H II REGION LUMINOSITY FUNCTION OF THE INTERACTING GALAXY M51

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ABSTRACT

We present a study of H II regions in M51 using the Hubble Space Telescope Advanced Camera for Surveys images taken as part of the Hubble Heritage Program. We have cataloged about 19,600 H II regions in M51 with Hα luminosity in the range of $L = 10^{38.5} - 10^{39.8}$ erg s$^{-1}$. The Hα luminosity function of H II regions (H II LF) in M51 is well represented by a double power law with its index $\alpha = -2.25 \pm 0.02$ for the bright part and $\alpha = -1.42 \pm 0.01$ for the faint part, separated at a break point $L = 10^{37.1}$ erg s$^{-1}$. This break was not found in previous studies of M51 H II regions. Comparison with simulated H II LFs suggests that this break is caused by the transition of H II region ionizing sources, from low-mass clusters (with $\sim 10^2 M_\odot$, including several OB stars) to more massive clusters (including several tens of OB stars). The H II LFs with $L < 10^{37.1}$ erg s$^{-1}$ are found to have different slopes for different parts in M51: the H II LF for the interarm region is steeper than those for the arm and the nuclear regions. This observed difference in H II LFs can be explained by evolutionary effects: H II regions in the interarm region are relatively older than those in the other parts of M51.

Key words: galaxies: individual (M51, NGC 5194, NGC 5195) – galaxies: ISM – galaxies: spiral – H II regions

Online-only material: individual (M51, NGC 5194, NGC 5195) – galaxies: ISM – galaxies: spiral – H II regions

1. INTRODUCTION

H II regions are an excellent tracer of recent star formation since the radiation from H II regions carries a signature of young OB stars. The total flux of the hydrogen recombination line (e.g., Hα) coming from an H II region is proportional to the total Lyman continuum emission rate of the ionizing stars, if we assume that all ionizing photons are locally absorbed. Thus, the Hα luminosity of the H II region ($L$) is an indicator of the Lyman continuum emission from ionizing sources.

In general, H II regions are classified into three groups, depending on their observed Hα luminosity and size (Hodge 1969, 1974; Kennicutt et al. 1989; Hodge et al. 1989a; Franco et al. 2004). (1) Classical H II regions with Hα luminosity fainter than $L \approx 10^{37}$ erg s$^{-1}$; with their sizes up to several parsecs, these H II regions are typical H II regions ionized by several OB stars. A representative example of this class is M42, the Orion Nebula. (2) Giant H II regions with Hα luminosity of about $L = 10^{37} - 10^{39}$ erg s$^{-1}$: these H II regions are ionized by a few OB associations or massive star clusters and usually smaller than 100 pc. Typical examples of this class in our Galaxy are W49, NGC 3603, and the Carina Nebula. (3) Super giant H II regions with Hα luminosity brighter than $L \approx 10^{39}$ erg s$^{-1}$; these may be ionized by multiple star clusters or super star clusters (Weidner et al. 2010). These H II regions have no known analog in the Galaxy, and they are mostly found in late-type galaxies or interacting systems. Two examples of this kind are 30 Doradus in the Large Magellanic Cloud (LMC) and NGC 604 in M33.

The Hα luminosity function of H II regions (H II LF) in a galaxy provides a very useful information on the formation and early evolution of stars and star clusters, and has been a target of numerous studies (Kennicutt & Hodge 1980; Kennicutt et al. 1989; Rozas et al. 1996; Hodge et al. 1999; Youngblood & Hunter 1999; Thilker et al. 2002; Bradley et al. 2006). It is usually represented by a power law of the following form:

$$N(L) dL = A L^\alpha dL,$$

where $N(L) dL$ is the number of H II regions with Hα luminosity between $L$ and $L + dL$, $\alpha$ is a power-law index, and $A$ is a constant. Kennicutt et al. (1989) found that the Hα luminosity functions of bright H II regions in 30 nearby spiral and irregular galaxies are represented approximately by a power law with $\alpha = -2.0 \pm 0.5$. For some galaxies, H II LFs are known to have a break at $L \approx 10^{38.9}$ erg s$^{-1}$, being steeper in the bright part than in the faint part (Kennicutt et al. 1989; Rand 1992; Rozas et al. 1996; Knapen 1998). The H II LFs with this break are called “Type II” and this break is called Strömgren luminosity (Kennicutt et al. 1989; Bradley et al. 2006). The H II LF slope also depends on the regions in a spiral galaxy: the H II LF for the interarm region is steeper than it is for the arm region (Kennicutt et al. 1989; Rand 1992; Thilker et al. 2000; Scoville et al. 2001).

Several scenarios have been suggested to explain the cause of the H II LF slope change at $L \approx 10^{38.9}$ erg s$^{-1}$, different molecular gas cloud mass spectra (Rand 1992), the evolution of H II regions and the variation in the number of ionizing stars (von Hippel & Bothun 1990; McKee & Williams 1997; Oey & Clarke 1998), the transition from ionization-bounded to density-bound H II regions (Beckman et al. 2000), and the blending of small H II regions caused by low-resolution observations (Pleuss et al. 2000). All of these scenarios, except for one involving the observational effect, basically suggest that the H II LF shape should depend on the physical conditions of the corresponding regions in a galaxy.

Most studies on the H II LFs are based on ground-based images, missing a significant fraction of faint H II regions (Kennicutt & Hodge 1980; Kennicutt et al. 1989; Beckman et al. 2000; Thilker et al. 2002; Bradley et al. 2006; Helmboldt et al. 2009) except for a small number of the galaxies in the Local Group (Kennicutt & Hodge 1986; Hodge et al. 1989a, 1989b, 1990; Hodge & Lee 1990). Therefore, the nature of the faint H II regions in galaxies is not well known. There are a few studies based on Hubble Space Telescope (HST) images, but they covered only a small fraction of the target galaxies (Pleuss et al. 2000; Scoville et al. 2001; Buckalew & Kobulnicky 2006). We started a project to study the H II regions in M51, using the...
M51 is a system of interacting galaxies, including a grand-design spiral galaxy NGC 5194 (Sbc) and a barred lenticular galaxy NGC 5195 (SB0), located in a relatively close distance (9.9 Mpc; Tikhonov et al. 2009). Its almost face-on orientation ($i = 20^\circ$; Tully 1974) enables us to observe its structure in detail with minimal obscuration by interstellar dust. Spiral structures in M51 have been used as a strong constraint to model the origin of spiral arms and the effect of galaxy interaction (Dobbs et al. 2010, and reference therein). M51 is abundant in interstellar regions outlining the spiral arms of M51 (Carranza et al. 1969; van der Hulst et al. 1988; Kennicutt et al. 1989; Rand 1992; Petit et al. 1996; Thilker et al. 2000; Scoville et al. 2001).

However, most of the existing studies on M51 H ii regions are based on the ground-based observations. In a study of 616 H ii regions with $L > 10^{36.4}$ erg s$^{-1}$ in M51, Rand (1992) reported that the H ii LF has an inverse slope in the $L < 10^{37.6}$ erg s$^{-1}$ and that the H ii LF slope changes at $L \approx 10^{39}$ erg s$^{-1}$. He also found that the H ii LF slope for the interarm region ($\alpha = -2.05 \pm 0.15$) is steeper than that for the arm region ($\alpha = -1.48 \pm 0.07$). Petit et al. (1996) estimated the H$\alpha$ luminosities and sizes of 478 H ii regions in M51 using the H$\alpha$ photograph taken with the Special Astronomical Observatory 6 m telescope, and the H$\alpha$ luminosity ranges from $L = 10^{36.4}$ to $10^{39.6}$ erg s$^{-1}$. They reported a nearly flat slope below $10^{37.6}$ erg s$^{-1}$, in contrast to the result of Rand (1992), and the H ii region size distribution is well fitted by an exponential function.

Later, Thilker et al. (2000) found about 1200 H ii regions from H$\alpha$ image data covering a central 6.7$\times$6.7 field of NGC 5194 using HIIPHOT that was developed for the detection and photometry of H ii regions. They showed that there is a change in the slope of the H ii LF at $L = 10^{38.8}$ erg s$^{-1}$, consistent with the result of Rand (1992). On the other hand, Scoville et al. (2001) detected about 1400 H ii regions using the HST Wide Field Camera 2 (WFC2) observation covering the central 4.5$\times$4.5 field of NGC 5194. The H ii LF turns out to be steeper for the interarm region ($\alpha = -1.95 \pm 0.05$) than for the arm region ($\alpha = -1.72 \pm 0.03$). However, they could not find any change in the H ii LF slope at $L = 10^{38.8}$ erg s$^{-1}$, in contrast to Rand (1992) and Thilker et al. (2000).

