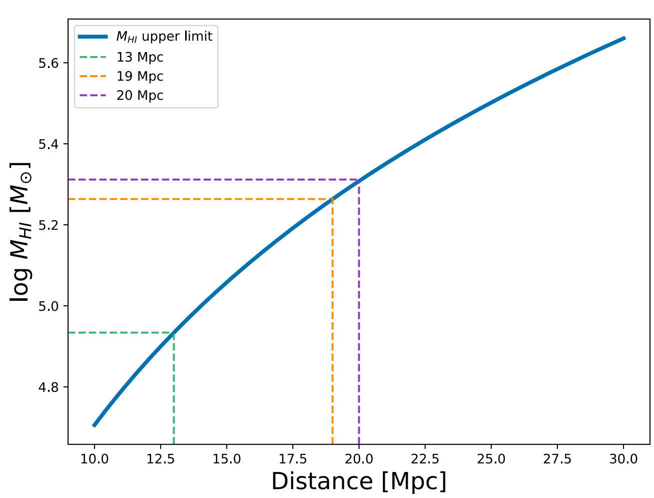

Figure 3. The blue line is our upper limit of the H I mass as a function of distance, as calculated by Equation (2). The sea green dashed line marks the 13 Mpc distance as proposed by Trujillo et al. (2018), the orange dashed 19 Mpc by van Dokkum et al. (2018b), and the purple dashed 22 Mpc by Blakeslee & Cantiello (2018).

found by Hallenbeck et al. (2012). These similarities provide further support for NGC 1052-DF2 as a dwarf elliptical.

One likely scenario for the mechanism of gas removal in NGC 1052-DF2 is through gas stripping as a result of its proximity to NGC 1052 (∼80 kpc in projection). The location of the source residing within the central galaxy's virial radius is an important factor in the amount of H I found in a satellite (Grcevich & Putman 2009; Spekkens et al. 2014). Because of the extended and loosely bound nature of H I in galaxies, it is more likely to be stripped from its galaxy than the stars (Boselli & Gavazzi 2006; Poggianti et al. 2017). The lack of H I that we find could be indicative of NGC 1052-DF2 residing within the virial radius of NGC 1052. It is possible that the H I in NGC 1052-DF2 was not detected due to the source residing at some greater distance than NGC 1052. In this case, the gas removal mechanism could be through bursts of star formation or through gas expulsion (Hopkins et al. 2014). However, finding an isolated galaxy without H I would be an unusual scenario and would require further explanation for its gas removal. The upper limit on the gas fraction $M_{\rm H\,I}/M_\star$ and the upper limit on the ratio of H I mass to dynamical mass

$M_{\rm H\,I}^{\rm lim}/M_{\rm dyn}$ could be consistent with either environmental scenarios of stripped gas by proximity to a larger galaxy or of a field galaxy with gas loss over time. While one scenario constrains the distance of NGC 1052-DF2, the other would prove to be an atypical finding of a galaxy without neutral gas when living in isolation. If there is any neutral gas present in NGC 1052-DF2, the insignificant amount would contribute extremely little to the baryonic mass of the galaxy.

We found the upper limit of H I mass in NGC 1052-DF2 to be $M_{\rm H\,I,lim} < 5.5 \times 10^5\, M_\odot$ with a gas fraction of neutral gas to stellar mass of $M_{\rm H\,I}/M_\star < 0.0027$. Such an extreme lack of neutral gas in this galaxy is consistent with known gas-poor dwarf ellipticals, dSphs, and tidal dwarfs. Further inspection is needed to constrain the origin and morphology of this source.

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