THE H I COMpanions OF H II GALAXIES AND LOW SURFACE BRIGHTNESS DWARF GALAXIES

CHRISTOPHER L. TAYLOR
McMaster University, Department of Physics and Astronomy, Hamilton, Ontario, L8S 4M1, Canada; taylorc@physun.physics.mcmaster.ca

Received 1996 September 27; accepted 1996 December 3

ABSTRACT

I study the VLA H I survey of H II galaxies by Taylor et al. and the VLA H I survey of low surface brightness (LSB) dwarf galaxies by Taylor et al. to investigate the role of galaxy interactions in triggering the bursts of massive star formation seen in H II galaxies. Comparing the two surveys, I find that H II galaxies have companions more than twice as often as LSB dwarfs (p = 0.57 for H II galaxies, compared to p = 0.24 for LSB dwarfs). I examine the completeness of the companion samples detected by the two surveys. For the companions to H II galaxies, the sample is likely complete in the distribution of velocity separations from their parent galaxies but is probably missing some companions at large projected linear separations because of the finite size of the VLA primary beam. For the companions of LSB dwarfs, the small number of detections means their distributions in velocity and linear separation are poorly determined, but the LSB dwarfs were observed with the same observational setup as the H II galaxies, so they will have the same levels of completeness. Because the two samples were observed in exactly the same fashion, there will be no relative bias in the number of companions introduced in this way. In addition, the redshift distributions of the two samples are very similar, so there will not be a distance-related relative bias.

Thus, I conclude that the difference in the number of H I rich companions is genuine, and signifies a difference in the local, small-scale environments between the two types of galaxy. I search through published galaxy catalogs to determine number of neighbors each galaxy has outside the area of the VLA observations. At these large separations, the number of neighbors is the same, within the errors, for the two types of galaxy. The high rate of companion occurrence at low separations for H II galaxies relative to LSB dwarfs supports the hypothesis that the bursts of star formation are triggered by galaxy interactions.

Subject headings: galaxies: clusters: general — galaxies: interactions — galaxies: stellar content — radio lines: galaxies

1. INTRODUCTION

The small-scale environment of a galaxy can have a profound impact on that galaxy’s evolution. Obviously, mergers and tidal interactions can alter a galaxy’s morphology by changing the distribution of its stars and gas. Interactions are also linked to nuclear star burst events, enhanced levels of massive star formation in galactic disks, and the formation of bars (e.g., Bushouse 1987; Kennicutt et al. 1987; Noguchi 1987). All of these processes are clearly most efficient in an environment of high galaxy density, where the likelihood for galaxies to interact is greatest. Even the type of galaxies available as interaction partners can be important, as shown by the examples of elliptical galaxies believed to have accreted gas from neighboring late type systems (e.g., NGC 1052; van Gorkom et al. 1986).

Taylor, Brinks, & Skillman (1993, hereafter TBS) used the idea that such interactions might trigger star formation to launch a program of searching for previously unknown companions. They selected a sample of nine dwarf galaxies currently experiencing a burst of star formation (H II galaxies) but without obvious interaction partners. If the bursts of star formation were related to interactions, then the companions must be optically faint to have avoided earlier detection. Dwarf galaxies were chosen because they are too small to sustain spiral density waves, which can trigger star formation episodes in spiral galaxies. TBS observed these H II galaxies with the NRAO1 Very Large Array (VLA) in the 21 cm transition of H I, looking for optically faint but H I rich companions. They found four of the nine had previously unknown companions.

Following the success of the pilot study of TBS, Taylor et al. (1995, hereafter TBGS) conducted a similar survey around a larger (N = 21), volume limited sample of H II galaxies, to put the result on a more solid statistical footing. They detected companions around 12/21 (= 0.57) H II galaxies. Taylor et al. (1996, hereafter TTBS) then surveyed a complementary sample (N = 17) of low surface brightness (i.e., nonstarbursting) dwarf galaxies to serve as a control on the H II galaxy sample. TTBS found that only 4/17 (= 0.24) of the LSB dwarfs had H I-rich companions. Thus, the H II galaxies are more than twice as likely to have H I rich companions as the LSB dwarfs.

The goal of this paper is to compare the data from these two H I surveys, to determine whether or not the presence of a nearby H I-rich companion can trigger bursts of star formation in low-mass galaxies. In §2, I review the properties of the H II galaxy and LSB dwarf samples. In §3, in which I compare the completeness of the companion searches for the two surveys and discuss their observational biases. I will

1 The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
show that the difference in the observed numbers of companions is not caused by such effects. In § 4, I compare the large-scale (0.5–2.5 Mpc) environments of the two samples, showing that on average, on the large scales, the number of neighbors around the H II and LSB galaxies is the same. Section 5 is a discussion of the relationship between interactions and star formation in dwarf galaxies. Section 6 presents the conclusions.

Throughout this paper, I adopt the following definitions: a companion to one of the H II galaxies or LSB dwarfs means one of the objects detected in the VLA H I surveys described above, while a neighbor is a cataloged optical galaxy in the vicinity of one of the H II galaxies or LSB dwarfs. Note that there is a degree of overlap between these two classifications, since some of the companions are cataloged galaxies (e.g., UM 477A = NGC 4116).

2. A DESCRIPTION OF THE TWO SAMPLES OF GALAXIES

The search for companions to H II galaxies is described in detail by TBGS. The sample of H II galaxies was selected from the galaxies studied by Salzer et al. (1989a, 1989b). Because they originally come from an objective prism survey, these galaxies tend to have emission lines that are strong relative to their stellar continuum. Thus, galaxies with inherently strong emission lines or a faint continuum are selected. The latter case can result in the inclusion of extremely low-mass systems, while the former can include AGNs. In order to restrict the sample to nearby dwarf galaxies, TBGS applied a velocity limit of $v_\odot \leq 2500$ km s$^{-1}$ and an absolute magnitude limit of $M_B \geq -19$. Despite these selection criteria, two nondwarfs—low-luminosity spirals—were included in the sample. I will discuss the effects of these two galaxies on the results of this paper in § 5.2. The H I masses of the H II galaxies range from a few $\times 10^7 M_\odot$ to a few $\times 10^9 M_\odot$. TBGS found that 12/21 of those H II galaxies had nearby companions rich in HI, for a measured companion frequency of 0.57, with a strong lower limit of 0.37. Because of the observational limitations (discussed in TBGS) it was not possible to derive a useful upper limit.

