Dark Galaxies and Lost Baryons
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Where are the Stars in Dark Galaxies?

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Abstract. Blind HI surveys provide a census of galaxies in the local universe that is unbiased by their optical properties. Even the Arecibo Dual-Beam Survey with a sample of only 265 galaxies discovered many low surface brightness galaxies and one galaxy with no obvious stellar component. Overall the galaxies in this survey display a diverse range of gas-to-stellar properties. The environment in which a galaxy resides is shown to be one of the factors responsible for this diversity, but it is not the only one. Clearly there are other factors affecting the complex processes responsible for the conversion of gas into stars rapidly in some galaxies, slowly in others, and rapidly in the center while slowly in the outskirts in still other galaxies. Nevertheless, even the inefficient star formation observed in a large fraction of the gas-rich galaxies appears to be a significant contributor to the overall star-formation rate density locally and therefore an important driver of galaxy evolution that must be understood. We focus on a discussion of the stellar and star formation properties in a 21 cm selected sample of galaxies because it is these measurements that contain the most information about the nature of star formation in galaxies.

Keywords. galaxies:stellar content, radio lines:galaxies, galaxies:fundamental parameters

1. Introduction

Are there galaxies that have lots of gas but have not formed any stars? This is one of the primary questions asked at this conference. These "dark" or "gas-only" galaxies would be an interesting test-bed for theoretical models of galaxy formation and evolution. However, these systems would be only the rare tip of a continuum of galaxy gas-to-stellar ratios. Searching for and measuring the properties of galaxies along this continuum can provide important information on the astrophysical processes driving galaxy evolution and is complementary to studies of dark galaxies.

Our understanding of the relationship between the global properties of gas and stars in galaxies has mostly been driven by studies of optically-selected, high surface brightness galaxies (e.g. Scodeggio and Gavazzi 1993; Huchtmeier and Richter 1985; Fisher and Tully 1981). Various efforts have been made to extend these studies to lower surface brightness galaxies, (e.g., Galaz *et al.* 2002; McGaugh *et al.* 2000; O'Neil and Bothun 2000; Sprayberry *et al.* 1995) revealing a great diversity of properties outside of the traditional "norms," but such surveys remain tied to the requirement that the galaxies have formed stars in sufficient numbers and surface densities to be detected optically. Extragalactic H I surveys provide one of the few ways to probe the galaxy population independent of their luminosity and surface brightness. We present here a discussion of the stellar properties of H I-selected galaxies from the Arecibo Dual-Beam Survey (see §2 for details). We discuss some sources in which we have not yet observed stars, but focus on the continuum of gas-richness in galaxies and what it can tell us about the processes driving the formation of stars.

2. The Arecibo Dual-Beam Survey

The ADBS is a "blind" survey that was carried out with the Arecibo 305 m telescope prior to the Gregorian upgrade. We have used this survey to identify galaxies out to 7977 km s^{-1} purely based on their gas content. The ADBS survey covered ~ 430 deg^2 in the main beam and detected 265 galaxies. The survey is described in detail in Rosenberg and Schneider (2000). The selection functions and HI mass functions have been studied in detail and are presented in (Rosenberg and Schneider 2002).

2.1. *Optical and Near-Infrared Imaging of ADBS Galaxies*

While blind 21 cm surveys like the ADBS are ideal for selecting galaxies with gas but no stars, the determination of the properties of the stellar populations in these systems still requires optical and/or near-infrared observations.

Optical imaging of the ADBS galaxies was carried out at the Kitt Peak National Observatory (KPNO) 0.9m telescope with the goal of obtaining B and V-band photometry for all of the ADBS galaxies that did not already have photometry and morphology information in the literature. The secondary goal was to observe as many of the bright ADBS galaxies as time allowed. In 5 semesters of observations, photometrically calibrated images were obtained for 209 of the 265 ADBS galaxies including all objects with B> 15.5. The 56 galaxies that were not observed all possess magnitude information and morphological types in the literature (Stevenson *et al.*, ApJ submitted).

The near-infrared imaging of the ADBS sample comes from the 2-Micron All-Sky Survey (2MASS, Skrutskie *et al.* 2006). We use the J-band observations because they are the most sensitive of the three 2MASS bands. The data are a combination of catalog data from Versions 2 and 3 of the catalog, and measurements from the full resolution images for sources that were detected but not cataloged. All but 38 of the ADBS galaxies has a 2MASS J-band measurement. For most of the galaxies that were not measured, the source was just too faint to be detected in the short 2MASS exposures. For a detailed description of the ADBS infrared data and results see Rosenberg *et al.* (2005).

