May 2015

Do Tidal Interactions Trigger Starbursts in Dwarf Galaxies?

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Abstract

Starburst dwarf galaxies are galaxies experiencing a period of intense star formation. These are extensively studied systems, though the mechanism that triggers the starbursts is poorly understood. Tidal interactions and gas accretion are thought to be potential starburst trigger mechanisms, although internal, secular drivers have not been ruled out. If starbursts are a result of external perturbations, then one would expect to see signatures of interaction in the gaseous disk of the galaxy. To examine this hypothesis, we study newly-obtained deep, wide-field HI maps from the Green Bank Telescope (GBT) of a sample of nine well-studied nearby starburst dwarf galaxies to search for signs of interactions, such as diffuse gas emission and potential companions. Our sample is unique in that we have multiwavelength data for all sources, including previously derived the star formation histories from Hubble Space Telescope imaging of the resolved stellar populations. In this work we first focus on NGC 784 and NGC 672 as a prototype system for evaluating methods to determine the presence and properties of low surface-brightness neutral gas in the outer disk region and then apply these methods to the rest of the sample. We found that three out of the nine GBT sources showed possible tidal interaction signatures, suggesting that tidal interactions may trigger starbursts in some systems but are not a universal cause.

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Do Tidal Interactions Trigger Starbursts in Dwarf Galaxies?

An Honors Thesis

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1. Introduction

In dwarf galaxies a starburst is defined as a period of intense star formation with an increased star formation rate lasting hundreds of Myr (Searle & Sargent 1972; McQuinn et al. 2010). During a starburst a galaxy and its environment can experience dramatic changes in morphology (Gallagher et al. 1984), which may in turn redirect and dictate its evolution (Richer & McCall 1995; Lee et al. 2009; Kennicutt & Evans 2012). Starbursts consume large quantities of gas to create new stars and strip gas from the galaxy via stellar winds and supernova feedback (Lee et al. 2009; Skillman & Bender 1995; Papaderos et al. 1996). The metallicity of a galaxy can be altered during a starburst period as well due to these kinds of mechanisms (Skillman et al. 1989; Richer & McCall 1995; Papaderos et al. 1996).

Throughout the starburst the star formation efficiency (SFE) increases from 1-2% to 10%. However, when classifying galaxies as starbursting or non-starbursting it is crucial to consider the relative SFE and relative timescales for each individual galaxy on a case-by-case basis (Roberts 1963; McQuinn et al. 2010). When a galaxy undergoes a starburst, it consumes its gas at a high rate. If the galaxy continued to consume gas at this rate, it would effectively use up all of its gas because the star formation rate (SFR) is unsustainable during a starburst (Papaderos et al. 1996; McQuinn et al. 2010; Kennicutt & Evans 2012). By comparing the SFR of the burst to the lifetime of the galaxy it is possible to determine whether the SFR is unsustainable for that particular galaxy and thus whether or not the star formation (SF) can be defined as a starburst (McQuinn et al. 2010). Star formation histories (SFH) help give a sense of these timescales (Kennicutt 1998; McQuinn et al. 2010). Comparing timescales and corroborating those results with the information gleaned from other starburst indicators, like color magnitude diagrams and Hα content, gives a holistic picture of the galaxy's SF, enabling the correct classification of the galaxy as starburst or not. Other useful starburst indicators include sites of high Hα emission, areas of high...
surface brightness, color, and color-magnitude diagrams (Lee et al. 2009; McQuinn et al. 2010; Kennicutt & Evans 2012).

It is useful to study starbursts at a variety of different wavelengths, such as optical, infrared, ultraviolet, and radio, to explore many timescales and aspects of the bursts (Gallagher et al. 1984; Kennicutt 1998; Lee et al. 2009; McQuinn et al. 2010; Kennicutt & Evans 2012; McQuinn et al. 2012, for example). For instance, Hα emission is an effective signal for recent star formation (Gallagher et al. 1984; van Zee 2001; McQuinn et al. 2010; Kennicutt & Evans 2012; McQuinn et al. 2012), but to investigate longer timescales and lower mass stars, ultraviolet emission is more practical (McQuinn et al. 2010, 2012). The focus indicator of this work, HI (neutral atomic hydrogen), provides information about the morphology of the gas of a galaxy (e.g. bridges, tidal structures, and filaments) because it is abundant and sensitive to changes in the structure of the galaxy due to gravitational forces (Barnes 2001; Johnson 2013).

Though multiwavelength studies enhance the picture of starbursts in dwarf galaxies, the starburst trigger mechanism for dwarf starburst galaxies remains unknown. Starbursts are not consistent between galaxies, and the phenomenon is even less understood in dwarfs than other types of galaxies like massive spirals (Gallagher et al. 1984). A study by McQuinn et al. (2012) shows that in dwarf starburst galaxies, the starbursts can be nuclear or distributed throughout the disk of the galaxy. The galaxy morphologies and the presence of a companion also varies between starburst dwarf galaxies. (Telles & Maddox 2000; Brosch et al. 2004).

Difficulties arise in identifying a single trigger mechanism for starbursts in dwarf galaxies due to these inconsistencies. Several studies investigated the fundamentals of starbursts in dwarf galaxies (see Larson & Tinsley 1978; Hashimoto et al. 1998; Telles & Maddox 2000; Brosch et al. 2004; Li et al. 2008, for details) but still today the results are inconclusive.
The literature on the starburst trigger mechanism for dwarf galaxies is bipartisan. Some literature suggests that localized gas accretion and internal drivers trigger starbursts. Studies investigated several dwarf starburst galaxies and found that some of the starburst galaxies lacked companions, or, if the galaxy had a companion, there were no indications of any tidal signatures (Telles & Maddox 2000; Brosch et al. 2004). These findings suggest that tidal interactions could not have played a role in those starburst systems and other mechanisms must be active within the systems (Telles & Maddox 2000; Brosch et al. 2004). These studies propose that localized gas accretion from the halo onto the galaxy and internal drivers (e.g. gravitational instabilities, stellar winds, supernovae) are more plausible (Brosch et al. 1998; Telles & Maddox 2000; Brosch et al. 2004; Zitrin & Brosch 2008; Johnson 2013; Pisano 2014). For tidal interactions to increase the SFE to a high enough level that a starburst begins, the environment of the galaxy must meet specific standards; at least one companion needs to exist and the companion must be close enough for tidal forces to have the potential to increase the SFE (Zitrin & Brosch 2008). Also, because the SF can be nuclear or distributed throughout the galaxy (sometimes asymmetrically), SF seems to be regional and driven by the inner machinations of the galaxy and not via a global driver like tidal forces (Brosch et al. 2004).

Yet, the literature also poses an argument for tidal interactions as a trigger mechanism. Though some starburst dwarf galaxies lack companions, many are in fact interacting and have enigmatic morphologies (Telles & Maddox 2000; Zitrin & Brosch 2008; Johnson 2013). Irregular features do not necessarily signify tidal interactions; processes like internal stellar winds and supernovae explosions create similar effects (Marlowe et al. 1995; Brosch et al. 2004; Pisano 2014), but investigation of the context reveals that tidal forces are a likely culprit (Conselice et al. 2000; Zitrin & Brosch 2008; Johnson 2013). Galactic interactions mix gas and condense it into denser clouds, which are necessary for star formation (Barnes 1999, 2001; Zitrin & Brosch 2008). The asymmetry of starburst galaxies, in addition to the
presence of tidal features and disturbed morphologies, also provides insight regarding the potential trigger mechanisms. When comparing the asymmetry parameter and the color of starbursting galaxies with those of non-starbursting galaxies (Conselice et al. 2000), the starbursts within the sample more closely resembled the merger galaxies than the Hubble-type galaxies (Conselice et al. 2000). Tidal interactions explain this result, though internal drivers like galactic bar instabilities cannot be ruled out (Conselice et al. 2000).

Several studies supported both the tidal interaction trigger argument and the localized gas accretion or internal driver theories (Conselice et al. 2000; Barnes 2001; Zitrin & Brosch 2008; Pisano 2014). These studies admitted that acquiring more data, such as SFHs and better statistics, may resolve the conflict surrounding the plausibility of tidal interactions as a starburst trigger mechanism (Brosch et al. 2004; Pisano 2014).

Addressing the concerns of these previous studies in attempt to definitively answer this question, we present part four of a multi-wavelength survey investigating starburst dwarf galaxies and their trigger mechanisms. Previous parts of the survey, dubbed the STARBIRDS (STARBurst IRregular Dwarf Survey) project, included acquiring SFHs and collecting HST, GALEX, Spitzer, VLA, Chandra, and Hα data on most or all of a 22 galaxy sample. The next step of the study, featured in this paper, uses deep, Green Bank Telescope (GBT) wide field HI observations of 9 galaxies in the sample to probe for signatures of tidal interactions in the target galaxy environments. With these observations, our survey possesses the arsenal to forge a complete picture of starbursts in dwarf galaxies and the mechanism that triggers them.

The outline of this paper is as follows. In section 2 I describe the observations and briefly explain the general data reduction method used to produce the moment maps of each galactic field. Section 3 provides a short overview of the sample used. Section 4 features two galaxies within the sample, NGC 784 and NGC 672, and details a prototype analysis
procedure for similar galactic maps. In sections 5 and 6 I outline the results from the other galaxies and discuss the findings, respectively. Section 7 briefly describes future work on this project.
2. Observations and Data Reduction

The data were obtained using the GBT L-band receiver with a central frequency of 1420.406 MHz. A bandwidth of 12.5 MHz was used with 16,538 channels. The velocity resolution before data reduction was about 0.8 km s$^{-1}$ per channel. For one 1 km s$^{-1}$ channel, the target sensitivity was $T_a = 25$ mK rms at 1$\sigma$. The observational technique used was On The Fly (OTF) mapping with the in-band frequency switching mode. OTF mapping works by mapping consecutive rows of the sky. The telescope scans the sky horizontally from the left boundary to the right boundary. Once the telescope hits the right boundary, it has finished one row and proceeds to swing back to the left boundary, but one row lower, until it scans the entire mapping region. The region is generally scanned in pieces which will eventually be stitched together during the data reduction process. When all observations of the target galaxy are complete, the entire region will have been scanned six times total to enable sampling at the Nyquist rate. At this rate each pixel in the image as a 36 second integration time. OTF mapping is ideal for this project because it combines position and frequency switching, allowing for greater efficiency because the telescope simultaneously calibrates for the sky and constantly takes data.

The data reduction process of the GBT data consists of five stages. GBTIDL was used for the first stage and AIPS was used for the other four stages. The data were directly imported from the GBT database into GBTIDL. The initial data for one scan, integration, and polarization looks like the spectrum of DDO 50 in Figure 1. The center of the scan features the galaxy, if the galaxy appears in that scan, and the Milky Way emission. The power appears as two negative reflections on the spectrum at the harmonic frequencies due to the nature of the data collection.

Before creating an image using this spectrum, it must be cleaned to remove radio frequency interference (RFI). Figure 2 displays an example of RFI in one DDO scan. RFI is typically
a very narrow, tall spike in the spectra. Often there are specific frequencies at which RFI signals occur due to external sources emitting waves at those frequencies that the telescope detects. The GBT itself has its own internal RFI that occurs at a known frequency and is removed. If RFI is not cut from the spectra, it could be misinterpreted as a potential source or negatively affect the data quality by adding significant excess noise.

