STEellar populations and the star formation histories of low surface Brightness galaxies. ii. H II regions

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ABSTRACT

The luminosities, colors, and \textsc{h}\textalpha\ emission for 429 H II regions in 54 low surface brightness (LSB) galaxies are presented. While the number of H II regions per galaxy is lower in LSB galaxies compared to star-forming irregulars and spirals, there is no indication that the size or luminosity function of H II regions differs from other galaxy types. The lower number of H II regions per galaxy is consistent with their lower total star formation rates. The fraction of the total \textit{L}_\textsc{h}\textalpha\ contributed by H II regions varies from 10\% to 90\% in LSB galaxies (the rest of the \textsc{h}\textalpha\ emission being associated with a diffuse component) with no correlation with galaxy stellar or gas mass. Bright H II regions have bluer colors, similar to the trend in spirals; their number and luminosities are consistent with the hypothesis that they are produced by the same H II luminosity function as spirals. Comparison with stellar population models indicates that the brightest H II regions in LSB galaxies range in cluster mass from a few $10^3 M_\odot$ (e.g., \rho\ Oph) to globular-cluster-sized systems (e.g., 30 Dor) and that their ages are consistent with clusters from 2 to 15 Myr old. The faintest H II regions are comparable to those in the LMC powered by a single O or B star. Thus, star formation in LSB galaxies covers the full range of stellar cluster mass.

Key words: galaxies: evolution -- galaxies: ISM -- galaxies: star formation

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1. Introduction

The observational tracers of star formation range from the near-UV (Boissier et al. 2008) to the far-IR (Bigiel et al. 2008) and, while each wavelength region has its advantages and disadvantages, low surface brightness (LSB) galaxies are difficult to observe outside the traditional optical bandpasses. The most visible feature of star formation in LSB galaxies is the \textsc{h}\textalpha\ line, produced by young, massive stars that compose the upper end of the initial mass function (IMF). The UV photons emitted by these stars will, in turn, ionize the surrounding gas to form an H II region. While the total \textsc{h}\textalpha\ luminosity of a galaxy measures its global star formation history, these H II regions map the amount and location of local star formation, providing a window into the details of the star formation process.

Studying H II regions in galaxies allows one to (1) investigate star formation both globally and locally, (2) examine the upper mass limit of stellar mass function, and (3) map the structure of the interstellar medium (ISM). While the UV and far-IR emission may provide a more nuanced view of the total star formation; the size, location, and luminosity of H II regions display the local variation of star formation directly and can be used to resolve stellar population questions. In addition, the size and luminosity of H II regions provide information on the number of ionizing stars and the mass of the underlying stellar associations.

Previous work on H II regions in galaxies focused on high surface brightness (HSB) spirals and irregular galaxies (e.g., Caldwell et al. 1991; Kennicutt et al. 1989; Youngblood & Hunter 1999). These studies found that the number of H II regions in a galaxy increases with later Hubble type, in correlation with the total star formation rate (SFR), and found various differences in the H II luminosity function as a function of galaxy properties. However, very little work has been completed on the \textsc{h}\textalpha\ emission in LSB galaxies due to the technical difficulty in measuring narrowband fluxes for object so close to the brightness of the night sky. Studies by Schombert et al. (1992), McGaugh et al. (1995), and recent work by Kim (2007) represent the deepest H\alpha\ studies in LSB galaxies.

The results from these previous works can be summarized that LSB galaxies have (1) small regions of the \textsc{h}\textalpha\ emission (assumed to be low in luminosity, although this early data was not flux calibrated), (2) weakly correlated with regions of enhanced surface brightness, and (3) no coherent patterns indicative of density wave scenarios. Small and weak H II regions are consistent with the low SFRs for LSB galaxies as a class of objects, and agreed with the hypothesis that these galaxies are quiescent and inhibited in their star formation histories.

This paper, the second in our series on optical observations of PSS-II LSB galaxies, presents the \textsc{h}\textalpha\ spatial results which map the size, location, and luminosities of H II regions in our sample galaxies. With this information, our goal is to compare the style of star formation in LSB galaxies with spirals and irregulars to detect any global differences in their star formation histories. The characteristics of importance to the star formation history of a galaxy are the number of H II regions, the luminosity of the brightest H II regions, the shape of the H II region luminosity function, and the spatial positions of H II regions with respect to the optical distribution of light. Lastly, we examine the optical colors of the H II regions in the hope of resolving the color dilemma in LSB galaxies, their unusually blue colors, yet low total SFRs.

2. Analysis

Observations, reduction techniques, and the characteristics of the sample are described in Paper I (Schombert et al. 2011). Our final sample contains 58 LSB galaxies selected from the
PSS-II LSB catalog (Schombert et al. 1997) with deep $B$, $V$, and Hα imaging from the KPNO 2.1 m. The Hα emission was detected in 54 of the 58 galaxies. All detected galaxies had at least one distinct H II region, although diffuse emission accounts for approximately 50% of the total Hα emission in most LSB galaxies.

The sample galaxies all have irregular morphology with some suggestions of a bulge and a disk for a handful. They range in size from 0.5 to 10 kpc and central surface brightnesses from 22 to 24 mag arcsec$^{-2}$. Their total luminosities range from $-14$ to $-19$ V mag, which maps into stellar masses from $10^7$ to $10^9 M_\odot$. The gas fractions for the sample are between 0.5 and 0.9, so the amount of H I gas covers a similar range.