3. Optical and Infrared Properties of ADBS Galaxies

The optical and infrared imaging provide a tracer of the stellar population in the ADBS galaxies. These observations show that selecting galaxies by their gas selects systems with a wide range in properties. Figures 1 and 2 show B-band images of spiral and low surface brightness galaxies detected in this survey. The galaxies in these two figures have been selected to come from similar distances so the systems in 2 are truly different than those in Figure 1, it isn't just a distance effect in the galaxy selection that is making them appear fainter.

While most of the galaxies in the ADBS are spirals, dwarfs, or low surface brightness galaxies there are other types identified as well. In addition to some of the rare galaxy types like blue compact dwarfs and luminous blue compacts, this survey also selects early type systems that possess gas. The optically detected systems include 4 lenticulars and 3 ellipticals.

Are there any "dark" galaxies in this survey? There are 8 galaxies in the survey that lack an optical counterpart. However, the ADBS passes through the Galactic plane making some of the galaxies very difficult to detect in the optical. The Galactic absorption at the position of 7 of the 8 galaxies ranges from $A_B = 1$ to 19.4 (Schlegel *et al.* 1998). For these systems we suspect that the lack of an optical counterpart is due to this absorption rather then to a lack of stars in the ADBS galaxy itself. The ADBS does, however, have one possible example of an H I cloud with no stellar emission as it is in a low absorption

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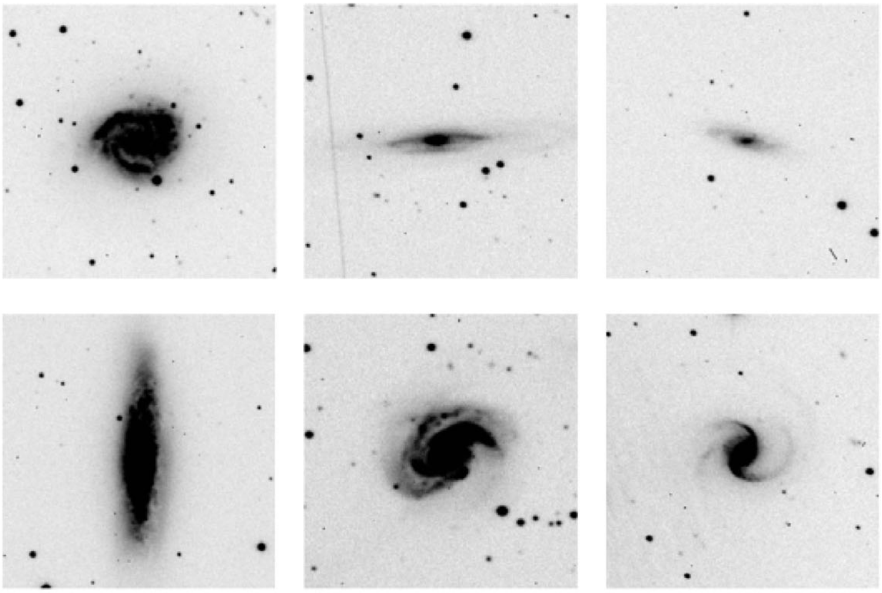

Figure 1. B-band images of 6 spiral galaxies from the ADBS.

($A_B = 0.1$) region. There is a spiral galaxy ∼76 kpc from the cloud at a very similar velocity and a strongly interacting system ∼114 kpc and 120 km s^{-1}away. This is an intriguing dark galaxy candidate but requires further investigation to determine the nature of the source.

Near infrared emission is a good tracer of the stellar mass in a galaxy. Figure 3 shows the relationship between the J-band luminosity and M_{HI} for the ADBS galaxies. These two quantities are correlated but there is more than two orders of magnitude spread in J-band luminosity at any given H I mass and vice-versa. Figure 4 shows the relationship between M_{HI} and M_{HI} /L_J. From this figure it is apparent that M_{HI} /L_B shows a lot of variation at every H I mass. There are dwarf galaxies with very little gas and more massive gas-depleted systems. These plots emphasize the lack of homogeneity in the relationship between gas and stars in galaxies. One of the challenges is going to be to decipher the factors responsible for driving these differences.