TBGS provide a detailed account of the search for companions to LSB dwarfs. The LSB dwarf galaxies were extracted from the list of low surface brightness galaxies studied by Bothun et al. (1993). To be included in the list used by Bothun et al., a galaxy had to have a low central surface brightness and exceed a minimum radius. The lists of LSB galaxies are not statistically complete samples (e.g., Schombert & Bothun 1988), and thus it is unknown how representative these galaxies are of whole LSB galaxy population. To obtain a sample useful for comparison with the H II galaxies, TBGS selected LSB dwarfs with a similar velocity limit (3000 km s$^{-1}$) and to resemble the H II galaxies in morphology, H I mass, and H I line width. For example, the range in H I mass of the LSB dwarf galaxies is a few $\times 10^7 M_\odot$ to a few $\times 10^9 M_\odot$, very similar to that of the H II galaxies. TBGS performed a Kolmogorov-Smirnov (K-S) test on the distribution of H I masses for the two samples and found the result consistent with the two samples coming from the same parent population. In the search for companions, TBGS found that only 4/17 (= 0.24) had H II-rich companions. Here again an upper limit was problematic.

It is important to distinguish between LSB and dwarf galaxies. The description “low surface brightness” generally refers to the central surface brightness of a galaxy being below some limit usually set at about 23 mag arcsec$^{-2}$. Dwarf galaxies often meet this criterion, although there are large numbers of LSB spiral galaxies (e.g., Schombert et al. 1992). As described above, TBGS used selection criteria to obtain a sample of galaxies that are both LSB and dwarf, and the similarities in H I properties between their LSB dwarf sample and the H II galaxy sample shows they were successful.

The samples of H II galaxies and LSB dwarfs were selected to be as similar as possible, within the constraints of the source catalogs from which they were drawn. In addition, identical observational parameters were used in conducting each survey. These similarities reduce the prospect of one sample being biased toward having more companions relative to the other. As an example of the similarity between the two samples, Figure 1 shows histograms comparing their velocity distributions. Clearly, the two are very similar, and the K-S test shows that the probability that the two distributions come from the same parent population is 0.98. In the next section, I will examine the sources of a possible relative bias between the two samples and show that such a bias does not exist.

3. THE COMPLETENESS OF THE COMPANION SAMPLES

3.1. The Completeness in Radial Velocity Separations

The necessity of a finite number of channels and the desire for reasonable velocity resolution restrict the region of velocity space around each target galaxy that can be included in the H I surveys. This could lead to a bias in the observed distribution of radial velocity differences by excluding companions with high velocities relative to their parent galaxies. I will examine this distribution for the companions of both the H II galaxies and the LSB dwarf galaxies to investigate the possibility of this bias.

3.1.1. The Companions of the H II Galaxies

The upper panel of Figure 2 shows a histogram of the
computing the velocity difference.

axies (i.e., found a cuto† for drawn from catalogs that consist largely of "normal" gal-

* physically associated pairs at LSB dwarfs and companions and computing the velocity di†erence. The ratio of mean mass of the H II galaxy companions, the largest velocity separation of the LSB dwarf companions is much lower than the maximum observable separation of 250 km s\(^{-1}\), but again, this could just be a result of the small number of detections. If the LSB dwarfs exist in an environment similar to the environments of the H II galaxies, the distributions of companions at large velocity di†erences will be similar as well. However, TTBS found that most of the companions to the LSB dwarfs were more massive galaxies, unlike the case for the H II galaxies, where the companions were of equal or less mass. Therefore, because the LSB dwarfs are bound to more massive galaxies, their velocity separations could be larger than was true for the H II galaxies while still allowing the systems to be bound.

Because the distribution of velocity separations falls off well before the end of the range of velocity coverage of the VLA, and because these counts seem to merge smoothly into the expected distribution of random background separations, I conclude that the sample of companions to H II galaxies is likely complete in velocity space.

3.1.2. The Companions of the LSB Dwarf Galaxies

Although the LSB dwarf galaxies have far fewer companions than the H II galaxies, the distribution of radial velocity separations shown in the lower panel of Figure 2 (solid line) does resemble the distribution of the H II galaxy companions in general shape. That is, the distribution peaks at low velocities and decreases at higher velocities. Unfortunately, the small number of companions found around the LSB dwarfs makes it difficult to argue that distribution is truly similar to the distribution of H II galaxy companions. Like the H II galaxy companions, the largest velocity separation of the LSB dwarf companions is much lower than the maximum observable separation of 250 km s\(^{-1}\), but again, this could just be a result of the small number of detections. If the LSB dwarfs exist in an environment similar to the environments of the H II galaxies, the distributions of companions at large velocity di†erences will be similar as well. However, TTBS found that most of the companions to the LSB dwarfs were more massive galaxies, unlike the case for the H II galaxies, where the companions were of equal or less mass. Therefore, because the LSB dwarfs are bound to more massive galaxies, their velocity separations could be larger than was true for the H II galaxies while still allowing the systems to be bound.

There is no evidence in the radial velocity distribution of companions to LSB dwarfs that there exist companions at large velocity separations. I conclude that I have not missed a large number of companions within one primary beam of the target galaxies due to the finite velocity coverage of the TTBS VLA observations.

3.2. The Completeness in Projected Physical Separation

The problem of assessing the completeness of the companion sample in spatial separation is entirely di†erent from the problem of velocity separation. This is because the amount of velocity space observed by the VLA does not depend upon redshift, whereas for a constant angular size of the VLA primary beam, a larger physical area is imaged as the distance increases. It is immediately apparent that companions at relatively large projected separations may fall outside the primary beam for galaxies at smaller distances.

