The Atomic Gas Mass of Green Pea Galaxies

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Abstract

We have used the Arecibo Telescope and the Green Bank Telescope (GBT) to carry out a deep search for HI 21 cm emission from a large sample of “Green Pea” galaxies, yielding 19 detections, and 21 upper limits on the HI mass. We obtain HI masses of $M_{\text{HI}} \approx (4-300) \times 10^8 M_\odot$ for the detections, with a median HI mass of $\approx 2.6 \times 10^8 M_\odot$; for the non-detections, the median 3\sigma upper limit on the HI mass is $\approx 5.5 \times 10^7 M_\odot$. These are the first estimates of the atomic gas content of Green Pea galaxies. We find that the HI-to-stellar mass ratio in Green Peas is consistent with trends identified in star-forming galaxies in the local universe. However, the median HI depletion timescale in Green Peas is $\approx 0.6$ Gyr, an order of magnitude lower than that obtained in local star-forming galaxies. This implies that Green Peas consume their atomic gas on very short timescales. A significant fraction of the Green Peas of our sample lie between $0.6$ dex ($2\sigma$) above the local $M_{\text{HI}}-M_\ast$ relation, suggesting recent gas accretion. Further, $\approx 30\%$ of the Green Peas are more than $\pm 2\sigma$ deviant from this relation, suggesting possible bimodality in the Green Pea population. We obtain a low HI 21 cm detection rate in the Green Peas with the highest O32 $\approx [\text{O III}] \lambda 5007/\lambda 3727$ luminosity ratios, O32 $> 10$, consistent with the high expected Lyman-continuum leakage from these galaxies.

Unified Astronomy Thesaurus concepts: Galaxies (573); HI line emission (690); Galaxy masses (607)

1. Introduction

The nature of “Green Pea” galaxies, the low-redshift ($z \lesssim 0.3$) extreme emission-line galaxies identified by the Galaxy Zoo project (Cardamone et al. 2009), has been of much interest over the last decade. Their low metallicity and dust content, strong nebular lines, compact or interacting morphology, and intense star formation activity are all reminiscent of high-$z$ Ly\alpha emitters (e.g., Izotov et al. 2011; Yang et al. 2017; Jiang et al. 2019). Indeed, for Green Peas studied at ultraviolet (UV) wavelengths, the Ly\alpha equivalent width distribution is similar to that of Ly\alpha emitters at $z \gtrsim 2.8$ (Yang et al. 2016), while the Ly\alpha and UV continuum sizes are similar to those of Ly\alpha emitters at $z \approx 3-6$ (Yang et al. 2017). Green Peas show a high $[\text{O III}] \lambda 5007/\lambda 3727$ luminosity ratio, similar to many high-$z$ star-forming galaxies, indicating optically thin ionized regions (e.g., Jaskot & Oey 2013; Nakajima et al. 2020). Perhaps most interesting, and unlike most galaxies in the low-$z$ universe, Green Peas have been found to commonly show leakage of Lyman-continuum radiation, with escape fractions of $\approx 2.5\%-73\%$ (Izotov et al. 2016, 2018a, 2018b). Such Lyman-continuum radiation escaping from star-forming galaxies is expected to have been the prime cause of the reionization of the universe, at $z \gtrsim 6$ (e.g., Fan et al. 2006); however, the dependence of the escape fraction on local conditions is still not understood today. Galaxies like the Green Peas that show strong Lyman-continuum leakage are the best low-$z$ analogs of the galaxies that drove cosmological reionization, and offer the exciting possibility of understanding this critical process in the nearby universe.

While detailed optical and UV imaging and spectroscopic studies have characterized the stellar, nebular, and star formation properties of the Green Peas (e.g., Amorín et al. 2010; Izotov et al. 2011, 2018b; Jaskot & Oey 2014; Yang et al. 2016, 2017; Lohfhouse et al. 2017; Jiang et al. 2019), little is known about the primary fuel for star formation in these galaxies, the neutral atomic, or molecular gas. As such, the cause of the intense starburst activity in the Green Peas remains unclear. Further, there is a natural tension between requiring cold neutral gas to fuel the starburst activity and having a sufficiently low HI column density to allow the resonantly scattered Ly\alpha and Lyman continuum to escape. This suggests that the HI column density distribution in Green Peas may be highly non-uniform, with HI porosity playing a key role (but see Henry et al. 2015).