After RFI identification, a region of the spectrum was excised, beginning at the point where the spectrum began to flatten after the leftmost negative reflection and ending just before the rightmost negative reflection. This selection maximized the amount of kept data while eliminating problematic features. The data were then calibrated using a new baseline fitting technique. This flux calibration technique goes row by row, averages the beginning and ending four pixels of the row, and subtracts the resulting average from its respective row in to eliminate residual baseline structure.

All calibrated maps were then sent to AIPS. Because the GBT mapped each galaxy in anywhere from 3-9 different pieces, or scans, the first reduction step in AIPS (and second
Fig. 2.— RFI identified in spectrum of one scan, integration, and polarization of the DDO 50 data.

The stage of the total reduction was to concatenate all scans of a galaxy into one file. The files were then spectrally smoothed to a 4 channel resolution and the SDGRID task was implemented to transform the two dimensional spectrum into a three dimensional data cube. The program works by performing a Fourier transform on the spectrum (see Mangum et al. (2007) for more details). Because each galaxy in our sample is close in space and velocity to the Milky Way, the Milky Way appeared in every cube and was removed before continuing onto the next stage. Each of these cubes was blanked at the $2\sigma$ rms level and then handblanked so that only sources and diffuse emission are selected for the next cube. The blanking and handblanking are necessary to isolate the galaxy and real features from the noise. As an example, an unblanked frame from the DDO 50 cube is shown in Figure 3.
Fig. 3.— A frame from the DDO 50 data cube. The border of the frame consists of edge effect artifacts due to the creation of the map. These edge effects were ignored when calculating RMS (noise) values for the cube and throughout the handblanking process.
DDO 50 and M81 dwA, located to the upper right of DDO 50, are evident, but the rest of the cube contains regions with slight over- and under-densities of pixels. Blanking the cube at even a low threshold of $2\sigma$ eliminates most noise and allows the user to more easily identify potentially real features. Figure 4 displays same frame of the DDO 50 cube with a $2\sigma$ threshold blank.

![Figure 4](https://example.com/image.png)

Fig. 4.— The frame from Figure 3 with a $2\sigma$ blanking. Notice that much of the noise and background pixels no longer exist. The column of pixels on the left side of the frame are pixel artifacts from the cube edge effects.
The frame in Figure 4 has more blank pixels and the galaxies are more easily identifiable. A $2\sigma$ blank was chosen because this threshold is enough to eliminate most noise while keeping very low surface brightness emission intact.

Handblanking is then done on the blanked cube, where the user selects features she identifies as real emission. Consistent features, or features that last through three or more frames in velocity, are kept in this process and considered to be possible real emission. The handblanking procedure presents challenges in that some noise and Milky Way features, in addition to diffuse emission from the target source, can last through three or more frames. Section 4 goes into more detail on distinguishing between target source emission and noise or Milky Way features. In the final stage, these handblanked cubes are used to create moment 0 and moment 1 maps. A moment 0 map is an image of the mapped field in which each pixel in the image is a summation of all real, non-blanked pixels throughout the entire data cube. Moment 1 maps are intensity weighted velocity maps. Each pixel in a moment 1 map represents the average velocity at that pixel.

It is important to note that this was the general data reduction procedure for each galaxy. Some galaxies required extra or different steps. These will be specified further in this work.
3. The Sample

The sample consists of 22 starburst dwarf galaxies: 9 galaxies with new, deep wide-field HI GBT data, 3 galaxies with recently acquired Parkes data (this data will not be processed in this work), 7 galaxies with archival GBT data, and 3 extra control galaxies that are not starbursting. In order to create the most complete picture of starbursts in dwarf galaxies as possible, the survey needs starburst dwarf galaxies that have extensive multiwavelength data (i.e. HST, GALEX, Spitzer, and potentially VLA, Chandra, and Hα), which this sample possesses. The sample contains galaxies with varying SFRs, stellar masses, and states of isolation, allowing the survey to probe for a universal trigger mechanism that is independent of galaxy properties. Finally, there are 3 control galaxies. These are isolated, non-bursting, quiescent dwarf galaxies with little recent SF (Weisz et al. 2011), which makes them ideal sources for comparison with the starbursting galaxy datasets.

Table 1 provides some basic properties of the galaxies in the sample. Note that because Parkes data and the control galaxy data are currently undergoing the data reduction process, data on those galaxies is still being acquired.
### Table 1. Galaxy Properties

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>R.A. (J2000)</th>
<th>Decl. (J2000)</th>
<th>Distance (Mpc)</th>
<th>Velocity (km s(^{-1}))</th>
<th>Peak SFR of Burst (10(^{-3}) M(_\odot) yr(^{-1}))</th>
<th>Peak GBT N(_{\text{HI}}) (1E20 cm(^{-2}))</th>
<th>Galaxy S(_{\text{HI}}) (Jy km s(^{-1}))</th>
<th>Field S(_{\text{HI}}) (Jy km s(^{-1}))</th>
<th>Galaxy M(<em>{\text{HI}}) (M(</em>\odot))</th>
</tr>
</thead>
<tbody>
<tr>
<td>DDO 187</td>
<td>14:15:56.70s</td>
<td>+23:03:16.2s</td>
<td>2.2</td>
<td>106</td>
<td>5.1 ± 1.0</td>
<td>0.37</td>
<td>11.69</td>
<td>12.43</td>
<td>1.34E7</td>
</tr>
<tr>
<td>HoII/U4483</td>
<td>08:37:03.28s</td>
<td>+69:46:29.2s</td>
<td>3.4</td>
<td>145</td>
<td>180 ± 20/11 ± 2</td>
<td>5.06</td>
<td>302.54</td>
<td>312.28</td>
<td>8.25E8</td>
</tr>
<tr>
<td>NGC 6789</td>
<td>19:16:41.16s</td>
<td>+63:58:23.9s</td>
<td>3.6</td>
<td>-106</td>
<td>15 ± 5</td>
<td>0.17</td>
<td>18.67</td>
<td>18.67</td>
<td>5.71E7</td>
</tr>
<tr>
<td>NGC 4068</td>
<td>12:04:02.25s</td>
<td>+28:50:14.1s</td>
<td>4.3</td>
<td>236</td>
<td>46 ± 3</td>
<td>1.02</td>
<td>38.87</td>
<td>38.87</td>
<td>1.70E8</td>
</tr>
<tr>
<td>DDO 165</td>
<td>13:06:24.85s</td>
<td>+67:42:24.9s</td>
<td>4.6</td>
<td>71</td>
<td>80 ± 5</td>
<td>0.95</td>
<td>45.37</td>
<td>46.99</td>
<td>2.27E8</td>
</tr>
<tr>
<td>NGC 2366</td>
<td>07:28:54.66s</td>
<td>+69:12:56.8s</td>
<td>3.2</td>
<td>130</td>
<td>160 ± 10</td>
<td>5.97</td>
<td>250.66</td>
<td>1641.62</td>
<td>6.06E8</td>
</tr>
<tr>
<td>NGC 784</td>
<td>02:01:16.93s</td>
<td>+28:50:14.1s</td>
<td>5.2</td>
<td>243</td>
<td>120 ± 20</td>
<td>1.73</td>
<td>57.12</td>
<td>61.43</td>
<td>3.63E8</td>
</tr>
<tr>
<td>NGC 6822</td>
<td>19:14:57.74s</td>
<td>-14:48:12.3s</td>
<td>0.5</td>
<td>-61</td>
<td>7.3 ± 2.5</td>
<td>16.5</td>
<td>5507.90</td>
<td>5507.90</td>
<td>3.25E8</td>
</tr>
<tr>
<td>NGC 672</td>
<td>01h47m54.5s</td>
<td>+27:45m58s</td>
<td>7.2</td>
<td>429</td>
<td>3.65 ± 0.1</td>
<td>4.25</td>
<td>229.23</td>
<td>233.82</td>
<td>3.12E9</td>
</tr>
<tr>
<td>IC 4662</td>
<td>17:47:08.8s</td>
<td>-64:38:30s</td>
<td>2.4</td>
<td>302</td>
<td>76 ± 15</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>NGC 625</td>
<td>01:35:04.6s</td>
<td>-41:26:10s</td>
<td>3.9</td>
<td>396</td>
<td>40 ± 5</td>
<td>...</td>
<td>...</td>
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</tr>
<tr>
<td>ESO 154-023</td>
<td>02:56:50.38s</td>
<td>-54:34:17s</td>
<td>5.8</td>
<td>574</td>
<td>120 ± 10</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>ANTLIA</td>
<td>10:04:04.1s</td>
<td>-27:19:52s</td>
<td>1.3</td>
<td>362</td>
<td>0.52 ± 0.01</td>
<td>...</td>
<td>...</td>
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<td>...</td>
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<tr>
<td>NGC 4163</td>
<td>12:12:09.1s</td>
<td>+36:10:09s</td>
<td>3.0</td>
<td>165</td>
<td>12 ± 3</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>UGC 6456</td>
<td>11:27:59.9s</td>
<td>+78:59:39s</td>
<td>4.450</td>
<td>-103</td>
<td>23 ± 3</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>NGC 1569</td>
<td>04:30:49.0s</td>
<td>+64:50:53s</td>
<td>3.4</td>
<td>-104</td>
<td>240 ± 10</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>NGC 5253</td>
<td>13:39:55.9s</td>
<td>-31:38:24s</td>
<td>3.8</td>
<td>407</td>
<td>400 ± 40</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>NGC 4214</td>
<td>12:15:39.2s</td>
<td>+36:19:37s</td>
<td>2.7</td>
<td>291</td>
<td>130 ± 40</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>NGC 4449</td>
<td>12:28:11.9s</td>
<td>+44:05:40s</td>
<td>4.2</td>
<td>207</td>
<td>970 ± 70</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
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<tr>
<td>IC 5152</td>
<td>22:02:41.5s</td>
<td>-51:17:47s</td>
<td>1.8</td>
<td>122</td>
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<td>01:35:04.6s</td>
<td>-41:26:10s</td>
<td>4.2</td>
<td>391</td>
<td>...</td>
<td>...</td>
<td>...</td>
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<td>ESO 410-005</td>
<td>00:15:31.5s</td>
<td>-32:10:48s</td>
<td>1.9</td>
<td>159</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Note. — Table 1. Basic characteristics of the galaxy sample. The first 9 galaxies are galaxies with the recent, deep, wide-field HI GBT images. The next 3 galaxies are the Parkes galaxies, and the following 7 galaxies are the archival galaxies within the sample. The final 3 galaxies are the non-bursting control sample. The velocity listed is the systematic velocity of the system. The Peak SFRs were found using data from the Hubble Space Telescope and are directly from the McQuinn et al. (2010) study. The galaxy S\(_{\text{HI}}\) is for most cases the S\(_{\text{HI}}\) of just the target galaxy in each field. The exceptions are NGC 784 (the S\(_{\text{HI}}\) includes AGC 111164 S\(_{\text{HI}}\)), NGC 672 (the S\(_{\text{HI}}\) includes IC 1727), DDO 165 (the S\(_{\text{HI}}\) excludes the linear feature extending from the left side), DDO 187 (the S\(_{\text{HI}}\) excludes all external features), and DDO 50 (the S\(_{\text{HI}}\) includes M81 dwA). The field S\(_{\text{HI}}\) column includes all features in the field. The M\(_{\text{HI}}\) was calculated using the target galaxy S\(_{\text{HI}}\), not the field S\(_{\text{HI}}\).
The diversity of the galaxy sample is evident in both Table 1 and Figure 5. The distances cover the range of 0.5 Mpc to 10.3 Mpc and the velocities from -104 km s\(^{-1}\) to 429 km s\(^{-1}\). The SFRs also cover a large range: about 0.52 \(10^{-3}\) M\(_\odot\) yr\(^{-1}\) up to about 970 \(10^{-3}\) M\(_\odot\) yr\(^{-1}\) (McQuinn et al. 2010). The galaxy environments of each galaxy are diverse as well. Galaxies like DDO 50 and NGC 784 have known galactic companions with which they are interacting, whereas galaxies like NGC 6798 and NGC 4068 are thought to be isolated. Such an expansive and varied sample eliminates selective bias from the results and enables
the ability to make generalized conclusions about starburst drivers for all kinds of starburst galaxies.
4. The NGC 784 and NGC 672 Mosaic: A Prototype System

INTRODUCTION TO THE FIELDS

This section focuses on the linked NGC 784 and NGC 672 fields. NGC 784 is an edge-on galaxy located in the NGC 784 group at a distance of 5.19 Mpc, and is a member of the 17+6 association (Tully et al. 2006; McQuinn et al. 2010). NGC 672 and its companion IC 1727 dominate their group, both in size and mass (Zitrin & Brosch 2008). They are located 7.2 Mpc away (McQuinn et al. 2014) and the distance between the two galaxies, as calculated in a study by Heald et al. (2011), is 16.3 kpc. NGC 672 and IC 1727 are located to the lower right of the NGC 784 field. This field suggests a possibility for companionship or interaction between NGC 672 and other galaxies in both the spatial and velocity fields. Because of their distance, similar kinematics, and the slightly disturbed morphology of IC 1727, it is suspected that NGC 672 and IC 1727 are engaging in an interaction (Heald et al. 2011).