3.2.1. The Companions to the H II Galaxies

The ratio of the largest and smallest distances in the H II galaxy sample is 2.6, corresponding to a ratio of imaged areas of 6.8. The distribution of projected separations for the companion population of H II galaxies is shown in the upper panel of Figure 3. The vertical line in the figure indicates the radius of the FWHM of the VLA primary beam for UM 533, the closest H II galaxy. At least one of the distant H II galaxies has a companion beyond this radius, suggesting that some of the nearer galaxies could as well. Such companions would have been undetected by TBGS.

An additional e†ect adding to the incompleteness of the survey is the decrease in sensitivity of the VLA primary beam with distance from the pointing center. For observations in the 21 cm line, the sensitivity falls to half-maximum at a radius of 15'. The farther from the target...
galaxy a companion lies, the more H I it must have to be detectable. Figure 4 shows the distribution of angular separation for the companion population. The dashed vertical line shows the radius of the FWHM of the VLA primary beam. The mean H I mass of the four systems beyond the line is $18.5 \pm 4.4 \times 10^7 M_\odot$, while for the entire population it is $6.5 \pm 2.7 \times 10^8 M_\odot$, illustrating the effect of the decreasing sensitivity. For the companion with the widest angular separation in Figure 4 the decrease in sensitivity is approximately 0.17. A typical sensitivity for the distances of the H II galaxies is $\sim 3 \times 10^7 M_\odot$ (discussed in greater detail in the following section). For the widest separation, this limit becomes $\sim 2 \times 10^8 M_\odot$. Five companions have low enough H I masses to become undetectable at this separation, and even six of the H II galaxies would have been missed if they had been toward the edge of the primary beam. Clearly, this effect could result in companions being missed in the survey.

Although it is likely that companions have been missed at large radii for the reasons discussed above, it is also possible that the true distribution of separations will tend toward companions with low separations, if the companions experience dynamical friction from dark matter halos in the H II galaxies (Lin & Tremaine 1983). For typical projected separations ($r = 60$ kpc) and radial velocities ($v = 40$ km s$^{-1}$), the crossing time is of order $6 \times 10^9$ yr. If the dark matter halos reach the distance of the companions and the companions are on circular orbits, then the timescale for dynamical friction can be written as

$$t_{\text{fric}} = \frac{1}{\ln \Lambda} \left( \frac{r}{60 \text{ kpc}} \right)^2 \left( \frac{v}{220 \text{ km s}^{-1}} \right) \times \left( \frac{2 \times 10^{10} M_\odot}{M_{\text{H II}}} \right) \text{ yr},$$

where

$$\Lambda = \frac{r v^2}{G (M_{\text{H II}} + M_{\text{comp}})}$$

(Binney & Tremaine 1987).

For $M_{\text{H II}} = 10^8 M_\odot$ and $M_{\text{comp}} = 10^8 M_\odot$ this timescale is approximately $1.2 \times 10^{10}$ yr. Thus, the companions would have had plenty of time to experience dynamical friction but not enough to have been swallowed by the H II galaxies. This time scale is, of course, a lower limit because I have used observed orbital parameters like projected separations and radial velocities for the true separations and relative velocities.

The conclusion to be drawn regarding the completeness of the companion sample in physical separation is a fairly weak one. Because of the range in distance of the H II galaxies, and the fall-off of sensitivity at the edges of the VLA primary beam, it is very likely that some companions have been missed. Unfortunately, because the distribution of the companions is unknown, the degree of incompleteness cannot be estimated.

### 3.2.2. The Companions of the LSB Dwarf Galaxies

The ratio of the largest and smallest distances in the LSB dwarf galaxy sample is 2.5, corresponding to a ratio of areas imaged of 6.3, nearly identical to the values for the H II galaxies. This is because the LSB dwarfs were chosen to span approximately the same range in redshift as the H II galaxies (recall Fig. 1). The distribution of projected separations for the companion population of LSB dwarfs is shown in the lower panel of Figure 3. The vertical line indicates the radius of the FWHM of the VLA primary beam at the distance of the closest galaxy in the LSB sample. The companions of the LSB dwarfs are, on average, further away from the LSBs than the companions of H II galaxies are from the H II
galaxies. This may, however, be a function of the small number of detected companions. It is also possible that because the companions to LSBs are mostly more massive galaxies the LSB/companion systems can remain bound to larger distances for roughly equivalent velocity separations.

Even less can be said about the completeness in spatial separation of the LSB dwarf sample than could be about that of the H II galaxies. If it is true that the companions of LSB dwarfs tend to larger physical separations, then the LSB dwarf sample is likely more incomplete in the companion count than is the H II galaxy sample. In this case, the variation of sensitivity of the VLA primary beam with radius will affect the LSB dwarf sample more than it does the H II galaxy sample. However, if the distribution seen in Figure 3 is just the result of a small sample size, then the level of incompleteness is likely the same as for the H II galaxies, in which case the primary beam effect will be the same on both samples. Thus, either:

1. The companions to LSB dwarfs are distributed at larger linear separations than are the companions of H II galaxies, in which case the incompleteness in the companion counts is greater than for the H II galaxies; or
2. The two distributions are roughly similar, in which case the incompleteness of the two samples is roughly the same.

Based on the current data there is no way of determining which of these possibilities is correct.

3.3. *Sensitivity Limits to Detectable Masses of H I Companions*

Another way in which companions might be missed by TBGS or TTBS is if they do not have enough H I to be detected. This is especially acute for dwarf ellipticals, since dEs have very little or no H I, but it will also affect the detection of low-mass dwarf irregulars (see the discussion below).

3.3.1. *The Companions of the H II Galaxies*

Regarding dwarf ellipticals as companions, I simply note that only one candidate was seen in any of the optical data (see UM 465 in TBGS), although the area of the CCD on the sky was much smaller than the area of the H I data. I will discuss a search for optical companions performed using the Center for Astrophysics (CfA) redshift survey in §4.