At present, only two Green Peas have published searches for HI 21 cm emission, both yielding upper limits on the HI mass of the galaxy (Pardy et al. 2014; McKinney et al. 2019). We report here Arecibo Telescope (hereafter, Arecibo) and Green Bank Telescope (GBT) HI 21 cm spectroscopy of a large sample of Green Peas at $z \approx 0.02-0.1$, which allow us to measure the atomic gas mass of these galaxies for the first time.6

2. Observations, Data Analysis, and Results

Jiang et al. (2019) have compiled the most comprehensive Green Pea galaxy sample to date, consisting of approximately 1000 galaxies at $0.01 \lesssim z \lesssim 0.41$, identified from the Sloan Digital Sky Survey (SDSS) spectroscopic Data Release 13. We used the correlation between $B$-band luminosity and HI mass (e.g., Dénes et al. 2014) to pre-select Green Peas from the above sample with HI masses high enough to show detectable HI 21 cm emission with Arecibo and the GBT in reasonable

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6 We assume a flat $\Lambda$-cold dark matter cosmology, with $\Omega_m = 0.685$, $\Omega_\Lambda = 0.315$, $H_0 = 67.4$ km s$^{-1}$ Mpc$^{-1}$ (Planck Collaboration 2020).
integration time (few hours). Our targets span a wide range of absolute 
B-band magnitudes (−20.0 ≤ MB ≤ −16.1) and gas-phase metallicities (7.6 ≤12+\[O/H]\) ≤8.35). We also 
carried out two-sample Kolmogorov–Smirnov tests to compare 
the distributions of metallicity, stellar mass, and absolute 
B-magnitude in our target sample with those of the parent 
Green Pea sample of Jiang et al. (2019). We find that the data 
are consistent with the null hypothesis that the two samples are 
drawn from the same distribution, in all three parameters.

We used Arecibo and the GBT to carry out a search for 
HI 21 cm emission from 44 Green Peas, at z ≈ 0.02–0.1 
(proposals GBT/19A-301: PI Malhotra; Arecibo/A3302: PI 
Rhoads), between 2019 February and August. To use the 
complementary strengths of Arecibo and the GBT, we 
observed lower-redshift targets (z ≲ 0.05) with higher expected 
HI 21 cm line flux densities over the entire northern and 
equatorial sky using the GBT. With Arecibo, we broadened 
the selection to include Green Peas with lower expected HI 21 cm 
line flux densities and higher redshifts (z ≳ 0.1), within the 
region of sky accessible to the telescope.

The Arecibo observations used the L-wide receiver, the 
WAPP backend, two orthogonal polarizations, and a 25 MHz 
band sub-divided into 4096 spectral channels and centered on 
the redshifted HI 21 cm line frequency. The GBT observations 
used the L-band receiver with the VEGAS spectrometer as the 
backend, two polarizations, and a 23.44 MHz bandwidth sub-
divided into 8192 channels, and centered on the redshifted 
HI 21 cm line frequency. Position-switching, with 5 m On and 
Off scans, was used to stabilize the system bandpass, while the 
system temperatures were measured using a blinking noise 
diode at the GBT, and a separate noise diode, switched on and 
off for 10 s, at Arecibo. Online Doppler tracking was not used. 
The total time on each source ranged from 0.75 to 4.5 hr, 
depending on the galaxy redshift, radio frequency interference 
(RFI) conditions, and observing exigencies.

All data were analyzed in the IDL package, following 
standard procedures, with the package GTIDL used for the 
GBT data. Each On/Off pair was initially calibrated and the 
final spectrum, for each polarization, shifted into the bary-
centric frame. Each spectrum was then inspected for the presence of 
RFI or systematic effects in the spectral baseline; 
spectra showing non-Gaussian behavior within ≈±200 
kms of the expected redshifted HI 21 cm line frequency 
were removed from the analysis. For each source, the 
remaining spectra, from both polarizations, were median-
averaged together, with the median used to obtain a more 
conservative (i.e., less sensitive to outliers) estimate of the 
average. For four sources, two from each telescope, all spectra 
were affected by RFI around the expected redshifted line 
frequency, and the data were essentially unusable.