Though the GBT observed the NGC 784 and NGC 672 fields separately and they are not in the same galaxy groups or associations, their maps actually overlap in position and velocity space, possibly because both likely lie in a line of dwarf galaxies that occupies about six degrees on the sky (Zitrin & Brosch 2008; McQuinn et al. 2014). It has been suggested that this filament connecting the galaxies is comprised of dark matter, where each galaxy signifies a point in the string where matter collapsed and stars formed (Zitrin & Brosch 2008). Though the galaxies are part of groups such as the NGC 784 group and the NGC 672/IC 1727 group, the filament of galaxies itself is isolated (Zitrin & Brosch 2008).

A system such as the NGC 784/NGC 672 galaxy strand proposes an interesting case study for starburst dwarf galaxies, especially with regards to investigating tidal interactions. Because the strand or filament is apparently isolated, any signatures of tidal interactions must come from one or more of the galaxies within the strand and not an external source,
simplifying the system. The system also contains two dwarf starburst galaxies from the sample (both NGC 784 and NGC 672), enabling the ability to compare possible trigger mechanisms of two different galaxies within the same system. In fact, the two separate maps of NGC 784 and NGC 672 can be stitched together to build one of the largest, deepest GBT HI maps ever created. Its sensitivity in the overlapping region allows for easier detection of any tidal signatures. The NGC 672 system specifically is an ideal prototype system for evaluation because there is already at least one known and extensively studied interaction (with IC 1727). The data cubes and moment maps from this field will then display what an interaction looks like for deep, wide-field GBT data like the data presented in this work. The images from NGC 672 can then be used as comparison images; if other fields in the sample resemble the NGC 672 field, then it is probable that an interaction is occurring.

Analysis of the galaxies in the sample presents several challenges; it is difficult to determine with certainty which features of the HI maps are real and which are spurious or Milky Way emission, provoking a need for a prototype system. There are a variety of ways to overcome these challenges and deal with this kind of interference, and the mosaic is an ideal canvas to perform tests and find effective ways to analyze these starburst dwarf galaxy systems. Because various surveys and research groups studied the two systems extensively, there is information that can confirm or deny the accuracy of these tests, for instance which galaxies should be detected, relative distances, and so on.

**Mosaic and Map Creation**

The mosaic creation procedure varies from the standard data reduction procedure used for the other galaxies (with the exception of NGC 2366, which is also a mosaic). Typically, all scans for one galaxy are simply concatenated into one file, as-is, and then AIPS transforms the file into a cube, and so on (see section 2 for details). However, while it is possible to concatenate all NGC 784 scans separately from all NGC 672 scans, more steps are required
to concatenate all NGC 784 and NGC 672 scans: cutting and shifting. The first step in the procedure was to cut the scans to excise only the parts of the NGC 784 and NGC 672 scans that overlap in frequency space. The next step was to change relevant image header information, like the reference pixel, to prepare the scans for concatenation by making them exactly identical. Once completed, each scan was concatenated to create one complete file, and eventually one of the deepest, largest HI GBT maps ever produced, using the data reduction techniques outlined in the data reduction section of this paper. Similar, but smaller maps have been created for the other galaxies as well, including separate NGC 784 and NGC 672 maps formed from their respective data scans.

The resulting mosaic is displayed in Figure 6
Fig. 6.— Mosaic of NGC 784/NGC 672 field. The NGC 784 field is on the left and the NGC 672 field is on the right. The two fields slightly overlap in the lower right corner of NGC 784 and the upper right corner of NGC 672, but no emission was detected in the overlap.

**CHALLENGES AND TESTS**

Interpreting galactic field maps is not a trivial task. The maps provide critical information, but the information must be teased out. The GBT maps of our sample, like those for NGC 784 and NGC 672, are especially tricky because the maps are so deep and so expansive in space, and thus particularly sensitive to low surface brightness material. This presents difficulties, however, when attempting to determine whether a map feature is low-surface brightness material or noise. Simply looking at the feature in the moment 0 map often is not enough to make this decision. As alluded to previously, distinguishing GBT target
features from Milky Way emission is also problematic for the same reasons. Milky Way emission was present in every data cube, and while the Milky Way clouds tend to have characteristic patterns, the target is sometimes too close in velocity and position to see a difference between the Milky Way and the target galaxy.

The strategy to overcome these challenges was to perform a variety of different tests on the fields to search for consistency between test results and the field map. If a feature survives the battery of testing, it is most likely real. The interpretation began with evaluating the column density map, and in particular the size of each feature relative to other features and the physical distance of the features from each other. This helps to eliminate features that cannot possibly be interacting with the target galaxy because it is unphysical; that is to say, the feature is out of the interaction range of each target galaxy. This brings up the question of how to determine the interaction range of a galaxy, which is difficult to define, but on a most basic level it is possible to eliminate features that, without question, could not be interacting.

Another somewhat standard method for checking the reality of a feature is to increase the threshold blanking value and compare the resulting column density maps. In the case of NGC 784, NGC 672, and the other galaxies in the sample, I used a threshold value of $2\sigma$ so as to retain all low surface brightness features the GBT observes that may be signatures of tidal interactions. $3\sigma$ maps can be dangerous in the sense that they may eliminate features that are actually real but dim. However, if a feature is already suspect with respects to other tests, the $3\sigma$ cube can provide necessary insight. If a feature withstands the $3\sigma$ blank it is either real emission, $3\sigma$ or greater noise, or Milky Way contamination. Comparing this result to other results could then definitively confirm or rule out a feature as real or not.

Many useful results come from learning as much about the field as possible, including the
moment 1, or velocity, map of the galaxy. Velocity maps show not only the velocity of each feature, but also the way in which the velocity changes throughout the feature and whether features possess similar velocities. Galaxy rotation manifests itself as a velocity gradient, so if the velocity of a feature changes spatially it might be rotating and is probably not spurious. Features that are almost exclusively one velocity throughout were then found in a few channels at that velocity that happened to have abnormal noise characteristics and are most likely not real emission. Checking the velocity between features is also useful. If a feature in the vicinity of the target galaxy, for example, is at a similar velocity to the target galaxy, or is within the galaxy velocity gradient, it may be near that galaxy or related to it in some way. Similarly, a feature found spatially between two galaxies with a velocity between the velocity of those galaxies is likely gas strewn from one galaxy due to its interaction with the other. And finally, noting the velocity values of the features provides the final velocity check. This is an important step for this project in particular because if the velocity of the feature is either definitely out of the interaction velocity range (a value that varies depending on the galaxy, but would typically be no greater than 500 km s\(^{-1}\)) of the target galaxy or is close to typical Milky Way emission velocities, the feature can probably be ruled out as a tidal feature.

Threshold blanking tests akin to those mentioned above provide solid insight about the features in the map, but the tests above were completed using the human eye and human selection. The human eye is quite sensitive to detecting features in a data cube, which is why handblanking is still a common procedure, but it is still a useful exercise to compare the maps above to maps created completely using strictly numerical techniques. We chose the task XGAUFIT in GIPSY to create these maps. The program fits a Gaussian function through frequency space searching for velocity coherence. For each test, we chose an amplitude of the 2\(\sigma\) rms value for that particular cube and a minimum dispersion threshold of 5 km s\(^{-1}\). We implemented no position bounds. The judgement of a computer is not
necessarily always sound but corroborating the GIPSY maps to the handblanked maps previously discussed provides an extra check for the reality of the features in each map.

With respect to this Milky Way emission in particular, a helpful test involves comparing the peculiar features in our maps to the Galactic dust maps to look for an overlap. If dust from the Galactic dust map overlaps with a feature from a target galaxy map map, it is most likely Milky Way HI gas.

Another test required cross-correlation with the SDSS and ALFALFA (Haynes et al. 2011) databases to determine whether or not the feature has a detected optical counterpart and whether or not the feature has been previously detected. While the possibility of new discovery exists, the cross-correlation tests, in addition to the other tests, help rule out if a potential new discovery is actually a cloud of gas, for example, or spurious noise. To perform the cross-correlation I navigated around the galaxy to look for objects, and evaluated whether those objects are within a reasonable redshift of the target galaxy. Again, ‘reasonable’ redshift is somewhat subjective, but in most cases sources could be ruled out because they had a redshift of, for instance $z = 0.1$, whereas the sources sampled in this work have redshifts of the order of $z = 0.0001$. Sifting through the ALFALFA data was more quantitative. I wrote a program in Python that read ALFALFA’s a70.csv (Haynes et al. 2011) file and searched for sources within specific spatial bounds of the target galaxy. I determined the spatial bounds to be the bounds of the GBT maps. The program then listed the velocities of each source. Similar to the SDSS cross-correlation, most could be eliminated because their velocities were unreasonable and on the order of thousands of kilometers per second instead of a few hundred kilometers per second like the target galaxies. Not every galaxy was located within the footprint of the ALFALFA catalog, but the program provided useful information for included galaxies, like NGC 784 and NGC 672. Each aforementioned test is applicable to HI maps in general, especially deep, wide-field
GBT maps like the maps featured in this work. The final test described in this paragraph is most beneficial if the SFHs of each galaxy are well understood, as in the case of this sample; the galaxies have been extensively studied McQuinn et al. (2010). The SFHs, and thus the duration of the starburst in the galaxy, provide an evolutionary timescale for each galaxy. If a map displays a feature that may be of tidal origin, and if the interaction resulting in that tidal feature triggered a starburst, then that feature should have formed around the same time as the starburst. Assuming that $1 \text{ km s}^{-1} = 1 \text{ pc yr}^{-1}$, the difference in velocity between the galaxy and its tidal feature or companion becomes a rate in pc yr$^{-1}$. Then, using a basic $D = v \times t$ formula, where $D$ is the distance between the galaxy and its feature or companion, $v$ is the velocity in pc yr$^{-1}$, the time it would take for the gas to travel that distance can be calculated. If the time it would take the gas to travel that distance is greater than or about equal to the length of the starburst, it is plausible that the interaction manifesting itself as that tidal feature initiated the starburst. It is crucial to note that this test provides solely a bound and loose estimation for the timescale of each feature, especially because the calculation also only accounts for the velocity in the GBT’s line of sight.

