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High Mass, OB Star Formation in M51:
HST H$\alpha$ and P$\alpha$ Imaging

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ABSTRACT

We have obtained Hα and Pα emission line images covering the central 3 — 4’ of M51 using the WFPC2 and NICMOS cameras on HST to study the high-mass stellar population. The 0.1 — 0.2” pixels provide 4.6 — 9 pc resolution in M51 and the Hα/Pα line ratios are used to obtain extinction estimates. A sample of 1373 Hα emission regions is catalogued using an automated and uniform measurement algorithm. Their sizes are typically 10 — 100 pc. The luminosity function for the Hα emission regions is obtained over the range $L_{H\alpha} = 10^{36}$ to $2 \times 10^{39}$ erg s$^{-1}$. The luminosity function is fit well by a power law with $dN/d\ln L \propto L^{-1.01}$. The power law is significantly truncated and no regions were found with it observed $L_{H\alpha}$ above $2 \times 10^{39}$ erg s$^{-1}$ (uncorrected for extinction). (The maximum seen in ground-based studies is approximately a factor of 5 higher, very likely due to blending of multiple regions.) The extinctions derived here increase the maximum intrinsic luminosity to above $10^{40}$ erg s$^{-1}$). The logarithmically binned luminosity function is also somewhat steeper ($\alpha = -1.01$) than that found ground-based imaging ($\alpha = -0.5 \rightarrow -0.8$) — probably also a result of our resolving regions which were blended in the ground-based images. The 2-point correlation function for the HII regions exhibits strong clustering on scales $\leq 2''$ or 96 pc.

To analyze the variations of HII region properties vis-a-vis the galactic structure, the spiral arm areas were defined independently from mm-CO and optical continuum imaging. Although the arms constitute only 25% of the disk surface area, the arms contain 45% of the catalogued HII regions. The luminosity function is somewhat flatter in spiral arm regions than in the interarm areas ($-0.72 \rightarrow -0.95$); however, this is very likely the result of increased blending of individual HII regions in the arms which have higher surface density. No
significant difference is seen in the sizes and electron densities of the HII regions in spiral arm and interarm regions. For 209 regions which had \( \geq 5\sigma \) detections in both P\( \alpha \) and H\( \alpha \), the observed line ratios indicate visual extinctions in the range \( A_V = 0 \) to 6 mag. The mean extinction was \( A_V = 3.1 \) mag (weighting each region equally), 2.4 mag (weighting each by the observed H\( \alpha \) luminosity) and 3.0 mag (weighting by the extinction-corrected luminosity). On average, the observed H\( \alpha \) luminosities should be increased by a factor of \( \sim 10 \), implying comparable increases in global OB star cluster luminosities and star formation rates. The full range of extinction-corrected H\( \alpha \) luminosities is between \( 10^{37} - 2 \times 10^{40} \) erg s\(^{-1}\).

The most luminous regions have sizes \( \geq 100 \) pc so it is very likely they are blends of multiple regions. This is clear based on their sizes which are much larger than the maximum diameter (\( \leq 50 \) pc) to which an HII region might conceivably expand within the \( \sim 3 \times 10^6 \) yr lifetime of the OB stars. It is also consistent with observed correlation (\( L \propto D^2 \)) found between the measured luminosities and sizes of the HII regions. We therefore generated a subsample of 1101 regions with sizes \( \leq 50 \) pc which constitutes those region which might conceivably be ionized by a single cluster. Their extinction-corrected luminosities range between \( 2 \times 10^{37} \) and \( 10^{39} \) erg s\(^{-1}\), or between 2/3 of M42 (the Orion Nebula) and W49 (the most luminous Galactic radio HII region). The upper limit for individual clusters is therefore conservatively \( \leq 10^{39} \) erg s\(^{-1}\), implying \( Q_{LyC} \text{ up} \simeq 7 \times 10^{50} \) s\(^{-1}\) (with no corrections for dust absorption of the Lyman continuum or UV which escapes to the diffuse medium). This corresponds to cluster masses \( \leq 5000 \) M\(_\odot\) (between 1 and 120 M\(_\odot\)).

The total star formation rate in M51 is estimated from the extinction-corrected H\( \alpha \) luminosities to be \( \sim 4.2 \) M\(_\odot\) yr\(^{-1}\) (assuming a Salpeter IMF
between 1 and 120 $M_\odot$) and the cycling time from the neutral ISM into these stars is $1.2 \times 10^9$ yr.

We develop a simple model for the UV output from OB star clusters as a function of the cluster mass and age in order to interpret constraints provided by the observed luminosity functions. The power-law index at the high luminosity end of the luminosity function ($\alpha = -1.01$) implies $N(M_d)/dM_d \propto M_d^{-2.01}$. The high mass clusters ($\sim 1000 M_\odot$) have a mass such that the IMF is well sampled up to $\sim 120 M_\odot$, but this cluster mass is $\leq 1\%$ of that available in a typical GMC. We suggest that OB star formation in a cloud core region is terminated at the point that radiation pressure on the surrounding dust exceeds the self-gravity of the core star cluster and that this is what limits the maximum mass of standard OB star clusters. This occurs at a stellar luminosity-to-mass ratio $\sim 500 - 1000 L_\odot/M_\odot$ which happens for clusters $\geq 750 M_\odot$. We have modelled the core collapse hydrodynamically and find that a second wave of star formation may propagate outwards in a radiatively compressed shell surrounding the core star cluster — this triggered, secondary star formation may be the mechanism for formation of super star cluster (SSC) seen in starburst galaxies.

**Subject headings:** galaxies: spiral — galaxies: ISM — galaxies: ISM — stars: early type — ISM: HII regions
1. Preamble

Were it not for the small number of youthful, luminous stars and their ongoing genesis, much of the beauty, vigor and evolution that is our fascination in the universe would be lost to the distant past. Energizing and enriching the disks of galaxies are the most massive stars of each generation. In youth, they illuminate the bright nebulae which so elegantly outline the spiral arms of distant galaxies; in death, their cataclysmic supernovae replenish the interstellar environment with gases, enriched in heavy elements. From these ashes the future generations of stars will arise. The springs of rejuvenation are giant molecular clouds encompassing millions of solar masses of cold gas. Inside these ponderous cocoons, the metamorphosis of stars takes place in dusty darkness.

2. Introduction

High mass OB stars play a critical role in the energetics and dynamics of the ISM and in the highest luminosity phases of galactic structure and evolution, specifically the luminous spiral arm and starburst activity. Nevertheless, the mechanisms for formation of OB associations remain poorly understood and indeed, it is uncertain whether high and low mass stars are formed by the same or different processes (e.g. Larson 1986). HII regions have long been a primary probe of high-mass star formation and the properties of OB star clusters (Hodge 1987, Kennicutt et al. 1989, Rand 1992, Thilker et al. 2001). The hydrogen recombination line fluxes (e.g. Hα) or radio free-free continuum are proportional to the volume-integrated emission measure of the HII regions. The latter is proportional to the total Lyman continuum emission rate of the associated high-mass stars under the assumption that all ionizing photons are locally absorbed. Thus the Hα luminosity of an emission region is indicative of the Lyman continuum emission and hence the mass of high-mass stars (correcting for extinction and assuming an IMF). The luminosity function
of the HII regions can then be used to study the distribution of masses and birth rates of OB associations. M51 is a Rosetta stone for studies of OB star formation — on account of its proximity — 9.6 Mpc (Sandage and Tammann 1975); its grand design spiral pattern; its orientation — i = $20^\circ$ (Tully 1974) and its abundant, dense ISM (Scoville & Young 1983).

M51 has been the focus of numerous ground-based H$\alpha$ studies (Kennicutt et al. 1989; Rand & Kulkarni 1990; van der Hulst et al. 1988; Rand 1992; Rozas et al. 1996; Petit et al. 1996; and Thilker et al. 2000), and these studies have contributed much of what is currently known regarding OB associations in other spiral galaxies. The distribution of HII region H$\alpha$ luminosities was approximately fit by a truncated power-law with $(N(L) \propto L^{-0.55 \rightarrow -0.75})$ — on the high luminosity end. In several previous H$\alpha$ studies (eg. Rand 1992 and Thilker et al. 2000), the luminosity function appears steeper in the interarm regions than in the arms (exponent $-0.93 \rightarrow -0.96$ versus $-0.48 \rightarrow -0.72$). The bright end ($L_{H\alpha} \geq 10^{38.8}$ erg s$^{-1}$) of the HII region luminosity function contributes the bulk ($\geq 50\%$) of the discrete HII region luminosity (Rand 1992), but approximately 55% of the total H$\alpha$ luminosity originates from diffuse ionized gas (DIG), i.e. not in discrete regions (Rand 1992; Greenawalt et al. 1998). Based on ground-based imaging, it remains uncertain whether the DIG is blended low luminosity regions or truly diffuse gas.

We have recently completed a comprehensive study of M51 comprised of HST (WFPC2 and NICMOS) imaging of the optical and near infrared continuum (Polletta et al. 2001) and the H$\alpha$ and P$\alpha$ emission lines (this paper). Related mm-CO interferometry has been presented in Aalto et al. (1999). The former probes the stellar disk, the dust, and the OB star formation while the latter probes the dense, molecular ISM which is the birthsite of OB star clusters.

The 0.1 — 0.2″ resolution available with HST imaging corresponds to 4.6 — 9.3 pc. These sizes correspond to those of individual resolved Galactic HII regions (eg. the Orion
Nebula). For comparison, ground-based Hα imaging at resolutions $\geq 1-2''$ corresponds to at least 50 — 100 pc, the size of a large Galactic giant molecular cloud (GMC). The latter resolution will clearly blend multiple sites of OB star formation which occur within a single GMC (for example M42 and NGC 2024 in the Orion GMC). At the same time, the ground-based resolution element will also contain enormous volumes of intervening neutral gas. The high angular resolution of the HST imaging is thus critical for the study of extragalactic HII region properties.

To date there have been surprisingly few studies of extragalactic H II regions using HST. A recent study of M101 by Pleuss et al. (2000) clearly demonstrates the advantages of HST. Specifically, the break in the luminosity function (LF) slope at $\log(L_{H\alpha}) = 10^{38.6}$ seen in some ground-based studies (Beckman et al. 2000 – attributed to the transition from ionization-bounded to density-bounded regions) was not apparent. And multiple HII regions were resolved into individual regions of lower luminosity, resulting in a very different distribution of HII region sizes and enabling an analysis of HII region clustering (Pleuss et al. 2000).

### 2.1. Our Study

This paper which presents HII emission line imaging addresses the following specific issues:

1) the global luminosity function of the HII regions and their associated OB star clusters;

2) comparison of the form of the luminosity function with theoretical expectations;

3) variations in the luminosity function from arm to interarm regions and between the nuclear region and the galactic disk;
4) the HII region sizes and densities; and

5) analysis of the reddening and extinction of the HII regions based on the observed ratios of Hα/Pα lines.

To address these issues in a meaningful way and fully understand the observational limitations, we develop automated routines for the definition of the HII region boundaries and a model to simulate the blending of multiple regions (§5.1). The temporal evolution of the Lyman continuum emission from an OB star cluster is also modelled and constraints on the cluster mass distribution are derived from the observed luminosity function of HII regions. Lastly, we analyze the physical processes important in determining the masses and sizes of OB star clusters forming within a molecular cloud core.

In the following sections, we present the observations and images for Hα and Pα (§3-4) and discuss the definition and measurement of the HII regions (§5). The clustering of HII regions, in particular a 2-point correlation function is derived in §6. The observed Hα luminosity function and Lyman continuum emission rates are presented in §7 & 8. The size and density distributions for arm and interarm regions are discussed in §9. The Hα/Pα ratios are used to estimate extinctions of 209 HII regions in §10 and hence derive extinction-corrected luminosities. In §11 we present a sample of HII regions with size ≤ 50 pc and then compare these with Galactic HII regions in §12. In §13 we present a simple model invoking instantaneous OB star formation with a standard IMF to provide a context for interpretation of the observational data. We also develop a model for the formation of OB star clusters in which the mass of the core cluster is limited by radiation pressure once the cluster has accumulated ∼ 1000 $M_\odot$. In §14, we use the total fluxes in Hα to estimate the overall Lyman continuum production and star formation rate in M51.
3. Observations

HST imaging of M51 using both WFPC2 and NICMOS was obtained in several observing programs as discussed in Polletta et al. (2001) and summarized in Table 1.

3.1. WFPC2

The WFPC2 continuum and Hα images were obtained in 1995 January (Ford, Tsvetanov & Kriss 1996) and in 1999 July by Scoville & Ewald (filling in the areas not covered in the Ford et al. archive data). The raw images were flat-fielded using the automatic standard pipeline at the STScI and cosmic rays were removed using our own procedure. The complete calibration procedures are described in Polletta et al. (2001). For subtraction of continuum from the F656N image, which includes Hα and continuum, the Y-band (F547M) image was used in the earlier epoch and I-band (F814W) for the later epoch. The broad band continuum image was first scaled by a constant such that the signal strengths on a sample of stars balanced those in the F656N image.