HI 21 cm emission was detected from 19 Green Peas at ≥5σ 
significance (two of which, in J0844+0226 and J1010+1255, 
have ≈5σ significance and hence should be viewed as tentative 
detections); the HI 21 cm spectra of these galaxies are shown in 
Figure 1. Twenty-one galaxies showed no clear signature of 
HI 21 cm emission. Table 1 summarizes the results of the 
Arecibo and GBT observations; we also include the relevant 
galaxy properties of each Green Pea, derived from the optical 
imaging and spectroscopy (e.g., Jiang et al. 2019). The upper 
limits are computed assuming a Gaussian line profile with a full 
width at half maximum (FWHM) of 50 km s−1, typical of 
dwarf galaxies (the HI mass limits are mostly ≲108 M⊙, i.e., in 
the dwarf galaxy range; e.g., Begum et al. 2008). We note that 
the errors quoted on the HI 21 cm line flux densities and the HI 
masses are statistical errors, and do not include the uncertainty 
in the flux scale; we estimate this uncertainty to be typically ≈10%.

3. Discussion

Our Arecibo and GBT HI 21 cm spectroscopy of Green Pea 
galaxies has yielded an ≈50% detection rate, with 19 
detections of HI 21 cm emission at redshifts z ≈ 0.023–0.091. 
These are the first measurements of the atomic gas content of 
Green Pea galaxies. The HI masses of the detected galaxies lie 
in the range ≈(4−300) × 108 M⊙, with a median value of 
2.6 × 108 M⊙. For the non-detections, the 3σ upper limits on 
the HI mass lie in the range (0.6–32) × 108 M⊙, with a median 
upper limit of 5.5 × 108 M⊙. Note that the large primary beams 
of Arecibo and the GBT imply that we cannot rule out the 
possibility that some of the HI 21 cm emission in the detections 
may arise from companion galaxies.

Figure 2(A) plots the HI-to-stellar mass ratio fHI ≡ MHI/M∗ 
against the stellar mass M∗ of the 40 Green Peas of our sample. 
We used the xGASS sample as the comparison sample, as this 
is a stellar mass-selected (M∗ ≳ 109 M⊙) sample of nearby 
galaxies, with HI 21 cm emission studies (Catinella et al. 2018). 
The dark green stars indicate the median value of fHI (treating 
the 3σ upper limits to fHI as detections) in two stellar mass bins, 
while the filled blue circles indicate the median values of fHI in 
galaxies in different stellar mass bins in the GALEX Arecibo 
SDSS Survey (xGASS) sample (Catinella et al. 2018), with 
the dashed blue line connecting the xGASS values. It is clear that 
the median value of fHI for Green Peas in the higher M∗ bin is in 
excellent agreement with the median value for xGASS galaxies 
at the same M∗, while the median fHI in the lower M∗ bin 
appears to lie close to the extrapolated xGASS relation 
(Catinella et al. 2018). It thus appears that the HI content of 
Green Pea galaxies, relative to their stellar mass, is in excellent 
agreement with that of “normal” galaxies in the nearby universe.

The atomic gas depletion timescale τdep ≡ MHI/SFR gives 
the timescale for which a galaxy can continue to form stars 
without replenishment of its HI reservoir. Lower values of τdep 
would imply that a galaxy’s star formation activity would be 
regulated by the availability of HI; for example, Chowdhury 
et al. (2020) argued that the cause of the decline of the star 
formation activity in the universe at z < 1 is because the HI 
reservoirs in star-forming galaxies are not sufficient to support 
their star formation activity for more than ≈1–2 Gyr. However, 
at z ≤ 0.35, the HI depletion timescale has been found to be 
relatively long in main-sequence galaxies, ≈5–10 Gyr (e.g., 
Saintonge et al. 2017; Bera et al. 2019). Figure 2(B) plots the 
τdep values of our Green Pea galaxies against stellar mass; the 
dashed green line shows the median value of the sample, 
τdep, med ≈ 0.58 Gyr (conservatively treating the upper limits on 
MHI as detections). For comparison, the median value of τdep, 
in the xGASS sample (again treating upper limits to MHI as 
detections), shown by the dashed blue line in the figure, is 
≈6 Gyr (Saintonge et al. 2017; Catinella et al. 2018), larger by 
an order of magnitude. It appears that the starburst activity in 
the Green Peas will exhaust their atomic fuel on very short 
timescales, far shorter than in most other galaxies in the nearby 
universe.
Figure 1. HI 21 cm emission profiles of the 19 Green Peas with HI 21 cm detections, ordered by R.A.. In each panel, the x-axis is barycentric frequency, in MHz; the top of the panel shows velocity, in km s$^{-1}$, relative to the Green Pea redshift (based on the optical spectra). The HI 21 cm spectra have been smoothed to, and resampled at, velocity resolutions of $\approx 10$–30 km s$^{-1}$. Note that the HI 21 cm detections in J0844+0226 and J1010+1255 have $\approx 5\sigma$ significance, and so should be treated as tentative detections.
The depletion time of star-forming material could be longer than the HI depletion timescale when the H$_2$ depletion timescale is taken into account. However, in star-forming galaxies in the local universe, with the dotted lines indicating the ±0.6 dex ($\approx 2\sigma$) spread around the local relation (e.g., Dénès et al. 2014). While the majority of the Green Peas are seen to lie within the spread of the local $M_{\text{HII}}$-$M_B$ relation, it is interesting that nine of the 40 galaxies of our sample (i.e., $\approx 22\%$) lie $\leq 0.6$ dex below the relation. This suggests that a significant fraction of Green Peas are gas-rich for their optical luminosity, possibly due to recent gas accretion from the circumgalactic medium or via a minor merger, or due to a gas-rich companion galaxy within the relatively large GBT or Arecibo beam.