It should not go unnoticed that my langauge throughout the description of these tests is non-definitive. This is because one test cannot prove a feature to be real or not. The corroboration of all tests and a feature’s consistency are the only way to reach any conclusions regarding whether or not the feature is real emission.

**Test Execution**

I applied all aforementioned tests to the NGC 784 and NGC 672 fields, and in this section I will go through each test and its effectiveness in interpreting the NGC 784 and NGC 672 fields, beginning with the column density maps. The maps are shown in Figures 7-10, with and without contours. Interferometer maps are displayed for comparison.
Fig. 7.— On the left is a GBT column density map of the 2 degree by 3 degree NGC 784 field. On the right is a WSRT interferometer column density map from the WISP survey (van der Hulst et al. 2001) of NGC 784. Note that the WSRT image is in Equatorial coordinates whereas the GBT map is in Galactic coordinates. The red box denotes an approximate field of view.
Fig. 8.— On the left is a GBT column density map of the 2 degree by 3 degree NGC 784 field with a 1σ contour level at 0.3 $10^{20}$/cm$^2$. Contour levels increase by a multiple of 2. On the right is a WSRT interferometer column density map from WISP (van der Hulst et al. 2001) of just NGC 784 with 1σ contours at 10 $10^{20}$/cm$^2$. Contour levels increase by a multiple of 2. The contours of this image were found by normalizing the image to the peak $N_{HI}$ value. As such, the column density values should be considered an approximation. Note this is the same figure as Figure 7 with added contours.
Fig. 9.— On the bottom is a column density map of the 2.5 degree by 2 degree NGC 672 field. On the top is a WSRT interferometer column density map from the WISP survey (van der Hulst et al. 2001) of just NGC 672. Note that the WSRT image is in Equatorial coordinates whereas the GBT map is in Galactic coordinates. The red box denotes an approximate field of view.
Fig. 10.— On the bottom is a column density map of the 2.5 degree by 5 degree NGC 672 field with a 1σ contour level at 0.1 \(1 \times 10^{20} / \text{cm}^2\). Contour levels increase by a multiple of 2. The upper image is a WSRT interferometer column density map from the WISP survey (van der Hulst et al. 2001) of just NGC 672 with 1σ contours at 0.4 \(1 \times 10^{20} / \text{cm}^2\). Contour levels increase by a multiple of 2. The contours of this image were found by normalizing the image to the peak \(N_{HI}\) value. As such, the column density values should be considered an approximation. Note this is the same figure as Figure 9 with added contours.

Neither target galaxy is the only object in its field, and neither galaxy has a completely
regular shape. NGC 784 has a long strip trailing from it, which has potential to be a tidal tail but could also be noise. The galaxy itself extends for about 40 kpc and the tail feature extends for roughly 117 kpc. The other features in that field are also irregularly shaped and comparable in size to NGC 784. The upper two features are in total 183 kpc across. The feature in the lower right corner is slightly smaller than the others but is well within a reasonable interaction range (142 kpc away from NGC 784). NGC 672, which is roughly 2 Mpc away from NGC 784, has similar qualities in its field. Two of its anomalous features seem to be connected either to NGC 672 or to each other by gas. Each feature is also relatively close to NGC 672, the farthest being about 178 kpc away from the NGC 672/IC 1727 cloud, placing them in potential interaction range of NGC 672/IC 1727.

The 3σ column density maps also provide information about this field. A comparison between the 2σ maps from above and 3σ maps is shown in Figures 11 and 12.
Fig. 11.— The upper left image is a $2\sigma$ threshold blank column density map of the NGC 784 field and the lower left image is the $3\sigma$ threshold blank column density map of the same field. The $2\sigma$ RMS threshold value was 0.03 K and the $3\sigma$ threshold value was 0.045 K. The upper right image is a $2\sigma$ threshold blank velocity field map of the NGC 784 field and the lower left image is the $3\sigma$ threshold blank velocity field map.
Fig. 12.— The upper left image is a $2\sigma$ threshold blank column density map of the NGC 672 field and the lower left image is the $3\sigma$ threshold blank column density map of the same field. The $2\sigma$ RMS threshold value was 0.026 K and the $3\sigma$ threshold value was 0.039 K. The upper right image is a $2\sigma$ threshold blank velocity field map of the NGC 672 field and the lower left image is the $3\sigma$ threshold blank velocity field map.

Again, a feature that disappears in the higher threshold map could just be very low surface brightness, but the check is still a useful exercise. Both fields undergo changes in the higher
threshold maps. The NGC 784 field adds a small feature in the lower right corner and
the NGC 672 field loses the leftmost feature. The added small feature in the NGC 784
field seems like handblanking error because the chances of a real feature not appearing in
a 2σ map but appearing in a more thoroughly blanked 3σ map is quite small, unless the
error is that the feature does actually exist in the 2σ cube and it was simply missed. The
disappearance of the NGC 672 feature suggests that the feature is either very low surface
brightness or is spurious and therefore did not make the 3σ cut. Most of the long NGC 784
tail also disappeared, however notice that a small portion still exists. The other features of
the NGC 784 and NGC 672 fields survived the more aggressive blanking threshold, implying
that those features have a high potential to be real.

Next, note the velocity maps from Figures 11 and 12, particularly the values of the
velocities. NGC 784 and NGC 672 cover velocity ranges that are not unreasonably far
apart from each other (175 km s\(^{-1}\) for NGC 784 and 450 km s\(^{-1}\) for NGC 672), and the
feature in the lower right corner of the NGC 784 field has a similar velocity to both NGC
784 and a feature of the NGC 672 field. Examining each field separately, starting with
NGC 784, notice that NGC 784 has a velocity gradient characteristic of rotation, consistent
with expectations. While none of the other features possess a similar gradient, they are
not one solid color either, meaning the features are not definitely noise. In fact, chaotic
velocity fields are characteristic of tidal interactions because gas can be strewn in a variety
of directions, so these features could be signs of interaction. Similar characteristics exist
in the NGC 672 field, though the feature in the lower left corner shows some potential for
rotation. In the NGC 672 field notice that the feature directly to the right of IC 1727 is the
same velocity as the gradient between NGC 672 and IC 1727, suggesting that it might be a
tidal remnant of the interaction between the large galaxies. The feature in the lower center
may also be a remnant of the interaction based on its velocity.
The GIPSY tests for each galaxy also provide some insight into the fields and are shown in Figures 13 and 14.

Fig. 13.— Gipsy output image of the NGC 784 field with an amplitude blanking threshold of $2\sigma = .03K$ and a velocity dispersion threshold of 5 km s$^{-1}$. Note that the units of the map are K and not K km s$^{-1}$.
Fig. 14.— Gipsy output image of the NGC 672 field with an amplitude blanking threshold of $2\sigma = 0.26\text{K}$ and a velocity dispersion threshold of 5 km s$^{-1}$. Note that the units of the map are K and not K km s$^{-1}$.

Both images have singular pixels scattered throughout. This is simply due to the way XGAUFIT fits the pixels statistically and the fact that each cube had one or two frames that contained high flux Milky Way emission that had been removed in the handblanking process because we recognized the emission as Milky Way and the computer could not. While velocity constraints were made on the fields, it was often not possible to remove all instances of Milky Way emission. The GIPSY images are similar to the column density maps above in that the galaxy is present and one or two features remained. In the NGC 784 field, the feature to the upper right of NGC 784 seems to still exist, as well as AGC 111977. All detected galaxies from the handblanked images of NGC 672 remain in the
GIPSY images, with the exception of the feature to the lower left of NGC 672, which has been reduced to two pixels. The GIPSY images seem to confirm the existence of those AGC galaxies in the NGC 672 field. The NGC 784 field is more problematic, as GIPSY did not seem to detect the AGC galaxies. Looking closely, however, it does seem that the GIPSY image displays an overdensity of pixels where the large cloud above NGC 784 and the feature to the lower right of NGC 784 exist in the handblanked column density maps, supporting the hypothesis that those features are also real. Overall, this test confirms that the original features detected are statistically detections.

Galactic dust maps were also evaluated for each galaxy. The results were negative; no high luminosity dust clouds exist in the region of either galaxy.

The next method to test is cross-correlation using both SDSS and searching through the ALFALFA catalog. I first considered SDSS. The idea behind this field evaluation technique is to search the SDSS optical field of the target galaxy using the navigation tool and attempt to find galaxies within reasonable position and velocity boundaries of the target galaxy. This is no trivial task; within a field of view as large as the GBT maps, there are several dozen potential sources to investigate. I was not able to find any sources using the SDSS navigate tool for either field.

The ALFALFA catalog, the second component of the cross-correlation, yielded more results. I began the process by searching for sources within the GBT map field of view with a velocity on the order of tens to hundreds of km s\(^{-1}\). The program produced 11 sources between the two fields that matched my parameters, three of which included NGC 784, NGC 672, and IC 1727. This provides a good check for the method because the program found three main sources I expected to see. The program also found several of the SHIELD survey galaxies (Cannon et al. 2011) I predicted to find (the AGC galaxies in both fields), demonstrating the legitimacy of the program and the method. The program detected two
additional AGC sources at velocities within the velocity field of the NGC 672 cube, but the positions were just out of range. One AGC source was common between the separate NGC 784 and NGC 672 fields, demonstrating that the two fields overlap and can be stitched together. The next step was to take the positions of the detected sources and see if they match the positions and velocities of the GBT map features. Each source had a corresponding feature on the NGC 784 and NGC 672 maps.

The final examination is to look at the SFH timescales for each galaxy. For the NGC 784 field, I compared the timescales for gas to travel between NGC 784 and three sources: AGC 111164, AGC 111977, and the center of the tail to the lower left of NGC 784. I calculated times of 995 Myr, 14,160 Myr, and 2146 Myr, respectively. For the NGC 672 field, I compared the gas timescales for the distance between NGC 672 and four other sources: AGC 111946, AGC 111945, IC 1727, and the lower left feature. I calculated times of 922 Myr, 1400 Myr, 372.5 Myr, and 156 Myr. According to the starburst durations determined by McQuinn et al. (2010), all starbursts within the sample, with the exception of NGC 6822, have lasted at least 450 Myr or longer. The calculated duration for the NGC 784 starburst is greater than 450 Myr (McQuinn et al. 2010), and though NGC 672 had not been studied at the time, to make basic timescale estimates I will assume that the NGC 672 starburst duration is also on the order of 450 Myr. The NGC 784 feature timescales are all at least 500 Myr greater than the starburst duration, revealing the possibility that the interaction manifesting itself as those features could have triggered a starburst for that system. The NGC 672 system is slightly different as two of its timescales are below the assumed burst duration, including the IC 1727 duration. However, like with the NGC 784 field, the longer timescales are closer to the duration of the burst, suggesting that those features and the NGC 672 starbursts could be related.

FIELD EVALUATION
With the results of all tests completed, it is now possible to formulate conclusions about the NGC 784/NGC 672 field. The goal is to determine which features are most likely real, and whether or not the field contains features characteristic of tidal interactions. The primary conclusion drawn from the tests is that any feature associated with an ALFALFA galaxy is real. This leaves a few other figures that need further evaluation. Beginning with the NGC 784 field, due to the fact that NGC 784 and AGC 111164 reside so close to one another, in both velocity and position, it seems reasonable to assume that the long feature extending from the NGC 784/AGC 111164 gas is tidal material from an NGC 784/AGC 111164 interaction. The remaining questionable feature in the NGC 784 field, the feature in the upper center of the map, seems to be real as well. It is close in velocity and spatial position to AGC 122834 and sustained through the $3\sigma$ cube test. The feature seems too large to be noise and is therefore likely real. As such, most of the features in the NGC 784 field are probably real HI sources, demonstrating the complex field of NGC 784 and the high potential for interaction and tidal influence within the field.