The upper panel of Figure 5 shows H I masses for the sample of both H II galaxies and companions, plotted as a function of redshift (distance). The solid line shows the sensitivity of the TBGS observations with distance for an unresolved point source with a typical single-channel noise of 1.3 mJy beam$^{-1}$. The lower envelope of H I mass of the combined sample is roughly constant with distance, at a few times 10$^7$ $M_\odot$, even at small distances where the detection threshold is significantly lower. The only point below this constant level corresponds to the H II galaxy UM 538, at a distance of 14.3 Mpc. It is the only galaxy or companion that could possibly have been lost if it were at a higher redshift within the limits of the survey. I take this as an indication that there are not large numbers of companions of H I mass $\sim 10^7$ $M_\odot$ missing from the sample at the larger distances. This is a result of the relatively narrow range in velocity covered by the H II galaxies (from 700 km s$^{-1}$ to 2500 km s$^{-1}$). On the other hand, there are a number of dwarf irregular galaxies in and around the Local Group with H I masses in the range $\sim 10^6$–$10^7$ $M_\odot$ (e.g., Leo A, Sag DIG, GR 8; Lo, Sargent, & Young 1993). Such objects are not limited to the Local Group (Côté 1995), so there could be a significant population of companions at low H I mass (of order $10^6$ $M_\odot$ or less), which would remain undetected unless closer H II galaxies were surveyed, or else a factor of 100 more integration time is spent on the current sample.

3.3.2. *The Companions of the LSB Dwarf Galaxies*

TTBS obtained optical images of each of the LSB dwarfs using the STScI Digitized Sky Survey. None of the systems had a potential dwarf elliptical companion visible in the images, though the images were restricted to a small region around each galaxy ($\sim 7.5$).

A plot of H I mass versus distance for the LSB dwarfs and their companions is shown in the lower panel of Figure 5. The detection limit is nearly identical to the limit for the H II galaxy observations, being slightly lower because most of the LSB dwarf observations took place after sunset, whereas nearly all of the H II galaxy took place during the day and close to the solar maximum. Thus, the LSB dwarf observations are less affected by solar interference, although they are not unaffected (TTBS).

As was true for the H II galaxies and their companions, the detections of LSB dwarfs and their companions do not approach the detection limit, suggesting that there are not large numbers of objects hiding below the detection threshold.

3.4. *Summary of the Two Samples’ Completeness*

In the above subsections it was shown that the H II galaxy companion sample is likely complete in the distribution of radial velocity separations. Although there are not enough detections of companions around LSB dwarfs to
show this is also true for that sample, the similarity of both the target galaxies' properties and the observing conditions makes it highly likely. It was also shown that the HII galaxy companion sample is likely incomplete in projected linear separation, in the sense of missing companions around the most nearby HII galaxies at separations greater than ~100 Mpc. Because the LSB dwarfs have approximately the same distribution in redshift, this is likely true for them as well.

Finally, it was argued that the two samples are not likely to be missing large numbers of companions at the sensitivity level of the observations (~10^5 M☉), although the data do not constrain the number of less massive companions. In any event, the sensitivity of the two surveys to H I mass is nearly identical, so the effects of this sensitivity limit will be the same on each sample.

The most important fact to keep in mind for this work is the great similarity between the two surveys being studied, in terms of the redshift distributions, galaxy masses and observing setups. Because of this, whatever biases imposed due to limitations in the samples (e.g., the projected linear separation) will affect both the HII galaxy and LSB dwarf samples equally. Therefore, the difference between the companion rates of the two types of galaxy noted in §1 and by TTBS is real and not caused by a relative bias between the samples.

4. A COMPARISON OF THE LARGE-SCALE ENVIRONMENTS OF HII AND LOW SURFACE BRIGHTNESS DWARF GALAXIES

The previous section showed that the difference in the number of H I companions around LSB dwarf and HII galaxies is not due to selection effects inherent in galaxy samples, nor is it due to limitations imposed by the observing conditions or setup. The observed difference in the number of companions therefore reflects a true difference in the small-scale environment of the two populations. However, it is likely that the small-scale environment is influenced by the larger scale environment (e.g., cluster vs. field, or supercluster vs. void). If, to give an extreme example, all the HII galaxies were found to be in the center of the Virgo Cluster, while all the LSB dwarfs were on the edge of a void, then the observation that HII galaxies have more companions would be a reflection of the generally denser environment of the particular sample of HII galaxies and not necessarily indicating an important difference in their evolution. On the other hand, if the two types of galaxy were found to have the same large-scale environment, then the difference in the companion rates would be significant.

To investigate the large-scale environments of the two samples, I will compare them to two galaxy catalogs: the CfA redshift survey catalog (Huchra et al. 1983) and the Nearby Galaxies Catalog (Tully 1988).

4.1. Comparison to the CfA Redshift Survey

The area of overlap of the CfA redshift survey with the TBGS and TTBS is in two regions, b₁ ≥ 40°, δ ≥ 0° and b₁ ≤ −30°, δ ≥ 2.5°. In these areas the catalog is complete to B ≤ 14.5 (Huchra et al. 1983). For the most and least distant galaxies in the two samples, this corresponds to M ≤ −18.4 and M ≤ −15.5, respectively. Only for the closest galaxies will any of the neighbors be dwarfs. A comparison with primarily massive galaxies will still be useful, because dwarf galaxies are known to trace the same structures as bright galaxies (e.g., Thuan et al. 1991).

These areas contain 11/21 of the HII galaxies and 15/17 of the LSB dwarfs. I obtained the catalog from the Astrophysics Data Service (ADS) Catalog Query Service available on the World Wide Web. I searched through the catalog looking for neighbors around each galaxy with velocities within 500 km s⁻¹ of the target galaxy. The choice of 500 km s⁻¹ as the velocity limit was not based on any physical reasons, but rather to allow for easy comparisons with similar studies by Bothun et al. (1993) and Campos-Aguilar & Moles (1991), which adopted that limit. Note that 500 km s⁻¹ is consistent with the typical velocity limits for samples of binary spirals discussed in §2.