Conversely, five of the non-detections and two of the detections of HI 21 cm emission lie $\geq 0.6$ dex below the local $M_{\text{HII}}$-$M_B$ relation. Further, most of the detections of HI 21 cm emission lie above the local relation, while most of the non-detections lie below it. This may suggest bimodality in the HI.
properties of Green Pea galaxies, with one group having exhausted its neutral gas in the starburst (which may have been itself triggered by a recent gas acquisition via infall or a merger), and the other having only consumed a fraction of its neutral gas in the starburst. We note that a caveat to the above result is that the $M_{\text{HI}}-M_*$ relation of Dénes et al. (2014) is based on an HI-selected galaxy sample from the all-sky HI Parkes All Sky Survey (HIPASS; Zwaan et al. 2005), and thus...
may be biased toward H\textsc{i}-rich galaxies. As such, objects lying below the $M_{\rm HI}-M_{\star}$ relation of Dénes et al. (2014) may not necessarily be H\textsc{i}-poor galaxies.

Despite the above caveat, it is tempting to identify the first group of galaxies above with the objects that are likely to show leakage of Ly$\alpha$ and Lyman-continuum radiation (i.e., to show Ly$\alpha$ emission). Eight of the Green Peas of our sample have Ly$\alpha$ spectroscopy, with seven detections of Ly$\alpha$ emission and one (J1448-0110) showing net Ly$\alpha$ absorption (McKinney et al. 2019). Interestingly, five of the detections of Ly$\alpha$ emission are not detected in H\textsc{i} 21 cm emission, as expected from the above argument. However, two of the Ly$\alpha$-emitting galaxies, J0213+0056 and J1200+2719, do show detections of H\textsc{i} 21 cm emission, and with relatively high H\textsc{i} masses, $\approx 3.2 \times 10^9 \, M_\odot$ (J0213+0056) and $\approx 1 \times 10^{10} \, M_\odot$ (J1200+2719). Further, both these galaxies are “gas-rich” systems in Figure 3(A). H\textsc{i} 21 cm mapping studies are needed to test whether the Green Pea galaxy itself is H\textsc{i}-rich, or if it might have a gas-rich companion. Such H\textsc{i} 21 cm mapping studies are also critical to directly determine the H\textsc{i} column density distribution within the Green Peas, to test for the presence of H\textsc{i} holes through which the Ly$\alpha$ and Lyman-continuum photons might escape. At any event, at the present time, no clear trend is apparent between the gas richness of the above eight Green Peas and their Ly$\alpha$ escape fraction, with high Ly$\alpha$ escape fractions obtained at both high and low H\textsc{i} masses (and gas richness) in the relatively small current sample (McKinney et al. 2019). Deeper H\textsc{i} 21 cm emission studies would be needed to test the possibility of bimodality in the gas content of Green Pea galaxies.

We also examined the dependence of the H\textsc{i} mass, H\textsc{i}-to-stellar mass ratio, and H\textsc{i} depletion time, on the metallicity ($\text{[O/H]}$) of the Green Peas of our sample, finding no evidence of a dependence of any of these properties on the metallicity.