Similarly, only one feature of the NGC 672 field remains enigmatic. This feature disappears in the $3\sigma$ cube and the GIPSY image and moves at a velocity close to 200 km s$^{-1}$ slower than the other features in the field. It does show stronger contour levels than the AGC sources in the field, so it is most likely real but not a tidal feature. Interestingly, this feature in the NGC 672 field possesses a similar velocity to the questionable feature in the NGC 784 field. This correlation does not necessarily signify the two features are related or both Milky Way emission, but it does provide stronger evidence towards such a conclusion. Finally, it is important to consider the NGC 672/IC 1727 interaction when evaluating the field. These objects display clear interaction signatures, confirming results from studies such as Zitrin & Brosch (2008). This interaction may explain other objects in the field, namely GC 111945 and AGC 111946. These two SHIELD galaxies are close to the NGC 672/IC 1727 interaction in both velocity and physical proximity. In fact, their velocities
are between those of NGC 672 and IC 1727, suggesting the possibility that AGC 111945 and AGC 111946 are gas remnants expelled from the interaction. This would imply an extremely active, shifting field with significant amounts of tidal material.

After careful assessment and consideration of the two fields I can conclude with some certainty that both the NGC 784 and NGC 672 fields contain at least one interaction and a high potential for tidal influence, indicating that the starbursts these two galaxies experience could have tidal origins.

SUMMARY

Assessing the prototype system of NGC 784 and NGC 672 provides several key insights into analyzing HI maps with spatial dimensions on the order of a few degrees, namely building an effective and efficient analysis procedure that employs the use of a variety of tests. The first step is to create two column density maps, one at a low threshold value (2σ) and one at a higher threshold value (3σ), and at least one velocity field map. The column density map is useful for visualizing the shapes of the map features and identifying potential tidal features that require further investigation. If the 2σ column density map contains several questionable features that resemble noise, the 2σ and 3σ maps should be compared to see which features disappear. The GIPSY maps are also useful for this purpose, as they provide a strictly objective map with which to compare. The velocity map provides beneficial information about whether or not the feature shows rotation characteristics and whether or not features may be related. The amount of chaos in a velocity map is also a signature of interaction. A velocity field may suggest possible interaction and tidal features that would not otherwise be noted from looking at just a column density map. Once the maps have been created and analyzed, it can be helpful to calculate the physical sizes of and distances between the features using the column density maps. These tests consistently provide the most information about the systems and should be performed on all galaxy fields.
I found that the SDSS navigate tool was not as helpful for evaluating the NGC 784/NGC 672 system as strategically searching the ALFALFA a70.csv spreadsheet because it was much easier to miss potential sources in SDSS and the technique is less systematic. The ALFALFA catalog is, however, biased against gas poor systems because Arecibo does not have the sensitivity to detect these systems. Still, despite this bias and the fact that the cross-correlation cannot provide any information regarding the extensiveness of the gas, it is still an extremely useful tool and should be used whenever possible to provide concrete and complete analysis of large HI maps. Cross-correlation appears to be a beneficial step in the analysis process.

The Galactic dust map is a useful tool for quickly determining whether the origins of a feature are definitely Galactic in nature, and is therefore recommended for map analysis similar to that of this work.

Finally, while the SFH timescale comparison only provides a basic estimate, if the SFHs are known this test can help formulate a general idea about the likelihood that the map feature coincides with the starburst. The results from this test should not be considered an absolute answer, but more of a guide towards making conclusions about the starburst origins with respect to tidal features.
5. **GBT Field Analysis: The Rest of the Sample**

This section applies the methods described in the previous section to the other galaxies in the sample. Note that only galaxies with new GBT data (galaxies within the first half of Table 1) were included; Parkes and control galaxy data are still undergoing the data reduction process, and the HI GBT archival data are not as deep or expansive as the new datasets so they were excluded in this section. Also note that all SFH durations come from the study by McQuinn et al. (2010).

**NGC 6822**

The NGC 6822 field was one of the more challenging fields in the sample due to the galaxy’s proximity in space and velocity to Milky Way emission. This problem was encountered with NGC 6789, but not to the extent of the NGC 6822 field. Figures 15 and 16 give a sense for the difficulty of evaluating fields like NGC 6822 (and to a lesser extent, NGC 6789).

![Frame from the 2σ blanked NGC 6822 cube](image)

**Fig. 15.** A frame from the 2σ blanked NGC 6822 cube prior to the appearance of Milky Way emission, resembling a typical blanked frame from a data cube of this variety.
Fig. 16.— A frame from the 2σ blanked NGC 6822 cube containing Milky Way emission. In most cases, Milky Way emission could be removed, but in the case of NGC 6822 and NGC 6789 the galaxy appeared with the Milky Way emission so excising Milky Way emission channels was not an option.

Figures 15 and 16 emphasize the difficulty in distinguishing between Milky Way, noise, and galaxy emission for situations like NGC 6822, even more so than for the other galaxies in the sample, like NGC 784 and NGC 672 above. As such, slightly different handblanking and analysis procedures needed to be implemented. Typically, a feature is kept when handblanking if the feature exists for three or more frames. In cases like NGC 6822, this method would result in keeping tremendous amounts of Milky Way. It is probable that some Milky Way will remain in the final maps in order to ensure that the entire galaxy and any low surface brightness material is kept, but ideally much of the Milky Way emission will be eliminated. In these cases, the more suitable approach was to only select emission that was certainly the galaxy, as long as the other emission in the field resembles the shape
and pattern of Milky Way emission. In the case of NGC 6822, most of the emission had Milky Way characteristics, so only NGC 6822 and some surrounding emission was kept. The resulting maps are in Figures 17 and 18.

Fig. 17.— On the bottom is a column density map of the 2 degree by 2 degree NGC 6822 field. The upper image is an Australia Telescope Compact Array interferometer column density map of just NGC 6822 (de Blok & Walter 2000). Note that the ATCA image is in Equatorial coordinates whereas the GBT map is in Galactic coordinates. The red box denotes an approximate field of view.
Fig. 18.— On the bottom is a column density map of the 2 degree by 2 degree NGC 6822 field with a 1σ contour level at \(0.6 \times 10^{20}/\text{cm}^2\). Contour levels increase by a multiple of 2. The upper image is an Australia Telescope Compact Array interferometer column density map of just NGC 6822 with 1σ contours at \(5 \times 10^{20}/\text{cm}^2\). Contour levels increase by a multiple of 2. Note this is the same figure as Figure 17 with added contours.

The HI gas of NGC 6822, according to Figures 17 and 18, has a somewhat elongated shape, with a higher concentration of gas towards the bottom. This column of gas extends to about 14 kpc in length. There appears to be a knot of gas extending roughly 7 kpc to the right of the galaxy’s center. Whether these are Milky Way emission features or features
related to NGC 6822 remains to be determined through further testing.

Comparing the $2\sigma$ moment maps to the $3\sigma$ moment maps reveal little new information, and the maps look almost identical, as shown in Figure 19.

![Figure 19](image)

Fig. 19.— The upper left image is a $2\sigma$ threshold blank column density map of the NGC 6822 field and the lower left image is the $3\sigma$ threshold blank column density map of the same field. The $2\sigma$ RMS threshold value was 0.0374 K and the $3\sigma$ threshold value was 0.0561 K. The upper right image is a $2\sigma$ threshold blank velocity field map of the NGC 6822 field and the lower left image is the $3\sigma$ threshold blank velocity field map.

The NGC 6822 gas cloud features and the shape of the cloud from the $2\sigma$ blank remain in the $3\sigma$ blank. This does not, however, indicate that these features are definitely real and
definitely related to NGC 6822. The fact that the two maps look so similar is a reflection of the intense Milky Way emission and the difficulty in distinguishing NGC 6822 from the Milky Way. Because most of the Milky Way emission is greater than $3\sigma$, very little of the cube vanished between the $2\sigma$ and $3\sigma$ cube, explaining why the maps appear to be nearly identical. As such, this test may not be the most effective form of analysis for this galaxy because little information is revealed.

The velocity fields to the right in Figure 19 offer slightly more information than the column density maps. There appears to be a smooth velocity gradient, suggesting that the galaxy is rotating. Additionally, the knot to the right of the galaxy’s center fits smoothly into the gradient. This knot could still be Milky Way emission, but the way it blends into the velocity gradient of NGC 6822 signifies that it may more likely be a gas extension from NGC 6822.

The map produced from GIPSY is shown in Figure 20.
Fig. 20.— Gipsy output image of the NGC 6822 field with an amplitude blanking threshold of $2\sigma = 0.0374 \text{K}$ and a velocity dispersion threshold of $5 \text{ km s}^{-1}$. Note that the units of the map are K and not K km s$^{-1}$.

The GIPSY map reveals that the NGC 6822 gas cloud has much less extension than the column density maps reveal. This result is difficult to interpret. The section of the galaxy that GIPSY missed is definitely real NGC 6822 emission, but according to the numerical technique GIPSY employs, that emission could not be considered real. This appears to be another issue with the high intensity Milky Way emission surrounding the galaxy. Because the Milky Way and NGC 6822 are right on top of each other, GIPSY had difficulties distinguishing between galaxy and Milky Way. Thus, little can be gleaned from the GIPSY test for this particular galaxy.

The Galactic dust image of the NGC 6822 field revealed strong dust within the cube, which is expected considering the amount of Galactic emission near NGC 6822, but no gas was directly on top of or near the galaxy.
The cross-correlation technique revealed little information about the field. NGC 6822 is not within the position boundaries of the SDSS or the ALFALFA catalogues.

The SFH test can provide little information about the NGC 6822 system because there are no enigmatic features or potential companions in the field besides the clump of gas attached to the central right side of the galaxy. Taking this feature, which has a velocity difference of 7 km s$^{-1}$ from the center of NGC 6822, I calculated that the feature would have a timescale of 970 Myr, which is much greater than the calculated starburst duration of 20 Myr (McQuinn et al. 2010). This signifies that the burst more likely occurred after the formation of that feature.

The test results for NGC 6822 suggest that the galaxy has no apparent companions and little morphological disturbance, implying that the starburst trigger for NGC 6822 is most likely not tidal in origin. However, this result is not entirely definitive due to the nature of the field; the overwhelming presence of the Milky Way emission increases the difficulty for distinguishing between NGC 6822 gas and Milky Way gas, and could potentially hide any low surface brightness emission disturbances in the galaxy, or any possible NGC 6822 companions.

NGC 6789

The NGC 6789 field, as alluded to in the NGC 6822 section, is one of the more challenging fields in the sample because it sits mostly amidst the Milky Way emission. As such, distinguishing between Milky Way and NGC 6789 is quite difficult, as demonstrated in the column density maps of Figures 21 and 22. For these maps potential low surface brightness emission was detected, so the handblanking approach described in the NGC 6822 section was not applied to the NGC 6789 maps.
Fig. 21.— On the bottom is a column density map of the 2 degree by 2 degree NGC 6789 field. The upper image is a VLA interferometer column density map of just NGC 6789 (Lelli et al. 2014). Note that the VLA image is in Equatorial coordinates whereas the GBT map is in Galactic coordinates. The red box denotes an approximate field of view.
Fig. 22.— On the bottom is a column density map of the 2 degree by 2 degree NGC 6789 field with a $1\sigma$ contour level at 0.03 $1\times10^{20}$/cm$^2$. Contour levels increase by a multiple of 2. The upper image is an interferometer column density map of just NGC 6789 with $1\sigma$ contours at 2.5 $1\times10^{20}$/cm$^2$. Contour levels increase by a multiple of 2. Note this is the same figure as Figure 21 with added contours.