These previous studies on the H ii regions in M51 have some limitations. The ground-based images used by Rand (1992), Petit et al. (1996), and Thilker et al. (2000) cannot resolve blended H ii regions into small or faint H ii regions due to its low spatial resolution of about 1.8 or 100 pc at the distance of M51. Also, it is difficult to distinguish blended low-luminosity H ii regions from diffuse ionized gas. On the other hand, Scoville et al. (2001) used HST image data with 0.0′-0.2′ resolution ($\approx$4.8-9.6 pc at the distance of M51), which enabled them to resolve blended H ii regions and to distinguish faint H ii regions from diffuse ionized gas. However, their data cover only the central part of NGC 5194.

Recently, M51 was observed with the HST ACS in H$\alpha$ band as well as other continuum filters as part of the Hubble Heritage Program, and the data were released to the astronomy community (Mutchler et al. 2005). These deep and wide field H$\alpha$ imaging data provide an excellent opportunity to study the global properties of H ii regions in M51. In this study, we present a result of H ii region survey over the field covering most of NGC 5194 and NGC 5195 regions using these data. We generate a catalog of resolved H ii regions, derive the H ii LF, and investigate the properties of H ii LF in different parts of M51.

During this study, Gutierrez & Beckman (2010) presented a study of over 2000 H ii regions detected in the same HST ACS image data and reported the dependence of the mean luminosity weighted electron density of the H ii regions on both H ii region size and galactocentric radius. Gutierrez et al. (2011) presented a catalog of the 2659 H ii regions in M51 and showed their H$\alpha$ luminosity function and size distribution.

This paper is composed as follows. Section 2 describes the data, and Section 3 introduces the H ii region detection and photometry procedures. Section 4 presents a catalog of M51 H ii regions. We analyze the properties of the H ii regions, including H ii LF and size distribution in Section 5, and discuss the primary results in Section 6. Finally, a summary and conclusion is given in Section 7.

2. DATA

M51 was observed with the HST ACS in 2005 January through the Hubble Heritage Program (Mutchler et al. 2005). The data set is composed of images in four filters $F_{435W}$ (B), $F_{555W}$ (V), $F_{814W}$ (I), and $F_{658N}$ (H$\alpha$) with the accumulated exposure times of 2720, 1360, 1360, and 2720 s, respectively. All the necessary data reduction processes were conducted by the Hubble Heritage Team, including the multi-drizzling for image combination before the public release of the data. One pixel of HST ACS mosaic data corresponds to 0.05′ after the multi-drizzling process. The FWHM of a point source is about 0.1. The size of the field of view is 7′2$\times$10′2. The spatial coverage is large enough to include the entire disk of NGC 5194 as well as its companion NGC 5195. Throughout this study, we adopt a distance to M51 of 9.9 Mpc derived using the tip of the red giant branch method (Tikhonov et al. 2009). At this distance, 1 arcsec corresponds to a linear scale of 48 pc.

3. H II REGION DETECTION AND PHOTOMETRY

Detection and photometry of H ii regions involve the following steps: (1) continuum subtraction from the H$\alpha$ images, (2) source detection and flux measurement on the continuum-subtracted images, and (3) correction for the [N ii] line contamination and the extinction to derive net H$\alpha$ fluxes of the H ii regions.

The effective bandwidth of the $F_{658N}$ filter is 74.8 Å, so that the images obtained with this filter include not only the H$\alpha$ line emission but also the [N ii] 6548 Å, 6583 Å line emission and the continuum emission. We need to subtract the continuum from the $F_{658N}$ images to find the H$\alpha$ line emitting objects and to measure their H$\alpha$ emission line fluxes. We used the average of $F_{555W}$ and $F_{814W}$ images to make a continuum image. We measured the flux of 22 non-saturated foreground stars in the $F_{658N}$ image and the combined continuum image and derived a scaling factor of 0.0878 from the average ratio of these intensities. Then, the combined continuum image was multiplied by the derived scaling factor and was subtracted from the $F_{658N}$ filter image to make a continuum-free H$\alpha$ image. Figure 1 displays the continuum-subtracted H$\alpha$ image of M51, showing bright, discrete H ii regions outlining the spiral arms of NGC 5194.
NGC 5194, and the significant amount of diffuse Hα emission in the region of NGC 5194.

We detected the H II regions and determined their fluxes and sizes in the continuum-subtracted image using HIIPHOT that was developed for the detection and photometry of H II regions by Thilker et al. (2000). HIIPHOT determines the boundaries of individual H II regions using the parameter that dictates the terminating gradient of the surface brightness profile. We adopted a value for the terminal surface brightness gradient, 10 EM pc$^{-1}$ where EM is Hα emission measure in the units of pc cm$^{-6}$. One EM corresponds to a surface brightness of $2 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$. The local background level for each H II region is obtained using a surface fit to pixels located within an annulus with 4′′ width outside the boundary. We used signal-to-noise ratio (S/N) $\geq 12$ as a detection limit. With this condition we found 19,598 H II regions. We calibrated the instrumental Hα fluxes ($F$(Hα)) of the H II regions using the photometric zero point (PHOTFLAM) given in the header of F658N image, $1.999 \times 10^{-18}$ erg cm$^{-2}$ Å$^{-1}$. Then we derived their Hα luminosity using $L = 4\pi d^2 \times F$(Hα) where $d$ is a distance to M51, 9.9 Mpc.

We applied two corrections before obtaining the final photometry: [N II] contamination and the Galactic foreground extinction. First, the Hα flux in the continuum-subtracted image includes contributions from the two satellite [N II] lines. At zero redshift, the [N II] lines are located on either side of the 6563 Å Hα line, one at 6548 Å and the other at 6583 Å. To measure the net Hα flux, we consider the redshift $(\approx 0.002475$ of M51, transmission values of the HST ACS F658N filter, and mean [N II]/Hα ratio $(\approx 0.5$ obtained from spectroscopic data for 10 H II regions in M51 by Bresolin et al. (2004). We used Hα/[Hα + [N II]] $\approx 0.67$ to derive the net Hα flux. Second, we applied the foreground reddening correction to the Hα flux using the values in Schlegel et al. (1998); $E(B - V) = 0.035$. For the corresponding extinction ($A_V = 0.115$ mag, $A_{H\alpha} = 0.092$ mag), the measured Hα flux is increased by a factor of 1.09. Internal extinctions for individual H II regions are not known. We adopted the mean extinction value $A_V \approx 3.1$ mag derived from Hα/Paα flux ratio for 209 H II regions in the central region of M51 by Scoville et al. (2001). This value corresponds to a change in Hα luminosity by a factor of $\approx 10$.

There are some sets of Hα photometry data for the M51 H II regions available in the literature: Rand (1992), Petit et al. (1996), Thilker et al. (2000), Scoville et al. (2001), and Gutierrez et al. (2011). Since the studies by Rand (1992), Petit et al. (1996), and Thilker et al. (2000) are based on the ground-based images, it is difficult to directly compare our photometric measurements with theirs. Therefore, we compared our result of H II region photometry with those of Scoville et al. (2001) and Gutierrez et al. (2011). We selected 54 isolated, compact, and bright H II regions common between this study and Scoville et al. (2001) by visual inspection, displaying the comparison of the measured fluxes in Figure 2(a). Figure 2(a) shows that our photometry is in good agreement with that of Scoville et al. (2001). The mean difference ($\log L$ [this study] $- \log L$ [Scoville et al. (2001)]) is 0.03 $\pm$ 0.12. For Figure 2(b), we selected 164 isolated, compact, and bright H II regions common between this study and Gutierrez et al. (2011) by visual inspection. Figure 2(b) shows that our photometry is also in excellent agreement with...
that of Gutierrez et al. (2011). The mean difference (log \( L \) [this study] – log \( L \) [Gutierrez et al. (2011)]) is 0.01 ± 0.07.

4. \( \text{H} \alpha \) REGION CATALOG

Measured properties of \( \text{H} \alpha \) regions in a galaxy are dependent on both the resolution of images and the procedures used to define the boundaries of \( \text{H} \alpha \) regions. For example, higher resolution images can resolve some large \( \text{H} \alpha \) regions into multiple components, reducing the number of the detected large \( \text{H} \alpha \) regions. In addition, the criteria adopted to separate the \( \text{H} \alpha \) regions from the background are critical. In this study, we present two \( \text{H} \alpha \) region catalogs: for the original and group samples. The original sample includes \( \text{H} \alpha \) regions detected and provided from HIIPHOT, and the group sample includes \( \text{H} \alpha \) regions produced by combining smaller ones in close proximity into one large one.