Identification of an H II region followed a slightly different prescription from previous studies. In our case, we have identified an Hα knot to be an H II region if (1) is distinct, i.e., not a filament or diffuse region, (2) has rough circular symmetry (where spatial resolution limits this determination), (3) has a clear peak in the Hα emission, and (4) falls off uniformly around the peak. Due to resolution limits, any particular region may include several H II complexes for more distant galaxies in the sample. However, even for the most distant galaxies, 1 arcsec corresponds to 400 pc which is sufficient to resolve the high-luminosity H II regions into smaller components. There was no correlation with the number of H II regions and distance (see Section 4) which would imply that confusion is not a factor in our sample.

Identification was made by visually guiding a threshold algorithm applied to smoothed Hα images. The center of confirmed H II knots was determined and the luminosity of each selected region was determined by a circular aperture. The radius of the aperture is determined to be the point where the flux falls to 25% of the peak emission. This value is used for the size of the H II region, regardless of any indication of non-circularity.

Four examples of our H II region selection process are shown in Figure 1 where the selected H II regions are shown inside red circles. A 5 kpc scale is indicated in each frame. Continuum images (Johnson $V$) can be found at our data Web site (http://abyss.uoregon.edu/~js/lsb), as well as all the information on individual H II regions plus color and surface brightness data on the sample. The four examples in Figure 1 were selected to illustrate several key points about the H II regions in LSB galaxies.

Galaxy D500-3 (upper left) displays two bright regions near the galaxy core and a number of fainter regions surrounding the core. None of the H II regions are evident as higher continuum surface brightness regions from $V$ frames. Even though the brightest two regions are relatively high in Hα luminosity (38.24 and 38.17 log $L_{\text{H}\alpha}$, approximately 20 Orion complexes), their stellar populations have no effect on the optical structure of the nearby region of the galaxy. The 5 kpc bar is indicated in the upper right of the frame, where the larger H II regions are 100–150 pc in size, ranging down to 25 pc for the fainter regions.

Galaxy D572-5 (upper right) exhibits a more luminous set of H II regions from other LSB galaxies, again several bright regions in the core and a few fainter H II regions in the outer regions. There is some indication of diffuse Hα emission in the outer disk, but insufficient to warrant inclusion by our selection algorithm. The brighter H II regions are just visible in the continuum $V$ frames as distinct blue knots.

Galaxy D646-11 (lower left) displays more scattered Hα emission. The selected H II regions are not centrally concentrated. In fact, the brightest region (more of a shell or bubble than a star complex) is located in the outer disk. There are several filaments and diffuse Hα regions in the core that were not selected as H II regions. The brighter H II regions are associated with bluer continuum colors, but this is not always the case for LSB galaxies as a whole (Pildis et al. 1997).

Galaxy F750-V1 (lower right) is a smaller, nearby LSB galaxy. While seven H II regions were selected, most of its Hα emission is diffuse. It is a subjective determination to select any knot in the core region. There is no signature from the H II regions in the continuum images; however, there are enhanced blue stellar colors in the diffuse regions.

Similar criteria to identify Hα knots were used to identify surface brightness knots in the $V$ frames. The mean surface brightness isophotes (based on ellipse fits) are subtracted from the raw image. This subtracted image is threshold searched for optical knots. As with the Hα knots, these regions are marked and measured with circular apertures defined by the 25% width. In the final analysis, 492 H II regions were identified in 54 LSB galaxies and 2 DDO objects (154 and 168). In addition, 271 optical knots were identified in the $V$ frames. Of the 492 H II regions, 207 had no distinct optical counterpart. Of the 271 $V$ knots, only 49 had no detectable Hα emission. The properties of these regions will be discussed in Section 7.

3. H II REGION SIZES AND LUMINOSITIES

In our total LSB sample, 54 (93%) galaxies had more than one identifiable H II region. The four galaxies undetected by our Hα imaging had the four lowest gas fractions (less than 0.4). A histogram of the number of H II regions per galaxy is shown in Figure 2. The typical of H II regions per galaxy is between 3 and 10, which is quite low for late-type galaxies with irregular morphology (Caldwell et al. 1991) but consistent with values from early studies of the Hα emission in LSB galaxies (McGaugh et al. 1995). We note that these mean values are much less than the numbers found by Youngblood & Hunter (1999) for H II regions in dIrrs. That number is usually above 20 H II regions per galaxy; but, this is due in part to our different selection schemes and the intrinsic nature of rich, star-forming dIrrs. We have two galaxies in common, DDO154 and DDO168. Youngblood & Hunter find 74 and 58 H II regions, respectively, whereas we only find 14 and 25 for the same systems. While this might appear that we are incomplete in our H II region selection, the total Hα fluxes are in agreement and the difference in number simply reflects our more stringent selection criteria in defining clear, isolated H II regions, rather than Hα filaments.