To test that the use of different continuum filters for the two fields did not introduce photometric differences, we compared the measured fluxes for regions in the overlap area of the separate images. In the Hα+continuum image the average difference was 1.6%. The Hα flux (after continuum subtraction) was different by ∼2% for faint regions and 6% for the brightest regions.

3.2. NICMOS

NICMOS (187N and 190N) images were obtained as part of the NICMOS GTO program with a mosaic of 9 NIC3 fields covering most of the area of the WFPC2 images.
NICMOS Camera 3 uses a $256 \times 256$ HgCdTe array with plate scales of 0.203859 and 0.203113" per pixel in x and y, providing a $\sim 52.19'' \times 52.00''$ field of view (Thompson et al. 1998). The F187N and F190N filters with effective wavelengths of 1.87 and 1.90 $\mu$m were used to obtain on and off-band images. The FWHM resolution is 0.19" at 1.87 $\mu$m. Observations at each of the 9 mosaic positions were done using a square dither in each filter setting and at each dither position, non-destructive reads (MULTIACCUM) were taken. The total integration times for each filter are listed in Table 1.

The data were reduced and calibrated using the CALNICA version 3.3 task (Bushouse & Stobie 1998) in IRAF/STSDAS and the reference files (static data quality, detector read noise, detector non-linearities files) from the Space Telescope Science Institute (STScI) NICMOS pipeline, with the exception of the flat-field, and dark frame corrections that were provided by the NICMOS Instrument Development Team. The dithered images were then shifted and mosaiced using the NICMOSAIC and NICSTIKUM IRAF tasks (D. Lytle 1998, private communication). The plate scales of the final "drizzled" images are 0.0381" and 0.0378" per pixel in x and y. The images were mosaiced with relative offsets determined from common stars in the overlap regions and rotated with north up and east to the left using the data-header orientation angle (see Polletta et al. 2001).

### 3.3. WFPC2 and NICMOS Flux Calibration

Flux calibration of the WFPC2 images is done as described in Polletta et al. (2001). For the NIC3 images, we employ scale factors of $5.050 \times 10^{-5}$ and $5.033 \times 10^{-5}$ Jy (ADU/sec)$^{-1}$

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at 1.87 (Pα) and 1.90 µm \cite{rieke2001}. The rms noise in the final images is typically 62 and 59 µJy (arcsec)$^{-2}$ at 1.87 and 1.90 µm. As a check on the flux calibration, three of the coauthors of this paper independently calibrated the Hα and Pα images with similar results (within 10%).

At zero redshift, the Hα filter on WFPC2 transmits the [NII] lines (6548.1 and 6583.4Å in addition to Hα and stellar continuum. At the redshift of M51 (Z = 0.00154), the transmissions are 98.7, 0.0 and 91.2 % for the two redshifted [NII] lines and Hα, respectively. Adopting a total flux in the [NII] lines of 0.4 × Hα in M51 and a flux ratio of 1:3 for the two [NII] lines, we find that the detected line flux will be 1.012 times that of Hα. This fortuitously happens because the redshift of reduces transmitted flux of Hα by nearly the same amount that the transmitted flux of the 6548.1Å[NII] line is increased. We therefore neglect this 1% correction.

4. Images

The mosaic of continuum-subtracted Hα images is shown in Fig. 1 for the central 281×223″. The Hα is displayed in red, the continuum B band in blue and the I or Y bands in green. Hα emission extends out 10″ from nucleus at PA $\sim -15^\circ$ and bright, discrete Hα emission regions outline the spiral arms. The locations of bright Hα emission are closely associated with the dark dust lanes, but relative to the dust (and the mm-CO emission, see \cite{polletta2001}), the Hα is often displaced to the outside or leading edge of the arms. In the standard picture of spiral pattern streaming shown in Fig. 2, this offset implies that the HII regions develop subsequent to the time of maximum concentration of the dust and molecular clouds. Close inspection of Fig. 1 also reveals a number of smaller dust lanes and HII regions in the interarm regions both to the east and west of the nucleus.
Two very luminous associations of stars are also seen — one approximately 32" NE of the nucleus with surrounding Hα emission, the other 99" W of the nucleus, just outside the spiral arm. The latter region is remarkable in being very large in extent (∼ 7" or 326 pc in diameter) and in having very little Hα emission. The continuum colors and the lack of Hα suggest that this is an aging association in which the O-stars have mostly evolved off the main sequence (≥ 10⁷ yr, see Polletta et al. 2001). The nature of the larger association is not at all clear since it is probably much more massive and more extended than any of the younger clusters required to power the Hα emission regions.

The NICMOS Pα (red) image is shown in Fig. 3 overlayed on the V (green) and B (blue) continuum. In Fig. 4, the Pα (green) is combined with the Hα (red) in order to highlight those regions with relatively high Pα/Hα ratios, indicating particularly high dust reddening. For a smaller area west of the nucleus, Fig. 5 shows the Hα and Pα emission with no optical continuum background. Although generally Pα shows the same emission regions as Hα, it is clear even from visual inspection of Fig. 4 and 5 that many of the arm HII regions have considerable reddening. There are several regions appearing green in Fig. 4, implying strong Pα but only very weak Hα. Many HII regions also exhibit strong gradients in the Pα/Hα ratio.

5. HII Region Parameters

In measuring HII regions, the high angular resolution HST is critical to resolving regions associated with individual OB star clusters. HST-NICMOS also enables measurement of Pα (which can’t generally be done from the ground); in combination with Hα, this line provides a probe of the dust extinction. These points are illustrated well in Fig. 6 which shows a region approximately 60" N of the nucleus at the full resolution Hα and the Hα smoothed to 1.5" resolution (to simulate ground-based imaging). Comparison of two the
two Hα images underscores the need for high angular resolution in order to resolve the multiple, distinct HII regions which often exist in a single complex.

In Fig. [7], the Hα and Pa are shown for the same region and large variations can be seen in their relative distributions due to variable reddening. For example, the southern end of the complex is strongest in Pa while the northern region is brightest in Hα.

5.1. HII Region Definition and Measurement

Measured HII region properties will be fundamentally dependent on both the resolution of the images and the procedures used to define the boundaries of the emission regions. For example, higher resolution images will resolve some of the larger regions into multiple components (and hence reduce the number of the most luminous regions). In addition, the criteria adopted to resolve (or break up) blended regions can be critical. Algorithms to separate out the regions from the background and break up blended regions might invoke logic based on a priori understanding of the characteristics of Galactic HII regions. For example, virtually all Galactic HII regions have diameters much less than 50 pc so it is reasonable to expect that extragalactic regions larger than this are likely to be blends, ionized by multiple OB star clusters. Lastly, data with higher sensitivity might join multiple regions which would have appeared separate at lesser sensitivity if the threshold for joining regions was set at a sufficiently low level.

The HII region measurement process may be broken into three steps: 1) the definition of the boundaries of emission regions at a specified intensity threshold, 2) the resolution of multiple strong peaks within a single boundary into separate, discrete emission regions and 3) measurement of HII region parameters such as peak and integrated fluxes, sizes and positions. Clearly, the breaking up of blended features is the most difficult (and subjective)

step — for this reason we developed an automated procedure (rather than an interactive process). This has the advantage that the results can be carefully compared for different input parameters and the selection algorithm is uniform across the entire image. Extensive trials of the selection parameters were used to test their effects on the results.

Prior to measurements of the discrete HII regions, we removed a very extended background in order to ‘partially’ remove the diffuse ionized gas (DIG) emission and to suppress any residual continuum which might result from color variations of the continuum in different regions of the galaxy. This background at each pixel was estimated from the 30’th percentile intensity for a histogram of pixels in an area of 64 × 64 pixels centered on each pixel (that is 70% of the pixels are brighter than the subtracted background). The local histograms of pixel values in the final background-subtracted image have a large number of pixels close to zero and a small fraction on the positive tail, representing real Hα emission (assuming the HII regions don’t fill a large fraction of the area). Sixty-four pixels corresponds to approximately 300 pc linear scale and this is much larger than any discrete HII regions. The 30’th percentile was chosen to avoid significant Malmquist bias and to avoid removal of discrete HII region line emission in areas with large numbers of HII regions (none of which fill 70% of the pixels in a surrounding 64 × 64 pixel box). After removing the background, the noise (σ) was estimated in areas not including obvious emission. Typically, \( \sigma \approx 4.8 \times 10^{-18} \) erg cm\(^{-2}\) s\(^{-1}\). The removed background varies between between -0.9 and 2.8σ and the average values are -0.04 (whole image), 0.08 (arms), 1.8 (nucleus) and -0.15 (interarms) \( \times \sigma \) (as quoted above). Discrete, but low surface brightness HII regions would still be catalogued, provided they have at least one pixel exceeding 6σ (see below).

The logic adopted for definition of the boundaries of the emission regions was: start from the brightest pixel, find all pixels connected to this peak down to a level of 65% of the peak value; then repeat the procedure starting from the brightest remaining pixel; and so
on until there are no pixels left above the adopted threshold for a 'significant' peak (here taken to be \(6\sigma\)). The only complication is that as one is collecting the neighboring pixels around a peak, one must also check that those new pixels wouldn’t more appropriately associate with one of the peaks found earlier in the process. In such instances where there were multiple regions neighboring on a pixel, the pixel was attached to the region which had the highest average value for its neighboring pixels.

that it is essentially assuming a constant 'curve of growth' as a function the percentage-of-peak for all HII regions, i.e. the HII regions must all have homologous morphology.

In detail, our procedure involved the following steps:

1) Find the peak pixel remaining in the image.

2) Let this pixel be the basis for starting a new "peak".

3) Generate a list of all pixels above 65% of this peak value.

4) For each of the pixels found in # 3, associate it with the new peak or whichever pre-existing peak has the highest average in pixels which touch the pixel in question. As pixels are assigned to HII regions, they are also removed from the original image to avoid further consideration. Any of the pixels in the list from # 3, not touching on a previous HII region, are left in the image for later consideration. Thus one is gradually working down in intensity through the image.

5) If there are remaining pixels above \(6\sigma\) which could form the basis for a new peak, then go back to step # 1.

6) Lastly, the algorithm examined all the HII regions defined in steps 1–5 to see if any should be collected into a single region. Any region which did not have a valley of at least
a $4.5\sigma$ (down from its peak value) between it and the border pixels of any neighboring HII region was added into the neighboring region.

For any regions with more than 3 pixels, a curve of empirical growth was derived to correct for flux outlying pixels beyond the lowest non-zero pixel value. The curve of growth was computed individually for each HII region, from measurements of the total integrated flux within each HII region as a function of the pixel intensity, starting from the peak value and working down to $2.5\sigma$. For example, including all pixels in the region with pixel values above 2.5, 4, 6, 8, 10 ... $\sigma$, the separate flux sums were calculated. These flux integral measurements were then fit by a straight line (as a function of the variable cutoff threshold) and the fit was extrapolated to 0 intensity cutoff value. This correction resulted in a median increase of only 15% in the flux. In this manner, we are not assuming a fixed morphology for all HII regions and the extrapolations are extremely modest since we have collected all connected pixels down to only $2.5\sigma$.

Although we are using a criterion based on a percentage-of-peak for the initial association of the nearby pixels with a given peak pixel, this technique is not the same as that developed by McCall et al. (1996). They collected pixels down to a fixed percentage of the local peak but then extrapolated the flux within this region using a fixed multiplicative factor to estimate the total flux of the HII region. Here, the 65% is simply used as the initial criteria for associating neighboring pixels with a particular local maximum. And as we continue working down in intensity, pixels below the 65% level (all the way down to $2.5\sigma$) are associated with the pre-existing nearby peaks. The technique employed by McCall et al. (1996) suffers the obvious problem Actually, our algorithm is somewhat similar in spirit to that developed by Thilker (2000). Both algorithms, let all HII regions grow simultaneously as one works down to lower flux levels in an image (see step 3 above). This ensures that as much flux as possible is gathered into each HII region without bias
towards the order with which each HII region was first found. In our case, new HII regions are always started from the highest remaining pixel in the entire image and we require that every distinct HII region must have a least a $4.5\sigma$ valley between its peak and any pixels in a neighboring HII region (see step 6 above).

In the course of refining the measurement technique several of the parameters were experimented with and the results compared with what we would have selected by 'eye' as distinct HII regions. For example, the percentage of the peak flux above which pixels can be added and the level below which the image was truncated (finally adopted at $2.5\sigma$) were varied. The results were not extremely sensitive to the precise values of these parameters. The sample area north of the nucleus is shown in contour form for Hα in the upper left panel of Fig. 7 and the derived features are illustrated in in the lower right panel of Fig. 7.