The original sample catalog includes about 19,600 \( \text{H} \alpha \) regions, containing resolved sources in blended \( \text{H} \alpha \) regions as well as isolated \( \text{H} \alpha \) regions. This catalog is useful for the study of the relation between classical \( \text{H} \alpha \) regions and star clusters since most \( \text{H} \alpha \) regions in the original sample are classified as classical \( \text{H} \alpha \) regions, and only 10% of them are giant \( \text{H} \alpha \) regions. There are no super giant \( \text{H} \alpha \) regions in the original sample. In Table 1, we list positions, \( \text{H} \alpha \) luminosities, and effective diameters (derived from \( D = 2 \times (\text{area}/\pi)^{1/2} \)) where the area is derived from the number of pixels contained in an \( \text{H} \alpha \) region.

To prepare the group sample, we found associations of \( \text{H} \alpha \) regions in the original sample using the friends-of-friends algorithm (FOF; Davis et al. 1985). Every source in a group has a friend source within a distance smaller than some specified linking length. If we increase the linking length, the number of members in individual groups increases, decreasing the number of groups. As a test, we made 20 group sample sets using the linking length ranging from 0.1 to 2.0 mean separation length with a step of 0.1. Through this test, we found that the linking length of 1.0 mean separation is the most suitable in reproducing large \( \text{H} \alpha \) regions found in ground-based images.

We refer to these associations of \( \text{H} \alpha \) regions as grouped \( \text{H} \alpha \) regions. The total number of the grouped \( \text{H} \alpha \) regions is 2294. We inspected these grouped \( \text{H} \alpha \) regions in the continuum-subtracted \( \text{H} \alpha \) image and revised the membership of 209 \( \text{H} \alpha \) regions. The final number of grouped \( \text{H} \alpha \) regions is 2296, and the number of the isolated \( \text{H} \alpha \) regions which do not belong to any group is 4919. Thus, the sum of these two kinds of \( \text{H} \alpha \) regions is 7215. The position of a grouped \( \text{H} \alpha \) region is derived from average values of the positions of all individual \( \text{H} \alpha \) regions in a group. The area and luminosity of a grouped \( \text{H} \alpha \) region are derived from summing the values of all individual \( \text{H} \alpha \) regions in a group. Among the 2296 grouped \( \text{H} \alpha \) regions, 80 \( \text{H} \alpha \) regions with \( L > 1.0 \times 10^{37} \) erg s\(^{-1}\), and 18 of them are super giant \( \text{H} \alpha \) regions.

5. RESULTS

5.1. \( \text{H} \alpha \) Luminosity Function of \( \text{H} \alpha \) Regions

The total number of M51 \( \text{H} \alpha \) regions listed in the original sample is about 19,600. The \( \text{H} \alpha \) luminosity of these \( \text{H} \alpha \) regions ranges from \( L = 10^{35.5} \) erg s\(^{-1}\) to \( 10^{39.0} \) erg s\(^{-1}\). The

| ID  | R.A.(J2000.0)a | Decl.(J2000.0)a | \( F(\text{H} \alpha)b \) | log \( L(\text{H} \alpha)c \) (\( \text{erg s}^{-1} \)) | \( D^a \) (\( \prime \)) | \( D \) (pc) | Pos.\(d \) | GID\(e \) |
|-----|---------------|---------------|----------------|-------------------|----------------|--------|--------|--------|
| 3   | 202.3956299   | 47.171803     | 4.402          | 36.573            | 0.53           | 25.26  | 1      |        |
| 4   | 202.3961639   | 47.169731     | 7.095          | 36.780            | 0.44           | 21.32  | 1      |        |
| 6   | 202.3963776   | 47.169849     | 1.259          | 36.029            | 0.34           | 16.47  | 1      |        |
| 7   | 202.3977661   | 47.172359     | 8.074          | 36.836            | 0.57           | 27.22  | 1      |        |
| 8   | 202.3983917   | 47.172512     | 1.597          | 36.133            | 0.38           | 18.37  | A      |        |
| 9   | 202.3992462   | 47.177734     | 1.669          | 36.152            | 0.38           | 18.37  | A      | 10     |
| 10  | 202.3993530   | 47.177658     | 1.290          | 36.040            | 0.28           | 13.27  | A      | 10     |
| 11  | 202.3993835   | 47.177444     | 13.960         | 37.074            | 0.79           | 38.11  | A      | 10     |
| 13  | 202.4014740   | 47.182098     | 13.420         | 37.057            | 0.58           | 27.75  | A      |        |
| 20  | 202.4026184   | 47.160851     | 4.296          | 36.562            | 0.68           | 32.83  | A      |        |

Notes.

\(a\) Measured in the F658N (\( \text{H} \alpha \)) image.

\(b\) In the unit of \( (10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1}) \).

\(c\) Calculated using \( L = 4\pi d^2 \times F(\text{H} \alpha) \) for \( d = 9.9 \text{ Mpc} \).

\(d\) Calculated using \( D = 2 \times (\text{area}/\pi)^{1/2} \) where the area is derived from the number of pixels contained in an \( \text{H} \alpha \) region.

\(e\) Position in the galaxy: A—arm region, I—interarm region, N—nuclear region, and C—NGC 5195.

| Position ID number for the group sample. | (This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Luminosity Function of \( \text{H} \alpha \) Regions

The total number of M51 \( \text{H} \alpha \) regions listed in the original sample is about 19,600. The \( \text{H} \alpha \) luminosity of these \( \text{H} \alpha \) regions ranges from \( L = 10^{35.5} \) erg s\(^{-1}\) to \( 10^{39.0} \) erg s\(^{-1}\). This
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Table 2
A Catalog of M51 H\(\text{\textsc{ii}}\) Regions in the Group Sample

| ID  | R.A.(J2000.0)* | Decl.(J2000.0)* | \(F(H\alpha)\) | \(\log L(H\alpha)\) | D\(\text{\textdegree}\) | D (pc) | Pos. |
|-----|----------------|----------------|--------------|------------------|----------------|--------|------|
| 3   | 202.3956299    | 47.171803      | 4.402        | 36.573           | 0.53           | 25.26  | I    |
| 4   | 202.3961639    | 47.167931      | 7.095        | 36.780           | 0.44           | 21.32  | I    |
| 5   | 202.3963776    | 47.169849      | 1.259        | 36.029           | 0.34           | 16.47  | I    |
| 6   | 202.3977661    | 47.172359      | 8.074        | 36.836           | 0.57           | 27.22  | I    |
| 7   | 202.3983917    | 47.172512      | 1.597        | 36.133           | 0.38           | 18.37  | A    |
| 8   | 202.3993530    | 47.177654      | 17.928       | 37.183           | 0.96           | 45.96  | A    |
| 9   | 202.4014740    | 47.182098      | 13.420       | 38.057           | 0.58           | 27.75  | A    |
| 10  | 202.4025269    | 47.178154      | 36.097       | 37.057           | 0.34           | 16.25  | A    |
| 11  | 202.4025269    | 47.178005      | 1.471        | 36.192           | 0.34           | 16.25  | A    |
| 12  | 202.4026184    | 47.160851      | 4.296        | 36.562           | 0.68           | 32.83  | A    |

Notes.

* Measured in the F658N(H\(\alpha\)) image. Mean R.A.(J2000) and decl.(J2000) of all individual H\(\text{\textsc{ii}}\) regions in a group.

* In the unit of \((10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1})\). Derived from summing the H\(\alpha\) fluxes of all individual H\(\text{\textsc{ii}}\) regions in a group.

* Calculated using \(L = 4\pi d^2 F(H\alpha)\) for \(d = 9.9 \text{ Mpc}\).

* Calculated using \(D = 2 \times (\text{area/\pi})^{1/2}\) where the area is derived from summing the numbers of pixels contained in all individual H\(\text{\textsc{ii}}\) regions in a group.

* Position in the galaxy: A—arm region, I—interarm region, N—nuclear region, and C—NGC 5195.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Figure 3. H\(\text{\textsc{ii}}\) LF for the original sample (histogram). Thick dashed and thick solid lines represent a double power-law fit for the faint part \((L < 10^{37.1} \text{ erg s}^{-1})\) and the bright part \((L > 10^{37.2} \text{ erg s}^{-1})\), respectively. The power-law indices are \(\alpha = -2.25 \pm 0.02\) for the bright part and \(\alpha = -1.42 \pm 0.01\) for the faint part. An arrow marks the break point.