The counts were binned in 0.5 Mpc bins running from 0 to 2.5 Mpc. Figure 6 shows the mean neighbor counts plotted versus distance for the HII galaxy (triangles) and LSB dwarf galaxy (circles), with associated error bars. The open symbols show the counts in each bin, while the filled points show the cumulative values. In all bins the counts per bin are the same within the errors, although in the last two bins (2 and 2.5 Mpc) the LSB dwarf neighbor counts begin to diverge from the HII galaxy neighbor counts. It is possible that if the samples were larger (and thus the errors smaller) that there might be a significant difference. The counts at smaller radii, however, are nearly identical, suggesting that the members of the two samples are in environments of similar galaxy density. It is important to reiterate that the CfA catalog contains few dwarfs, so that most of the neighbors in the counts are massive galaxies. I am thus using the massive galaxies as indicators of the environment, which is justified because we know that dwarfs and larger galaxies trace the same large-scale structures. From neighbor counts using the CfA redshift survey catalog, I conclude that, on average, the HII galaxies and LSB dwarfs are found
in environments of similar galaxy density on scales larger than the VLA primary beam (i.e., ~250 kpc).

How does this result compare with other studies of galaxy environments? Bothun et al. (1993) have done a very similar analysis on much larger samples (N between 135 and 870) for galaxies in the redshift range 2000–12,000 km s\(^{-1}\). Most of the galaxies from that work are not dwarfs like the galaxies of this study, but rather are more massive spirals and ellipticals, with large \(H\) line widths. For the portion of the Bothun et al. (1993) sample cataloged by Schombert et al. (1992), the mean \(H\) line width measured at half the maximum intensity is 147 ± 8 km s\(^{-1}\), while for the LSB dwarf sample of TTBS the line width measured at zero intensity is only 107 ± 8 km s\(^{-1}\). If the LSB dwarfs had been measured on the half-maximum too, the line widths would be even smaller, emphasizing even more the difference between the Bothun et al. and the TTBS LSB samples.

Bothun et al. (1993) searched for neighbors within a projected radius of 2.4 Mpc and ±500 km s\(^{-1}\) of each of their sample galaxies. They binned their neighbor counts in 0.5 Mpc bins, finding that at every bin the cumulative number of neighbors for LSB galaxies was larger than for LSB galaxies. The difference was most pronounced for the 0–0.5 Mpc bin. This is consistent with my VLA result that in the range of distances 0–0.25 Mpc \(H\) galaxies have more \(H\) companions than do LSB dwarfs. In my neighbor counts using the CfA redshift survey, however, I find that the \(H\) galaxies and the LSB dwarfs have the same number of neighbors at \(H\) separations within the errors, although the counts do seem to be diverging from each other at larger radii. Thus, based only on the neighbor counts from optical catalogs, my results would not agree with the Bothun et al. result, but this may simply be because I have far fewer galaxies in my samples than they had, resulting in larger error bars. The Bothun et al. samples have from 7 to 50 times as many galaxy as the samples of this paper. When including the VLA discovered companions, I find that the \(H\) galaxies have an excess of companions in the 0–0.25 Mpc range, but most of these companions are not bright enough to be in the catalogs searched by Bothun et al. (1993). Thus, within the errors of the neighbor counts, there is no significant difference in the environments of the two samples on the scales of 0.5–2.5 Mpc. Overall, I find that LSB dwarfs have fewer companions at short radii than do \(H\) galaxies, but at larger radii the two sample have similar numbers of (optical) neighbors. This is the same result arrived at by Bothun et al. for their samples of LSB and LSB galaxies.

Other studies have investigated the environments of \(H\) galaxies, but unlike my study and that of Bothun et al. (1993), they did not compare LSB and LSB systems. Work by Campos-Aguilar & Moles (1991), Campos-Aguilar, Moles, & Masegosa (1993), and Telles & Terlevich (1995) have found that \(H\) galaxies tend to be isolated from luminous, massive galaxies. These authors used various optical galaxy catalogs to search for bright neighbors. Typically, from one-third to three-fourths of the \(H\) galaxies were found to be isolated, with isolation criteria of 1 Mpc and ±500 km s\(^{-1}\). By restricting themselves to magnitude limited optical catalogs, however, these authors could not have found the faint dwarfs that form the majority of the optical counterparts to the TBGS \(H\) detections.

For a quantitative comparison, 19 out of 21 \(H\) galaxies from the TBGS sample are also included in the Campos-Aguilar & Moles (1991) sample. If we consider these 19 \(H\) galaxies then using just the Campos-Aguilar & Moles (1991) detections of neighbors, the fraction of isolated galaxies is 0.11. The fraction of isolated \(H\) galaxies for their entire sample is much higher, 0.33. With such a high fraction of isolated \(H\) galaxies in their sample they argue that galaxy interactions are not responsible for the bursts in all \(H\) galaxies.

This difference between the 0.11 and 0.33 fractions occurs because the TBGS sample has been restricted to less than 2500 km s\(^{-1}\). All these galaxies lie within the Local Supercluster, whereas the much larger sample of Campos-Aguilar & Moles (1991) contains galaxies of velocity up to ~15,000 km s\(^{-1}\) and in a variety of large-scale environments. In fact, Campos-Aguilar et al. (1993) do find that the mean redshift of \(H\) galaxies without neighbors is higher than that of those with companions. They suggest this is because the CfA redshift survey, which they use to search for companions, is magnitude limited, making faint neighbors at higher redshifts more difficult to detect. It is likely, therefore, that a VLA \(H\) survey of the entire Campos-Aguilar & Moles (1991) sample would yield a higher fraction of galaxies with interaction partners than is currently known.

4.2. Comparison to the Nearby Galaxies Catalog

As mentioned previously, the CfA survey does not have complete coverage over the area of all the galaxies in the \(H\) galaxy and LSB dwarf samples. Because of this, I could only compare the parts of those samples that did overlap with the CfA coverage. The sample in the Nearby Galaxies Catalog (Tully 1988, hereafter NBG), however, has nearly uniform coverage across the entire sky (except what is obscured by the Galactic plane). This catalog has roughly the same number of galaxies as the portion of the CfA survey used above, but distributed across the entire sky. Therefore, the limiting magnitude is not as deep. Rather than compute projected separations with the somewhat sparsely distributed galaxies in the NBG, I will compare the positions and velocities of the sample galaxies with the positions and velocities of the groups defined in the NBG. For this purpose, I defined a sample from the NBG that contained all galaxies within three degrees and 500 km s\(^{-1}\) of a galaxy in either the \(H\) galaxy or LSB dwarf samples.