One of the most likely factors in driving the efficiency with which stars form which results in differences in M_{HI} /L_B is the environment in which a galaxy resides. Spiral galaxies in clusters are known to be gas deficient (e.g., Solanes *et al.* 2001). However, the broader impact of environment on the H I in galaxies is more difficult to discern. Meyer *et al.* (2007) have used the correlation function of gas-rich galaxies to show that these systems are only weakly clustered. If these gas-rich galaxies do not tend to occupy the densest regions then the correlation function is only going to provide a partial picture of the effect of environment. As a different probe of environment, we have used the density of CfA galaxies surrounding the H I source. The densities were computed using

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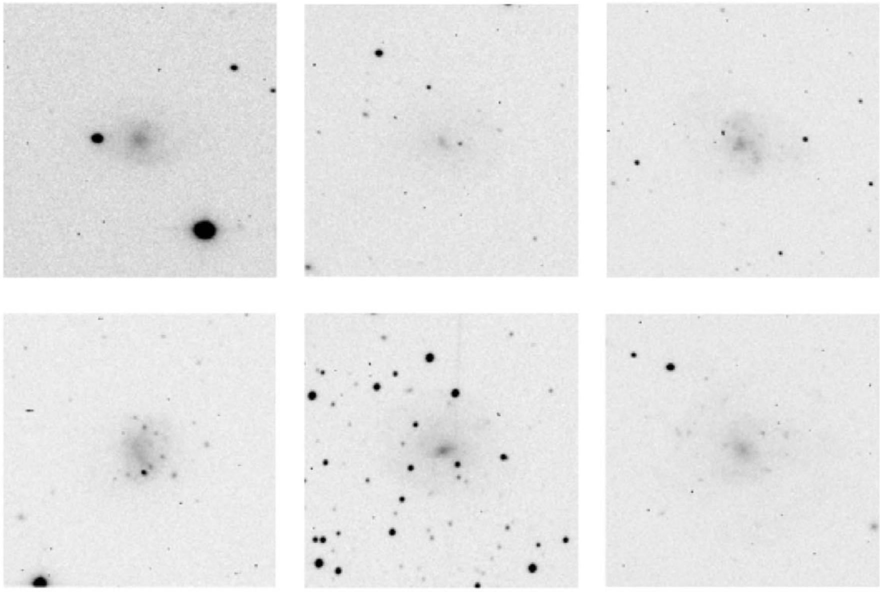

Figure 2. B-band images of 6 low surface brightness galaxies from the ADBS.

the CfA redshift survey galaxies to establish the underlying galaxian distribution. Since the ADBS is redshift limited to 8000 km s^{-1}, the CfA survey has sufficient depth to be used as a reference sample. The densities were computed by determining the distance to the 10 closest galaxies to each ADBS source, then using the distance to the 10th galaxy to compute the volume of the sphere that contains all 10. The density is then 10/volume. This is a robust density estimate because a region with 10 galaxies is always sampled. The only thing that varies is the size of the sample volume. For high density regions the 10th galaxy has a small distance from the target ADBS galaxy so that the density is high; for galaxies in voids you have to go out a long way to reach the 10th galaxy. Figure 5 shows the result of this analysis. The most massive galaxies are actually in slightly less dense regions using this density estimator possibly due to gas stripping in higher density environments.

3.1. *ADBS 113845+2008*

One of the most interesting objects in this survey is ADBS 113845+2008. This galaxy was "discovered" in both the KISO Ultraviolet galaxy survey (Miyauchi-Isobe and Maehara 2000) and the Arecibo Dual-Beam Survey (Rosenberg and Schneider 2000). The VLA was used to obtain follow-up H I spectral line data for this galaxy as part of observing program AC841 targeted at select ADBS detections (Cannon *et al.* in preparation). The C and D array observations of this source (243 and 87 minutes respectively) show an extremely extended gas disk with an inner ring. Figure 6 shows the zero-moment map derived from the robust weighted cube. The peak column density within the ring of gas is 3.8 $\times 10^{20}$ cm^{-2}. These observations are superposed on the Sloan Digital Sky Survey