The Hα luminosities for all the H II regions in our sample are shown in Figure 3 (note we distinguish the total Hα of a galaxy, $L_{\text{H}\alpha}$, versus the Hα luminosity of an individual H II region, $L_{\text{H}\alpha}$). The H II region luminosities range from $5 \times 10^{36}$ erg s$^{-1}$ for the faintest regions to $10^{39.5}$ for the brightest regions. A single O7V star results in an H II region of log $L_{\text{H}\alpha} = 37.0$ (Werk et al. 2008), although H II regions powered by single B0 stars are found in the LMC with $L_{\text{H}\alpha} = 36.0–36.2$ (Zastrow et al. 2013). Thus, the faintest regions are difficult to explain under the observation that very few O or B stars are born in isolation (Chu & Gruendl 2008) or may be the result of PN ionization (Walterbos & Braun 1992). The brighter regions correspond to a 30 Doradus sized complexes and would contain $10^8 M_\odot$ solar masses of H II gas; however, even these individual regions would not be detected in CO surveys of LSB galaxies (Schombert et al. 1990).

In some ways, the distribution of H II region luminosities in LSB galaxies is similar to the distribution in early-type spirals.
rather than irregulars. In early-type spirals, there are more low-luminosity H\textsc{ii} regions relative to the brightest ones (Kennicutt et al. 1989), with fewer of the massive star-forming regions found in dwarf irregulars. On the other hand, LSB galaxies with H\textsc{ii} regions brighter than log $L_{\text{H\textsc{ii}}}$ $> 38$ do exist, but H\textsc{ii} regions of this size are not found in Sa spirals (Caldwell et al. 1991). Thus, it seems that the H\textsc{ii} regions in LSB galaxies follow more closely the pattern of other galaxies with irregular morphologies; unfortunately, we lack sufficient statistics to construct an H\textsc{ii} luminosity function for individual galaxies in order to rigorously examine this effect.

Flux completeness for our H\textsc{ii} region selection is a greater concern for our sample, for we explore a larger volume of the universe than other samples as the original PSS-II catalog was surface brightness selected with an angular size limit, not luminosity limited. The individual H\textsc{ii} region luminosities are shown in Figure 3 as a function of galaxy distance. As can be seen in this figure, the brightest H\textsc{ii} regions are found in the most distant galaxies (which are also the most massive/brightest galaxies). In addition, the galaxies farther than 40 Mpc are deficient in H\textsc{ii} regions fainter than log $L_{\text{H}\alpha} = 38$. Interestingly, the 40 Mpc limit is the same limited distance found by Kennicutt

Figure 1. H\textalpha\ maps for four galaxies in our sample. The selected H\textsc{ii} regions are indicated using our criteria of distinctiveness and symmetry. The solid blue bar in the upper right of each panel indicates a spatial scale of 5 kpc.

(A color version of this figure is available in the online journal.)
et al. (1989) based on resolution experiments with their Hα imaging study. The lack of fainter H II regions for the more distant galaxies is probably due to a lack of spatial resolution to distinguish an H II complex from diffuse Hα emission. To test this hypothesis, we selected a subset of galaxies between 20 and 30 Mpc and deconvolved their Hα images to simulate their appearance at 80–120 Mpc. As expected, the fainter H II regions (log \( L_{\text{H} \alpha} < 38 \)) dropped below the threshold of detection. However, due to the typical wide spacing of H II regions in LSB galaxies, there was no significant increase in the brightness of the remaining H II regions due to blending. We conclude that our sample will severely undersample low-luminosity H II regions for objects greater than 40 Mpc in distance and, thus, any discussion of an H II region luminosity function must take this bias into account.

Even for the more complete nearby portion of our sample (\( D < 40 \) Mpc), the ratio of \( L_{\text{H} \alpha} / L_{\text{H} \alpha} \) is dramatically different from those found by Youngblood & Hunter. Their distribution (their Figure 10) displays very few galaxies with ratios less than 80\%, such that a majority of the Hα emission comes from distinct star-forming regions, although the determination method differs from our calculations in the sense that they assign H II regions to complexes and then compare the amount of Hα flux from complexes versus their total fluxes. For our sample, a significant amount of the Hα emission in LSB galaxies (typically 50\%) arises from a warm, diffuse component, rather than directly from H II complexes, in agreement with the dwarf galaxies studied by van Zee (2000). The ionizing source of this diffuse component is difficult to determine (Hoopes et al. 2001). Although the ratio of the flux from H II to the total Hα luminosity is strongly dependent on whether one can isolate small, weak H II regions in the diffuse component, objects that our more stringent selection criteria would miss.

Another concern is that the brightest H II regions are found in the most distant galaxies. This may be due to confusion, where the H II regions selected by this study are, in fact, blends of fainter H II regions blurred by distance. While this may be true for some individual cases, the number of H II regions as a function of distance does not show a decreasing trend with distance, a relationship one would expect if a number of fainter H II regions are being mistakenly grouped together as one complex. The more likely trend is that fainter H II regions are simply indistinct and confused with diffuse Hα emission, therefore, not selected by our criteria.

Figure 2. Histogram of the number of H II regions found in each galaxy. The number we find, per galaxy, is typically much lower than other studies due to our more stringent selection criteria, with most LSB galaxies having less than 10 H II regions. However, LSB galaxies still display much lower numbers of H II regions than other star-forming galaxy types, in line with their low total SFRs.