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

detection limit is similar to the deep survey of H\(\text{\textsc{ii}}\) regions in the dwarf galaxies of the Local Group (Kennicutt & Hodge 1980; Hodge et al. 1989a, 1989b; Hodge & Lee 1990). The total H\(\alpha\) luminosity of all these H\(\text{\textsc{ii}}\) regions is derived to be \(L = 10^{41.2} \text{ erg s}^{-1}\). There are 3653 H\(\text{\textsc{ii}}\) regions with \(L > 10^{37} \text{ erg s}^{-1}\), and their total luminosity corresponds to 70\% of the total H\(\alpha\) luminosity of M51. There are only 160 H\(\text{\textsc{ii}}\) regions with \(L > 10^{38} \text{ erg s}^{-1}\).

We derived the H\(\text{\textsc{ii}}\) LF for the original sample, as shown in Figure 3. The lower limit of H\(\text{\textsc{ii}}\) luminosities is determined by the observational threshold on the surface brightness. The H\(\text{\textsc{ii}}\) LF shows a maximum at \(L \approx 10^{36.1} \text{ erg s}^{-1}\) and declines rapidly as the luminosity decreases. This value is similar to the one for M33 H\(\text{\textsc{ii}}\) regions, \(L \approx 10^{35.9} \text{ erg s}^{-1}\), found from the completeness-corrected H\(\text{\textsc{ii}}\) LF by Wyder et al. (1997), and those for NGC 6822 and the Magellanic Clouds, \(L \approx 10^{36} \text{ erg s}^{-1}\) (Hodge et al. 1989a; Wilcots et al. 1991). Correcting this value for the adopted mean extinction value for M51 H\(\text{\textsc{ii}}\) regions leads to \(10^{37.1} \text{ erg s}^{-1}\). This value is similar to that for M42, \(10^{36.9} \text{ erg s}^{-1}\) (Scoville et al. 2001). Considering that the H\(\text{\textsc{ii}}\) LF for M33 shows a flattening for \(L = 10^{35}–10^{36} \text{ erg s}^{-1}\) (Hodge et al. 1999), the rapid decline for \(L < 10^{36} \text{ erg s}^{-1}\) in our H\(\text{\textsc{ii}}\) LF appears to be due to incompleteness in our catalog.

The H\(\text{\textsc{ii}}\) LF appears to be fitted by a double power law with a break at \(L \approx 10^{37.1} \text{ erg s}^{-1}\). We used a double power-law function to fit the H\(\text{\textsc{ii}}\) LF:

\[
N(L) dL = A L^{\alpha_1} dL \quad \alpha_1 : \text{Bright power-law index for } L \geq L_b,
\]

and

\[
N(L) dL = A' L^{\alpha_2} dL \quad \alpha_2 : \text{Faint power-law index for } L < L_b,
\]

where \(L_b\) is the break point luminosity, and \(A' = A L^{(\alpha_2 - \alpha_1)}\). For the bright H\(\text{\textsc{ii}}\) regions \((10^{37.1} \text{ erg s}^{-1} < L < 10^{38.8} \text{ erg s}^{-1})\), we obtained a power-law index, \(\alpha = -2.25 \pm 0.02\). For the faint part \((10^{36.1} \text{ erg s}^{-1} < L < 10^{37.1} \text{ erg s}^{-1})\), the H\(\text{\textsc{ii}}\) LF becomes flatter than for the bright part, having \(\alpha = -1.42 \pm 0.01\).

A distinguishable point with this H\(\text{\textsc{ii}}\) LF is a break at \(L = 10^{37.1} \text{ erg s}^{-1}\). This break has not been observed in previous studies of the H\(\text{\textsc{ii}}\) regions in M51, because the data used in previous studies were not deep enough to detect it (Rand 1992; Petit et al. 1996; Thilker et al. 2000; Scoville et al. 2001). However, the H\(\text{\textsc{ii}}\) LF break at similar luminosity is known to exist for some nearby galaxies: MW (Paladini et al. 2009), M31 (Walterbos & Braun 1992) and M33 (Hodge et al. 1999). This break may be caused by the transition of H\(\text{\textsc{ii}}\) region ionizing sources, from low-mass clusters (including several OB stars) to more massive clusters (including several tens of OB stars; Kennicutt et al. 1989; McKee & Williams 1997; Oey & Clarke 1998). This will be discussed in detail in the next section.

We compared the H\(\text{\textsc{ii}}\) LF for the original sample (solid line) with that in Thilker et al. (2000; dashed line), as shown in
Those in Thilker et al. (2000, dashed line in (a)), in Scoville et al. (2001, sample range from $L < 10^{37.1} \, \text{erg s}^{-1}$, $L < 10^{38.6} \, \text{erg s}^{-1}$). The ACS images used in this study have longer exposure time than that of the WFPC2 images used in Scoville et al. (2001), so that we found many more faint H_II regions than Scoville et al. (2001). Both H_II LFs are fitted by a power law for the bright part ($10^{7.0} \, \text{erg s}^{-1}$, $< L < 10^{38.6} \, \text{erg s}^{-1}$). The H_II LF for the original sample is slightly steeper with $\alpha = -2.24 \pm 0.03$ than the H_II LF with $\alpha = -1.91 \pm 0.04$ reported by Scoville et al. (2001).

Figure 4(c) shows the H_II LF for the original sample (solid line) and that in Gutierrez et al. (2011, dashed line). The H_II luminosity of the H_II regions for the original sample ranges from $L = 10^{35.5} \, \text{erg s}^{-1}$ to $10^{39.0} \, \text{erg s}^{-1}$, while it ranges $L = 10^{35.8} \, \text{erg s}^{-1}$ to $10^{60} \, \text{erg s}^{-1}$ in Gutierrez et al. (2011). While this study shows a break at $L = 10^{37.1} \, \text{erg s}^{-1}$, the study by Gutierrez et al. (2011) shows a break at $L = 10^{38.7} \, \text{erg s}^{-1}$, much brighter than that in this study. The power-law indices in this study are $\alpha = -2.21 \pm 0.02$ for the bright part $\alpha = -1.41 \pm 0.02$ for the faint part, and those in Gutierrez et al. (2011) are $\alpha = -2.29 \pm 0.17$ and $\alpha = -1.67 \pm 0.03$. This large discrepancy between the two studies is primarily due to two factors: (1) we considered the small local peaks for the large H_II regions in Gutierrez et al. (2011) as separate H_II regions in this study and (2) we found many isolated faint H_II regions, missed in Gutierrez et al. (2011).

In Figure 5(a) we compare the H_II LF for the group sample (solid line) with that for the original sample (dashed line). Although both H_II LFs are fitted by a double power law, the location of a break and the power-law indices are different. The locations of the break are $L = 10^{37.1} \, \text{erg s}^{-1}$ and $10^{38.8} \, \text{erg s}^{-1}$, respectively. The power-law indices for the bright part are $\alpha = -2.21 \pm 0.02$ and $-2.60 \pm 0.21$, and those for the faint part are $\alpha = -1.41 \pm 0.02$ and $-1.69 \pm 0.01$ for the original and group samples, respectively.

Figure 5(b) shows the H_II LFs for the grouped H_II regions (dotted line), the group sample (solid line), and the H_II regions in Thilker et al. (2000, dashed line). The locations of the break and the power-law indices for the latter two samples are similar. The locations of the break for both the group sample and Thilker et al. (2000) are $L = 10^{38.8} \, \text{erg s}^{-1}$. The power-law indices for the group sample are $\alpha = -2.60 \pm 0.21$ for the bright part and $\alpha = -1.69 \pm 0.01$ for the faint part, and those in Thilker et al. (2000) are $\alpha = -3.41 \pm 0.08$ and $\alpha = -1.61 \pm 0.03$.

In conclusion, the H_II LF break seen at $L = 10^{38.8} \, \text{erg s}^{-1}$ in the previous studies based on the ground-based images (Rand 1992; Petit et al. 1996; Thilker et al. 2000) can be explained by the blending of multiple H_II regions.

In Figure 5(c) we compare the H_II LFs for the group sample (solid line), the grouped H_II regions (dotted line), and the H_II regions in Gutierrez et al. (2011) (dashed line). The H_II LFs for the latter two samples show nearly the same shape. The locations of the break and the power-law indices for the group sample and in Gutierrez et al. (2011) are similar. The location of the break for the group sample and that in Gutierrez et al. (2011) are $L = 10^{38.8} \, \text{erg s}^{-1}$ and $10^{38.7} \, \text{erg s}^{-1}$, respectively. The power-law indices for the group sample are $\alpha = -2.60 \pm 0.21$ for the bright part and $\alpha = -1.69 \pm 0.01$ for the faint part, and those in Gutierrez et al. (2011) are $\alpha = -2.29 \pm 0.17$.
and $\alpha = -1.67 \pm 0.03$. Both studies show a good agreement at $L > 10^{37.4}$ erg s$^{-1}$, however, there is a large difference in the number distribution of H II regions at $L < 10^{37.4}$ erg s$^{-1}$. It is primarily due to the existence of many isolated faint H II regions that were found in our survey, but missed in Gutierrez et al. (2011).