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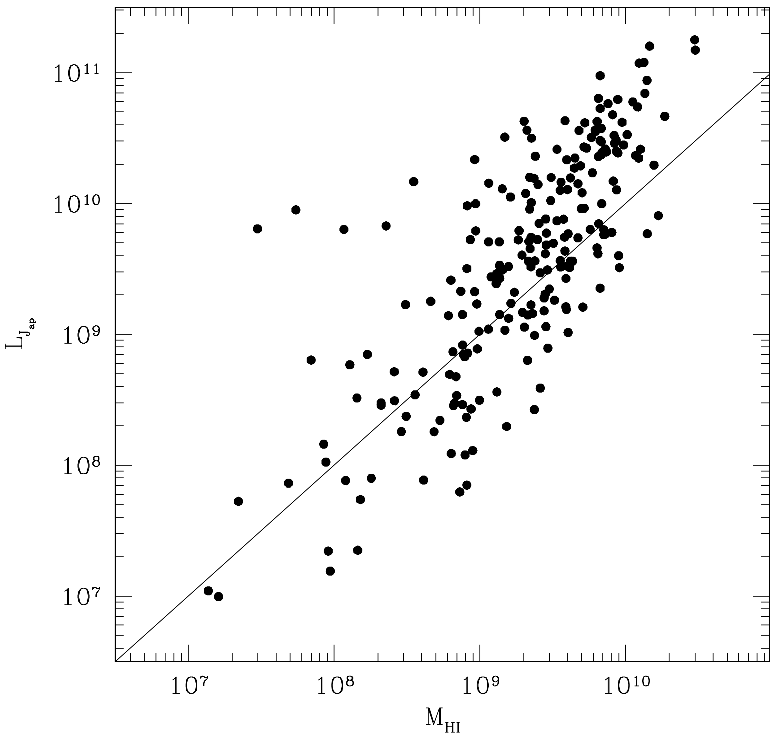

Figure 3. The relationship between L_J and M_{HI} in ADBS galaxies. The line shows a one-to-one correlation between these values.

(SDSS) r-band image and on an Hα image takes with the Kitt Peak National Observatory 0.9m telescope. The gaseous disk in this galaxy extends to more than 20 kpc which is $\gtrsim$28 optical scale lengths. This is one of the most extreme examples of a large H I disk surrounding a compact optical galaxy. Nevertheless, this is not a quiescent low surface brightness galaxy sitting in the middle of a large gas disk, it is a blue compact dwarf galaxy with a star-formation rate of $\sim$0.05 $M_\odot yr^{-1}$. The optical spectrum indicates that the system is actually a metal-poor ($Z\sim0.2Z_\odot$) "post-starburst" galaxy (see Figure 7). The previous epoch of star formation is likely responsible for creating the ring seen in Figure 6. Despite the fact that a previous episode of star-formation has clearly disrupted the interstellar medium in this large gas disk causing a ring, there is no evidence for triggered star formation even in the Hα image.

The compact nature of ADBS 113845+2008 makes this galaxy very difficult to detect optically except in UV-excess selected (KISO) or object-prism selected (KISS) surveys which specifically target these kinds of galaxies. Nevertheless it is a system with a large gas disk easily picked out at 21 cm. In this case, the stars are all concentrated in the center embedded within a large quiescent disk that despite all of its disruption shows no evidence for star formation.

4. Star-Formation Rate in Gas-Rich Galaxies

Gas-rich galaxies show a wide range in optical and infrared properties and include large numbers of dwarf and low surface brightness systems. While most of these systems have very low star-formation rates, it is still relevant to ask whether, because of their large numbers, they can make a significant contribution to the star-formation rate density of