Figure 3. Hα luminosity of individual H II regions (\( L_{\text{H} \alpha} \)) as a function of galaxy distance. Fainter H II regions are missing from the sample of galaxies farther than 40 Mpc due to decreasing spatial/luminosity resolution (an \( L \propto D^2 \) cutoff is shown). The brightest H II regions are found in the more distant galaxies, indicating that 30-Doradus-sized star-forming complexes are rare in LSB galaxies, and a larger volume of the universe must be searched to locate them.

(A color version of this figure is available in the online journal.)

Figure 4 displays the luminosity of the brightest H II region (\( L_{\text{max}} \)) and the baryon mass of a galaxy (stellar mass plus gas mass) as a function of distance. As noted in Paper I, the most massive LSB galaxies in our sample are in the largest distances. The brightness of the brightest H II region also increases with distance, in synchronous with the baryon mass (see Section 6). We conclude that the reason that the brightest H II regions in LSB galaxies are found in the most distant galaxies is due to a volume selection effect. The more distant objects in our sample are the brightest by luminosity (and the largest in baryon mass) and are also galaxies with the highest Hα fluxes in the sample. The low-mass, low Hα luminosity galaxies in the sample would not be found at large distances due to the angular size limit to the PSS-II catalog. There is no reason to believe that Malmquist bias plays a role in our sample, as it was not selected by the total or Hα luminosity. The brighter H II regions in distant galaxies simply reflect the diversity of LSB galaxies, where LSB galaxies with bright 30-Doradus-sized star-forming complexes are rare. However, due to the loss of fainter H II regions with distance in the sample, in our following discussions we will distinguish between the distant sample (\( D > 40 \) Mpc) and the more complete nearby sample.

For the sample as a whole, about 50\% of the imaged galaxies have a resolution between 75 and 200 pc pixel\(^{-1}\), 25\% have a resolution less than 50 pc pixel\(^{-1}\), where the radius of an H II region is estimated by the point where the flux falls to 25\% the peak flux. A plot of \( \dot{H} \) region radius (\( r, \) in pc) versus their Hα luminosity is shown in Figure 5. The slope of the relationship is consistent with \( \log L_{\text{H} \alpha} \propto r^2 \) meaning that we detect all the Hα photons produced in the complexes. Foreground extinction by dust is very small in LSB galaxies compared to spirals, in agreement with the lack of far-IR detection for LSB galaxies and their low mean metallicities (Kuzio de Naray et al. 2004).
Figure 4. Luminosity of the brightest H\textsc{ii} region in a galaxy and baryon mass as a function of distance. The brightest H\textsc{ii} regions and most massive galaxies are also the most distant objects in our sample, i.e., a larger volume of the universe must be sampled to find the largest LSB galaxies.

Figure 5. Size of an H\textsc{ii} region in parsecs vs. the H\textsc{a} luminosity of the same region. A linear fit (blue line) is consistent with a relation of $\log L_{\text{H}a} \propto r^2$ meaning that there is little extinction by dust in LSB galaxy H\textsc{ii} regions. (A color version of this figure is available in the online journal.)

Hence, we make no corrections for internal extinction in any of our quoted flux values.

4. H\textsc{ii} REGION NUMBERS

The number of H\textsc{ii} regions as a function of galaxy mass is shown in Figure 6. There is a similar relation between the number of H\textsc{ii} regions and galaxy mass as found by Youngblood & Hunter (1999; blue line in Figure 6). Again, the distant galaxies in our sample fail to display any relationship due to the undercounting of fainter H\textsc{ii} regions. The nearby sample displays the same slope as Youngblood & Hunter, although our more stringent detection criteria shifts our number counts to lower values.
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Figure 7. H\textsc{ii} region luminosity as a function of distance from the galaxy center in terms of absolute kpc and normalized scale lengths. The artificial relation between kpc and luminosity in the left panel is due to the fact that the largest galaxies have the brightest H\textsc{ii} regions. When galactic distance is normalized by galaxy scale length ($\alpha$), the relationship disappears. Since the H\textsc{i} densities of LSB galaxies are relatively constant (de Blok et al. 1996), this diagram simply reflects the fact that local density drives star formation in LSB galaxies rather than global patterns found in spirals.

The relationship between the number and galaxy mass may simply reflect the statistical effect as more gas material in a larger volume results in more star formation events. As star formation is driven by local density (Helmboldt et al. 2005), then more volume will produce more individual star-forming regions. There is also a trend of brightest H\textsc{ii} region flux with the number of H\textsc{ii} regions; but, again, this reflects that the statistical behavior of larger volume provides a greater chance of a larger star formation event.

The number density of H\textsc{ii} regions per kpc$^{-2}$ has a weak trend of decreasing density with increasing galaxy mass where the typical number density (for the $D < 40$ Mpc sample) is between 0.1 and 1 H\textsc{ii} regions per kpc$^{-2}$ with a mean of 0.3. This is similar to the mean value for Sm/Im type galaxies from Kennicutt et al. (1989). There is no trend of number density with galaxy mass/size; however, the $D < 40$ sample has a limited dynamic range in galaxy size and mass.