Jaskot & Oey (2013) argued that the high luminosity ratio O32 $\equiv [\text{O III}]$5007/[$\text{[O II]}$]3727 observed in a number of Green Pea galaxies at $z \approx 0.1$–0.3 makes them excellent candidates for the escape of ionizing Lyman-continuum radiation. A high Lyman-continuum leakage was indeed later found in galaxies with high O32 values, both at high redshifts (e.g., Nakajima & Ouchi 2014; Nakajima et al. 2016; Fletcher et al. 2019) and low redshifts (including Green Pea galaxies; e.g., Izotov et al. 2016, 2018a, 2018b, 2020), for typical O32 values $\gtrsim 10$. One would expect easier leakage of Lyman-continuum photons from galaxies with a lower average H\textsc{i} column density, and also with a lower H\textsc{i} mass. We hence examined the H\textsc{i} properties in our Green Peas as a function of their O32 value; Figure 3[B] shows the measured H\textsc{i} mass for the 40 Green Peas plotted against the O32 values; the median O32 value is $\approx 5.5$, indicated by the dashed vertical line. Among the 20 Green Peas with O32 values below the median, there are 12 detections of H\textsc{i} 21 cm emission, with an average H\textsc{i} mass of $5.6 \times 10^8 \, M_\odot$, while for Green Peas with O32 values above the median there are seven detections and an average H\textsc{i} mass of $3.2 \times 10^7 \, M_\odot$. Further, there is only a single detection of H\textsc{i} 21 cm emission in the 11 Green Peas with O32 $\gtrsim 10$ (i.e., a detection fraction of $0.091^{+0.025}_{-0.016}$), and 18 detections in the 29 Green Peas with O32 $< 10$ (i.e., a detection fraction of $0.62^{+0.18}_{-0.14}$). Thus, although the numbers are still small, both the detection rate and the average H\textsc{i} mass appear to be significantly lower in galaxies with O32 $\gtrsim 10$, consistent with the expected high Lyman-continuum leakage.

Tilvi et al. (2009) modeled star formation in Ly$\alpha$ emitters by assuming that the accretion of gas rapidly results in star formation, to obtain a star formation efficiency ($f_\star$) of $\approx 2.5\%$. This is similar to the estimate of $f_\star$ $\approx 4$–8\% obtained by Baldry et al. (2008), by comparing the cosmic stellar mass density to the cosmic baryon density (see also Fukugita et al. 1998). Assuming $f_\star \approx 2.5\%$ yields a median star formation timescale of $75 \times f_\star \approx f_\star \times (M_{\text{HI}}/\text{SFR})_{\text{med}} \equiv f_\star \times \tau_{\text{dep,med}} \approx 15$ Myr. Interestingly, this is similar to the age of the young stellar population that dominates the starlight of the Green Peas of our sample ($\approx 3$–8 Myr, with a median age of $\approx 4$ Myr; Jiang et al. 2019). We note, however, that the above $f_\star$ estimates (Baldry et al. 2008, Tilvi et al. 2009) are for all baryonic material, including the ionized gas. The agreement between the star formation timescale and the age of the young stellar population in Green Peas might then suggest that the timescale of conversion from ionized gas to neutral gas is short in these galaxies.

4. Summary

We report an Arecibo and GBT search for H\textsc{i} 21 cm emission from a large sample of Green Pea galaxies at $z \approx 0.02$–0.1, obtaining 19 detections of H\textsc{i} 21 cm emission and 21 upper limits to the H\textsc{i} mass, and yielding the first estimates of the gas content of these starbursting systems. The H\textsc{i} properties of the majority of the Green Peas appear similar to those of galaxies in the local universe, in terms of the H\textsc{i}-to-stellar mass ratio and the $M_{\text{HI}}-M_{\star}$ relations. However, a significant fraction of the Green Peas ($\approx 22\%$) have an H\textsc{i} mass that is $\gtrsim 0.6$ dex (i.e., $\gtrsim 2\sigma$) above the local $M_{\text{HI}}-M_{\star}$ relation, indicating either recent gas accretion or a gas-rich companion galaxy. A similar fraction lie $\gtrsim 0.6$ dex below the local relation, suggesting possible bimodality in the gas properties of Green Peas. This large fraction of outliers ($\approx 30\%$) from the $M_{\text{HI}}-M_{\star}$ relation and the young ages of the stellar populations are indicative of a possible “boom and bust” nature of star formation in Green Peas. Further, the H\textsc{i} depletion times in Green Peas are an order of magnitude lower than values in local galaxies, indicating that the starburst activity will consume their H\textsc{i} on timescales less than a Gyr. The detection rate of H\textsc{i} 21 cm emission appears low in galaxies with the highest O32 values, O32 $\gtrsim 10$, consistent with the high Lyman-continuum leakage expected from these galaxies.