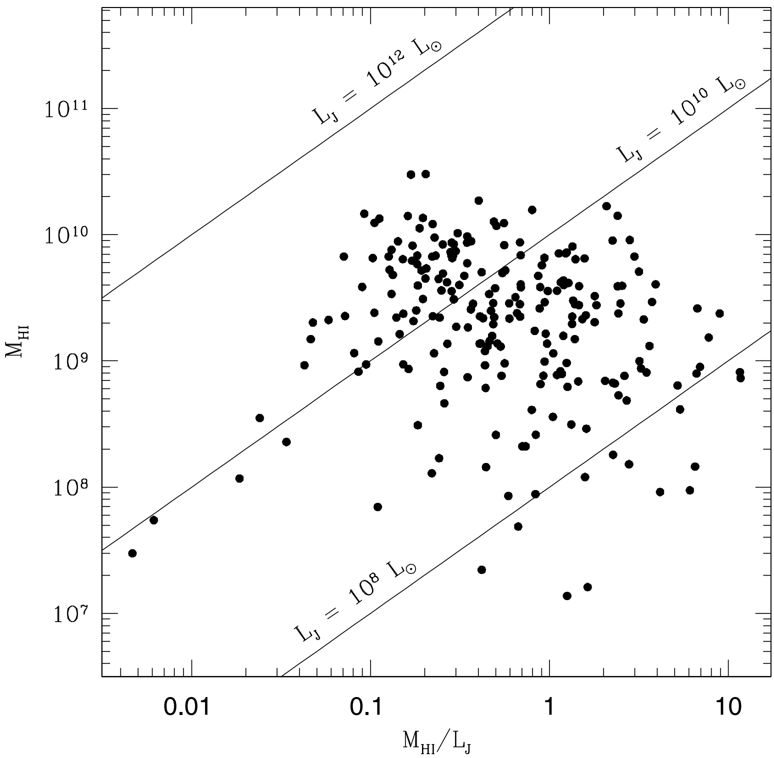

Figure 4. The relationship between M_{HI} and M_{HI} /L_J for galaxies in the ADBS. the lines show constant J-band luminosity (10^8, 10^{10}, and 10^{12} $L_\odot$ respectively.

the local universe. This quantity is of particular importance because it is a commonly used probe of the evolution of galaxies over cosmic time. However, all of the previous estimates are derived from UV-excess or objective-prism surveys which select only the galaxies with the highest star-formation rates. An H I selected sample should include all of the galaxies that have the fuel available to form stars and should therefore provide a less biased measurement. To determine the star-formation rate density we have obtained Hα images for a sub-sample of the ADBS galaxies and used these observations to constrain the star-formation rate density in the local universe. The value that we derive from the ADBS galaxies is a factor two higher than in previous studies. This result indicates that the gas-rich low surface brightness galaxies do contribute significantly to the star-formation rate density in the local universe even though these galaxies do not contribute much individually.

5. Metallicity of Gas-Rich Galaxies

For a galaxy in which there has been no significant infall or outflow, metallicity is a measure of the enrichment of the gas through star formation. Low metallicity galaxies either formed recently so there has not been time for star formation to significantly enrich the interstellar medium, or the rate of star formation over cosmic time has been low. Finding low metallicity galaxies is very difficult because they tend to be very faint – brighter galaxies have, by definition, had a significant amount of star formation. Alternatively, "dark" galaxies have formed no stars and should, therefore, be primordial. Of course there is no way to get an optical measurement of metallicity in a truly primordial,

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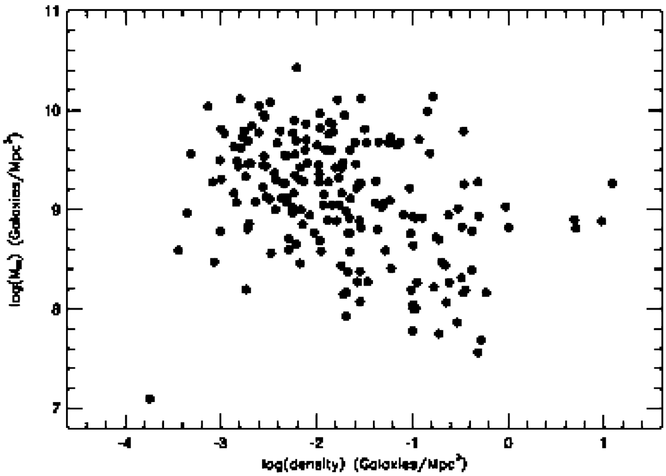

Figure 5. The relationship between M_{HI} and the density of CfA galaxies surrounding the H I source. The method for determining the galaxy density is described in detail in the text.