5. H\textsc{ii} REGION LOCATIONS

The relationship between the H$\alpha$ luminosity of each H\textsc{ii} region and its distance from the galaxy center is shown in Figure 7. While the absolute distance, in kpc, displays a trend that the brightest H\textsc{ii} regions are found in the outer regions (left panel), this is an artifact of the effect that the largest (brightest) galaxies in the sample have the brightest H\textsc{ii} regions. When the distance from the galaxy core is displayed in terms of the scale length of the galaxy ($\alpha$, from exponential fits to the V frames), the relationship disappears (right panel). The lack of radial correlation in Figure 7 is reinforced by the fact that the location of the brightest H\textsc{ii} regions is also independent of their distance from the galaxy center.

Our interpretation for a lack of correlation between H\textsc{ii} region luminosity and distance from the galaxy center is that this reflects the underlying gas distribution in LSB galaxies. In general, the H\textsc{i} gas density in LSB galaxies is much more extended than the optical image and the density levels are flat out to several optical scale lengths (de Blok et al. 1996). While it is the molecular gas, not neutral hydrogen, that drives star formation (Scoville 2012), the distribution of H$_2$ gas in LSB galaxies is not directly known (Matthews et al. 2005) and H\textsc{i} serves as a necessary proxy. However, since the density of H\textsc{i} gas in LSB galaxies is low (as are their stellar densities) and typically constant with radius (stellar surface brightness profiles are also very shallow exponentials), the lack of a radial trend in decreasing gas density with radius means that star formation will be dominated by local density enhancements rather than global processes. And, as concluded by other studies, it is clear that the spatial distribution of star formation in LSB galaxies differs from the global patterns found in spirals (Bigiel et al. 2008; O’Neil et al. 2007).

Presumably, the SFR will halt when the molecular gas surface density drops below a critical value, but an estimate of where that radius occurs requires more H\textsc{i} information than is available for our sample. However, there are numerous examples of H\textsc{ii} regions at very low surface brightnesses in LSB galaxies (see Figure 10, for an example, where the H$\alpha$ emission is found beyond 5 scale lengths). Over 1/3 of the H\textsc{ii} regions in our sample occur in regions where the surface brightness is below 25 V mag arcsec$^{-1}$ (which corresponds to less than 4 $L_{\odot}$ pc$^{-2}$) and 1/2 the H\textsc{ii} regions have no optical signature (an optical knot or surface brightness enhancement) even at such low surface brightnesses (indicating a very low cluster mass). This is an important observation with respect to LSB galaxies as star
formation has always been assumed to be inhibited in low-density environments, but not non-existent.

Star formation, as traced by Hα, is loosely correlated with optical surface brightness in LSB galaxies, in the sense that for H II regions without detectable optical knots there is the trend that the brightest H II regions are located in regions of the galaxy with higher surface brightness. However, the trend is by no means exact and there exist many examples of strong H II regions in areas of very low stellar density. Gravitational instability models suggest a threshold for star formation where the gas density falls below a critical value (Kennicutt 1998) and star formation efficiency in HSB galaxies generally follows stellar densities more strongly than gas densities (Leroy et al. 2008). But, star formation in the LSB regions of our sample suggests that some other method allows the formation of the cold phase of the ISM without the gravitational pull from stellar mass (see also Thornley et al. 2006) and that gravitational instability from stellar density does not play a dominant role.

H II regions tend to avoid the cores of LSB galaxies, as can be seen in the scale length panel of Figure 7. While the central peak of stellar luminosity in LSB galaxies is ill-defined, due to their irregular morphology, their outer isophotes are usually fairly regular and can be used to define a center of stellar mass. The fact that H II regions tend to be found in regions outside the core may simply reflect the lumpy distribution of stars and gas in LSBs (Pildis et al. 1997) rather than formation effects (i.e., spiral bulges). LSB galaxies rarely have the central concentrations, bulges, or even active galactic nucleus behavior that would indicate present, or past, nuclear star formation that is common in many starburst and spiral galaxies (Schombert 1998).

6. BRIGHTEST H II REGIONS

One area where completeness is not an issue is the characteristics of the brightest H II region in each galaxy. This region represents the largest site of star formation in each galaxy and, presumably, the largest concentration of ionizing O stars. While the H II region luminosity function predicts the number of bright H II regions in a galaxy, there is no particular model or framework for understanding the relationship between the luminosity/mass of the brightest region and global characteristics of a galaxy (Leroy et al. 2008).

There are clear, distinct correlations between the luminosity of the brightest H II region (L_{max}) and the galaxy luminosity (i.e., a proxy for stellar mass), gas mass, and the total Hα luminosity of the galaxy. The first two correlations are shown in Figure 8, where stellar luminosity is converted to stellar mass following the prescription of McGaugh & de Blok (1997) and gas mass is corrected from H I mass for metallicity and molecular contributions. The correlation with the total Hα luminosity is shown in Figure 9.

If the amount of local star formation is determined by a random process of gas collection (e.g., cloud-cloud collisions), then the correlations with galaxy mass would simply reflect the statistical nature of more star formation with larger gas mass and a higher chance of building a large, bright H II complex with more available gas. In that scenario, the correlations should be stronger with gas mass versus stellar mass (as the available gas reservoir is the fuel for star formation, not stellar mass), and the fact that there is no significant difference may signify at strong evolutionary connection between the formation of stellar mass and the available gas supply. At the very least, the current SFR in an LSB galaxy has a strong evolutionary connection with its past as defined by stellar mass buildup, even if a significant fraction of the current star formation is occurring in low stellar density regions (perhaps future HSB regions).