5.2. **Spatial Variation of Hα Luminosity Function for H II Regions**

We investigated the spatial variation of the H II LF for the original sample. We separated H II regions in the original sample into four groups, according to their positions in the galaxy: arm, interarm, and nuclear regions of NGC 5194 and NGC 5195. The positions of the H II regions are listed in Table 1. There are 12,245 H II regions in the arm region, 4422 H II regions in the nuclear region, and 2639 H II regions in the interarm region of NGC 5194. We found only 292 H II regions in the region of NGC 5195. The total luminosity of the arm H II regions is derived to be $L = 10^{41.1}$ erg s$^{-1}$ and that of the nuclear H II regions is $L = 10^{40.8}$ erg s$^{-1}$, while that of the interarm H II regions is only $L = 10^{40.1}$ erg s$^{-1}$, 8% of the total Hα luminosity of all NGC 5194 H II regions.

Figure 6(a) shows the H II LFs for the arm (solid line), interarm (dotted line), and nuclear (dashed line) regions of NGC 5194. The minimum luminosities ($L \approx 10^{35.5}$) in the H II LFs are nearly the same in three regions, but the maximum luminosities are different depending on the position. The maximum luminosities for the arm and nuclear regions are $L = 10^{39.0}$ erg s$^{-1}$ and $L = 10^{38.8}$ erg s$^{-1}$, respectively. However, there is no H II region brighter than $L = 10^{38.2}$ erg s$^{-1}$ for the interarm region.

These H II LFs are fitted by a double power law with a break at $L = 10^{37}$ erg s$^{-1}$. The power-law indices for the bright part are $\alpha = -1.92 \pm 0.03$, $-2.01 \pm 0.09$, and $-2.08 \pm 0.05$.

![Figure 5](image1.png)  
![Figure 6](image2.png)
for the arm, interarm, and nuclear regions, respectively. On the other hand, the power-law indices for the faint part are \( \alpha = -1.33 \pm 0.01, -1.53 \pm 0.05, \) and \(-1.33 \pm 0.03. \) Although the H\textsc{ii} LFs for the bright part \( (L > 10^{37} \text{ erg s}^{-1}) \) have similar power-law indices in three regions, the H\textsc{ii} LF for the faint part \( (L < 10^{37} \text{ erg s}^{-1}) \) is steeper in the interarm region than in the arm and nuclear regions.

Figures 6(b) and (c) shows the spatial variation of the H\textsc{ii} LFs for the grouped H\textsc{ii} regions and the group sample, respectively. The H\textsc{ii} LFs for the grouped H\textsc{ii} regions in Figure 6(b) are truncated at \( L = 10^{37} \text{ erg s}^{-1}. \) We used a single power law to fit the H\textsc{ii} LFs for the range from \( L = 10^{37.0} \text{ erg s}^{-1} \) to \( L = 10^{38.4} \text{ erg s}^{-1}. \) The power-law indices are \( \alpha = -1.57 \pm 0.04, -1.74 \pm 0.08, \) and \(-1.45 \pm 0.06 \) for the arm, interarm, and nuclear regions, respectively. The H\textsc{ii} LF is steeper in the interarm region than in the arm and nuclear regions. On the other hand, the H\textsc{ii} LFs for the group sample in Figure 6(c) are truncated near \( L = 10^{36} \text{ erg s}^{-1}. \) The power-law indices are \( \alpha = -1.78 \pm 0.04, -1.95 \pm 0.08, \) and \(-1.58 \pm 0.06 \) for the arm, interarm, and nuclear regions, respectively. The H\textsc{ii} LF is also steeper in the interarm region than in the arm and nuclear regions.

5.3. Size Distribution of H\textsc{ii} Regions

The size distribution of the H\textsc{ii} regions in the original sample is displayed in Figure 7, showing that their sizes (diameters) range from 8 pc to 110 pc. Most of the previous H\textsc{ii} region studies show that the cumulative size distribution of the H\textsc{ii} regions in a galaxy can be well fitted with an exponential function (van den Bergh 1981; Hodge 1987; Cepa & Beckman 1990; Knapen 1998; Hakobyan et al. 2007). However, some other studies suggested that the power-law form fits the differential size distribution better than the exponential function (Kennicutt & Hodge 1980; Elmegreen & Salzer 1999; Pleuss et al. 2000; Oey et al. 2003; Buckalew & Kobulnicky 2006).

Figures 7(a) and (b) display the cumulative and differential size distributions of the H\textsc{ii} regions, respectively. The cumulative size distribution of the H\textsc{ii} regions with \( 15 \text{ pc} < D < 80 \text{ pc} \) is fitted well with an exponential law: \( N(D) = N_0 \exp (-D/D_0) \) where \( N_0 = 77,880 \) and \( D_0 = 9.3 \text{ pc}. \) The differential size distribution of these H\textsc{ii} regions is fitted by a double power law with a break at \( D = 30 \text{ pc}. \) The power-law index for small H\textsc{ii} regions with \( 15 \text{ pc} < D < 30 \text{ pc} \) is \( \alpha_D = -1.78 \pm 0.04, \) whereas \( \alpha_D = -5.04 \pm 0.08 \) for large H\textsc{ii} region with \( 30 \text{ pc} < D < 110 \text{ pc}. \) The small H\textsc{ii} regions with \( D < 30 \text{ pc} \) may be ionized by several OB stars. On the other hand, the large H\textsc{ii} regions with \( D > 30 \text{ pc} \) are considered to be superpositions of small H\textsc{ii} regions, and they can be associated with stellar associations including several tens of OB stars.

Figure 8(a) shows the H\textsc{ii} LF for small H\textsc{ii} regions with \( D < 30 \text{ pc}. \) Most of the small H\textsc{ii} regions with \( D < 30 \text{ pc} \) are fainter than \( L = 10^{37.1} \text{ erg s}^{-1}, \) and only 1065 H\textsc{ii} regions are brighter than \( L = 10^{37.1} \text{ erg s}^{-1} \) (solid line). Out of the H\textsc{ii} regions with \( D < 30 \text{ pc}, \) we selected 4320 H\textsc{ii} regions which are neither blended with neighbor sources nor located in the crowded regions (dashed line). Most of them are in the range from \( L = 10^{35.8} \text{ erg s}^{-1} \) to \( 10^{37.2} \text{ erg s}^{-1}. \) The maximum \( L \) for the isolated H\textsc{ii} regions corresponds to about 10 times of M42, with an extinction-corrected value, \( L \approx 10^{36.9} \text{ erg s}^{-1}. \) On the other hand, Figure 8(b) shows the H\textsc{ii} LF for large H\textsc{ii} regions with \( D > 30 \text{ pc}. \) There are 1808 H\textsc{ii} regions brighter than \( L = 10^{37.1} \text{ erg s}^{-1} \) and 632 H\textsc{ii} regions fainter than \( L = 10^{37.1} \text{ erg s}^{-1}. \)

We compared the size distribution of the H\textsc{ii} regions in this study with those in Thilker et al. (2000), Scoville et al. (2001), and Gutierrez et al. (2011). Figure 9(a) plots the size distribution of the H\textsc{ii} regions in the original sample (solid line), the group sample (dashed line) and Scoville et al. (2001, dot-dashed line). In comparison with Scoville et al. (2001), we found that there are many more small H\textsc{ii} regions in the original sample. We used a single power law to fit the size distributions of H\textsc{ii} regions for the range from 30 pc to 125 pc. The power-law indices are \( \alpha_D = -5.94 \pm 0.26, -3.23 \pm 0.10, \) and \(-2.79 \pm 0.06 \) for the original sample, the group sample, and Scoville et al. (2001), respectively. Thus, the size distribution of the original sample is much steeper than that of the group sample and that of Scoville et al. (2001) sample, while the latter two samples have similar power-law indices.