The algorithm was also tested on a simulation image in which spherical HII regions with a uniform distribution of Lyman continuum output (with a range of $10^{2}$) were positioned randomly within a 3-d spatial cube. The regions were postulated to have identical electron densities so as the the Lyman continuum increased, the HII region diameter would be larger. The cube was then projected on two dimensions and processed with the HII region finding algorithm. The HII regions found agreed very closely with the input HII region locations and sizes. The simulation and measurement was run for increasing numbers of input HII regions ranging from 10 to 100 in order to test the effects of blending. (Given the input sizes of the HII regions and the size of the 3-d cube, the case with 150 regions corresponded to very severe blending.) In all instances, the HII region finding algorithm found the correct number and parameters for the input regions (to within $\leq 20\%$). Test fits for the dependence of the total flux on the measured diameter was typically $L_\alpha \propto D^{2.75}$, compared to the theoretical $D^3$ dependence – probably due to limited spatial resolution. The fact that the results came so close to recovering the input parameters was particularly
reassuring in the case of the 100 region simulation since the images were heavily blended in this case.

Once the boundaries of the H$\alpha$ emission regions were defined, the peak, the integrated flux, the emission centroid coordinates and number of pixels within each region were catalogued. The size of each region was calculated as (area)$^{1/2}$.

The final list has 1373 H$\alpha$ emission regions: 1321 having at least 3 pixels and 1273 having 5 or more pixels. The largest region associated with the nuclear AGN jet had 895 pixels was excluded from the following analysis. The total flux of the 1373 discrete HII regions constitutes 31% of the total H$\alpha$ flux from the area of the galaxy covered in the WFPC2 images; the remaining flux constitutes the DIG emission, discrete HII regions with peak flux below our 6$\sigma$ peak requirement and possibly some unremoved continuum. Given the low surface brightness of the residual flux (and its low SNR) we do not feel the data enable an investigation of the source of the DIG emission – specifically whether it is truly diffuse or simply discrete, but low surface brightness HII regions.

As a check of the HII region definition and measurement routines, we compared our results for selected individual regions with ground-based H$\alpha$ measurements (Rand 1992, Petit et al. 1996, Thilker et al. 2000). Although Rand (1992) did not publish his individual HII region measurements, he did provide us with his HII region list in tabular form. Fig. 8 shows the locations of the H$\alpha$ emission regions from Rand’s and our samples. Generally, good agreement can be seen in the areas of common coverage (i.e. excepting the nucleus which was not measured by Rand and the outer disk which was not covered in our images). However, in most cases, the higher resolution HST data resolves multiple HII regions within individual regions identified in the ground-based imaging. This is illustrated in Fig. 8 which shows the HST data in a small area north of the nucleus at the original HST resolution and smoothed to 1.5″ resolution to simulate ground-based imaging. In the area covered in
our study, there were 17 regions catalogued by Rand which were not catalogued by us. We therefore also compared with the HII region catalogue of Petit et al. (1996) and in most cases the regions catalogued by Rand but not seen by us were also not present in Petit et al. (1996); however, the Petit survey had lower sensitivity than Rand’s. As an additional check, we also examined on a case by case basis the 17 Rand regions which we did not find. For one, we saw no evidence of a source in either the Hα or the Hα+continuum image; one was on the edge of our field; and the remaining regions had peaks between 3.4 and 5.6σ in our images. Thus the latter sources did not meet our 6σ criterion for the peak flux. In fact, the excellent correspondence between our sample and Rand’s is quite impressive given the fact that our resolution is approximately 100 times smaller in area and therefore an extended, low surface brightness feature in Rand’s image could easily be missed here.

Comparison of our fluxes with Rand’s was not straightforward since he did not remove the large-scale diffuse background but rather a local background (immediately around each region). Nevertheless, the results appear consistent: for 10 regions with well-defined, bright Hα emission, the integrated fluxes were found to agree within 25% in all cases. The peak fluxes and sizes are of course resolution dependent and perfect agreement should not be expected. Thilker et al. (2000) also compared their results with Rand’s (1992) measurements and found good agreement.

Thilker developed an iterative grouping algorithm for delineation of HII region structures and he kindly made his routines available. In the end, we developed our own algorithm for reasons of simplicity, familiarity with our routine and speed of execution. Nevertheless, we did test the two procedures in the area of the northern spiral arm shown in Figs. [3] the regions which were defined were consistent but not identical.

Our algorithm was also run on the Pα image (using the same parameters specified in terms of the image noise level), yielding 232 Pα regions. All except three of these regions
were inside one of the previously found Hα regions; however, in most cases the boundaries were somewhat different. Usually, the Pα region was smaller in size, due to the intrinsically lower flux and SNR of Pα. In a few instances, the peak of the Pα was very significantly shifted from the Hα peak and it appears that these are regions with particularly high extinction at the location of maximum Pα emission.

6. Clustering of HII Regions

In order to quantify the effects of HST versus ground-based image resolution and to illustrate the clustering of the HII regions measured here, we have computed the two-point angular correlation function for the measured centroid positions of the 1373 HII regions (top panel of Fig. 9). In the lower panel of Fig. 9, the correlation function is shown for pixels with Hα emission exceeding 3σ (in the same Hα image with background subtraction which was used for defining and measuring the discrete HII regions. In both instances, the angular sampling of the images was normalized by the correlation function for pixels sampled randomly within the observed region. However, due to the linear association of HII regions along the spiral arms and the fact that their number is generally increasing towards small galactic radii, the purely random normalization does not remove large-scale correlations – thus neither correlation function goes asymptotically to 0 at large angles nor does the integral equal 0.

Both correlation functions clearly show a strong clustering inside 2″, corresponding to 92 pc. This is inside the spatial scale sampled in ground-based Hα images, indicating that a large number of the regions classified from ground-based imaging are resolved into multiple regions at the 0.1″ resolution used here. Pleuss et al. (2000) reached a similar conclusion based on a Minimal Spanning Tree analysis of HST images for M101.
The correlation function for the discrete HII regions (top panel) shows a decrease inside 1″ which is a result of the fact that the algorithm used to define the HII regions necessarily requires at least one pixel lower by 40% between any two HII regions in order to subdivide an Hα emission region into two regions.

In Fig. 10 the percentage of HII regions with nearest neighbors with separation less than θ is shown as a function of θ. 47% have their nearest neighbor within 1″ and 81% within 2″. Only 10% have their closest nearby HII region more than 4″ away. Both the correlation function and Fig. 10 clearly show that the HII regions are strongly correlated on scales less than 2″.

7. Luminosity Functions

The observed (uncorrected for extinction) Hα luminosity function is shown in Fig. 11 together with those derived by Rand (1992) and Petit et al. (1996), using only HII regions from their studies which are in the same area of the galaxy covered by us. The two ground-based luminosity functions extend at least a factor of 5 higher in luminosity. This is due to the fact that all of the most luminous regions catalogued in the ground-based studies were either resolved into multiple regions in our sample.

To characterize the luminosity function, we express it as a truncated power law: in differential form,

\[
\frac{d N(L_{H\alpha})}{d \ln L_{H\alpha}} = N_{up} \left( \frac{L_{H\alpha}}{L_{up}} \right)^\alpha
\]

and in integral form,
\[ N(\geq L_{H\alpha}) = \frac{N_{up}}{-\alpha} \left[ \left( \frac{L_{H\alpha}}{L_{up}} \right)^{\alpha} - 1 \right] \]  

(McKee & Williams 1997). (Note that we adopt the opposite sign convention for \( \alpha \) from that used by McKee & Williams 1997.) As pointed out by McKee & Williams (1997), this form has the advantage of having clear physical interpretations for the parameters. Specifically, \( L_{up} \) is the highest luminosity region, \( N_{up} \) is approximately the number of regions between 0.5 \( L_{up} \) and \( L_{up} \) for \( \alpha \sim -1 \) and \( N_{up}/-\alpha \) is the number of regions expected above \( L_{up} \) if the distribution were not truncated (i.e. one can directly see if the distribution is 'significantly' truncated or terminated by low number statistics).

Fitting Eq. 2 to the apparent luminosity function yields \( \alpha = -1.01 \pm 0.04 \), compared to \(-0.50 \) and \(-0.32 \) derived for the Rand (1992) and Petit et al. (1996) samples over the range \( 40 - 800 \times 10^{36} \text{ erg s}^{-1} \). (Since these fits are for source counts binned logarithmically in \( L_{H\alpha} \), the exponents should be decreased by 1 for \( N(L)dL \).) Our power-law index is substantially steeper than that derived from previous studies (Kennicutt et al. 1989, Rand 1992, Petit et al. 1996 & Thilker et al. 2000) due to the fact that the higher angular resolution resolves the more luminous, apparently blended regions. The slope derived here is similar to that of Galactic radio HII regions (\( \alpha = -1 \) to \(-1.3 \); see §12).

In addition to a steeper slope, we also find that the observed luminosity function doesn’t extend to as high luminosity as the ground-based LFs due to our resolving the larger regions. However, the lower maximum-observed luminosity obtained here is compensated by high extinction corrections (see §10). The mean extinction derived in §10.2 for the discrete H\( \alpha \) emission regions is \( A_{H\alpha} = 0.798 \times <A_V> = 0.798 \times 3.1 = 2.47 \text{ mag} \). If this is applied on-average to all HII regions, then the observed H\( \alpha \) luminosity functions are increased by a factor of \( \sim 10 \) (§10.2).

The observed luminosity functions differentiated between arm, interarm and nuclear
areas are shown in Fig. [12]. These three areas are defined and illustrated in Polletta et al. (2001). Over the luminosity range $L_{H\alpha} = 12 \rightarrow 500 \times 10^{36}$ ergs s$^{-1}$, logarithmic truncated power-law fits have exponents $-0.72 \pm 0.03$, $-0.95 \pm 0.05$, and $-1.12 \pm 0.11$ for the arm, interarm and nuclear (excluding the nuclear jet) regions, respectively (see Table 2). Thus, the luminosity function is significantly flatter in the spiral arms than in the interarm regions. Rand (1992) and Thilker et al. (2000) also found steeper luminosity functions in the interarm regions (exponent $-0.93 \rightarrow -0.96$ versus $-0.48 \rightarrow -0.72$); however, the actual values of their slopes in the interarm and arm areas are somewhat different from ours.

There are several possible explanations for the flatter luminosity functions in the arms and the nucleus compared to the interarm regions: 1) the surface density of HII regions is higher in the arms, causing more blending/clustering which in turn produces a large number of apparently high luminosity regions; 2) the OB star cluster mass functions are significantly different in the two areas; and 3) the interarm HII regions and associated OB star clusters are, on average, older and therefore have evolved to lower Ly continuum output levels. The only way there could be a systematically older population of clusters in the interarm regions than in the arms would be if the OB star clusters in the disk formed within the arms and then aged as they moved into the interarm regions. However, the duration of the Lyman continuum emission from a coeval cluster is far too short ($\leq 3 \times 10^6$ yr; see §13.2) compared to the time ($\geq 3 \times 10^7$ yr) needed to migrate into the interarm regions for this explanation to be viable. Although the second explanation can not be ruled out at present, we think that the level of blending/clustering expected in the spiral arms is entirely consistent with the notion that many of the most luminous regions are, in fact, blends. One supporting piece of evidence for this is the clear trend for the most luminous regions to be the most extended and to have the lowest densities (see §9).

The fitting results summarized in Table 2 clearly show a significant truncation of the
luminosity functions at \( L_{up} \simeq 4 \times 10^{38} \) erg s\(^{-1}\). The last columns of Table 2 give the fitted \( N_{up} \) and \( N_{obs}(L > L_{up}) \). As noted in the discussion following Eq. 2, the truncation is significant if \( N_{up}/-\alpha > > N_{obs}(L > L_{up}) \). This is indeed true for all four fits (based on comparison of the last two columns in Table 2), strongly suggesting a physical or observational limitation to the maximum luminosity of the HII regions.

In none of the luminosity functions do we see evidence of the break in the slope at \( L_{H\alpha} \sim 10^{38.6} \) ergs s\(^{-1}\) which has been reported in some ground-based studies (Kennicutt et al. 1989 and Rand 1992). (We did experiment with smoothing our H\( \alpha \) images by a factor of 4, then redefining the boundaries and determining the luminosity function. The result was that the derived luminosity function became shallower and developed a spectral break; however, since the break was somewhat lower in luminosity than \( 10^{38.6} \) ergs s\(^{-1}\) and we cannot say that it is a result of blending.)