An \(H\) galaxy or LSB dwarf was considered to be a group member if it met both the following criteria:

1. Its projected separation from the group center had to be less than twice the mean of the separations of each pair formed by pairing each group member with every other group member.
2. Its velocity had to be within 2 \(\sigma\) of the group mean velocity, where \(\sigma\) was the velocity dispersion of the group.

This is a conservative definition, but one that is unlikely to falsely call one of the sample galaxies a group member. To test how well this definition works, I applied it to the NBG sample defined above, to see whether or not known group members would be wrongly excluded. Out of 32 groups with 131 members, only two galaxies (1.5%) would have been excluded by my criteria. Thus, it is unlikely that I have incorrectly labeled an \(H\) or an LSB galaxy as not being a member of any group. However, if incorrect assignments occur, they should happen with equal frequency to both samples, assuming the groups near the different samples are similar to each other. To check the validity of this assumption, I calculated the separation of each pair in every group in the NBG sample. The mean of this pairwise...
separation within groups near H II galaxies is 0.48 ± 0.10 Mpc, and 0.50 ± 0.05 Mpc for groups near LSB dwarfs. There is no evidence that groups near H II galaxies are different than groups near LSB dwarfs.

Using the above conservative definition of group membership, I searched through the groups in the NBG sample, checking for any to which an H II galaxy or LSB dwarf might belong. I find that 5 out of 21 (≈ 0.24) H II galaxies belonged to groups, while 7 of 17 (≈ 0.41) of the LSB dwarfs did. Following TBS and TBGS, I can use the binomial distribution to calculate upper and lower limits on these fractions. Using this method to determine, for example, the lower limit for the number of H II galaxies in groups, will yield the lowest fraction of H II galaxies in groups, which is consistent with observing 5 out of 21 at least 5% of the time if the experiment were repeated many times. With these calculations, the fraction of H II galaxies in groups is 0.24 ± 0.13 and the fraction of LSB dwarfs in groups is 0.41 ± 0.20. These fractions are within the uncertainties of each other, indicating that there is no significant difference between the group environments of the LSB dwarfs and the H II galaxies.

4.3. Contamination from the Virgo Cluster

Nineteen of the 21 H II galaxies from TBGS lie in an area of the sky on the periphery of the Virgo Cluster. All of these 19 are within 30° of the cluster center. Thus, there is the possibility that some of the H II galaxy—companion pairs are not physically associated but caused by a chance occurrence between a cluster member and a nonmember at similar velocities.

To assess this possibility, I will use the data of the Virgo Cluster study by Binggeli, Tammann, & Sandage (1987, hereafter BTS). According to BTS, the Virgo Cluster contains several distinct substructures. Cluster A, centered on M87, and cluster B, centered on M49, are the two largest units, together containing most of the galaxies. The surface density of number counts for late-type galaxies can be described with an exponential profile: \( I(r) = I_0 \exp(-r/r_0) \), where \( I_0 = 5 \text{ arcsec}^{-2} \) and \( r_0 = 3.3 \) degrees. Taking \( r \) to be the angular distance of each H II galaxy from the center of cluster A \((12^m 25^s, 13° 0')\), this expression yields the number of Virgo galaxies expected within a VLA primary beam that is pointed at each H II galaxy. I then determine the fraction of Virgo galaxies that have velocities within ± 250 km s⁻¹ of each H II galaxy to estimate the probability that if a galaxy did fall within the VLA primary beam, it would also be in the correct velocity range so that TBGS would detect it. Thus, I obtain for each observation of an H II galaxy the number of members of cluster A expected to be detected. Summing this over all the H II galaxies, only 0.16 galaxies are expected to contaminate the experiment. Thus, it is likely that no members of cluster A are contaminating the experiment.

BTS did not derive a radial profile from the number counts of cluster B, presumably because it is not symmetric. However, it lies closer \((12^h 25^m 8, 8° 51')\) to the TBGS H II galaxies than does cluster A, so some measure of the possible contamination is desirable. BTS found that cluster B has one-fifth the population of cluster A. To get a rough idea of the possible contamination caused by cluster B, I will assume an exponential distribution as per cluster A, with the same scale length, but total number of galaxies scaled down by a factor of 5. Repeating the calculation done for cluster A, shows that the number of contaminating galaxies is 0.09, less than 1, and less than what is expected from cluster A. I therefore conclude that interlopers from the Virgo Cluster are not likely affecting the counts of companions.

Only eight of 16 LSB dwarf galaxies from TTBS are within 30° of the cluster center, but some of these LSB dwarfs are closer to the center than any of the H II galaxies. Repeating the calculations above for the LSB dwarfs, I find the number of contaminating galaxies to be expected is 0.41. This is somewhat larger than for the H II galaxies, but still so small as to make it unlikely. However, if one of the H II companions found by TTBS is in fact a chance alignment and not a physical pair, then removing it from the sample would make the companion rate even lower than 0.24 and increase difference between H II galaxies and LSB dwarfs.

5. DISCUSSION

5.1. Interaction Triggered Star Formation in Dwarf Galaxies

By comparing the data from TBGS and TTBS I have shown that H II galaxies have more H II-rich companions than do LSB dwarfs. The fraction of H II galaxies found to have such companions is 0.57, with a lower limit of 0.37 (TBGS). The fraction of LSB dwarfs that have companions is 0.24, with a lower limit of 0.08 (TTBS). In the previous sections, I showed that this difference is real, not caused by observational biases, selection effects, or differences in the large-scale environments of the two samples.

Because H II galaxies are currently experiencing bursts of massive star formation, while LSB dwarfs have relatively low star formation rates, I interpret the difference in companion rates between the two types as evidence that interactions with such companions can trigger bursts of star formation. This interpretation suggests that H II galaxies may be LSB dwarfs in which interactions have lead to a burst of star formation. The similarities in the global properties of H II galaxies and LSB dwarfs (e.g., H I mass, H I line width) are consistent with this, although larger and more complete samples (especially for the LSB dwarfs) should be studied to confirm this idea.