NGC 6789 itself is obvious because it is the bright region in the center of the field, but the legitimacy of the rest of the field and the extent of the NGC 6789 gas is questionable,
as previously discussed. A brighter stream of gas seems to extend from the lower right of NGC 6789, but this feature could also exist as part of the Milky Way. The clouds of gas as a whole extend 69 kpc in the vertical direction and 106 kpc in the horizontal direction.

The $2\sigma$ and $3\sigma$ maps are shown in Figure 23.

![Figure 23](image-url)

**Fig. 23.**—The upper left image is a $2\sigma$ threshold blank column density map of the NGC 6789 field and the lower left image is the $3\sigma$ threshold blank column density map of the same field. The $2\sigma$ RMS threshold value was 0.03 K and the $3\sigma$ threshold value was 0.045 K. The upper right image is a $2\sigma$ threshold blank velocity field map of the NGC 6789 field and the lower left image is the $3\sigma$ threshold blank velocity field map.
They are not vastly different other than the elimination of some extended gas in the left feature and the elimination of the feature located at around a Galactic Longitude of 95.4 degrees and a Galactic Latitude of 21 degrees. The bright feature of gas extending from the lower right of NGC 6789 exists in both maps, signifying that this feature is most likely not noise, but it could still be Milky Way emission. The feature’s proximity to NGC 6789 and its brightness suggest that the feature may be related to NGC 6789 and a part of its structure, but the distinct velocity jump between the feature and NGC 6789 negates this possibility somewhat. As for the leftmost feature in the $3\sigma$ map, its survival at $3\sigma$ implies that the feature is real, but its relationship with NGC 6789 remains unknown at this stage in the testing.

The velocity fields above provide more information about the clouds, suggesting that all features other than the teal colored feature representing NGC 6789 are not tidal tails or features of NGC 6789 because a stark velocity difference exists between NGC 6789 and all other features. This is not to say, however, that none of the features influence NGC 6789; further information is needed to make this conclusion.

The results from GIPSY are shown in Figure 24.
Fig. 24.— Gipsy output image of the NGC 6789 field with an amplitude blanking threshold of $2\sigma = .03K$ and a velocity dispersion threshold of $5 \text{ km s}^{-1}$. Note that the units of the map are K and not K km s$^{-1}$.

This test reveals similar structures detected in the handblanked maps in Figure 23. Because the Milky Way emission is so invasive for this particular galaxy, the GIPSY image provides little information regarding which features are Milky Way and which are not. It is interesting to note, however, that the feature extending from the lower right of the galaxy is rather prominent in the GIPSY image. This does not necessarily indicate that this feature is or is not Milky Way, but the fact that the feature appears in both the handblanked and the GIPSY maps suggests the feature could have origins other than Milky Way emission.

The Galactic dust maps revealed little correlation between features in the above maps and Galactic dust. Because most of the features in the map do appear to actually be Milky
Way emission, this result is somewhat unexpected. Thus, this test concludes that none of the NGC 6789 features are definitely Galactic dust features.

The cross-correlation technique reveals little about the system. The ALFALFA survey does not cover the NGC 6789 field, and as discussed in the NGC 784/NGC 672 analysis, the SDSS navigation tool provides little information for maps of such a great size, though it can be said with certainty that no galaxies capable of creating such massive interaction clouds reside in the near vicinity of NGC 6789.

The SFH test was not executed on this galaxy field because there are no obvious tidal features or companions that would benefit from timescale comparison testing.

At the present time few conclusions can be made with certainty regarding the legitimacy of the features in the field and their relation to NGC 6789. Because of its disappearance in the $3\sigma$ cube and its high velocity relative to the rest of the field, the feature located at around a Galactic Longitude of 95.4 degrees and a Galactic Latitude of 21 degrees seems to be most likely a spurious, or at the very least, an irrelevant feature for NGC 6789. The trail of gas extending from NGC 6789 in the column density maps and the GIPSY map is most likely real but probably Milky Way emission based on its velocity. That said, the initial conclusion about the NGC 6789 field is that the only possible interference for NGC 6789 is Milky Way emission, and the galaxy seems to have no tidal signatures in its structure.

NGC 4068

The NGC 4068 field differs from the other sample galaxies in that all features other than the galaxy itself are seemingly attached to the galaxy, where the galaxy sits in the midst of an oblong, 146 kpc long feature, as seen in the column density maps from Figures 25 and 26.
Fig. 25.— On the bottom is a column density map of the 2 degree by 2 degree NGC 4068 field. The upper image is a WSRT interferometer column density map from the WISP survey van der Hulst et al. (2001) of just NGC 4068. Note that the WSRT image is in Equatorial coordinates whereas the GBT map is in Galactic coordinates. The red box denotes an approximate field of view.
Fig. 26.— On the bottom is a column density map of the 2 degree by 3 degree NGC 4068 field with a 1σ contour level at 0.04 \(1\text{E}20/\text{cm}^2\). Contour levels increase by a multiple of 2. The upper image is an interferometer column density map from the WISP survey van der Hulst et al. (2001) of just NGC 4068 with 1σ contours at \(0.7\ 1\text{E}20/\text{cm}^2\). Contour levels increase by a multiple of 2. The contours of this image were found by normalizing the image to the peak \(N_{HI}\) value. As such, the column density values should be considered an approximation. Note this is the same figure as Figure 25 with added contours.

The vertical distance of the galaxy field and feature is 47 kpc. The map reveals no obvious discontinuity between NGC 4068 and the long feature, so it is not immediately evident whether the feature is attached to NGC 4068, behind it, or in front of it. Additionally,
Figures 25 and 26 show that the amount of gas in the long feature increases with decreasing RA. The significance of this is unknown using exclusively the column density map and more information will need to be compiled to make an accurate conclusion, though the feature appears to be a banding effect from the calibration stage of the data reduction process because of its shape.

Most of this oblong feature vanishes in the $3\sigma$ map, displayed in Figure 27, with the exception of a small piece to the lower right of NGC 4068. The long feature could still be real and just low surface brightness, but the results of the $3\sigma$ cube indicate that the feature is most likely spurious.

Fig. 27.— The upper left image is a $2\sigma$ threshold blank column density map of the NGC 4068 field and the lower left image is the $3\sigma$ threshold blank column density map of the same field. The $2\sigma$ RMS threshold value was 0.032 K and the $3\sigma$ threshold value was 0.048 K. The upper right image is a $2\sigma$ threshold blank velocity field map of the NGC 4068 field and the lower left image is the $3\sigma$ threshold blank velocity field map.
The velocity fields from Figure 27 of NGC 4068 are similar to those of NGC 6789 in that there is a sharp difference in velocity between the galaxy and the other extended features in the field. NGC 4068 itself shows rotation but the oblong feature has no obvious rotation signatures. The velocity field of the long feature is slightly chaotic, a potential signature of interaction, but its velocity is upwards of 150-200 km s\(^{-1}\) higher than NGC 4068 and no apparent velocity gradient exists between NGC 4068 and the feature.

The GIPSY map of the NGC 4068 field is shown in Figure 28.

![GIPSY map of the NGC 4068 field](image)

Fig. 28.— Gipsy output image of the NGC 4068 field with an amplitude blanking threshold of \(2\sigma = 0.032\)K and a velocity dispersion threshold of 5 km s\(^{-1}\). Note that the units of the map are K and not K km s\(^{-1}\).

The GIPSY map exclusively features NGC 4068 with no evidence of the oblong feature, except for a few pixels directly to the lower right of NGC 4068 and a small grouping of
pixels at a Galactic Longitude of 137.5 degrees and a Galactic Latitude of 62.8 degrees. It closely resembles the $3\sigma$ map in this sense, suggesting the oblong feature may be noise or a calibration artifact.

The dust maps displayed no evident Galactic dust overlapping with any feature in the NGC 4068 map, suggesting the oblong feature is most likely not Galactic dust.

The cross-correlation method provided little additional information, other than that there are no obvious galaxies within the vicinity of NGC 4068 that could create such a feature in the NGC 4068 map and the feature appears to have no optical counterpart associated with it. The ALFALFA survey did not cover the NGC 4068 field so no information could be gleaned from it.

The next test is the SFH test. I performed a calculation from NGC 4068 to the end of the oblong feature, which is a velocity difference of $150 \text{ km s}^{-1}$ and thus a timescale of 477 Myr. The duration of the NGC 4068 starburst is over 450 Myr (McQuinn et al. 2010), placing the feature potentially within the timeframe of the starburst.

No conclusions could be drawn with certainty regarding the legitimacy of the oblong feature below NGC 4068, however based on the stark velocity contrast between the feature and NGC 4068 and the feature’s disappearance in the $3\sigma$ and GIPSY maps, it appears that the feature is spurious in nature or is an artifact from the calibration process, especially because NGC 4068 shows no other structural disturbances characteristic of a galaxy participating in an interaction with another source.

NGC 2366

The NGC 2366 field is the other mosaic in the sample and it contains NGC 2403 on the far left and NGC 2366 towards the right. The field is divided into two parts because of the intervening Milky Way emission; the two sections are the field before and after the Milky Way.
Way. NGC 2403 and NGC 2366 make an appearance in the first half, shown in Figures 29 and 30, and an enigmatic cloud appears in the center of the second half.
Fig. 29.— On the bottom is a column density map of the 6 degree by 4 degree NGC 2366 field. This is the map from the first half of the cube. The upper image is a VLA interferometer column density map of just NGC 2366 from the LITTLE THINGS survey (Hunter et al. 2012). Note that the VLA image is in Equatorial coordinates whereas the GBT map is in Galactic coordinates. The red box denotes an approximate field of view.
Fig. 30.— On the bottom is a column density map of the 6 degree by 4 degree NGC 2366 field with a $1\sigma$ contour level at $0.4\,1E20/cm^2$. This is the map from the first half of the cube. Contour levels increase by a multiple of 2. The upper image is a VLA interferometer column density map (Hunter et al. 2012) of just NGC 2366 with $1\sigma$ contours at $5\,1E20/cm^2$. Contour levels increase by a multiple of 2. Note this is the same figure as Figure 29 with added contours.
Both fields have other extraneous features. First I will evaluate the first half. NGC 2403 has a more regular shape that extends for 78 kpc, though it has a sharp upper left corner because the map cuts it off prematurely. Two linear features exist in the nearby vicinity of NGC 2403, no more than 80 kpc from the center of the NGC 2403 gas. These distances are reasonable for arguing that these features could be tidal in nature, however their strictly linear shape is more characteristic of noise. The next closest feature to NGC 2403 is NGC 2366, sitting at roughly 236 kpc from the center of the NGC 2403 gas. NGC 2366 is slightly irregular in shape, particularly the left half, and is about 44 kpc long in the horizontal direction. The galaxy, like NGC 2403, has two nearby features, one of which is also oddly linear. The other feature directly to the right of NGC 2366 is 48 kpc long and with an irregular, noise-like shape. Like the upper feature, and the features surrounding NGC 2403, this feature is suspect, but for somewhat different reasons. The creation of this method included stitching together three separate maps of the field, akin to the NGC 784/NGC 672 field. The left and center maps have similar noise statistics, but the third map, which appeared exactly in the location of that feature, has higher RMS noise values. When the cube of the field was blanked to the average field RMS value, that third section of the field remained high noise and was difficult to handblank. While the feature to the right of NGC 2366 may be real, its location in the noisy section of the field suggests it may be a noise remnant. The second half of the cube shows oddly shaped features in the noisy section of the field as well, indicating those features too may simply be noise. This half also has a suspect feature in the lower left corner of the field, though this feature remains questionable not because the map is noisy but because the feature is similar in velocity to Milky Way emission. The cloud in the center of the field is at most 148 kpc from any feature in the field. This central feature is most likely a cloud because of its more regular shape, aside from the tail-like feature extending 21 kpc from the cloud, and its strong detection in both the $2\sigma$ and $3\sigma$ cubes in Figure 32. The origins of the upper feature in the lower left corner
of the map are still unknown because the shape of the feature is not obviously noise or Milky Way, and it is a little less than 125 kpc from the central feature.