8. Lyman Continuum Emission Rate

The observed HII regions range in luminosity from \( L_{H\alpha} = 2 \times 10^{36} -- 2 \times 10^{39} \) erg s\(^{-1}\). For case B recombination the \( H\alpha \) luminosity is

\[ L_{H\alpha} = 3.55 \times 10^{-25} \left( \frac{T_e}{10^4 K} \right)^{-0.91} n_e n_p V \ \text{erg s}^{-1} \tag{3} \]

where \( V \) is the volume of the HII region and \( n_e \) and \( n_p \) are the electron and proton volume densities (Osterbrock 1989). Since absorptions by He do not significantly reduce the number of photons available to ionize H (Osterbrock 1989), the required Lyman continuum production rate, \( Q_{LyC} \), is then given by
The observed Hα luminosities therefore translate to $Q_{\text{LyC}} = 2.2 \times 10^{48} \text{--} 1.5 \times 10^{51} \text{ s}^{-1}$ for $T_e = 10^4 \text{ K}$. Extinction corrections are discussed in §10.

9. HII Region Sizes and Densities

The HII region luminosities and their Lyman continuum emission rates constrain the implied masses of the OB star clusters; similarly the sizes and electron densities of the HII regions reflect on the evolution of their Strömgren spheres and the surrounding ISM.

9.1. Sizes

The distribution of HII region sizes ($D = 2 \times (\text{area}/\pi)^{1/2}$) is shown in Fig. [3] for all regions with at least 2 pixels. They range from 10 to 250 pc in diameter; those $\geq 120$ pc were not plotted since they are clearly blends. The lower limit of 10 pc is due to the minimum 2 pixel criterion. The mean sizes are 30 — 34 pc in arm, interarm and nuclear regions (Fig. [3]). Both the shapes of the distributions and the mean sizes are similar for all three areas. The majority of the HII regions have size $\leq 50$ pc and thus could be associated with a single or a few OB star cluster(s). Those regions with larger sizes are very likely blended superpositions of multiple (but possibly related) OB associations (see §11).

9.2. Electron Densities ($n_e$)

Since the Hα luminosities are proportional to the volume-integrated emission measures, the mean electron density can be obtained using the measured sizes:

$$Q_{\text{LyC}} = 7.32 \times 10^{11} L_{\text{H} \alpha} \left( \frac{T_e}{10^4 \text{K}} \right)^{0.11} \text{ s}^{-1}. \quad (4)$$
\[
< n_e > = 43 \left( \frac{\left( L_{H\alpha \ cor} / 10^{37} \text{ erg s}^{-1} \right)}{(D/10 \text{ pc})^3} \right)^{1/2} \left( \frac{T/10^4 K}{10} \right)^{0.91} \text{ cm}^{-3}.
\] (5)

In Eq. 5, we normalized to typical values of \( L_{H\alpha \ cor} = 10^{37} \text{ erg s}^{-1} \) and a size of 10 pc. The derived \( < n_e > \) for the HII regions are distributed mostly between 5 and 20 cm\(^{-3}\).

In Fig. 14 the HII region luminosities and sizes are plotted as functions of mean electron density. The sharp boundaries to the distributions on the lower side are due to the surface brightness threshold and the minimum size of 1 pixel within the HII region. The average value is \( < n_e > \simeq 13 \text{ cm}^{-3} \) for sizes less than 40 pc. If the apparent \( n_e \) are corrected for the average extinction correction (Eq. 8), the mean densities are increased by a factor of 3 to \( < n_e > \simeq 39 \text{ cm}^{-3} \) which is similar to that of resolved Galactic HII regions (\( n_e \sim 100 \text{ cm}^{-3} \)).

In the above estimates we have made no corrections for the fact that many of the HII regions are only marginally resolved; such corrections would of course increase the mean densities further. Some of the larger regions undoubtedly do include substantial empty or neutral volumes. Moreover, there are substantial gradients in the \( H\alpha \) surface brightness within individual regions, indicating that the internal densities are non-uniform and commonly increase several-fold at the peaks.

### 9.3. Luminosity vs Size: HII Region Blending

In Fig. 15, the HII region luminosities are plotted as a function of their measured sizes. There is a clear trend for the more luminous regions to be more spatially. Although such a trend is certainly expected, since more luminous OB associations can ionize a larger volume of gas, the observed dependence is shallower than the \( D^3 \) dependence expected if the electron densities were constant. Specifically, the more luminous and larger regions appear to have lower average \( n_e \). The luminosity versus size data is fit well by \( L \propto D^2 \).
(The lower limit of the data points in Fig. 13 is caused by the observational threshold on the surface brightness. However, this threshold can not account for the decrease in density for larger regions – if the larger regions had the same densities as the smaller regions, they would more easily make it into our sample.) The proper explanation for the correlation is almost certainly that the larger regions are blended and they include substantial empty or neutral volumes or equivalently, that the large HII regions may have expanded outside their progenitor GMCs.

In fact, it is easily shown that for superposed or blended HII regions one expects precisely the $L \propto D^2$ correlation which is observed. If the boundaries of 'N' multiple regions of the same size just overlap as projected on the plane of the sky, their total projected 'size' ($D_T$), computed as the square root of the sum of the total area, is given by $D_T^2 = N \times D_i^2$. Since the total luminosity of the blended region is $L_T = NL_i$, then we expect $L_T = D^2 \times L_i/D_i^2$. This result is obviously not dependent on the HII regions being identical; the observed correlation between luminosity and size is thus strong evidence that the high luminosity regions are blends or superpositions of multiple lower luminosity regions. This is certainly not surprising based on observations of Galactic HII regions which often showed multiple centers of ionization on scales of less than a few parsec (see §12).

10. HII Region Extinctions from $H\alpha/P\alpha$

For case B recombination in an ionization-bounded HII region, the intrinsic flux ratio for $H\alpha/P\alpha$ is 8.15 and the non-Lyman series lines should be optically thin (Osterbrock 1989). (For a density-bounded HII region, the case A recombination line ratio is $H\alpha/P\alpha = 6.14$ but Case B is generally adopted as more appropriate for high surface brightness, discrete HII regions.) The observed flux ratios can be less than 8.15 due to the higher extinction at the $\lambda = 6563$Å ($H\alpha$) compared to 1.87µm ($P\alpha$). We have used the observed
ratios to estimate the mean extinctions of each HII region detected in both lines, using the relation

\[ A_V = 3.75 \times \log \left( \frac{8.15 \, F_{P\alpha}}{F_{H\alpha}} \right) \text{ mag.} \]  

(6)

The constant in Eq. 3 was derived assuming the standard Galactic extinction curve (Rieke & Lebofsky 1985, Cardelli et al. 1989) and assuming the dust is distributed in a foreground screen, uniformly covering each pixel.

After smoothing the H\(\alpha\) to the same resolution as P\(\alpha\), we measured the H\(\alpha\)/P\(\alpha\) flux ratios and extinctions at all pixels within the HII region boundaries using only pixels which had both H\(\alpha\) and P\(\alpha\) detected at \(\geq 5\sigma\). 209 HII regions met these criteria. (If the H\(\alpha\) is smoothed to the P\(\alpha\) resolution, the HII region finding algorithm found 702 regions. However, for the extinction analysis here, we adopted the original high resolution HII region definitions simply because they yielded better boundary definition.) Flux ratios and extinctions were then estimated for each HII region by averaging the pixel- ratios and extinctions, rather than from ratios of the HII region-integrated fluxes. The distribution of these average flux ratios and \(A_V\)s for the 209 regions is shown in Fig. [10]. The mean extinctions are: \(A_V = 3.1\) mag (weighting each region equally), 2.4 mag (weighting each by the observed HII region luminosity) and 3.0 mag (weighting by the extinction-corrected luminosity). The derived mean extinctions are in reasonable agreement with the values (\(A_V = 0.8 - 4\) mag) obtained by van der Hulst et al. (1988) for a sample 37 HII regions in M51 comparing H\(\alpha\) and radio free-free fluxes at 8" resolution. For 14 of the regions, the Balmer decrements yielded considerably lower values (in the range \(A_V = 0.4 - 2.4\) mag; van der Hulst et al. 1988) but these are optically biased towards lower extinction regions. It should be pointed out that since the HII region boundaries were defined from the H\(\alpha\) images, the analysis above excludes regions of extremely high extinction in which the P\(\alpha\) emission is
significantly offset from H$\alpha$. The derived extinctions would have very likely been higher if
the P$\alpha$ had been used to define the HII regions. We used H$\alpha$ for delineating the HII region
boundaries simply because of the higher SNR and resolution.

In Fig. 17, the derived extinctions of the 209 regions are plotted against the observed
(not extinction-corrected) H$\alpha$ luminosities. In this figure, the filled circles are the average
values in separate luminosity bins. No strong correlation (or anti-correlation) is seen
between the observed luminosities and the derived extinctions as might be expected if the
flux variations were largely due to extinction variations. The filled-circle averages do show
a weak correlation in the sense that the fainter regions have somewhat higher extinction,
but the dispersion within bins is clearly much larger than the trend.

We also measured the flux ratios and derived extinctions for all pixels in the H$\alpha$ and
P$\alpha$ images which were both detected at $\geq 5\sigma$, independent of whether or not they were
inside one of the discrete H$\alpha$ regions. The results (shown in Fig. 18) are entirely consistent
with those found within the discrete HII regions (Fig. 16). When the selection threshold
was increased to 10$\sigma$, the results were also similar, implying that the larger extinction
values are not simply the result of poor signal-to-noise or a bias in either image.

10.1. Extinction Gradients Across HII Regions

Detailed comparison of the H$\alpha$ and P$\alpha$ images reveals that most individual HII regions
also have very large variations in the H$\alpha$/P$\alpha$ ratio across their areas. (It is for this reason
that the ratios and extinctions for each region were computed in §8.0 as averages of the
values from individual pixels rather than from ratios of the integrated fluxes.) In Fig. 18
the area to the west of the nucleus is shown with H$\alpha$ in red and P$\alpha$ in green (with no
continuum added). Several of the emission regions show entirely different morphology and
peak locations in the optical and near infrared lines. The gradients and peak offsets vary from region to region; they therefore aren’t due to misalignment of the images. In fact, there are several examples in this image of emission regions in P\(\alpha\) which are hardly detected in H\(\alpha\), indicating extinctions in excess of 4 mag. There are also many regions which are seen in H\(\alpha\) but not P\(\alpha\) but this is simply due to the intrinsically high flux of H\(\alpha\) together with the lower sensitivity of the P\(\alpha\) image.

### 10.2. Extinction-Corrected HII Region Luminosities

The extinction-corrected H\(\alpha\) luminosity is obtained from

\[
L_{H\alpha\ cor} = 10^{0.320 \times A_V} \times L_{H\alpha\ uncor},
\]

using the standard ISM extinction curve \cite{Rieke1985} for which \(A_{H\alpha} = 0.798 A_V\). For the mean extinction (\(A_V = 3.1\) mag; \S 10), the observed luminosities are increased by factors of \(\sim 9.9\) and we will adopt the an average correction factor of

\[
< f_{H\alpha\ ext-cor} > \simeq 10
\]

as an appropriate general extinction correction where individual extinctions are not available.

The extinction-corrected and observed luminosity distributions are shown in Fig. 19 for the 209 regions detected in both H\(\alpha\) and P\(\alpha\). (The extinction-corrected luminosity of each region was calculated by correcting each pixel for its extinction and then summing the extinction-corrected pixel luminosities.) The extinction-corrected distribution exhibits a broad peak at approximately \(L_{H\alpha} = 10^{38}\) erg s\(^{-1}\) and the most luminous region is at \(3 \times 10^{39}\)
erg s$^{-1}$. The falloff on the low luminosity side is not real since the sample has a detection threshold and there are no regions from below the threshold which can populate the low end after being corrected for extinction. The distributions shown in Fig. 19 should not be interpreted as luminosity functions since they do not include all pixels in each region, only those pixels detected at $\geq 5\sigma$ in both lines. The critical point we make from Fig. 19 is that the net result of extinction corrections when they are derived on a case-by-case basis is to shift the luminosity distribution up a factor of 10 in luminosity.

11. HII Region Sample with Diameter $\leq 50$ pc

The most luminous emission regions in our sample are quite clearly blends or superpositions of HII regions with multiple OB star clusters producing the ionization. Their sizes are typically $> 50$ pc (see Fig. 15 and $\S 9.1 - \S 9.2$). Fifty pc is a very conservative upper limit to the size of a region which might plausibly be ionized by a single compact OB cluster. This is because the MS sequence lifetime is only $3\times10^6$ yrs for the OB stars which produce most of the ionizing photons. Within this time, the ionized gas can expand only to radius $\sim 30$ pc even if it is freely expanding at the sound speed ($10$ km s$^{-1}$) of the $10^4$ K gas and after the source of ionization is turned off, the gas recombines on a relatively short timescale ($\leq 10^4$ yrs for $n_e \geq 10$ cm$^{-3}$). Thirty parsec is therefore a very conservative maximum radius for the HII region ionized by a single, coeval cluster of stars. It is a 'conservative' maximum since the expansion is usually much slower than $10$ km s$^{-1}$ even if the surrounding, neutral gas has density $\leq 10$ cm$^{-3}$ (e.g. Osterbrock 1989).