The statistical nature can be understood better in terms of comparing the total SFR of galaxy (as given by the total L_{Hα}) and the luminosity of the brightest H II region (L_{max}). The SFRs of LSB galaxies are low compared to other irregular galaxies...
per luminosity bin, the mean brightest HⅡ region luminosity was determined as a function of $L_{\text{H}\alpha}$. The results from these simulations are shown as the blue lines in Figure 9.

The agreement between the $L_{\text{max}}$ simulation and the data (the top panel in Figure 9) is excellent and demonstrates that, despite previous claims of truncated luminosity functions in LSB galaxies (O’Neil et al. 2007; Helmboldt et al. 2005), the luminosity of the brightest HⅡ regions is consistent with the same pattern of HⅡ regions for dwarf irregulars. The ratio of $L_{\text{max}}$ and the total Hα luminosity is also in agreement with the simulations, where a lack of $L_{\text{max}}/L_{\text{H}\alpha}$ near unity simply reflects the statistical improbability of finding a single HⅡ region that contains all the Hα flux of a galaxy including any diffuse emission.

### 7. OPTICAL COLORS AND HⅡ REGIONS

The identification of HⅡ regions in the Hα images allows us to use the same apertures on the $B$ and $V$ images to extract continuum luminosities and $B - V$ colors. As described in Section 2, we have divided the sample of identified optical and Hα knots into three types: (1) those regions with Hα emission, but no enhanced optical flux above the mean surface brightness of the local isophote value, (2) knots with both Hα and optical emission, and (3) knots only visible in $V$ images without detectable Hα emission. These three regions would, presumably, correspond to a low-luminosity HⅡ region (no visible stars), a young HⅡ region with some blowout and visible stars (Orion-type HⅡ region), and an evolved stellar cluster or association sufficiently old to be free of any remaining hot gas. The regions of the first type (no optical enhancement) are slightly redder than those HⅡ regions with an optical knot, but display no extra reddening compared to the regions surrounding them. They may, in fact, simply represent regions where the luminosity of the underlying star cluster is small compared to the local galaxy light, although this is a problematic interpretation due to the LSB nature of these regions.

An example of Hα versus optical knots is shown in Figure 10. In this figure, the Hα and V frames for F608-1 are plotted at the same scale (150 arcsec to a side). The HⅡ regions are marked in both panels by red circles, as determined from the Hα image. There are several examples of Hα knots with no visible optical emission (the two HⅡ regions farthest to the right and topmost). There are also several examples of an HⅡ region with a distinct optical knot in the V image (e.g., the three brightest Hα regions). The faintest HⅡ regions correspond to log $L_{\text{H}\alpha}$ between 36.2 and 36.5. The brightest three HⅡ regions are log $L_{\text{H}\alpha}$ of 36.8, 36.9, and 37.0, comparable to a cluster of stellar mass between $3 \times 10^3$ and $7 \times 10^3 M_\odot$ ionized by a dozen O stars.

For the 429 regions with the Hα emission, we have plotted their Hα luminosities versus their $B - V$ colors (determined through the same apertures as the Hα fluxes, in Figure 11). No internal extinction corrections have been applied, although gas and dust are probably available in sufficient quantities to alter the colors. And, more importantly, no effort was made to subtract out the underlying galaxy light (see below) which is necessary to compare to regions without any obvious optical emission.

Figure 11 displays a very weak trend for bluer optical colors with increasing Hα luminosity. This trend is as expected with greater Hα flux implying a larger number of ionizing O stars per HⅡ region and, therefore, greater blue flux (see Caldwell et al. 1991). However, the poor relationship only emphasizes the rich color structure that is found in LSB galaxies where star-forming

**Figure 9.** Relationship between the brightest HⅡ region Hα luminosity ($L_{\text{max}}$) and the total galaxy Hα luminosity ($L_{\text{H}\alpha}$) and the fraction of the brightest HⅡ region to the total galaxy flux. The brightest HⅡ regions ($\log L_{\text{max}} > 39$) correspond to a cluster of several hundred O7V stars. Yet, the fractional contribution to the total galaxy Hα luminosity decreases to less than 20% for the brightest galaxies. The blue dashed lines display the result of a Monte Carlo simulation that selects HⅡ regions from the luminosity function defined for dwarf irregulars by Youngblood & Hunter (1999). There is no indication that the HⅡ regions in LSB galaxies display any difference from the HⅡ regions in other irregular galaxies.

(A color version of this figure is available in the online journal.)
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Figure 10. V and Hα images for LSB galaxy F608-1. Each frame is 150 arcsec to a side. There are several examples of Hα knots with no visible optical emission (the two H II regions farthest to the right and toplost). There are also several examples of an H II region with a distinct optical knot in the V image (e.g., the three brightest Hα regions). The faintest H II regions correspond to log \( L_{\text{H}\alpha} \) between 36.2 and 36.5. The brightest three H II regions are log \( L_{\text{H}\alpha} \) of 36.8, 36.9, and 37.0, comparable to a cluster of stellar mass between \( 3 \times 10^3 \) and \( 7 \times 10^3 \) \( M_\odot \) ionized by a dozen O stars.