Next the $3\sigma$ maps were evaluated; the maps for both field halves are shown in Figures 31 and 32.

![Fig. 31.](image)

Fig. 31.— The upper left image is a $2\sigma$ threshold blank column density map of the first half of the NGC 2366 field and the lower left image is the $3\sigma$ threshold blank column density map of the same field. The $2\sigma$ RMS threshold value was 0.0388 K and the $3\sigma$ threshold value was 0.0582 K. The upper right image is a $2\sigma$ threshold blank velocity field map of the first half of the NGC 2366 field and the lower left image is the $3\sigma$ threshold blank velocity field map.
Fig. 32.— The upper left image is a $2\sigma$ threshold blank column density map of the second half of the NGC 2366 field and the lower left image is the $3\sigma$ threshold blank column density map of the same field. The $2\sigma$ RMS threshold value was 0.0396 K and the $3\sigma$ threshold value was 0.0594 K. The upper right image is a $2\sigma$ threshold blank velocity field map of the second half of the NGC 2366 field and the lower left image is the $3\sigma$ threshold blank velocity field map.

The results for the first half of the map are somewhat suspect. Though the curious feature to the right of NGC 2366 remained, extra features appeared in the $3\sigma$ cube that did not previously exist. This could simply be handblanking error, or it could indicate that for this particular map the $3\sigma$ test is not an effective evaluation method because features that appear with a $3\sigma$ blank but not a $2\sigma$ blank are unrealistic. The $3\sigma$ blanking for the second half of the cube seemed to be more effective because while a few features survived the new
threshold, no new features appeared. The disappearing features are then either spurious or very low surface brightness.

The velocity fields, shown in Figures 31 and 32, provide ample information about the field. NGC 2403 and NGC 2366 display characteristic rotational signatures, but the feature in the center of the second half of the NGC 2366 map also shows signatures of rotation. No known galaxy exists there, though the feature was previously discovered (Chynoweth et al. 2009). Its velocities are generally between the velocities of NGC 2403 and NGC 2366, and the feature is spatially between the two larger galaxies, presenting the possibility that this cloud is a tidal remnant from an interaction between NGC 2403 and NGC 2366. The other features found in both halves of the NGC 2366 map are slightly more difficult to determine. They vary in velocity from -400 km s\(^{-1}\) to 400 km s\(^{-1}\). None appear to be rotating. The feature directly to the right of NGC 2366 is puzzling because it is comprised of gas at essentially two different velocities 200 km s\(^{-1}\) apart. The second half of the NGC 2366 map has similar irregular features, though each is at a different velocity. For these features, the velocity map provides no additional useful information other than the actual velocity range of each feature. The velocity does give insight regarding the feature positioned on the right side of the cloud. The velocity map of the cloud individually shows a relatively continuous velocity gradient across the galaxy, flowing smoothly into the upper right feature, suggesting it may be real emission.

The GIPSY map results from each half are shown in Figures 33 and 34.
Fig. 33.— Gipsy output image of the first half of the NGC 2366 field with an amplitude blanking threshold of $2\sigma = 0.0388K$ and a velocity dispersion threshold of 5 km s$^{-1}$. Note that the units of the map are K and not K km s$^{-1}$.
Fig. 34.— Gipsy output image of the second half of the NGC 2366 field with an amplitude blanking threshold of $2\sigma = 0.0396K$ and a velocity dispersion threshold of $5 \text{ km s}^{-1}$. Note that the units of the map are K and not K km s$^{-1}$.

These GIPSY images reveal that many of the clumped features from both halves of the NGC 2366 map, according to GIPSY, do not actually exist and are most likely noise. The exceptions are the central cloud feature in the second half of the map, which GIPSY recognizes, and a few small overdensities of pixels, one located at the coordinates (146, 27.5) in the first map, and the other two located in the second map at (151, 28) and (151, 28.6). The first overdensity is located in the region of the map with higher relative noise, so it is more likely to be intensities GIPSY determined to be coherent in velocity space. The feature in the second map located at (151, 28) appeared very close to the Milky Way and is most likely Milky Way emission. The origin of the feature in the second cube, a feature
both handblanking and GIPSY identified, is unknown at this point.

The Galactic dust maps revealed no significant dust that corresponds with features of the NGC 2366 map.

Cross-correlation was not beneficial for this field. NGC 2366 is outside of the both the SDSS and the ALFALFA fields of view.

The SFH test is most useful for the NGC 2366 half of the field for investigating the feature to the right of the cloud in the second half of the map. The velocity difference between the cloud and the end of the tail is 10 km s$^{-1}$, resulting in a time frame of 2136 Myr, a time well over the SF duration of 450 Myr for NGC 2366.

Compiling all the information gleaned from the tests the only confident conclusion that can be made is that the central cloud in the second half of the field is real, and there is a high possibility that the tail is also real due to the smooth velocity gradient, but it would have to be low surface brightness because the feature did not appear in the 3$\sigma$ cube or the GIPSY image. The legitimacy of the feature to the right of NGC 2366 requires more information to evaluate. The feature appears at two completely different velocities and is located directly in the portion of the field with higher RMS, indicating it is more likely noise.

**DDO 50**

The DDO 50 field showcases three galaxies and two interesting features. The column density maps are shown in Figures 35 and 36.
Fig. 35.— On the right is a column density map of the 2 degree by 2 degree DDO 50 field. The left image is a VLA interferometer column density map of just DDO 50 from the LITTLE THINGS survey (Hunter et al. 2012). Note that the VLA image is in Equatorial coordinates whereas the GBT map is in Galactic coordinates. The red box denotes an approximate field of view.
Fig. 36.— On the left is a column density map of the 2 degree by 2 degree DDO 50 field with a 1σ contour level at 0.1 \(1 \times 10^{20}/cm^2\). Contour levels increase by a multiple of 2. The left image is a VLA interferometer column density map from the LITTLE THINGS survey (Hunter et al. 2012) of just DDO 50 with 1σ contours at 5 \(1 \times 10^{20}/cm^2\). Contour levels increase by a multiple of 2. Note this is the same figure as Figure 35 with added contours.

The map reveals that the gas surrounding DDO 50 merges with the gas from its immediate neighbor to the upper right, M81 dwA. This strongly suggests interaction between DDO 50 and M81 dwA. UGC 4483 is located only about 109 kpc from DDO 50 and M81 dwA, placing it in a reasonable interaction zone with the two other galaxies. Otherwise the general shapes of each galaxy are fairly regular, though the odd edges and tails surrounding UGC 4483 are questionable in terms of whether the origins are noise or interaction related. The other two features are also suspect because of their small size (26 kpc for the leftmost feature and 13 kpc for the rightmost feature) and irregular, noise-like shape.

Similarly, the 3σ map gives little new information besides eliminating the two noise-like features and constricting the gas surrounding the known galaxies. It confirms that our
galaxies are indeed real, including the bridge of gas between DDO 50 and M81 dwA, which was robust enough to withstand the $3\sigma$ threshold. The maps are shown in Figure 37.

Fig. 37.— The upper left image is a $2\sigma$ threshold blank column density map of the DDO 50 field and the lower left image is the $3\sigma$ threshold blank column density map of the same field. The $2\sigma$ RMS threshold value was 0.04 K and the $3\sigma$ threshold value was 0.06 K. The upper right image is a $2\sigma$ threshold blank velocity field map of the DDO 50 field and the lower left image is the $3\sigma$ threshold blank velocity field map.
The primary piece of information the velocity maps in Figure 37 provide is that both DDO 50 and UGC 4483 show rotation signatures. M81 dwA could be rotating, but because of the other elements in the field and the extreme overlap of gas between DDO 50 and M81 dwA its rotation signatures, if any exist, are hidden. It is important to note that the gradient is smooth between DDO 50 and M81 dwA, suggesting that the gas bridge is real.

The resulting GIPSY maps are displayed in Figure 38.

![GIPSY output image of the DDO 50 field with an amplitude blanking threshold of $2\sigma = .04K$ and a velocity dispersion threshold of $5\ km\ s^{-1}$. Note that the units of the map are K and not K km s$^{-1}$.](image)

Fig. 38.— Gipsy output image of the DDO 50 field with an amplitude blanking threshold of $2\sigma = .04K$ and a velocity dispersion threshold of $5\ km\ s^{-1}$. Note that the units of the map are K and not K km s$^{-1}$.

The image resembles the $3\sigma$ map but without a bridge between DDO 50 and M81 dwA and an extra feature to the lower left of the map. This feature is most likely leftover from the edge effects of the data cube based on its location on the map and the fact that the feature
did not show in any of the other maps. The lack of the bridge, which appeared strongly in both the 2σ and 3σ maps, may be attributed to the fact that the bridge is very low surface brightness and was excluded by XGAUFIT.

The Galactic dust maps revealed no significant dust overlapping any features from the DDO 50 map.

No new information can be gleaned from SDSS or ALFALFA cross-correlation either because the field is out of range for both.

The SFH tests were done on the DDO 50 - M81 dwA pair and the DDO 50 - UGC 4483 pair. With a velocity difference of 39 km s$^{-1}$, the DDO 50 - M81 dwA pair has a timescale of 4220 Myr. The DDO 50 - UGC 4883 pair has a velocity difference of 3 km s$^{-1}$ and a timescale of 3.6E5 Myr. Both timescales are above the minimum starburst duration for DDO 50, which is about 570 Myr.

Though the tests for this field were relatively uneventful, they were able to confirm the existence of a previously undiscovered bridge of gas extending between DDO 50 and M81 dwA. All maps, besides the GIPSY map, support this theory and point towards interaction between the two galaxies. The possibility of interaction between all three galaxies remains uncertain, but due to the relatively short distances between the galaxies, interaction is not unreasonable.