Of course, the early growth of the HII region to its initial Strömgren radius can be faster but this initial phase takes place in higher density regions and the resulting Strömgren radius is much smaller. The subsequent evolution is hydrodynamic and this is certainly the phase in which we see the observed HII regions. In late phases if the HII
region becomes density-bounded, the ionization front might expand at a higher speed but this would correspond to the DIG HII regions.

In Fig. 20 we show the distribution of observed Hα luminosities for all 1101 HII regions in our sample with diameters ≤ 50 pc. The range of observed $L_{H\alpha}$ is $2 \times 10^{36}$ to $1 \times 10^{38}$ erg s$^{-1}$. Since the derived extinctions are approximately independent of apparent Hα luminosity (Fig. 17), we conclude that the maximum intrinsic luminosity of unblended HII regions is a factor of 10 higher or

$$Max\ single\ cluster\ L_{H\alpha\ cor} \simeq 10^{39}\ ergs^{-1}$$  \hspace{1cm} (9)

and the maximum Lyman continuum production is

$$Max\ single\ cluster\ Q_{LyC} \simeq 7 \times 10^{50}\ s^{-1}.$$  \hspace{1cm} (10)

Once again, this is a conservative upper limit since some of the regions in the ≤ 50 pc sample are also likely to be blends.

12. Comparison with Galactic HII Regions

For comparison with Galactic HII regions we make use of radio continuum observations of the free-free continuum to avoid Galactic line-of-sight dust obscuration. Radio studies have concentrated on ‘compact’ HII regions which are relatively young and have high surface brightness. Schraml & Mezger (1969) observed 18 free-free emission complexes at $\lambda = 2$ cm with 2’ resolution (typically corresponding to 0.5 — 5 pc) and we make use of their sample for our discussion. Their results are summarized in Table 3 for M43, M42(Orion Nebula), IC1795(W3), W51, and W49 (ordered with increasing luminosity).
Comparing the implied L$_{H\alpha}$ of the Galactic HII regions with the extinction-corrected Hα luminosities ($\S$11) for the sample with D $\leq$ 50 pc, it can be seen that the first value in the M51 distribution function corresponds to a few times M42 and the max single cluster L$_{H\alpha \, cor}$ (Eq. 9) corresponds to W49. Since W51 and W49 are the most luminous Galactic HII regions, we conclude that the M51 sample spans approximately the full range of Galactic compact HII regions (perhaps not sampling to the lowest luminosities but that depends on the order of magnitude extinction correction adopted for M51). For reference, we also note that the 30Dor cluster in the LMC is a few times more luminous than W49. The diameter of the 30Dor stellar cluster is $\sim$ 20 pc and the associated Hα emission extends over $\sim$ 100 pc. In the full sample of M51 regions (Fig. 11), the most luminous is at an observed $L_{H\alpha} = 2 \times 10^{39}$ erg s$^{-1}$; if this region has a modest extinction, it’s luminosity would be 20 times that of W49. This is another reason for believing that the most luminous Hα regions in M51 are blended.

Although the luminosity range of M51 HII regions with D $\leq$ 50 pc is similar to that of the Galactic regions listed in Table 3, their sizes are typically several times larger and their mean densities lower. These differences have several likely explanations: the Galactic regions were selected for high surface brightness free-free emission (ie. compact radio HII regions) in order to avoid possible extended, missing flux; the M51 regions are still only marginally resolved and undoubtedly would include compact cores at higher resolution; or some of the Galactic regions may be in an earlier stage of their evolution before they have fully expanded. Despite these differences, the ionizing luminosities are similar and it is those luminosities which we use in the next section to probe the OB star cluster mass distributions and temporal evolution in M51.

The luminosity function of Galactic radio HII regions has been fit by Smith & Kennicutt (1989) and McKee & Williams (1997) who found power law indexes of -1.3
and -1.0, respectively – consistent with our value of -1.01 for M51. Although McKee & Williams (1997) derive an upper limit for the Lyman continuum emission rate from Galactic HII regions of $Q_{LyC \, up} = 4.9 \times 10^{51} \, s^{-1}$ (including a correction of 25% for absorption by internal dust), the actual maximum observed (W49) is only $7 \times 10^{50} \, s^{-1}$. The latter value is consistent with our M51 extinction-corrected upper limit $Q_{LyC \, up} \sim 7 \times 10^{50} \, s^{-1}$ (eq. 10, from the 50 pc sample). Our estimate has no corrections for dust absorption of the ionizing photons or UV escaping into the diffuse medium. The latter factor adopted in the McKee & Williams (1997) study is very large ($1/0.29 = 3.45$). They obtained this number by assuming the entire discrepancy between the far-infrared COBE measurements of [NII] and the sum of the Ly continuum from discrete HII regions was due to leakage of ionizing UV out of the regions measured in radio free-free. Alternatively, much of the discrepancy might be due to older or lower mass OB associations (which are undetected in the Galactic radio sample), ionization by other sources or even uncertainties in the analysis of the COBE data. We do not include this factor in view of its large uncertainty and because we wish to compare discrete HII regions in M51 with comparable objects in the Galaxy.

13. OB Star Clusters and HII Region Evolution

In order to understand the nature of the constraints provided by the observed HII region Hα luminosities and their distribution, we develop here a simplified model for OB star clusters and HII region evolution. The critical constraints which we wish to understand are:

1) the slope of the luminosity function on the high luminosity end ($d\,N(L)/d\,\ln L \propto L_{H\alpha}^{-1.01}$, Eq. 1) — to what extent is this due to the evolutionary decay of the Lyman continuum emission from clusters as they age, as opposed to the mass spectra of the clusters and their high-mass stars; and
2) the existence of an 'approximate' maximum luminosity for individual OB star clusters at $L_{\text{H}\alpha} \sim 10^{39}$ erg s$^{-1}$. (This maximum is surprising in view of the fact that it corresponds to a cluster of only a few $\times 10^3$ $M_\odot$ yet GMCs contain $10^{5-6}$ $M_\odot$ of molecular gas; thus, there is sufficient mass available to form much more massive clusters.)

### 13.1. Model Stellar and Cluster Parameters

For each OB star cluster, we assume the star formation occurs on a timescale short compared to stellar evolution timescales. We adopt a Salpeter initial mass function (IMF) with $N(m_*) dm_\ast \propto m_\ast^{-2.35}$ over the range $m_l - m_u$ (here, taken to be 1 and 120 $M_\odot$, respectively) rather than the local Galactic IMF (Scalo 1987). The Salpeter IMF is consistent with the recent determinations for OB associations which have power-law indexes in the range $-2.1 \rightarrow -2.45$ (Massey et al. 1995) and the 30Dor cluster in the LMC (Selman et al. 1999).

The stellar lifetimes and Lyman continuum emission rates are based on stellar models with constraints provided by observations of individual high-mass stars. Main sequence lifetimes and bolometric luminosities are from Renzini and Buzzoni (1986) and Maeder (1987) for $\leq 10 M_\odot$ and $\geq 10 M_\odot$, respectively. For reference, the MS lifetimes are 8.6, 4.5, 3.8 and 3.3 $\times 10^6$ yr for 20, 40, 60 and 80 $M_\odot$. The ionizing photon production rates ($Q_{LyC}$) are from Vacca, Garmany & Shull (1996). These are shown in Fig. 21.

In building up the stellar population of a star cluster, we take advantage of the fact that the stellar IMF should be interpreted as a probability distribution and that even the low mass clusters will have the same proportion of high and low mass stars, independent of the cluster mass (subject to the condition that a very low mass cluster can’t have a star of mass greater than that of the cluster). Thus, if one samples enough low mass clusters,
their average population is the same as a single high mass cluster with the entire range of stellar masses sampled. An ensemble of lower mass clusters will therefore have the same Lyman continuum output per unit cluster mass as a higher mass cluster with a 'saturated' IMF (Oey & Clarke 1999). For this reason, if one is interested in the behavior of the high luminosity tail of the luminosity function (and not the dispersion of the luminosity function at lower 'unsaturated' luminosities), one can calculate the evolution of a single 'saturated' cluster and scale the properties directly with cluster mass to derive the mean properties of lower mass clusters.

13.2. Evolution of Cluster Luminosity and $Q_{LyC}$

Once assembled, we track the evolution of the cluster Lyman continuum and luminosity, removing high mass stars after their MS lifetimes. In Fig. 22 the temporal evolution of the Lyman continuum emission rate and total luminosity are shown scaled to a cluster mass of $10^3 \, M_\odot$ (between 1 and 120 $M_\odot$). For lower or higher mass clusters the mean $Q_{LyC}$ and $L$ can be scaled linearly with mass (as long as one is analyzing a large population of clusters). Assuming formation of all stars in the cluster in a time short compared to the stellar evolution times, the Lyman continuum emission rate will remain constant until an age equal to the main sequence lifetime of the most massive stars ($\sim 3 \times 10^6$ yrs – see above and Fig. 21). Subsequently, Q will decay exponentially in time with an e-folding time of $\sim 10^6$ yrs out to $10^7$ yrs at which point the Ly continuum is relatively insignificant (Fig. 22).

Integrating over the lifetime of the $10^3 \, M_\odot$ cluster, the total number of Lyman continuum photons is $1.2 \times 10^{64}$. This implies $1.2 \times 10^{61}$ Lyman continuum photons per solar mass of stars between 1 and 120 $M_\odot$ or equivalently $4.8 \times 10^{60}$ Lyman continuum photons per solar mass of stars between 0.1 and 120 $M_\odot$. The latter estimate is 65% greater than that derived by Kennicutt, Tamblyn & Congden (1994) for the same IMF
and mass range. The agreement is quite acceptable given the fact that their relation was derived using Kurucz (1992) model atmospheres rather than the Vacca et al. 1996 observationally-constrained ionizing outputs which are generally higher than Kurucz’s.

Thus for a steady state star formation rate SFR, the OB clusters yield

\[ \frac{Q_{LyC}}{SFR} = 1.52 \times 10^{53} \text{sec}^{-1}(M_\odot\text{yr}^{-1})^{-1} \]  

(11)

for a Salpeter IMF between 1 and 120 $M_\odot$. This result is useful for estimates of time- and global-averaged star formation rates (see §14).

13.3. Cluster Masses

The extinction-corrected H\(\alpha\) luminosities for the HII region sample with diameters \(\leq 50\ \text{pc} \) (§11) imply maximum Lyman continuum emission rate of $Q_{LyC} = 7 \times 10^{50} \text{ s}^{-1}$. This corresponds to cluster mass of \(7 \times 10^3\ M_\odot\) (see Fig. 22) and a typical mean mass is \(\sim 10^3\ M_\odot\). Above approximately \(10^3\ M_\odot\), the cluster contains a reasonable sampling of all stellar masses and the stellar population is said to be 'saturated' (cf. Oey & Clarke 1999). The Lyman continuum production rate grows linearly for further increases in the cluster mass. If the Salpeter IMF is extended down to 0.1 $M_\odot$, the total cluster mass estimate is increased by a factor of 2.5.

We should stress that given the large number of HII regions occupying the unsaturated (flat) part of the luminosity function, estimates of the individual cluster masses for these unsaturated HII regions is clearly very risky based on H\(\alpha\) luminosities (or any Lyman continuum measure). Since their stellar populations are poorly sampled, the ratio of UV output to total stellar mass must fluctuate greatly from one unsaturated region to another. And of course, since these regions are selected for having detectable H\(\alpha\), they will be biased
towards high ratios of LyC per solar mass of stars.

13.4. HII Region Luminosity Functions

In order to model the observed HII region luminosity function, one must sample the modelled OB star clusters over a range of cluster masses and over the lifetime of the OB stars. Assuming approximately coeval star formation, the temporal evolution of the Lyman continuum luminosity from the clusters is determined by stellar evolution of the highest-mass stars. The luminosity function of the HII regions can then be modelled by sampling uniformly in time the Lyman output from each cluster mass, weighted by the initial mass distribution of clusters.