This Letter is dedicated to the Arecibo Observatory and its people.

De estas calles que ahondan el poniente, Una habrá (no sé cual) que he recorrido, Ya por última vez, ...³

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³ “Limites”, Jorge Luís Borges.
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References
Amorín, R. O., Pérez-Montero, E., & Vílchez, J. M. 2010, ApJL, 715, L128
Baldry, I. K., Glazebrook, K., & Driver, S. P. 2008, MNRAS, 388, 945
Begum, A., Chengalur, J. N., Karachentsev, I. D., Sharina, M. E., & Kaisin, S. S. 2008, MNRAS, 386, 1667
Bera, A., Kanekar, N., Chengalur, J. N., & Bagla, J. S. 2019, ApJL, 882, L7
Cardamone, C., Schawinski, K., Sarzi, M., et al. 2009, MNRAS, 399, 1191
Catinella, B., Saintonge, A., Janowiecki, S., et al. 2018, MNRAS, 476, 875
Chowdhury, A., Kanekar, N., Chengalur, J. N., Sethi, S., & Dwarakanath, K. S. 2020, Natur, 586, 369
Dénes, H., Kilborn, V. A., & Koribalski, B. S. 2014, MNRAS, 444, 667
Fan, X., Carilli, C. L., & Keating, B. 2006, ARA&A, 44, 415
Fletcher, T. J., Tang, M., Robertson, B. E., et al. 2019, ApJ, 878, 87
Fukugita, M., Hogan, C. J., & Peebles, P. 1998, ApJ, 503, 518
Henry, A., Scarlata, C., Martin, C. L., & Erb, D. 2015, ApJ, 809, 19
Izotov, Y. I., Guseva, N. G., & Thuan, T. X. 2011, ApJ, 728, 161
Izotov, Y. I., Schaerer, D., Thuan, T. X., et al. 2016, MNRAS, 461, 3683
Izotov, Y. I., Schaerer, D., Worseck, G., et al. 2018a, MNRAS, 474, 4514
Izotov, Y. I., Schaerer, D., Worseck, G., et al. 2020, MNRAS, 491, 468
Izotov, Y. I., Worseck, G., Schaerer, D., et al. 2018b, MNRAS, 478, 4851
Jaskot, A. E., & Oey, M. S. 2013, ApJ, 766, 91
Jaskot, A. E., & Oey, M. S. 2014, ApJL, 791, L19
Jiang, T., Malhotra, S., Yang, H., & Rhoads, J. E. 2019, ApJ, 872, 146
Lofthouse, E. K., Houghton, R. C. W., & Kaviraj, S. 2017, MNRAS, 471, 2311
McKinney, J. H., Jaskot, A. E., Oey, M. S., et al. 2019, ApJ, 874, 52
Nakajima, K., Ellis, R. S., Iwata, I., et al. 2016, ApJL, 831, L9
Nakajima, K., Ellis, R. S., Robertson, B. E., Tang, M., & Stark, D. P. 2020, ApJ, 889, 161
Nakajima, K., & Ouchi, M. 2014, MNRAS, 442, 900
Pardy, S. A., Cannon, J. M., Östlin, G., et al. 2014, ApJ, 794, 101
Planck Collaboration, Aghanim, N., Akrami, Y., et al. 2020, A&A, 641, A6
Saintonge, A., Catinella, B., Tacconi, L. J., et al. 2017, ApJS, 233, 22
Tacconi, L. J., Genzel, R., & Sternberg, A. 2020, ARA&A, 58, 157
Tilvi, V., Malhotra, S., Rhoads, J. E., et al. 2009, ApJ, 704, 724
Yang, H., Malhotra, S., Gronke, M., et al. 2016, ApJ, 820, 130
Yang, H., Malhotra, S., Rhoads, J. E., et al. 2017, ApJ, 838, 4
Zwaan, M. A., Meyer, M. J., Staveley-Smith, L., & Webster, R. L. 2005, MNRAS, 359, L30