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Figure 11. Contour density plot of the Hα luminosity vs. H II region B − V color for 349 H II regions. There is a weak trend for bluer optical colors with increasing Hα luminosity, consistent with more blue ionizing stars in the brighter H II regions. These colors are for all H II regions with and without optical emission (star clusters) without subtraction of the underlying galaxy light. Regions with blue optical enhancement will have much bluer B − V colors when the surrounding galaxy is subtracted.

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regions are often associated with blue shells and filaments and color features uncorrelated with star-forming regions (to be studied in a later paper). It is worth noting that the color–Hα trend is not as blue as H II regions in early-type spirals (Caldwell et al. 1991). In that sample, H II regions with log \( L_{\text{H}\alpha} = 38.5 \) have \( B − V \) colors less than zero. Many of the regions with optical emission have much bluer colors (see below) and the colors for low-luminosity H II regions are correlated with the nearby galaxy colors. We anticipate that the underlying colors will be less than \( B − V = 0.0 \) once the galaxy light is subtracted.

A comparative histogram of \( B − V \) colors within the various Hα and V knots is shown in Figure 12. These colors were calculated by subtracting the local galaxy isophote from those H II regions with optical knots, leaving only the luminosity above the underlying galaxy luminosity density. For H II regions without optical knots, the local galaxy color is used. This technique does not bias the calculated color for the optical knots, but it was unsurprising to find that the majority of them have \( B − V \) colors bluer than the local galaxy color as was noted in the two color maps from Paper I.

Here, the reddest colors are found for the Hα knots without any optical signature. It should be noted that these Hα-only knots also typically have the lowest Hα luminosities. In other words, these are regions that are ionized by a single or a very small number of O or B stars. Their mean \( B − V \) color is 0.45, which basically confirms that these regions have little effect on the surface brightness or local color as these values conform to the mean total color of LSB galaxies. The underlying stellar association lacks sufficient luminosity to alter the galaxy’s isophotes and colors, even at these LSB regimes (\( L_\odot \) pc\(^{-2} \) = 1–4).

Regions which display H II emission and an optical enhancement tend to be bluer than sole Hα knots (mean \( B − V = 0.25 \)) and are also brighter in Hα luminosity with values that correspond to between tens to hundreds of O stars per region. This trend of optical detection correlated with the Hα emission was also seen in early-type spirals by Caldwell et al. (1991). The bluest knots agree well with the bluest regions for spirals (\( B − V = −0.2 \)). Lastly, the optical knots without Hα emission span a full range of \( B − V \) colors, although with a mean color slightly redder than the optical knots with Hα emission. The slightly redder colors probably indicates an evolutionary effect, i.e., as a cluster ages and the ionizing stars die off, the H II region dissipates and the cluster ages and reddens (see below).
Figure 12. Normalized absolute V luminosity and color histogram for all 318 knots with B − V colors. H II knots are regions with only Hα emission and no visible optical enhancement above the local isophote. V and H II knots are regions with a distinct knot in both the Hα and V images (typically brighter in Hα than sole Hα knots). V knots have optical emission but no detectable Hα emission.

(A color version of this figure is available in the online journal.)

Figure 13. For H II regions with optical signatures in the V frames, the magnitude of the underlying cluster is plotted vs. the H II region Hα luminosity. The correlation with brighter clusters for increasing Hα luminosity is clear. Dividing the sample by a B − V color of 0.3 displays a trend for the bluer clusters to be brighter in Hα luminosity than red clusters. Single star H II regions from the LMC (Zastrow et al. 2013) are shown as starred symbols. Stellar population models are shown as dotted tracks for cluster masses from 10^3 to 10^6 M⊙. Model ages are indicated in Myr. Typical data errors are shown in the bottom right.

(A color version of this figure is available in the online journal.)

To examine this evolutionary processes in greater detail, we plot in Figure 13 the absolute V magnitude of the knot (presumably a stellar association), the H II region Hα luminosity versus M_{cluster}. The absolute V magnitude of the stellar association or cluster ranges from values of −8 to −14, which would correspond to a range of cluster masses from open clusters to globular sized if age were not a factor. However, assigning a cluster mass in solar masses to the V magnitude is a difficult procedure, for while the L_{Hα} luminosity relates the number of ionizing O stars per region, the total number of stars (as given by the IMF) will be extremely sensitive to the age of the H II region (Leitherer et al. 2010). For example, a 10 Myr 10^4 M⊙ cluster has the same V magnitude as a 100 Myr 1.5 × 10^5 M⊙ cluster and a 500 Myr 10^6 M⊙ cluster (Bruzual & Charlot 2003).

We have divided the sample into red (B − V > 0.3) and blue (B − V < 0.3) clusters. The division of the sample by color is clear, the blue clusters have higher L_{Hα} values than red clusters at constant V cluster luminosity. The inverse interpretation, that red clusters having brighter V magnitudes at a constant Hα value is opposite to what one would expect from spectroevolutionary models where an aging cluster will redden by 0.3 in B − V over 500 Myr, but the luminosity of the underlying cluster will have
decreased by 3 mag. A more plausible scenario is that age is the defining factor in the difference between red and blue clusters in Figure 13. The blue clusters are younger and have more ionizing stars per unit cluster mass producing higher Hα luminosities. Over 100 Myr, the number of ionizing stars decreases by a factor of three (Werk et al. 2008) while the $B-V$ color has reddened by 0.2. This is consistent with the trend seen in Figure 13.