In analogy with the treatment of stellar IMF, we assume that the initial cluster masses can also be represented as a power-law:

\[ N(M_{cl})dM_{cl} \propto M_{cl}^\Gamma. \]  

(12)

In Fig. 23 the luminosity functions are plotted for 5 values of the mass power law index \( \Gamma \) between -1 and -3 (Eq. 12). The slope of high luminosity end of the luminosity function is directly determined by the cluster mass spectrum index \( \Gamma \) (McKee & Williams 1998) since the highest luminosities are contributed by 'saturated' clusters during their initial constant luminosity phase \((< 3 \times 10^6 \text{ yrs})\). The model luminosity functions shown in Fig. 23 clearly show that flat or nearly flat distributions of cluster mass are ruled out by the observed luminosity functions. An excellent match to the observed luminosity function power law index -1.01 is thus provided by \( N(M_{cl})dM_{cl} \propto M_{cl}^{-2.01} \) with variations of \( \Delta \Gamma = \pm 0.15 \) between arm and interarm regions. The derived power law index for the cluster mass spectrum is close to but not identical to that \((\Gamma \simeq -1.6, \text{ Scoville & Sanders 1978})\) of
Galactic GMCs.

Thilker et al. (2001) did a similar analysis of their Hα measurements to obtain an initial cluster mass spectrum \( N(M_{cl})dM_{cl} \propto M_{cl}^{-2} \) (after exploring a range of \(-1.75 \rightarrow 2.25\)). Both ours and their results provide strong evidence of a steeply falling cluster mass spectrum. These cluster mass spectra are also in excellent agreement with the value \( \Gamma = -2 \) derived by Larsen (2000) and Bik et al. (2001) from UBV photometry of the clusters in M51 (as opposed to the ionized gas).

The luminosity functions shown in Fig. 23 were computed for a cluster mass range between 500 and 5000 \( M_\odot \). The adopted upper limit in the cluster mass produces the cutoff in the luminosity function at \( Q_{LyC} = 4 \times 10^{50} \text{ s}^{-1} \). For cluster with a 'saturated' IMF, the location of this break will scale linearly with the upper limit to \( M_{cl} \). The upper limit to cluster mass is \( \leq 7000 \ M_\odot \) (between 1 and 120 \( M_\odot \)) for the \( D \leq 50 \text{ pc} \) sample, assuming a factor of 10 increase for extinction. Moreover, since some of the most luminous regions in the sample are possibly blends, the real upper mass limit is probably less.

13.5. Upper 'Cutoff' of Cluster Mass

Here we briefly explore the possibility that there is a physical mechanism limiting the buildup of clusters more massive than a few \( \times 10^3 \ M_\odot \). In the following, we track the feedback of radiation pressure on buildup of a stellar cluster in a molecular cloud core. The important role of radiation pressure in high-mass star formation has not been amply recognized.

We posit a simple model for cluster buildup in which the protocluster forms at the center of a molecular cloud core in which the density rises with decreasing radius. We assume that initially the entire cloud core is in free-fall collapse. The stars within the
growing cluster have a Salpeter IMF — thus since lower mass stars form with a higher probability the initial low mass cluster will have few high mass stars. However, as the cluster grows and becomes more massive, the IMF is populated to higher mass. The surrounding gas feels the gravitational attraction of the interior mass $M_R$ (stars plus the interior core gas). Lastly, we assume that gas accreted inside the adopted cluster radius is added to the cluster and the total cluster mass is instantaneously redistributed with the Salpeter IMF.

This approach thus neglects the complication that low or high mass stars might preferentially form at different epochs due differences in the physics of their formation or their different pre-main-sequence evolutionary times. However, we should note that the assumptions made by us do not really require that all stars form at the same time but rather that the prestellar condensations which become stars of different mass have formed and accreted into the cloud core region. Since the low-mass stars have low luminosity, they are only important for their gravitational mass as far as our model is concerned. Thompson et al. (1998) find evidence that the low and high mass star formation in NGC 2264 is coeval to within $10^3$–$10^4$ yr.

Initially, the cluster will contain only a few low-mass stars and the gas dynamics will be entirely determined by the self-gravity of the cloud core and cluster. Since we neglect rotational or magnetic stresses, this is clearly the most favorable situation for accretion and maximal growth of the cluster. On the other hand, as the cluster becomes more massive and populates the upper main sequence, the higher luminosity-to-mass ratio of high-mass stars will result in increased radiation pressure on the surrounding dust — eventually terminating further accretion to the cloud core. The outward radiation pressure will dominate self-gravity at radius $R$ when
\[
\frac{L}{4\pi R^2 c} < \kappa > \geq \frac{GM_R}{R^2},
\]
(13)
where \(< \kappa >\) is the effective radiative absorption coefficient per unit mass.

Although the original stellar radiation is primarily UV and visible, the dust in the cloud core absorbs these photons and reradiates the luminosity in the infrared. The 'effective' absorption coefficient takes account of the fact that outside the radius where \(A_V \sim 1\) mag, the luminosity is at longer wavelengths where the dust has a reduced absorption efficiency. For the standard ISM dust-to-gas ratio (Bohlin 1978), \(A_V = 1\) mag corresponds to a column \(N_H = 2 \times 10^{21}\) cm\(^{-2}\). We therefore adopt

\[
< \kappa > = 312 \frac{\lambda_V}{\lambda_{eff}(R)} \text{cm}^2 \text{gr}^{-1}
\]
(14)
and \(\lambda_{eff}(R)\) is the absorption coefficient-weighted mean wavelength of the radiation field at radius \(R\) and we adopt a \(\lambda^{-1}\) variation of the absorption efficiency with wavelength.

Combining Eq. 13 and 14, we find that the radiation pressure will exceed the gravity of the cluster stars when

\[
(L/M)_{cl} \geq 42 \frac{\lambda_{eff}}{\lambda_V} \frac{L_\odot}{M_\odot}.
\]
(15)
If \(\lambda_{eff} \sim 3\) \(\mu\)m, \(\lambda_{eff}/\lambda_V \sim 10\). Thus, for clusters with luminosity-to-mass ratios exceeding \(\sim 500 L_\odot/ M_\odot\), radiation pressure will halt further accretion. This luminosity-to-mass ratio is reached at about the point when the upper main sequence is first fully populated, i.e. a cluster with approximately 2000 \(M_\odot\) distributed between 1 and 120 \(M_\odot\). In the above discussion, we conservatively adopt luminosities corresponding to the main sequence rather than the much larger, short term pre-MS luminosities. This assumption is thus most
conservative in estimation of the radiation pressure effects. We have also assumed the density of dust and gas to be only a function of radius. If the material is instead contained in optically thick clumps (possible individual pre-stellar condensations) or a disk, then the strength of the radiation pressure compared to gravity is reduced by a factor which depends on the opacity of the clumps and their areal covering factor at each radius. Since neither of these factors are constrained by existing observations, we have adopted the simplest case of uniform areal coverage and spherical symmetry. In reality, the gas is likely to be clumped and there will be multiple core regions within each GMC. The latter would certainly be unresolved in ground based Hα imaging and probably even at the higher resolution used here. On the other hand, it may be that even if there are multiple cores, not all will have their cluster formation synchronized to within $10^5$ yrs (the timescale of the phenomena we have been discussing).

In the above, we assumed the most favorable conditions for cluster growth — free-fall collapse and no rotational or magnetic impediments. Additional outward pressure can of course arise from the hot ionized gas associated with the OB stars and their stellar winds; these effects are undoubtedly important later in the evolution of the cluster but they are also more dependent on the HII region geometry. By contrast, radiation pressure is inescapable during the early phases of cluster formation and therefore must play a central role in regulating the initial cluster growth. The subsequent dynamic evolution of cloud core will be affected by all three: radiation pressure, HII expansion and stellar winds.

Elmegreen (1983) has also pointed out the importance of radiation pressure from a forming star cluster in possibly limiting the maximum mass of star clusters. He used somewhat different numerical values for the dust opacity and did not consider the reduced effective dust absorption cross section due to the reprocessing into the infrared. Although he used a higher effective dust cross section, this was compensated by his assumption that
there will be substantial gas mass in the intracluster space and he arrives at a similar
limiting cluster mass of $\sim 10^3 \, M_\odot$.

13.6. OB Star Cluster Formation and Expanding Associations

To understand better the limit on the core stellar population of OB star clusters, we
have numerically modelled the collapse of a cloud core with a growing star cluster. The
cloud core, having an initial power-law radial density profile,

$$n = n_0 \left( \frac{R}{R_{cl}} \right)^{-2},$$

(16)
is assumed to start in free-fall collapse with $V_R = V_{ff} = -(2GM_R/R)^{1/2}$. In the subsequent
dynamic evolution of the cloud core, envelope gas getting inside the adopted cluster radius
$R_{cl}$ (taken to be 0.01 pc) is added to the cluster with an efficiency of 50%. At each time step,
the cluster mass is distributed into stars with a Salpeter IMF and the cluster luminosity
updated.

To compute the radiation pressure at each radius we adopt an effective wavelength for
the radiation from

$$\lambda_{eff}(R) \simeq \frac{T_V \lambda_V}{(1 - e^{-\tau_V(R)})T_D(R) + T_{cl}e^{-\tau_V(R)}},$$

(17)

where the dust temperature is given by

$$T_D(R) = 70 \left( \frac{L}{10^5 L_\odot} \right)^{1/5} \left( \frac{2 \times 10^{17}}{R} \right)^{2/5} K.$$

(18)

This scaling with $L$ and $R$ is based on infrared observations of the OMC-1 cloud core.
Eqs. 15 and 16 provide a reasonable approximation to the variation of dust temperature in an optically thick cloud heated by a central luminosity source. Due to the high opacity of the cloud core, the dust is heat mainly by reradiated emission from interior shells (as opposed to direct stellar photons). For the effective temperature of the cluster luminosity, we adopt a constant value $T_{cl} = 30,000$ K, independent of the cluster mass.

The Lagrangian form of the hydrodynamic equation of motion was advanced in time with gravity, thermal and radiation pressure terms. Mass shells were distributed logarithmically with the less massive shells on the inside in order that the transition from $\tau_V = 0 \rightarrow 5$ was well resolved. Artificial viscosity with a coefficient of 3 was introduced to stabilize the radiatively compressed shells (Christy, R. F. 1967). The gas was taken to be isothermal with an 'effective' sound speed of 1 km s$^{-1}$. The initial density scale had $n_0 = 10^8$ cm$^{-3}$ at 0.01 pc and the cloud core extended out to a radius such that its total mass was $2 \times 10^4 M_\odot$.

The density and velocity profiles at 50,000 yr intervals after the initial free-fall collapse are shown in Fig. 24. As expected from the discussion above, the radiation pressure becomes dominant over gravity for the inner shells of the infalling gas when the cluster has reached $\sim 500 M_\odot$. At this point, the infall of the inner shells is reversed and they rapidly accelerate outwards and collide with the still falling, exterior shells. The outer shells have high dust opacity (to the central cluster) and therefore are not subjected to such high radiation pressures.

Where the outward and inward moving gas collide, a dense, shock-compressed shell forms and accelerates outwards. Typical outward radial velocities are $\sim 2$ to 6 km s$^{-1}$ and the density of the shocked layer is greatly enhanced over that of the initial density profile (Fig. 24). At this point, further accretion to the cluster core is effectively shut off. For
the parameters used in this calculation, the cluster ended up with $881 \, M_\odot$ after 500,000 yr. Without radiation pressure, free-fall collapse with the same parameters would have produced a cluster mass of $5800 \, M_\odot$ in the same interval.

It is interesting to note that the outward moving shell may propagate a second phase of stimulated star formation into the cloud envelope. The compressed gas in this shell can be unstable, collapse and fragment into a second generation of stars. The density of the compressed layer is typically enhanced a factor of 100-1000, becoming $10^{5-6} \, \text{cm}^{-3}$ at radii of a few pc. At $T = 50 \, \text{K}$ these densities yield a Jeans length of $\sim 1/3 \, \text{pc}$ and mass of $50 \, M_\odot$. This second-generation star formation could become a significant enhancement to the initial cluster core mass provided the density scale $n_0$ is high enough. Eventually the density in the outward moving shell will drop due to spherical divergence and the falloff of the outer envelope density. The shell would then no longer be unstable and stimulated star formation would stop. Stars formed within the expanding shell will of course have a net outward radial velocity of a few km s$^{-1}$ and be unbound from the core cluster. Evidence of radial expansion in OB associations is seen in the I Orion subgroup d (Trapezium cluster; Blaauw, A. 1964) with a radial expansion of 2.5 km s$^{-1}$ at the outer edge ($R \sim 0.7 \, \text{pc}$) of the cluster. It would be interesting to analyze the Hipparcos data for nearby OB star clusters to look for evidence of similar expansions. Dreher et al. (1984) discovered a ring ($R \sim 0.4 \, \text{pc}$) of ultra-compact HII regions in the W49 complex, each of which is ionized by an internal star or star cluster; this ring of high mass star formation might correspond to the second wave of triggered star formation discussed above.

Recent observations of luminous IR galaxies have shown considerably more luminous (presumably more massive) super star clusters (SSC; eg. Whitmore et al. 1999). In the context of the discussion above, it might be speculated that such clusters could form as a result of a particularly prodigious second-wave of triggered star formation in unusually
massive and dense molecular clouds. The galaxies hosting SSCs are largely interacting starburst systems (e.g., M82 and the 'Antennae' galaxies) in which the molecular clouds are likely to be both more massive and of higher density. Clearly, if the density remains high further out from the star cluster core, the triggered wave of star formation can propagate further and generate a more massive and more extended cluster.