Taylor et al. (1994) suggested a possible physical mechanism by which companions could trigger bursts of star formation in H II galaxies. It was proposed that the interaction drove gas to the center of the galaxy, where it accumulated until some physical condition (such as rising above a threshold surface density) was met and a burst of star formation began. Radial inflows of gas have been seen to occur in numerical models of interacting galaxies (e.g., Noguchi 1987, 1988; Hernquist 1989; Mihos & Hernquist 1994). Many, but not all, of the H II galaxies have their star formation bursts occurring at the center of the galaxy (Salzer et al. 1989b); therefore, some alternate mechanism is needed to explain the off-center systems.

Under the Taylor et al. (1994) scenario, LSB dwarfs should have H I distributions where the surface central density of H I is lower than in H II galaxies. It is known that the total surface density of LSB galaxies in general is less than for HSB systems (e.g., McGaugh 1996). To explore any relationship between the H II galaxies and the LSB dwarfs will require high-resolution observations to compare their H I distributions, kinematics, and rotation curves. Some of the necessary data have already been obtained. LSB galaxies are usually dominated by their dark matter com-
ponents (Zwaan et al. 1995), a situation that would tend to make them stable against global perturbations that could trigger star formation bursts. This stability could play a role in determining which LSB dwarfs become H II galaxies and which do not, although some H II galaxies are also known to be dark matter dominated (e.g., NGC 2915; Meurer et al. 1996), so clearly dark matter cannot always provide enough stability to prevent a star formation burst. There is a lack in the literature of computer simulations of dwarf galaxy encounters that might shed some light on the role of dark matter and what sorts of dwarf-dwarf encounters are necessary dynamically to lead to the kind of interaction described by Taylor et al. (1994).

The result of this paper suggests that interactions play an important part in triggering bursts of star formation in H II galaxies. However, interactions cannot be the only mechanism at work because in the sample of TBGS 9/21 H II galaxies had no detected companions. In § 3.2.1, I showed that there were likely companions missing from the TBGS survey at large radii from the H II galaxies, but I could not determine the extent of this incompleteness. It is possible that some H II galaxies have no companions, in which case some other mechanism would be responsible for the bursts of star formation. It is also apparent that the mere presence of a companion to interact with is not sufficient to trigger a burst of star formation because 4/17 LSB dwarfs have companions but no bursts. This could be explained if LSB dwarfs were more dark matter dominated than H II galaxies, but questions of how much dark matter is needed to stabilize against interactions of any given strength are best sorted out by numerical simulations that explore the parameter spaces relevant to encounters among dwarf galaxies.

5.2. Caveats

There are two items that could cloud the relatively straightforward interpretation discussed above. The first concerns two of the galaxies in the H II galaxy sample. As discussed by TBGS, two of the H II galaxies are in fact small spirals (UM 477 and UM 499) and not dwarf galaxies. They were retained in the analysis because they have bursts of star formation in their nuclei (Salzer et al. 1989b), and the goal of the study is to investigate a possible connection between bursts and galaxy interactions. Dwarf galaxies are excellent for such a study because they are less complex systems than spirals and do not have spiral density waves, which can also serve as a star formation trigger. Thus, by including two spirals in the sample, I am possibly adding two galaxies to the sample that may not belong there. I feel justified in including the two spirals because their bursts are at the galaxy centers, where the rotation curve shows solid body rotation. Thus, the centers of these galaxies have physical conditions similar to the other H II galaxies (Taylor et al. 1993; TBGS). However, I note that if the two spiral galaxies are excluded from the sample, the companion rate becomes 10/19 = 0.53, with a lower limit of 0.32. This is compared to 12/21 = 0.57, with a lower limit of 0.37. Thus, the companion rate decreases, but the lower limit is still above the companion rate measured for the LSB dwarfs (0.24).

The second item concerns the sample of LSB dwarfs. Because of the difficulties inherent in identifying LSB galaxies (Disney & Phillipps 1983) no complete samples exist. This is true of the source lists from which TTBS drew their sample of LSB dwarfs (e.g., Schombert et al. 1992). Thus, it is difficult to quantitatively characterize the LSB dwarf sample. One example of how this can lead to trouble is the case of LSB dwarf L1-137 and its H I-rich companion, L1-137A. Inspection of digitized POSS images found that the companion has a faint, low surface brightness optical counterpart, one that was not included in the original source list of LSB dwarfs. If this galaxy had been included in the original sample of LSB dwarfs, then both L1-137 and L1-137A would be considered as companions to LSB dwarfs (in a binary pair) and the companion rate would be 5/18 = 0.28 instead of 4/17 = 0.24. Because the LSB sample is incomplete, I cannot estimate how many more binary LSB dwarf systems there are where not even one member made the TTBS sample. The L1-137 system is the only such case found by TTBS, and would make a small change in the companion rate, but it does amply illustrate the need for both larger samples and more complete samples (or at least samples with better quantified incompleteness). The best solution to this problem would be a highly sensitive H I mapping survey over a relatively large (~300 degrees²). Such a survey would have similar sensitivities to both LSB dwarfs and H II galaxies, which could be distinguished from each other in follow-up optical work.

6. Conclusions

I have used H I surveys of H II galaxies (Taylor et al. 1995; Taylor et al. 1996) and LSB dwarf galaxies (Taylor et al. 1996) to study the relationship between galaxy environment and bursts of star formation in dwarf galaxies. The primary result of this work is this:

1. H II galaxies have a rate of companion occurrence more than twice as high as do LSB dwarfs (0.57 compared to 0.24). The lower limit on the companion frequency for H II galaxies is 0.37, still higher than the observed rate for LSB dwarfs. Because of the incompleteness in projected separation from the parent galaxy that affects the companion samples, upper limits are impossible to determine. However, I have shown that this incompleteness will affect both samples in the same way and will not cause a relative bias between them. Thus, I conclude that this difference in the companion frequency is genuine. This is supported by the following results:

2. The distribution of companions to H II galaxies detected by Taylor et al. (1995) is likely complete in velocity separation from the H II galaxy. It is unlikely that any physically associated companions were missed because they were outside the velocity coverage of the observations. The distribution of companions to LSB dwarfs detected by Taylor et al. (1996) is not well determined due to the small number of objects detected. However, because the LSB dwarfs have dynamical masses similar to the H II galaxies and were observed in exactly the same fashion as the H II galaxies, their distribution is likely complete as well.