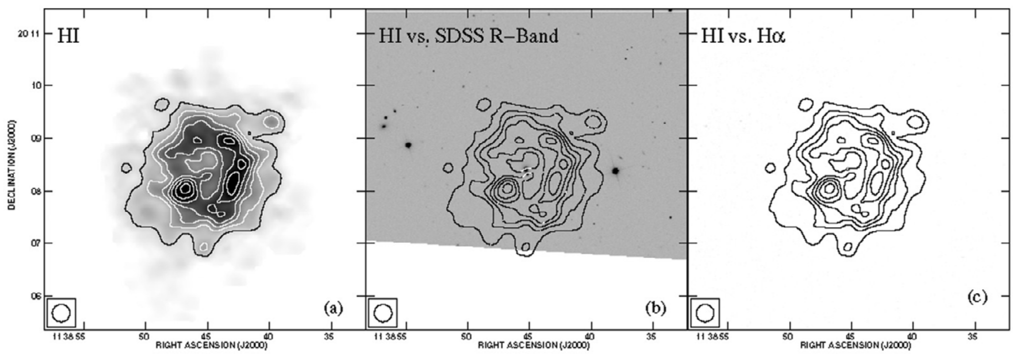

Figure 6. The robust weighted zero-moment map of ADBS 1138+2008. This data cube is the combined VLA C and D array observations of this source. The left-hand panel shows the H I contours overlaid on the greyscale representation of the H I column densities. The center panel shows the H I contours overlaid on the SDSS r-band image of the galaxy. The right-hand panel shows the H I contours overlaid on the Hα image of the galaxy.

star-free galaxy so we examine the degree to which the most gas-rich galaxies are metal poor. In order to address this question we have been obtaining spectroscopic observations of ADBS galaxies with the 6.5m MMT and the 5.0m Palomar telescopes. These data will allow us to determine metallicities with an accuracy of 1–2% even for very faint H II regions. In our first night of MMT observations we observed 8 galaxies at least 4 of which have [O/H] $<$ 10% $Z_{\odot}$. These gas-rich galaxies *do* tend to be very poor indicating that they are either young of extremely inefficient at forming stars.

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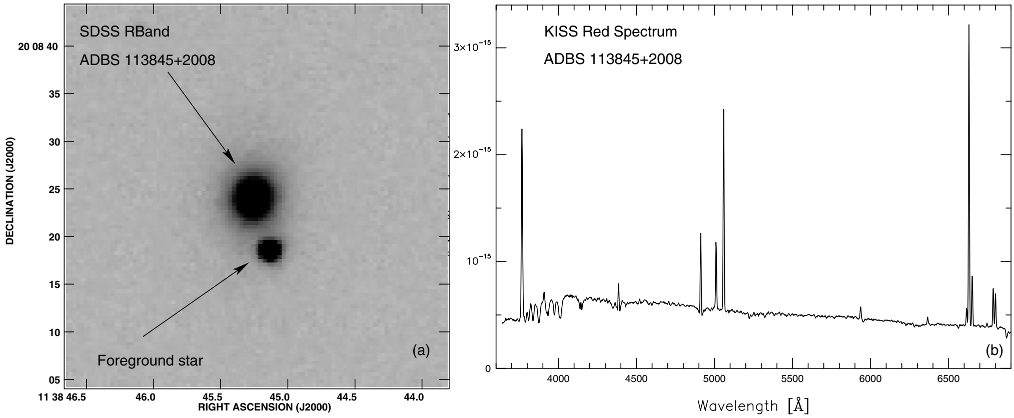

Figure 7. The left-hand panel shows the SDSS r-band image of ADBS 113845+2008. Note that it is barely more resolved than the neighboring foreground star. The optical spectrum in the right-hand panel is from the KISS survey (Salzer *et al.* 2000). This galaxy is a low-metallicity ($Z\sim0.2Z_{\odot}$ “post-starburst system.

6. Discussion

Blind H I surveys are the only way that galaxies with gas but no stars are going to be found if they exist. While finding one of these “dark” galaxies would be incredibly interesting for our understanding of how stars are formed in galaxies, we have already identified numerous systems that highlight the large reservoirs of gas that can exist with relatively little star formation. These galaxies with high gas-to-stars ratios are as important for understanding the drivers of star formation in galaxies as a galaxy found to contain only gas.

What the 21 cm surveys show us is that there is a tremendous diversity of properties of galaxies and of their gas-to-stars ratios. While the environment is clearly one of the factors that can drive changes in the relationship between gas and stars, there are much more complex processes at work. It remains to be determined what other factors are responsible for the formation of low density disks in galaxies that result in extremely inefficient star formation and galaxies with disks that can resist star formation despite central starbursts like in ADBS 113845 + 2008. These data also suggest that these galaxies may be significant contributors to the local star-formation rate density and therefore important for understanding the evolution of galaxies despite their extremely inefficient star formation.

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