In order to test this hypothesis, we have constructed a series of stellar population models taking the population colors and luminosities from Bruzual & Charlot (2003) for low-metallicity ([Fe/H] = −0.4) tracks. Starting with a given stellar mass, we apply the IMF from Kroupa et al. (2013) to determine the number of stars with ionizing photons. We then apply the ionization Q curves from Martins et al. (2005) to determine the Hα luminosity of the cluster as a function of age. Each zero-age model is then aged using a standard stellar lifetime as a function of mass, the Q values are recalculated, and new cluster luminosities are determined. The resulting tracks are shown in Figure 13.

As can be seen in Figure 13, the star-forming regions in LSB galaxies range in stellar mass from globular cluster sized ($10^6 M_\odot$), such as 30 Doradus, to small associations ($10^3 M_\odot$), such as the California nebula and the Taurus cloud in our own Galaxy. In addition, H II regions vary in age from 2 to 15 Myr, although a majority of the detected H II regions has ages between 10 and 15 Myr. We note that the position of the model tracks with respect to Hα luminosity is extremely sensitive to the shape of the upper end of the IMF. However, the top edge of our sample agrees well with the zero-age line from our models, indicating that the upper end of the Kroupa IMF appears to closely represent the IMF in LSB galaxies.

Low-luminosity H II regions, lacking any optical signature, would presumably fall to the bottom left of this diagram. For comparison, we have plotted the data from Zastrow et al. (2013) for single O or B clusters in the LMC (black symbols in Figure 13). Also shown are single star ionization curves for single star mass of 10–50 $M_\odot$. H II regions with log $L_{H\alpha}$ less than 36.5 would fall in this region, and have visual luminosities and mean surface brightnesses below detection levels (a $10^3 M_\odot$ cluster within a 100 pc pixel would only increase the surface brightness of that pixel by 1%).

8. CONCLUSIONS

LSB galaxies typically have low total SFRs and, thus, fewer H II regions to study compared to spirals and irregulars. We have attempted to overcome this deficiency by observing a larger sample over a greater volume of the local universe. Our sample of 54 LSB galaxies produced 429 H II regions for study, most having sufficient S/N in their optical images to compare broadband luminosities and colors. Four galaxies in our sample were undetected in Hα and have the lowest gas mass fraction of the sample, suggesting that their lower gas supply is responsible for their lack of star formation.

We summarize our results as follows.

1. LSB galaxies typically have fewer H II regions per galaxy than other irregular galaxies; however, LSB galaxies have a full range of H II region sizes from complexes that encompass regions powered by a single O or B star (log $L_{H\alpha} < 36.5$) to 30-Doradus-sized complexes with log $L_{H\alpha} > 40$. The correlation between the H II region luminosity and size is well defined with a slope of two, indicating that we are observing all of the photons from the ionized gas.

2. LSB galaxies have a wide range in the fraction of H II region’s contribution to the total $L_{H\alpha}$ luminosity from 10% to 90%. The fraction has no correlation with galaxy baryon mass.

3. There is no correlation between the H II region luminosity and spatial position in a galaxy. The brightest H II regions do not preferentially appear at any particular radius as normalized by the disk scale length.

4. Roughly 1/2 of the H II regions have a distinct optical enhancement above the surrounding isophote. This is interpreted to be stellar mass produced by the star formation event (which is confirmed by their bluer colors compared to surrounding galaxy color). H II regions without enhancement are still, loosely, associated with local stellar density (i.e., surface brightness) in proportion to their $L_{H\alpha}$. However, there are numerous examples of bright H II regions in faint galaxy regions.

5. The luminosity of the brightest H II region in each galaxy is correlated with the galaxy’s stellar mass, gas mass, and total SFR. Monte Carlo simulations confirm that these correlations are replicated by an underlying H II region luminosity function that matches for star-forming irregulars. In other words, there is no evidence that the distribution of H II region luminosities in LSB galaxies differs from that of star-forming HSB galaxies, and the underlying star formation mechanisms appear to be the same.

6. As observed in spiral galaxies, there is a weak correlation between the color of an H II region and its Hα luminosity. And, while regions with the Hα emission are bluer with increasing Hα luminosity, there are blue regions in an LSB galaxy without the Hα emission.

7. Comparison with stellar population models indicates that the H II regions in LSB galaxies range in mass from a few $10^3 M_\odot$ to globular cluster sized systems. Their ages are consistent with clusters from 2 to 15 Myr old. The faintest H II regions are also similar to single O or B star associations seen in the LMC. Thus, star formation in LSB galaxies covers the full range of stellar cluster mass and age.

The hope in studying LSB galaxies was to reveal, perhaps, a new realm of star formation processes or conditions. While the class of LSB galaxies differs from HSB galaxies in terms of their bluer colors, lower stellar densities, and higher gas fractions; however, there is nothing particularly unusual about the individual sites of star formation under more detailed examination. The local process of star formation, cluster size and mass, IMF and gas physics, all are consistent with the style of star formation found in H II regions in spirals and irregulars. With respect to their global properties, the H II regions in LSB galaxies are more similar to other irregular galaxies, again reflecting the sporadic distribution of gas over coherent kinematic processes (i.e., spiral patterns).

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