Figure 9(b) shows the size distribution of the grouped H\textsc{ii} regions (solid line), the H\textsc{ii} regions in the group sample (dashed line), in Thilker et al. (2000, dotted line) and in Gutierrez et al. (2011, dot-dashed line). The sizes of the H\textsc{ii} regions in the group sample range from 8 pc to 310 pc, while those of the H\textsc{ii} regions in Thilker et al. (2000) range from 80 pc to 480 pc. This large discrepancy between the two studies is considered to come from the different spatial resolutions. We found that there are many more small H\textsc{ii} regions in the group sample, compared with Gutierrez et al. (2011). In comparison between the grouped H\textsc{ii}
regions and the H II regions in Gutierrez et al. (2011), we found that although the size distribution for the small H II regions ($D < 50$ pc) have similar shapes, the size distribution for the large H II regions ($D > 50$ pc) shows different shapes, having a steeper power slope for the grouped H II regions. The power-law indices are $\alpha_D = -3.48 \pm 0.08$ and $-2.75 \pm 0.11$ for the grouped H II regions and in Gutierrez et al. (2011), respectively. In other words, the size of the H II regions derived from this study is generally smaller than in Gutierrez et al. (2011). It is because we derived the sizes of the grouped H II regions from summing the numbers of pixels contained in all individual H II regions in a group, while Gutierrez et al. (2011) considered the substantial empty volumes to measure the size of H II regions.

6. DISCUSSION

6.1. Model Predictions for H$\alpha$ Luminosity Functions

In order to understand the nature of the observational H$\alpha$ LF, we performed Monte Carlo simulations of H$\alpha$ LFs, following Oey & Clarke (1998). The H$\alpha$ luminosity of an H II region depends on (1) the stellar initial mass function (IMF) and (2) the relation of Lyman continuum emission rate ($Q_{\text{LyC}}$) and stellar mass. We adopted a Salpeter IMF (Salpeter 1955) with $N(m_\ast)dN_\ast \propto m_\ast^{-2.35}$ over the range from 1 $M_\odot$ to 100 $M_\odot$. We used $Q_{\text{LyC}}$, depending on stellar mass, given by Vacca et al. (1996) which is based on stellar models with constraints provided by observations of individual high-mass stars.

We considered artificial clusters with the number of stars per cluster ($N_\ast$) ranging from 1 to 10,000 and estimated the total $Q_{\text{LyC}}$ radiating from each cluster. To reduce the statistical noise, we repeated the experiment 10,000 times, and derived the average $Q_{\text{LyC}}$ of the individual cluster with a specific $N_\ast$. Then we obtained the H$\alpha$ luminosity of this cluster using $L = 1.37 \times 10^{-12} Q_{\text{LyC}}$ given in Scoville et al. (2001).

We represented the distribution of numbers of stars in each model cluster by a power law: $N(N_\ast)dN_\ast = N_\ast^\beta dN_\ast$, where $N(N_\ast)dN_\ast$ is the number of stars per cluster in the range from $N_\ast$ to $N_\ast + dN_\ast$ and $\beta$ is a power-law index. We assumed that the star formation in each cluster occurs on a short timescale compared with stellar evolution timescales and that all clusters in a galaxy are created at the same time. We converted simulated H$\alpha$ LFs into observational H$\alpha$ LFs for comparison, considering the internal extinction as adopted above.

The shape of the H$\alpha$ LFs is determined by two parameters: $\beta$ and the maximum number of stars per cluster, $N_{\ast,\text{max}}$. To know how these two parameters affect the H$\alpha$ LF, we constructed nine H$\alpha$ LFs with 300,000 zero-age clusters for three power-law indices ($\beta = -1.60, -2.00$, and $-2.40$) and three values of $N_{\ast,\text{max}}$ (330, 1000, and 10,000), plotting them in Figure 10. The masses of clusters with $N_{\ast,\text{max}} = 330$ and $\beta = 2.0$ are 1000 $M_\odot$ and 2500 $M_\odot$, respectively, for the stellar mass range of 1–100 $M_\odot$ and 0.1–100 $M_\odot$. The masses of clusters with

![Figure 8](image-url)

**Figure 8.** (a) The H II LFs for the small H II regions with $D < 30$ pc (solid line) and the isolated H II regions which are neither blended with neighbor sources nor located in the crowded regions (dashed line). (b) The H II LF for the large H II regions with $D > 30$ pc.

![Figure 9](image-url)

**Figure 9.** (a) The size distributions of the H II regions in the original (solid line) and group (dashed line) samples in comparison with those in Scoville et al. (2001) (dot-dashed line). Thick solid lines represent power-law fits for $1.5 < \log D < 2.1$. (b) The size distributions for the grouped H II regions (solid line) and the H II regions in the group sample (dashed line) in comparison with those in Thilker et al. (2000) (dotted line) and in Gutierrez et al. (2011) (dot-dashed line). Thick solid lines represent power-law fits for $1.7 < \log D < 2.4$. (A color version of this figure is available in the online journal.)
The values of these two parameters get similar as \( N_\text{ii} \) decreases. The \( H_\alpha \) of stars per cluster (\( N_\text{ii,max} = 330, 1,000, \) and 10,000) in the upper panels of Figure 10 are truncated at \( L = 10^{37.0} \) erg s\(^{-1}\). Clusters with \( N_\text{ii} < 330 \) produce few \( H_\alpha \) regions brighter than \( L = 10^{37.0} \) erg s\(^{-1}\). They show nearly flat slopes for \( \beta = -1.60 \) and \(-2.00\), but show some slope for \( \beta = -2.40 \). In the middle panels, the \( H_\alpha \) LFs with \( N_\text{ii,max} = 1000 \) show the existence of some bright \( H_\alpha \) regions with \( L > 10^{37.0} \) erg s\(^{-1}\). They show a change in slope at \( L \approx 10^{37.0} \) erg s\(^{-1}\), which is similar to the value found for M51 \( H_\alpha \) regions in this study (Figure 3). We fit the bright part (\( L > 10^{37.0} \) erg s\(^{-1}\)) with a power law, obtaining \( \alpha = -1.48, -1.86, \) and \(-2.23\) for \( \beta = -1.60, -2.00, \) and \(-2.40\), respectively. Thus the values of \( \alpha \) decreases as \( \beta \) decreases. The \( H_\alpha \) LFs with \( N_\text{ii,max} = 10,000 \) in the low panels show a more obvious break at \( L = 10^{37.0} \) erg s\(^{-1}\). Fitting the bright part (\( L > 10^{37.0} \) erg s\(^{-1}\)) yields \( \alpha = -1.55, -1.94, \) and \(-2.36\) for \( \beta = -1.60, -2.00, \) and \(-2.40\), respectively. Thus the values of \( \alpha \) are very similar to those for \( \beta \), showing that the values of these two parameters get similar as \( N_\text{ii} \) increases.

For comparison of the \( H_\alpha \) LFs in Figure 10 with the observational ones, we need to consider the effect of evolution of \( Q_{\text{sys}} \). We assumed that \( Q_{\text{sys}} \) remains constant during the main-sequence lifetimes and is zero thereafter. Main-sequence lifetimes \( (t_{\text{ms}}) \) for individual OB stars are obtained from Maeder (1987). Figure 11 shows the \( H_\alpha \) LFs with \( \beta = -2.40 \) and \( N_\text{ii,max} = 10,000 \) derived for four ages 0, 2, 4, and 6 Myr. We adopted a value for \( \beta \), similar to the observational value derived in this study. The number of bright \( H_\alpha \) regions decreases as ages increase. Fitting the bright part (\( L > 10^{37.0} \) erg s\(^{-1}\)) yields \( \alpha = -2.35, -2.39, \) and \(-2.35\) for age = 0, 2, and 4 Myr, respectively. There are few bright \( H_\alpha \) regions in the case of age = 6 Myr, but a fit including the faint part (\( L > 10^{36.0} \) erg s\(^{-1}\)) yields a similar index, \( \alpha = -2.35 \). Thus the values of \( \alpha \) change little depending on age, and they are almost the same as the input value of \( \beta \).

### 6.2. A Change in Slope of \( H_\alpha \) Luminosity Function for \( H_\alpha \) Regions and the Initial Cluster Mass Function

A controversial point in the \( H_\alpha \) LF for M51 has been a break at \( L \approx 10^{38.8} \) erg s\(^{-1}\) shown in previous studies based on the ground-based imaging (Kennicutt et al. 1989; Rand 1992; Thilker et al. 2000). Kennicutt et al. (1989) argued that the cause of this break might be a transition from the normal to the super giant \( H_\alpha \) regions. On the other hand, the break is possibly a feature caused by the low spatial resolution. Scoville et al. (2001) compared their \( H_\alpha \) LF of M51 derived from \( HST \) WFPC2 with that of Rand (1992) based on the ground-based images. They demonstrated that the high-resolution \( H_\alpha \) LF is significantly steeper than the low-resolution one and showed that the break at \( L \approx 10^{38.8} \) erg s\(^{-1}\) is not seen in their \( H_\alpha \) LF.