A similar scenario for stimulated star formation in successive OB associations was suggested by Elmegreen & Lada (1970). In their model, the compression wave was due to expansion of the hot, ionized Strömgren sphere rather than radiation pressure and the motivation was to account for the temporal sequence of separate OB associations. Their model is different in both the physical mechanism for gas compression (HII region shock fronts) and in geometry — separate OB associations formed in the compressed shell surrounding a large, expanding HII region. The model described above is discussed in more detail in a forthcoming paper.

A different scenario for the formation of SSCs has been modeled by Tan & McKee (2000). They suggest that in a clumpy GMC with multiple cloud core regions each of a few $\times 10^3 \, M_\odot$, the SSC might form simply from have a simultaneously high efficiency of star formation in all of the cores and the SSC is then the composit of the multiple star clusters and whether it is gravitationally bound or not then just depends on the overall efficiency of star formation for the entire GMC and consequently an assumption that a large fraction of the original GMC mass is contained in the core regions as opposed to the intraclump medium. (It is worth noting, that the individual cores or clumps in their model are posited to have mass of a few $\times 10^3 \, M_\odot$ so the clusters forming in each core still obey the radiation pressure limit discussed above.)
14. Total LyC and Star Formation Rates

The total Hα luminosity can be used to estimate the overall Lyman continuum output and formation rate of OB stars in M51. In doing this, we separate the diffuse and discrete HII regions and we must make corrections for the outer galaxy not covered in the WFPC2 images. In Table 4, we summarize the observed Hα luminosities, the adopted ‘typical’ extinctions, extinction-corrected Hα luminosities and implied Lyman continuum outputs for the separate components and regions of the galaxy.

For the discrete HII regions, we adopt $A_V = 3.1$ mag (see §10) and therefore increase their luminosity by a factor of 10 (Eq. 8). For the diffuse gas, the extinction is probably less and we adopt $A_V \approx 1$ mag and thus increase the diffuse luminosity by a factor of 2.1 (Eq. 7). (The extinction of the diffuse gas could not be reliably estimated from our Pa since it would require extremely accurate determination of the backgrounds. The adopted 1 mag is simply based on the presumption that since the diffuse gas is more widespread, both between the dust clouds and at higher scale height, its extinction is lower than for the discrete HII regions measured here.) The Hα emission in the outer galaxy which was not covered in the WFPC2 images was estimated by multiplying the luminosity measured in the WFPC2 area by a simple scale factor ($= 1.92$). This factor is equal to the ratio of the total observed Hα flux in M51 (Rand 1992) to that measured by us in the WFPC2 area.

The total Lyman emission rates for the WFPC2 area and M51 are $3.0$ and $7.3 \times 10^{53}$ s$^{-1}$. The steady-state star formation rate as $2.00$ and $4.79 M_\odot$ yr$^{-1}$ of stars between 1 and 120 $M_\odot$ for the WFPC2 and total M51 areas (using Eq. 11). The inferred rates are increased by a factor of 2.5 if the IMF is extended down to $0.1 M_\odot$.

The total mass of star forming gas can be estimated from single dish CO observations (eg. Scoville & Young 1983). The H$_2$ mass within 4 kpc radius is approximately $3 \times 10^9 M_\odot$ and the total for the galaxy is $6 \times 10^9 M_\odot$ (Scoville & Young 1983) after scaling for a
conversion factor of \( N_{H_2}/I_{CO} = 2.2 \times 10^{22} \text{ cm}^{-2} / \text{ K km s}^{-1} \) rather than 50\% larger value used there). The implied cycling times for a typical H nucleus to pass into a new generation of stars is therefore \( 1.2 \times 10^9 \text{ yr} \) for both the inner galaxy and total M51. On the one hand, this time would be shortened if the star formation associated with the HII regions extends below 1\( M_\odot \); on the other hand, approximately 50\% of the mass absorbed in the stars actually gets recycled back into the ISM through stellar evolution on a timescale of \( 10^9 \text{ yr} \) (see Norman & Scoville 1988).

15. Conclusions

High resolution HST imaging of H\( \alpha \) and P\( \alpha \) has been used to analyze the properties of HII regions and OB star formation in M51. The critical aspects of these data are : the high resolution (4 — 9 pc as compared with \( \sim 100 \text{ pc} \) in earlier ground-based imaging) which enables the clear separation of individual star formation regions, the ability to determine and correct for dust extinction using the H\( \alpha \)/P\( \alpha \) flux ratio and the high sensitivity which enables us to probe HII regions with luminosity well below that of M42 (the Orion Nebula). From the observational data we find :

1) A total of 1373 H\( \alpha \) emission regions were defined (using automated procedures). The total flux of these discrete regions constitutes about 31\% of the total H\( \alpha \) emission in the central \( 281 \times 223'' \) of M51. The observed H\( \alpha \) luminosities range from \( 10^{36} \) to \( 2 \times 10^{39} \) erg s\(^{-1} \) and their diameters are mostly from 10 to 100 pc with a mean value of \( \sim 30 \text{ pc} \). (For the higher luminosity and usually larger regions, the mean electron density is generally lower, strongly suggesting that some of these regions are likely to be blends of multiple HII regions.)

2) The observed H\( \alpha \) luminosity function exhibits a broad peak at \( L_{H\alpha} \sim 10^{37} \text{ erg} \)}
s$^{-1}$, falling as $L_{H\alpha}^{-1.01}$ on the high luminosity side. No evidence is seen for the break in the luminosity function at $\log(L_{H\alpha})=10^{38.6}$ erg s$^{-1}$ reported in ground-based studies. Compared with ground-based determinations, the luminosity function derived here is much less populated at high luminosity — very likely most of the regions above $10^{39}$ erg s$^{-1}$ seen in ground-based studies were blends of multiple lower luminosity regions which are separated here.

3) Significant differences are seen in the luminosity functions of spiral arm, interarm and nuclear HII regions with the spiral arm luminosity functions being flatter.

4) The observed correlation between HII region luminosity and apparent size ($L \propto D^2$) strong implies that the high luminosity regions are blends or superpositions of multiple lower luminosity regions.

5) For 209 regions which had $\geq 5\sigma$ detections in both P$\alpha$ and H$\alpha$, the observed line ratios were used to derive the overlying visual extinction assuming standard Galactic dust extinction curves and intrinsic line ratios given by Case B recombination. The implied extinctions range from $A_V = 0$ to 6 mag, with an intensity-weighted mean value of $<A_V> = 3.1$ mag. Thus the observed H$\alpha$ luminosities should be increased by an average factor of 10, implying similar increases in the OB star cluster luminosities and implied star formation rates. The high extinctions underscore the need for extinction estimates in analyzing the properties of HII regions and their associated OB star clusters.

6) The extinctions are also highly variable from region to region and across individual regions. (In deriving the estimates quoted above, the line ratios were computed pixel by pixel and then averaged over each region.)

7) The most luminous regions have sizes $\geq 100$ pc and they are undoubtedly blends of multiple regions. This is clear since their sizes are much larger than the maximum diameter
(≤ 50 pc) to which an HII region might conceivably expand within the ∼ 3 × 10^6 yr lifetime of the OB stars and it is also consistent with observed correlation (L ∝ D^2) found between the measured luminosities and sizes of the HII regions.

8) A subsample of 1101 regions with sizes ≤ 50 pc therefore constitutes those regions which might conceivably be ionized by a single cluster. Their extinction-corrected luminosities range between 2 × 10^{37} and 10^{39} erg s^{-1} (with no corrections for dust absorption of the Lyman continuum or UV which escapes to the diffuse medium). The range is roughly comparable to HII regions ranging between 2/3 of M42 (the Orion Nebula) and W49 (the most luminous Galactic radio HII region). The upper limit for individual cluster HII regions is therefore conservatively ≤ 10^{39} erg s^{-1}.

In addition to the observational data, we have modelled the Lyman continuum luminosity as a function of total cluster mass with stars distributed with a Salpeter IMF (1 — 120 M☉) and as a function of cluster age. This model is used to derive the cluster properties. We find:

1) The upper limit to the ≤ 50 pc sample luminosity function corresponds to an ionizing photon production rate Q_{LyC up} ≃ 7 × 10^{50} s^{-1} and the corresponding upper limit for cluster masses is ≤5000 M☉. (The implied masses are increased by a factor of 2.5 if the Salpeter IMF is extended down to 0.1 M☉.)

2) For a power-law distribution of cluster masses, we find that the observed peak in the luminosity function at 10^{37} erg s^{-1} clearly rules out flat or slowly falling cluster mass spectra. The observed −1.01 power-law index on the high luminosity tail of the luminosity distribution implies a cluster mass spectra N(M_{cl})/d M_{cl} ∝ M_{cl}^{-2.01}.

3) The highest mass clusters are approximately ∼1000 M☉. The parent molecular clouds are much more massive and one must ask: why don’t the OB star clusters generally
build up to much greater mass? We suggest that the formation of a massive cluster in a molecular cloud core is likely to be terminated at the point when the luminosity-to-mass ratio of the cluster reaches $\sim 1000 \, L_\odot/M_\odot$ when radiation pressure begin to dominate the self-gravity of the cluster. This is roughly the point at which the Salpeter IMF first becomes fully populated.

4) A hydrodynamic model with an initial $R^{-2}$ density distribution in free-fall collapse verifies that the core star cluster is likely to self-limit at $\sim 10^3 \, M_\odot$. At this point, radiation pressure effectively terminates further gas and dust accretion to the central core. However, we also find that a radiatively-compressed shell will then propagate outwards at a few km s$^{-1}$, possibly triggering a second wave of star formation out to a few pc radius. This may, in fact, be the mechanism for forming the more massive star clusters (SSC) seen in starburst galaxies where the densities are likely to be higher out to larger radii in the cloud envelopes. The stars formed in the expanding shell will have significant outward radial motion and will probably be unbound.

Lastly, we have combined our modelling results with measurements of the total line emission to evaluate the total Lyman continuum output and global star formation rate. From the extinction-corrected H$\alpha$ luminosity, we find $Q_{LyC\ total} = 7 \times 10^{53} \, s^{-1}$ and $SFR(1-120M_\odot) = 4.17 \, M_\odot \, yr^{-1}$.

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Fig. 1.— The full mosaic of WFPC2 Hα (continuum subtracted) images for the central 281 × 223 ″ of M51. The Hα emission is shown in red and continuum V and B bands are in green and blue, respectively. (In the red, we also added the I band image in order to balance the colors on the stars.)

Fig. 2.— The flow streamlines are shown for material at 3, 3.2, 6 and 6.2 kpc in a spiral potential like that of M51 based on the model of Roberts & Stewart (1987) with the spiral arms starting at R = 2 kpc and PA=15°. Since the pattern speed is approximately half the circular velocity, the gas approaches the spiral arm from the underside, is deflected along the arm toward smaller radius and then leaves the arm on the front. Orbit crowding is due to the spiral arm streaming motions. The cross-marks correspond to 250 Myr time intervals.

Fig. 3.— The mosaic of NIC3 Pα (continuum subtracted) images covering the central 186 × 188 ″ of M51. The Pα emission is shown in red and continuum V and B bands are in green and blue, respectively. (In the red, we also added the I band image in order to balance the colors on the stars.)

Fig. 4.— The Hα (red) and Pα (green) images are shown for the area of overlap. The blue was made by the combination (V-H)+V in order to show the dust lanes and the background disk stars. Areas with yellow color have strong Hα and Pα.

Fig. 5.— The Hα (red) and Pα (green) are shown for the area to the west of the nucleus with all continuum removed. Although virtually all reasonably bright Hα emission regions are seen in Pα, extremely large variation in the line ratio are apparent from region to region and the morphology of individual regions can be very different in Hα and Pα.

Fig. 6.— The Hα emission structure apparent at 0.1″using HST (left) is compared with the same image smoothed with a 1.5″ FWHM Gaussian to simulate typical ground-based resolution. The sub-image area shown here is approximately 60″ north of the nucleus. The
length bar corresponds to 100 pc. Galactic GMCs have diameters typically 2 to 5 times smaller and their associated HII regions have still smaller sizes. This comparison illustrates well that the ground-based and HST imaging are clearly studying very different physical structures — the former, associations of OB star formation, the latter, perhaps individual OB star formation regions.

Fig. 7.— For the same area shown in Fig. 6 (60'' north of the nucleus), we show contours for Hα and Pα emissions (top panels). In the lower right panel, the Hα (red) and Pα (blue) are shown together. It is clear that significant differences are seen in the Hα and Pα due to the higher extinction in Hα. The areas of the Hα emission regions as defined by our automated algorithm are shown (the peak positions are indicated by the black pixels). The length bar corresponds to 1'' or 46 pc.