3. The distribution of companions to H II galaxies is likely not complete in projected linear separation. This is because the fixed angular size of the VLA primary beam images larger areas as the distance of the target galaxy increases. Taylor et al. (1995) detected companions around the most distant H II galaxies that were so far from their parent galaxies that they would not have been seen around the closest H II galaxies. Without knowing in an unbiased fashion how the companions are distributed with respect to their parent galaxies, the incompleteness due to this effect
cannot be estimated. Similarly, the distribution of companions to LSB dwarfs is likely not complete in projected linear separation.

4. The lower limit \( H_\text{I} \) sensitivity of the two surveys is approximately a few \( \times 10^7 M_\odot \) over most of the distance range of the two samples. The samples of companions are not likely missing objects down to this level of sensitivity, though there could be objects less massive than this that remain undetected.

5. The large-scale environments (out to separations of 2.5 Mpc) of the \( H_\text{II} \) galaxies and the LSB dwarfs are very similar, based on searches for nearby neighbors and groups in published galaxy catalogs. Within the errors, the distribution of neighbor separations for \( H_\text{II} \) galaxies and LSB dwarfs is the same. Also, there is no significant difference in the fraction of \( H_\text{II} \) galaxies and LSB dwarfs that belong to galaxy groups.

The high rate of companion occurrence for \( H_\text{II} \) galaxies relative to LSB dwarfs supports the hypothesis that interactions can trigger the bursts of star formation seen in \( H_\text{II} \) galaxies. This implies that \( H_\text{II} \) galaxies may be LSB dwarfs in which a burst of star formation has occurred, but more evidence is needed to confirm this idea. The data in the two surveys do not suggest by what mechanism star formation bursts can be triggered, although Taylor et al. (1994) do offer one possibility.

I thank Evan Skillman and Elias Brinks, my thesis advisors, for their many contributions, both direct and indirect, that led to this paper. I am also grateful to John Salzer for helpful conversations and to Christine Wilson and Ralph Pudritz for comments on an early version of the manuscript. I thank Greg Bothun and the anonymous referee for useful comments that improved the paper. 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 NASA’s Astrophysics Data System Catalog Service.

REFERENCES

Binney, J., & Tremaine, S. 1987, Galactic Dynamics (Princeton: Princeton Univ. Press)

Binnggeli, B., Tammann, G. A., & Sandage, A. 1987, AJ, 94, 251 (BTS)

Bothun, G. D., Schombert, J. M., Impey, C. D., Sprayberry, D., & McGaugh, S. S. 1993, AJ, 106, 530

Bushouse, H. A. 1987, ApJ, 320, 49

Campos-Aguilar, A., & Moles, M. 1991, A&A, 241, 358

Côte, S. 1995, Ph.D. thesis, Australia National Univ.

Disney, M., & Phillipps, S. 1983, MNRAS, 205, 1253

Hernquist, L. 1989, Nature, 340, 687

Huchra, J., Davis, M., Latham, D., & Tonry, J. 1983, ApJS, 52, 89

Kennicutt, R. C., Keel, W. C., van der Hulst, J. M., Hummel, E., & Roetti, K. A. 1987, AJ, 93, 1011

Lin, D. N. C., & Tremaine, S. 1983, ApJ, 264, 364

Lo, K. Y., Sargent, W. L. W., & Young, K. 1993, AJ, 106, 507

McGaugh, S. S. 1996, MNRAS, 280, 337

Meurer, G. R., Carignan, C., Beaulieu, S. F., & Freeman, K. C. 1996, AJ, 111, 1551

Mihos, J. C., & Hernquist, L. 1994, ApJ, 425, L13

Noguchi, M. 1987, MNRAS, 228, 635

———. 1988, A&A, 203, 259

Peterson, S. D. 1979, ApJ, 232, 20

Salzer, J. J., MacAlpine, G. M., & Boroson, T. A. 1989a, ApJS, 70, 447

———. 1989b, ApJS, 70, 479

Schombert, J. M., & Bothun, G. D. 1988, AJ, 95, 1389

Schombert, J. M., Bothun, G. D., Schneider, S. E., & McGaugh, S. S. 1992, AJ, 103, 1107

Taylor, C. L., Brinks, E., Grashuis, R. M., & Skillman, E. D. 1995, ApJS, 99, 427 (TBGS); erratum 102, 189 (1996)

Taylor, C. L., Brinks, E., Pogge, R. W., & Skillman, E. D. 1994, AJ, 107, 971

Taylor, C. L., Brinks, E., & Skillman, E. D. 1993, AJ, 105, 128 (TBS)

Taylor, C. L., Thomas, D. L., Brinks, E., & Skillman, E. D. 1996, ApJS, 107, 143 (TTBS)

Telles, E., & Terlevich, R. 1995, MNRAS, 275, 1

Thuan, T. X., Alimi, J.-M., Gott, J. R., & Schneider, S. E. 1991, ApJ, 370, 25

Tully, R. B. 1988, Nearby Galaxies Catalog (Cambridge: Cambridge Univ. Press) (NBG)

Turner, E. L. 1976a, ApJ, 208, 20

———. 1976b, ApJ, 208, 304

van Gorkom, J. H., Knapp, G. R., Raimond, E., Faber, S. M., & Gallagher, J. S. 1986, AJ, 91, 791

van Moorsel, G. A. 1987, ApJ, 176, 13

Zwaan, M. A., van der Hulst, J. M., de Blok, W. J. G., & McGaugh, S. S. 1995, MNRAS, 273, L35