**DDO 165**

The DDO 165 column density map is shown in both Figure 39 and Figure 40.
Fig. 39.— On the bottom is a column density map of the 2 degree by 2 degree DDO 165 field. The upper image is a VLA interferometer column density map of just DDO 165 from the LITTLE THINGS survey (Hunter et al. 2012). Note that the VLA image is in Equatorial coordinates whereas the GBT map is in Galactic coordinates. The red box denotes an approximate field of view.
Fig. 40.— On the bottom is a column density map of the 2 degree by 2 degree DDO 165 field with a $1\sigma$ contour level at $0.1 \times 10^{20}$/cm$^2$. Contour levels increase by a multiple of 2. The upper image is a VLA interferometer column density map from the LITTLE THINGS survey (Hunter et al. 2012) of just DDO 165 with $1\sigma$ contours at $2.5 \times 10^{20}$/cm$^2$. Contour levels increase by a multiple of 2. Note this is the same figure as Figure 39 with added contours.
Inspecting the map reveals several enigmatic features. Low surface brightness gas about 37 kpc long sits to the upper right of DDO 165, making it a possible candidate to be a tidal tail of the galaxy. The other features lie no more than 106 kpc from the center of DDO 165 (in fact, most are closer). The farthest feature to the left of DDO 165, directly connected via a strand of pixels, could be a tidal tail, however the shape of the feature (a straight line of pixels) is suspect and resembles more of a spurious feature. All other objects in the cube are irregularly shaped, characteristic of gas resulting from tidal interaction, though the origins of the features cannot be deemed tidal features from this map alone.

Here the $3\sigma$ map appears to be useful. The maps are shown in Figure 41. All peculiar features in the $2\sigma$ map disappear in the $3\sigma$ map, suggesting they may be noise and not real features.
Fig. 41.— The upper left image is a $2\sigma$ threshold blank column density map of the DDO 165 field and the lower left image is the $3\sigma$ threshold blank column density map of the same field. The $2\sigma$ RMS threshold value was 0.033 K and the $3\sigma$ threshold value was 0.0495 K. The upper right image is a $2\sigma$ threshold blank velocity field map of the DDO 165 field and the lower left image is the $3\sigma$ threshold blank velocity field map.

The velocity fields from Figure 41 show clear rotation of DDO 165. The most significant piece of information to be learned from the velocity field is that the features extending from the left and upper right do not integrate themselves smoothly into the velocity gradient of DDO 165. If those features really extended directly from DDO 165 the upper right feature would exist at around 35 km s$^{-1}$ and the feature to the left would exist at roughly 45 km s$^{-1}$, which is not the case. That said, the velocities of those features are still well within the interaction range of DDO 165 (approximately 20 km s$^{-1}$ higher) so the notion that those
features are tidal in nature remains plausible.

The GIPSY map is shown in Figure 42.

\[ 
\text{Fig. 42.— Gipsy output image of the DDO 165 field with an amplitude blanking threshold of } 2\sigma = \text{.033K and a velocity dispersion threshold of } 5 \text{ km s}^{-}\!\!^{-1}. \text{ Note that the units of the map are K and not K km s}^{-}\!\!^{-1}. 
\]

The image is somewhat chaotic, with large clouds and streams strewn throughout the map. These features in the GIPSY image resemble the shape of Milky Way cloud emission. Some of those features coincide with features in the $2\sigma$ map, signifying those features could be Milky Way emission. Other than those features, the GIPSY map lacks the feature to the upper right of DDO 165 from the $2\sigma$ map, similar to the $3\sigma$ map. While this does not eliminate the possibility that the feature is simply low surface brightness, it does suggest that the feature is most likely noise.
The Galactic dust map revealed some dust to the lower left of the galaxy, but it does not directly correspond to any features in the DDO 165 maps. Cross-correlation revealed no new information about the field. SDSS shows no optical tails extending from DDO 165 where the tail-like features exist in the maps, and no potential interaction partners were found in the vicinity of DDO 165. The galaxy is out of range of the ALFALFA survey. For the SFH timescale test I calculated the timescale for DDO 165 and the end of the feature to the upper right of the galaxy. A velocity difference of 13 km s\(^{-1}\) led to a time frame of 5691 Myr. The starburst duration has been calculated to be 1300 Myr, so this timescale is well above the starburst duration.

Few definite conclusions can be drawn from the tests. While it seems unlikely that the tidal-like features are real because their velocities do not match the velocity gradient of DDO 165 and those features disappear in the 3\(\sigma\) map, the velocities are also within a reasonable interaction range and the 3\(\sigma\) map is questionable. The other features in the map seem to be spurious because they vanish at 3\(\sigma\) and the velocities are upwards of 300 km s\(^{-1}\) higher than the velocities of DDO 165.

**DDO 187**

The DDO 187 field is displayed in Figures 43 and 44.
Fig. 43.— On the bottom is a column density map of the 2 degree by 2 degree DDO 187 field. The upper image is a VLA interferometer column density map of just DDO 187 from the ANGST survey (Ott et al. 2012). Note that the VLA image is in Equatorial coordinates whereas the GBT map is in Galactic coordinates. The red box denotes an approximate field of view.
Fig. 44.— On the bottom is a column density map of the 2 degree by 2 degree DDO 187 field with a 1σ contour level at 0.06 1E20/cm². Contour levels increase by a multiple of 2. The upper image is a VLA interferometer column density map from the ANGST survey (Ott et al. 2012) of just NGC 6789 with 1σ contours at 0.8E19 cm². Contour levels increase by a multiple of 2. Note this is the same figure as Figure 43 with added contours.

The pixels near the lower left of the galaxy are of unknown origin and are most likely noise or Milky Way emission due to the shape and location on the very edge of the cube. The other feature to the upper right of DDO 187, which is 54 kpc from the galaxy with a diameter of 12 kpc, could be either a tidal remnant or noise and further investigation is
required to reach a conclusion.

The $3\sigma$ map clears up the field to leave only DDO 187. That is to say, the tail-like feature and the feature in the upper right corner of the field vanish at $3\sigma$, indicating it is either low surface brightness or noise. The map is shown in Figure 45.

![Map showing DDO 187 field with threshold column density and velocity fields](image)

Fig. 45.— The upper left image is a $2\sigma$ threshold blank column density map of the DDO 187 field and the lower left image is the $3\sigma$ threshold blank column density map of the same field. The $2\sigma$ RMS threshold value was 0.044 K and the $3\sigma$ threshold value was 0.066 K. The upper right image is a $2\sigma$ threshold blank velocity field map of the DDO 187 field and the lower right image is the $3\sigma$ threshold blank velocity field map.
The velocity fields from Figure 45 show some rotation of DDO 187. The velocity map also indicates that the feature in the upper right corner may be noise. That feature and the right tip of the DDO 187 cloud are comprised of one or two velocities, which is characteristic of noise features. Their velocities are also sharply different from those of DDO 187, though the entire map only covers 10 km s\(^{-1}\) so all features, if real, are potential interaction indicators.

The GIPSY result is shown in Figure 46.

![GIPSY output image of the DDO 187 field](image)

Fig. 46.— Gipsy output image of the DDO 187 field with an amplitude blanking threshold of 2\(\sigma\) = .0252K and a velocity dispersion threshold of 5 km s\(^{-1}\). Note that the units of the map are K and not K km s\(^{-1}\).

Like the 3\(\sigma\) map, the GIPSY map exclusively features DDO 187 and none of the features from the 2\(\sigma\) map. The 2\(\sigma\) features, then, are either low surface brightness emission, noise, or Milky Way emission.
The Galactic dust map reveals no significant dust content in the vicinity of DDO 187.

Cross-correlation in SDSS revealed that the slight elongation of the DDO 187 is evident in the optical image. SDSS reveals no other galaxies at first glance that have the potential to stretch the gas in that manner, and neither does the ALFALFA catalog. The ALFALFA catalog may be misleading in the case of this field, however, because DDO 187 was not found by the cross-correlation program like NGC 784 and NGC 672 were.

The SFH timescale test was done between DDO 187 and the end of the tail like feature to the upper right of the galaxy. With a velocity difference of 27 km s$^{-1}$ a timescale of 1177 Myr was calculated. This is not greater than the SF duration for DDO 187 of 1300 Myr, signifying the feature may not have been formed before the starburst.

To first order it appears as though DDO 187 is likely alone in its field. The upper right feature is a sharply different velocity, only exists in three or so velocity channels, and fails to pass the $3\sigma$ threshold test, suggesting it may be a noise feature.
6. Discussion

The goal of this project was to probe deep, wide-field GBT maps of starburst dwarf galaxies for signatures of tidal interactions to definitively conclude that tidal interactions either are or are not a possible cause of starbursts. After a thorough investigation of 9 fields, at this point in the project we see evidence both for and against tidal interactions as a driver for star formation in dwarf galaxies. The origins of several features in the field remain questionable. Even some basic properties about the target galaxies, like their structure, are still somewhat elusive for the galaxies embedded in Milky Way emission.

Though a definitive answer is not yet in hand, it is reasonable to make educated speculations using the results from the observations. It is fair to surmise that tidal interactions could play a role as a starburst trigger in specific systems. The NGC 672 field is the most obvious of the nine fields. It already has a known companion, IC 1727. These galaxies are known to be interacting, and the interferometer maps from Section 4 display a gaseous bridge between the two galaxies. Assuming NGC 672 is a prototypical interacting system and comparing this field to the other nine fields, it becomes relatively clear that the only other systems that appear to contain interactions are the NGC 784 and DDO 50 fields. These are the only fields with clear gas bridges and nearby features close in both position and velocity. If the other galaxies were undergoing interactions, the features in their fields would be more consistent with the features observed in the NGC 672 field.

This kind of analysis does, however, bring up the question of how long low surface brightness tidal features last. It could be possible that the other galactic fields had diffuse emission or tidal features but the gas simply settled back onto the galactic disk or became too diffuse for detection, though more information is needed to draw conclusions about these timescales.

Another point to consider is that the scale of the observations is huge. Compare the GBT maps to the interferometer maps. Galaxies that show small-scale structure indicative of
some kind of perturbation, like DDO 165 and NGC 2366, look mostly undisturbed in the GBT maps. This seems to indicate that most activity occurs at a small, local scale rather than at the large scale of the GBT, with the exception of systems like NGC 672, NGC 784, and DDO 50. Taking this consideration into account, and based on the evidence presented throughout this manuscript, at the very least tidal interactions have the ability to spark these sudden, intense periods of star formation in some dwarf galaxy systems. However, they are not the only mechanism to do so and are therefore not the universal starburst trigger mechanism.
7. Future Work

In the hopes of obtaining a confident answer to the question of research, the team will employ two more techniques. The first step to further analyze the data requires simulations. These simulations will test the plausability of tidal interactions creating the apparent gas structures in the moment maps. If, within the contraints of realistic parameters, the simulations build galactic fields that resemble those detected in the GBT and the simulated galaxies undergo starburst periods, then is is possible that tidal interactions play a role in the fields.

The final step of the project is cross-correlating the results from this GBT project with the database of multi-wavelength data and results acquired throughout the STARBIRDS project to create a holistic picture of starburst dwarf galaxies. This includes folding in GBT HI data from Parkes galaxies, the control galaxies, and the archival galaxies. With these tools in hand, and the extensive previous research on the sample, we hope to definitively determine the role tidal interactions play in the triggering of starbursts in dwarf galaxies.
8. Acknowledgements

I would like to acknowledge all who helped and advised me throughout the process of creating this thesis, especially John Cannon, Kristy McQuinn, Evan Skillman, and Megan Johnson. Your help and support is very much appreciated. This project would not be what it is without the four of you. Thank you to my STARBIRDS team as well for your insight at each stage of the project. I also would like to thank John Cannon, Kristy McQuinn, and Tonnis ter Veldhuis for serving on my defense committee. My appreciation also to the NSF for the funding during my REU at the University of Minnesota in the summer of 2014.

I would also like to acknowledge and thank my lab peers for your advice and good sense of humor during some of the more trying times of this project; I am not horsing around, this is not negotiable. I would additionally like to thank my friends and family for your support throughout the entire process, with special thanks to Philip for your arrow placement recommendations.
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This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

This manuscript was prepared with the AAS \LaTeX{} macros v5.2.