This break is not seen either in the \( H_\alpha \) LF for the original sample in this study, as shown in Figure 3. However, we can observe a break at \( L = 10^{38.8} \) erg s\(^{-1}\) in the \( H_\alpha \) LF for the
group sample in Figure 5. From the similarity between this H\textsc{ii} LF and that in Thilker et al. (2000) in Figure 5(b), we conclude that the break seen at $L \approx 10^{38.8}$ erg s\(^{-1}\) in the previous studies may be due to the blending of multiple H\textsc{ii} regions.

On the other hand, we found a break at $L = 10^{37.1}$ erg s\(^{-1}\) in the H\textsc{ii} LF for the original sample as shown in Figure 3. To understand the shape of the H\textsc{ii} LF with this break we compared the observational H\textsc{ii} LF for the original sample with the simulated H\textsc{ii} LF in Figure 10. The shape of the observational H\textsc{ii} LF is remarkably similar to that of the simulated H\textsc{ii} LF in Figure 10(i) derived for $\beta = -2.40$ and $N_{\ast,\text{max}} = 10,000$. The observational H\textsc{ii} LF shows a break at $L = 10^{37.1}$ erg s\(^{-1}\), which is consistent with the simulated H\textsc{ii} LF with a break at $L = 10^{37.0}$ erg s\(^{-1}\). The power-law indices of the observational H\textsc{ii} LF are $\alpha = -2.35 \pm 0.02$ for the bright part and $\alpha = -1.42 \pm 0.01$ for the faint part, agreeing with those in the simulated H\textsc{ii} LF, $\alpha = -2.36 \pm 0.03$ and $\alpha = -1.43 \pm 0.02$. Thus, it is concluded that the break at $L = 10^{37.1}$ erg s\(^{-1}\) is due to the different $N_{\ast}$ in clusters associated with individual H\textsc{ii} regions. In other words, the faint H\textsc{ii} regions with $L < 10^{37.1}$ erg s\(^{-1}\) are ionized by low-mass clusters with $N_{\ast} < 330$ (including several OB stars) or single massive stars, while the bright H\textsc{ii} regions with $L > 10^{37.1}$ erg s\(^{-1}\) are ionized by massive clusters with $N_{\ast} \geq 330$ (including several tens of OB stars).

It is noted that the cluster mass $M_{\text{cl}}$ is related with $N_{\ast}: M_{\text{cl}} \propto N_{\ast}$. Therefore, the power-law index $\alpha$ of H\textsc{ii} LF in the bright end is expected to be similar to the index $\beta (-2.25)$ of the IMF of the clusters in M51 that may be represented by a power law: $N(M_{\text{cl}})dM_{\text{cl}} \propto M_{\text{cl}}^{-2.25}dM_{\text{cl}}$. This slope ($\beta$) is similar to or slightly steeper than those derived from previous studies for M51 young clusters: from the observation of young star clusters in M51, the cluster mass function is known to have power-law form with its index ranging from $\alpha = -1.70 \pm 0.08$ (Gieles et al. 2006) to $\alpha = -2.23 \pm 0.34$ (Hwang & Lee 2010).

### 6.3. Spatial Variation of H\textalpha Luminosity Function

Figure 6 shows that the shape of the H\textalpha LFs varies depending on the location within a galaxy. In Figure 6(a) for the original sample, we found that although the H\textalpha LFs for the bright part ($L > 10^{37}$ erg s\(^{-1}\)) have similar power-law indices in three regions, the H\textalpha LF for the faint part ($L < 10^{37}$ erg s\(^{-1}\)) is steeper in the interarm region than in the arm and nuclear regions. In addition, there is no H\textalpha region brighter than $L = 10^{38.5}$ erg s\(^{-1}\) in the interarm region. In Figures 6(b) and (c) for the grouped H\textalpha regions and the group sample, we also found that the H\textalpha LF is steeper in the interarm region than in the arm and nuclear regions.

Although the shape of the H\textalpha LF can be affected by several factors, including variation in the metallicity, extinction, stellar IMF, and underlying gas dynamics, Kennicutt et al. (1989) argued that the most significant factor is the change in the total number of stars produced in typical star formation events. Rand (1992) attributed the difference between the arm and the interarm H\textalpha LF to the existence of a more massive molecular clouds in the arm region. In other words, the higher proportion of massive clouds gives rise to relatively more H\textalpha regions of the higher luminosity. It is reasonable to infer that the high gas surface densities combined with the compression by the strong density wave in the arms may cause a concentration of bright H\textalpha regions.

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**Figure 11.** Evolution of simulated H\textalpha LFs for four ages (0, 2, 4, and 6 Myr), the parent power-law index $\beta = -2.40$, and the maximum number of stars per cluster $N_{\ast,\text{max}} = 10,000$. Thick solid lines represent power-law fits for $L > 10^{37.0}$ erg s\(^{-1}\). The values of the index ($\alpha$) are given in each panel.

(A color version of this figure is available in the online journal.)
regions on the arm region. Later Oey & Clarke (1998) suggested that the interarm H II regions are on average fainter than those in the arm region because the ionizing sources in the arm region are younger than those in the interarm region.

In Figure 11, we show the evolution of H II LFs with β = −2.40 and Nα,max = 10,000 for different ages (0, 2, 4, and 6 Myr). The H II LFs shift to faintward as a function of time. A maximum luminosity after 4 Myr (panel (c)) is 0.5 dex fainter than at zero-age (panel (a)), and the power-law index for the faint part (L < 10^37.1 erg s^{-1}) after 4 Myr is steeper than at zero age. The interarm H II LF in Figure 6 has a lower maximum luminosity and a steeper slope for the faint part than the arm H II LF. Thus the difference between the arm and the interarm H II LFs can be explained by an effect of evolution, supporting the suggestion by Oey & Clarke (1998).

6.4. Relation between Luminosities and Sizes of H II Regions

Both the Hα luminosity function and the size distribution of H II regions in the original sample are fitted by a double power law as shown in Figures 3 and 7(b), respectively. Since the total Hα luminosity of an H II region is integrated from the nebular volume emission, it is expected that L ∝ D^3. Then the power-law indices (α and αD) of the Hα luminosity function and the size distribution for H II regions are related as αD = (2–3)α (Oey et al. 2003).

The H II LF for the original sample in Figure 3 shows that the break appears at L = 10^{37.1} erg s^{-1}, and that the power-law indices are α = −1.42 ± 0.01 for the faint part and α = −2.25 ± 0.02 for the bright part. Using these values we derived expected values, αD = −2.26 and αD = −4.75 for the faint and bright part, respectively. On the other hand, the observational size distribution in Figure 7(b) shows that the power-law index for the small H II regions with D < 30 pc is αD = −1.78 ± 0.04, whereas αD = −5.04 ± 0.10 for the large H II regions with D > 30 pc. Therefore, there is a good agreement between expected and observational indices for the size distribution of H II regions.

Figure 12(a) displays Hα luminosities versus sizes of the H II regions in the original sample. It shows a clear correlation between the two parameters. The relation between the luminosity and the size of H II regions is fitted by L ∝ D^{3.04±0.01} (solid line). This value is in good agreement with our expectation of L ∝ D^3. However, Scoville et al. (2001) derived a flatter relation, L ∝ D^{2.16±0.02} for H II regions in the central region of M51 (dashed line). They explained that the this flatter slope is due to blending effect: large H II regions are blended so that they include substantial empty or neutral volumes. This indicates that this study separated blended H II regions better than Scoville et al. (2001).

Figures 12(b) and (c) display Hα luminosities versus sizes of the grouped H II regions and the H II regions in the group sample, respectively. The relation between the luminosity and the size of H II regions for the two samples is fitted by L ∝ D^{2.78±0.02} (panel (b); solid line) and L ∝ D^{2.78±0.01} (panel (c); solid line). Gutierrez et al. (2011) derived a flatter relation, L ∝ D^{2.29±0.03} (dashed line). This discrepancy between the two studies is due to the different procedure used to derive the size of the H II region, as mentioned in Section 5.3.

7. SUMMARY AND CONCLUSION

We detected and analyzed the H II regions in M51 using the wide field and high-resolution HST ACS Hα images taken as part of the Hubble Heritage Program. We found about 19,600 H II regions using the automatic H II photometry software, HIIPHOT (Thilker et al. 2000). Primary results are summarized as follows.