Fig. 8.— The locations of the Hα emission regions selected by our automated procedure are shown together with those measured interactively by Rand (1992). In general, there is very close correspondence between the two samples, although in many instances we have catalogued multiple regions where Rand had just one. The outer areas were not covered in our images and therefore a number of Rand’s HII regions don’t have a counterparts in our sample; the converse is true in the nuclear region which was excluded from Rand’s analysis due to blending. There are 17 regions in Rand’s sample which do not appear in ours although they are in the area analyzed by both studies. All of these regions are have peak intensities just below our 6 σ criterion for the peak intensity.

Fig. 9.— The two point angular correlation function is shown for centroid positions of the 1373 discrete HII regions (top panel) and pixels (bottom panel) with Hα emission exceeding 3σ in the same Hα image with diffuse background subtracted. The angular sampling of the images was normalized out by dividing the correlation functions with those computed for pixels sampled randomly within the observed image areas. This normalization does not
remove large-scale correlations such as the concentration of HII regions toward small galactic radii and along spiral arms; thus neither correlation function goes asymptotically to 0 at large angles and their integrals are not equal to zero.

Fig. 10.— The percentage of HII regions with nearest neighbors within the specific angular offset ($\theta$) is shown.

Fig. 11.— The observed H$\alpha$ luminosity function for all HII regions defined and measured in the WFPC2 images (not corrected for extinction) is compared with the luminosity functions derived from ground-based imaging by Rand (1992) and Petit et al. (1996). The fact that the HST luminosity function appears to shift to lower luminosity is due largely to the ability to separate individual HII regions which become blended in ground-based images (see text). Fits to logarithmically binned distributions are over the range $L_{H\alpha} = 40 \rightarrow 800 \times 10^{36}$ erg s$^{-1}$. Typical extinctions of $A_{H\alpha} = 0.798 A_V = 0.798 \times 3.2$ will shift the luminosity functions a factor of 5.9 higher.

Fig. 12.— The observed H$\alpha$ luminosity functions separated for arm, interarm and nuclear regions. These areas are defined and shown in Polletta et al. (2001). Fits to logarithmically binned distributions are over the range $L_{H\alpha} = 12 \rightarrow 500 \times 10^{36}$ erg s$^{-1}$. The power-law fits to the high luminosity tail are also shown. A significant flattening of the luminosity function is seen in the nucleus and spiral arms, compared to the interarm regions.

Fig. 13.— The distribution of HII region diameters are shown for regions containing at least 2 pixels, separated between arm, interarm and nuclear regions. No significant difference is seen in the diameter distributions between the different regions. The mean diameters are given for all regions smaller than 100 pc. Regions with diameter $\geq 120$ pc were not plotted since these are certainly blends of multiple regions.

Fig. 14.— The apparent H$\alpha$ luminosities (upper panel) and HII region diameters (lower
panel) are plotted as functions of mean electron density with the arm, interarm and nuclear regions plotted in blue, red, and green, respectively.

Fig. 15.— The observed luminosities of the HII regions are plotted as a function of HII region diameter.

Fig. 16.— Upper Panel: The measured flux ratios (Hα/Pα) for 209 HII regions with boundaries defined from Hα (shown in Fig. 7), restricted to those pixels detected at ≥ 5σ in both Pα and Hα. For Case B recombination in an ionization bounded HII region with no extinction, the intrinsic ratio is 8.15 (dashed vertical line). The lower measured Hα/Pα ratios reflect the higher extinction at the wavelength of Hα (6563Å) than that of Pα (1.87 μm). Lower Panel: The distribution of average visual extinctions for the HII regions inferred from the measured flux ratios assuming an intrinsic ratio of 8.15 and the standard ISM extinction curve (Rieke & Lebofsky 1985, Cardelli et al. 1989). Dashed vertical line is the average extinction A_V = 3.2 mag. (The extinctions were determined at individual pixels and then averaged for each region.)

Fig. 17.— The derived extinctions as a function of observed Hα luminosity for 209 HII regions with boundaries defined from Hα (shown in Fig. 7), restricted to those pixels detected at ≥ 5σ in Pα and Hα. The extinctions were determined for individual pixels within each HII region and then averaged. The solid circles are the averages for equal logarithmic bins in Hα luminosity.

Fig. 18.— Upper Panel: The measured flux ratios (Hα/Pα) for all individual pixels detected at ≥ 5σ in both Pα and Hα. For Case B recombination in an ionization bounded HII region with no extinction, the intrinsic ratio is 8.15 (dashed vertical line). Lower Panel: The derived visual extinctions for the same pixels obtained from the measured flux ratios assuming an intrinsic ratio of 8.15 and the standard ISM extinction curve (Rieke & Lebofsky 1985, Cardelli
Fig. 19.— The Hα luminosities as observed for the 209 regions for which the extinction was derived and as corrected for extinction. The extinction-corrected luminosity of each region was calculated by correcting each pixel for its extinction and then summing the extinction-corrected pixel luminosities. These distributions should not be interpreted as luminosity functions since they include only those pixels in each region detected at $\geq 5\sigma$ in both lines.

Fig. 20.— The observed Hα luminosities plotted for the 1011 HII regions with diameter $< 50$ pc. For the reasons discussed in the text, HII regions larger than 50 pc are almost certainly ionized by multiple clusters; the distribution shown here therefore shows the maximum luminosity likely to arise from a single OB star cluster.

Fig. 21.— The adopted Lyman continuum production, stellar luminosity and main sequence lifetimes are shown as a function of stellar mass. The Lyman emission rate is from Vacca, Garmany & Shull (1996) and the main sequence lifetimes and luminosities are from Renzini and Buzzoni (1986) and Maeder (1987) for $\leq 10M_\odot$ and $\geq 10M_\odot$, respectively.

Fig. 22.— The Lyman continuum emission rate and luminosity are shown for a 'saturated' cluster as a function of time scaled to a total cluster mass of $10^3 M_\odot$ with a Salpeter IMF from 1 to 120 $M_\odot$. Both the luminosity and $Q_{LyC}$ can be scaled directly proportional to cluster mass for lower and higher mass cluster.

Fig. 23.— The expected luminosity functions are shown for 5 values of the cluster mass power law index ($\Gamma$). The normalized luminosity functions per logarithmic interval in Lyman continuum emission rate were computed assuming an equal probability of observing a given cluster at any time during its active lifetime.

Fig. 24.— The density profile for the cloud core, cluster formation is shown at 0(black),
50(green), 100(turquoise), 150(blue), and 500(red) ×10³ yr. The initial state was free-fall collapse in a R⁻² density distribution normalized to 10⁸ cm⁻³ at 0.01 pc. The final mass of the core cluster was 881 M☉ (compared to 5800 M☉ for free-fall collapse) and the luminosity was 10⁶ L☉. The core accretion was fully halted by radiation pressure within 100,000 yr. After that the radiatively compressed shell moves outward at 2 — 6 km s⁻¹. Since the compressed shell is likely to be Rayleigh-Taylor and Jeans unstable and star formation may continue in the outward moving shell.
### TABLE 1
M51 Hα and Pa Observations

| Instrument | Prog. ID | Date          | Filter       | λ (µm) | Exposure/s (s) | Orient. angle^a |
|------------|----------|---------------|--------------|--------|----------------|-----------------|
| WFPC2      | 5123     | Jan 24, 1995  | F656N (Hα)   | 0.6561 | 400 + 1400     | 93.1998         |
| WFPC2      | 5123     |               | F547M (Y)    | 0.5361 | 260 + 600      |                 |
| WFPC2      | 7375     | Jul 21, 1999  | F656N (Hα)   | 0.6561 | 1300 + 700     |                 |
| WFPC2      | 7375     |               | F814W (I)    | 0.8386 | 700 + 300      |                 |
| NICMOS3    | 7237     | Jun 28, 1998  | F187N        | 1.8740 | 576            | −113.168        |
| NICMOS3    | 7237     |               | F190N        | 1.9005 | 576            | −113.168        |

^aFor WFPC2 it corresponds to PA-V3: angle between the axis V3 of the camera and the North. For NICMOS it corresponds to the angle between the y axis of the camera and the North.
| HII region sample | No. HII | $\alpha$ | $L_{up}$ $\text{erg s}^{-1}$ | $N_{up}$ | $N_{obs}(L > L_{up})$ |
|-------------------|---------|---------|-----------------|---------|-----------------|
| All w/o Jet$^b$   | 1223    | -1.01 ± 0.04 | $4.0 \pm 0.5 \times 10^{38}$ | 12.5 ± 3 | 5 |
| All w/o Jet$^c$   | 1223    | -0.85 ± 0.02 | $4.0 \pm 0.5 \times 10^{38}$ | 16.1 ± 3 | 5 |
| Arm$^c$           | 563     | -0.72 ± 0.03 | $3.3 \pm 0.5 \times 10^{38}$ | 13.1 ± 3 | 4 |
| Interarm$^c$      | 431     | -0.95 ± 0.05 | $2.0 \pm 0.9 \times 10^{38}$ | 8.1 ± 2  | 1 |
| Nucleus w/o Jet$^c$ | 205     | -1.12 ± 0.11 | $1.1 \pm 0.4 \times 10^{38}$ | 4.3 ± 2  | 0 |

$^a$Obtained from fits to logarithmically binned distributions.

$^b$Fit range $L_{H\alpha} = 40 \rightarrow 800 \times 10^{36}$ erg s$^{-1}$.

$^c$Fit range $L_{H\alpha} = 12 \rightarrow 500 \times 10^{36}$ erg s$^{-1}$. 
TABLE 3
GALACTIC COMPACT HII REGIONS

| Region     | Diameter (pc) | n_e cm$^{-3}$ | U (pc cm$^{2/3}$) $^b$ | Q$_{LyC}$ (s$^{-1}$) | L$_{H\alpha}$ (ergs s$^{-1}$) $^c$ |
|------------|---------------|---------------|------------------------|----------------------|-------------------------------------|
| M43        | 0.6           | 610           | 20                     | $2.5\times10^{47}$   | $3.5\times10^{45}$                 |
| M42        | 0.7           | 2237          | 55                     | $5.3\times10^{48}$   | $7.1\times10^{36}$                 |
| IC1795(W3) | 2.3           | 400           | 179                    | $1.8\times10^{50}$   | $2.5\times10^{38}$                 |
| W51        | 4.9           | 372           | 208                    | $2.9\times10^{50}$   | $3.9\times10^{38}$                 |
| W49        | 8.4           | 536           | 276                    | $6.6\times10^{50}$   | $9.1\times10^{38}$                 |

$^a$Data obtained from 2-cm radio continuum observations of Schraml & Mezger (1969)

$^b$Excitation parameters (U = $R_s n_e^{2/3}$) from Schraml & Mezger (1969) have been summed for all HII region components except in the case of W51 where we took only the strongest component since this direction is along a spiral arm tangent and there is likely to be confusion.

$^c$Implied extinction-corrected L$_{H\alpha}$ (=1.37×10$^{-12}$ Q)
| Region          | HII Type | Obs. $L_{H\alpha}^b$ | $<A_V>^c$ | $f_{H\alpha \text{ ext-cor}}^d$ | Ext. Cor. $L_{H\alpha}^e$ | $Q_{LyC}^f$ |
|-----------------|----------|----------------------|-----------|---------------------------|---------------------------|-------------|
| WFPC Area       | Discrete | $2.81 \times 10^{40}$ | 3.1       | 10.0                      | $2.8 \times 10^{41}$     | $2.0 \times 10^{53}$ |
| WFPC Area       | Diffuse  | $6.56 \times 10^{40}$ | 1.0       | 2.1                       | $1.4 \times 10^{41}$     | $1.0 \times 10^{53}$ |
| WFPC Area       | All      | $9.37 \times 10^{40}$ | 5.2       | $5.2 \times 10^{41}$      | $3.0 \times 10^{53}$     |
| M51 Total$^g$   | All      | $1.80 \times 10^{41}$ |           |                           | $1.0 \times 10^{42}$     | $7.3 \times 10^{53}$ |

$^a$ 'Discrete' if contained in our HII region sample; otherwise 'diffuse'.
$^b$ $H\alpha$ luminosity
$^c$ Adopted visual extinction $A_V$ in mag.
$^d$ Factor to multiply the observed $H\alpha$ by, see Eq. 8
$^e$ Extinction-corrected $H\alpha$ luminosity
$^f$ Required Lyman continuum emission rate
$^g$ The total $H\alpha$ flux in M51 (Rand 1992). The total extinction corrected luminosity and Q were computed by multiplying the WFPC totals by a factor 1.92, based on the ratio of the observed $H\alpha$ in the WFPC and total areas.