The Hα luminosity of the H II regions ranges from L = 10^{35.5} erg s^{-1} to 10^{39.0} erg s^{-1}. The H II LF is fitted by a double power law with a break at L = 10^{37.1} erg s^{-1}, and the power-law indices are α = −2.25 ± 0.02 for the bright part and α = −1.42 ± 0.01 for the faint part. Comparison with the simulated H II LFs suggests that this break is caused by the transition of H II region ionizing sources, from low-mass clusters (including several OB stars) to massive clusters (including several tens of OB stars).

To understand the break in the H II LF at L = 10^{38.8} erg s^{-1} reported in the ground-based studies, we produced a group sample, finding associations of H II regions in the original sample using the FOF (Davis et al. 1985). From the comparison of the H II LF for the group sample with that of Thilker et al. (2000), we concluded that most H II regions brighter than L = 10^{38.8} erg s^{-1} seen in the ground-based studies may be blends of multiple lower luminosity H II regions that are resolved as separate H II regions in this study. The H II LFs for the original sample have a different shape according to their positions in the galaxy. Although the
H II LF s are fitted by a double power law with a break at \( L = 10^{37.1} \) erg \( \text{s}^{-1} \), the H II LF for the faint part \( L < 10^{37.1} \) erg \( \text{s}^{-1} \) is steeper in the interarm region than in the arm and nuclear regions. There is no H II region brighter than \( L = 10^{38.2} \) erg \( \text{s}^{-1} \) in the interarm region. Observed variations in the H II LF can be explained by an effect of evolution of an H II region.

The size distribution of the H II regions in the original sample shows that the size of H II regions ranges from 8 pc to 110 pc in diameter. The cumulative and differential size distributions of the H II regions are fitted well by an exponential and power-law form, respectively. The cumulative size distribution of the H II regions is fitted well by a double power law with a break at \( D_0 < 3 \) pc. The differential size distribution of these H II regions is fitted by a double power law with a break at \( D = 30 \) pc. The power-law index for the small H II regions with \( 15 < D < 30 \) pc is \( \alpha_D = -1.78 \pm 0.04 \), whereas \( \alpha_D = -5.04 \pm 0.08 \) for the large H II region with \( 30 < D < 110 \) pc. The small H II regions with \( D < 30 \) pc may be ionized by several OB stars. On the other hand, the large H II regions with \( D > 30 \) pc are considered to be superpositions of small H II regions, and they can be associated with stellar associations involving several tens of OB stars. In addition, power-law indices of the size distribution for the original sample are related with those of H II regions in M51. M.G.L. was supported by Grant-in-Aid for JSPS Fellow No. 20-08325.

**REFERENCES**

Beckman, J. E., Rozas, M., Zurita, A., Watson, R. A., & Knapen, J. H. 2000, *AJ*, 119, 2728
Bradley, T. R., Knapen, J. H., Beckman, J. E., & Folkes, S. L. 2006, *A&A*, 459, 13
Bresolin, F., Garnett, D. R., & Kennicutt, R. C. 2004, *ApJ*, 615, 228
Buckalew, B. A., & Kobulnicky, H. A. 2006, *AJ*, 132, 1061
Calzetti, D., et al. 2005, *ApJ*, 633, 871
Carranza, G., Crill, R., & Monnet, G. 1969, *A&A*, 1, 479
Cepa, J., & Beckman, J. E. 1990, *A&A*, 231
Davis, M., Efremov, G., Frenk, C. S., & White, S. D. M. 1985, *ApJ*, 292, 371
Dobbs, C. L., Theis, C., Pringle, J. E., & Bate, M. R. 2010, *MNRAS*, 403, 625
Egusa, F., Koda, J., & Scoville, N. 2011, *ApJ*, 726, 85
Elmegreen, D. M., & Salter, J. J. 1999, *AJ*, 117, 764

**Franco, J., Kurtz, S. E., García-segura, G., & Hofner, P. 2004, *ApJ*, 272, 169**
**Gieles, M., Larsen, S. S., Bastian, N., & Stein, I. T. 2006, *A&A*, 450, 129**
**Guerrero, L., & Beckman, J. E. 2010, *ApJ*, 710, L44**
**Gutierrez, L., Beckman, J. E., & Buenrostro, V. 2011, *AJ*, 141, 113**
**Hakobyan, A. A., Petrovkin, A. R., Yeghiazaryan, A. A., & Boulesteix, J. 2007, *Astrophysics*, 50, 426**
**Helmholtz, J. F., Walterbos, R. A. M., Bothun, G. D., O'Neil, K., & Oey, M. S. 2009, *MNRAS*, 393, 478**
**Hitschfeld, M., Kramer, C., Schuster, K. F., García-Burillo, S., & Stutzki, J. 2009, *A&A*, 495, 795**
**Hodge, P. W. 1969, *ApJS*, 18, 73**
**Hodge, P. W. 1974, *PASP*, 86, 845**
**Hodge, P. W. 1987, *PASP*, 99, 915**
**Hodge, P. W., Balsley, J., Wyder, T. K., & Skelton, B. P. 1999, *PASP*, 111, 685**
**Hodge, P. W., & Lee, M. G. 1990, *PASP*, 102, 26**
**Hodge, P. W., Lee, M. G., & Gurwell, M. 1990, *PASP*, 102, 1245**
**Hodge, P. W., Lee, M. G., & Kennicutt, R. C. 1989a, *PASP*, 101, 32**
**Hodge, P. W., Lee, M. G., & Kennicutt, R. C. 1989b, *PASP*, 101, 640**
**Hwang, N., & Lee, M. G. 2008, *AJ*, 135, 1567**
**Hwang, N., & Lee, M. G. 2009, *AJ*, 138, 2193**
**Hwang, N., & Lee, M. G. 2010, *ApJ*, 710, L44**
**McKee, C. F., & Williams, P. J. 1997, *ApJ*, 476, 144**
**Oey, M. S., & Clarke, C. J. 1998, *AJ*, 115, 1543**
**Oey, M. S., Parker, J., Mikles, V., & Zhang, X. 2003, *AJ*, 126, 2317**
**Paladini, R., De Zotti, G., Noriega-Crespo, A., & Carey, S. J. 2009, *ApJ*, 702, 1056**
**Petit, H., Hua, C. T., Bersier, D., & Courtes, G. 1996, *A&A*, 309, 446**
**Pleuss, P. O., Heller, C. H., & Fricke, K. J. 2000, *A&A*, 361, 913**
**Rand, R. J. 1992, *ApJ*, 403, 815**
**Rozas, M., Beckman, J. E., & Knapen, J. H. 1996, *A&A*, 307, 735**
**Salpeter, E. E. 1955, *ApJ*, 121, 161**
**Scheepmaker, R. A., Lamers, H. J. G. L. M., Anders, P., & Larsen, S. S. 2009, *A&A*, 494, 81**
**Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, 500, 525**
**Schuster, K. F., Kromer, C., Hintschfeld, M., & Mookerjea, B. 2007, *A&A*, 461, 143**
**Scoville, N. Z., Polletta, M., Ewald, S., Stolovy, S. R., Thompson, R., & Rieke, M. 2001, *AJ*, 122, 3017**
**Thilker, D. A., Braun, R., & Walterbos, R. A. M. 2000, *AJ*, 120, 3070**
**Thilker, D. A., Walterbos, R. A. M., Braun, R., & Hoopes, C. G. 2002, *AJ*, 124, 3118**
**Tikhonon, N. A., Galazutdinova, O. A., & Tikhonon, E. N. 2009, *Astron. Lett.*, 35, 59**
**Tully, R. B. 1974, *ApJS*, 27, 437**
**Vacc. W. D., Garmany, C. D., & Shull, J. M. 1996, *ApJ*, 460, 914**
**van den Bergh, S. 1981, *AJ*, 89, 1464**
**van der Hulst, J. M., Kennicutt, R. C., Crane, P. C., & Rots, A. H. 1988, *A&A*, 195, 38**
**von Hippel, T., & Bothun, G. 1990, *AJ*, 100, 403**
**Walterbos, R. A. M., & Braun, R. 1992, *A&A*, 292, 625**
**Weidner, C., Bonnell, I. A., & Zinnecker, H. 2010, *ApJ*, 724, 1503**
**Wilds, E. E., & Hodge, P. W. 1991, in IAU Symp., 148, The Magellanic Clouds, ed. R. Hayens & D. Milne (Dordrecht: Kluwer), 226**
**Wyder, T. K., Hodge, P. W., & Skelton, B. P. 1997, *PASP*, 109, 927**
**Youngblood, A. J., & Hunter, D. A. 1999, *ApJ*, 519, 55**