STAR FORMATION IN LUMINOUS H\textsc{ii} REGIONS IN M33

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ABSTRACT

We present a multiwavelength (ultraviolet, infrared, optical, and CO) study of a set of luminous H\textsc{ii} regions in M33: NGC 604, NGC 595, NGC 592, NGC 588, and IC131. We study the emission distribution in the interiors of the H\textsc{ii} regions to investigate the relation between the dust emission at 8 \(\mu\)m and 24 \(\mu\)m and the location of the massive stars and gas. We find that the 24 \(\mu\)m emission is closely related to the location of the ionized gas, while the 8 \(\mu\)m emission is more related to the boundaries of the molecular clouds consistently with its expected association with photodissociation regions. Ultraviolet emission is generally surrounded by the H\alpha emission. For NGC 604 and NGC 595, where CO data are available, we see a radial gradient of the emission distribution at the wavelengths studied here: from the center to the boundary of the H\textsc{ii} regions we observe ultraviolet, H\alpha, 24 \(\mu\)m, 8 \(\mu\)m, and CO emission distributions. We quantify the star formation for our H\textsc{ii} regions using the integrated fluxes at the set of available wavelengths, assuming an instantaneous burst of star formation. We show that a linear combination of 24 \(\mu\)m and H\alpha emission better describes the star formation for these objects than the dust luminosities by themselves. For NGC 604, we obtain and compare extinction maps derived from the Balmer decrement and from the 24 \(\mu\)m and H\alpha emission line ratio. Although the maps show locally different values in extinction, we find similar integrated extinctions derived from the two methods. We also investigate here the possible existence of embedded star formation within NGC 604.

Key words: galaxies: individual (M33) – galaxies: ISM – H\textsc{ii} regions – infrared: galaxies – ultraviolet: galaxies

Online-only material: color figures

1. INTRODUCTION

After the launch of the Spitzer Space Telescope and the Galaxy Evolution Explorer (GALEX) satellites the study of the star formation rate (SFR) in galaxies has improved considerably. The 24 \(\mu\)m and 8 \(\mu\)m Spitzer bands have been proposed as new SFR indicators in galaxies of different types (e.g., Calzetti et al. 2005, 2007; Alonso-Herrero et al. 2006). While the classical H\alpha and far-IR (FIR) emissions are directly linked to the star formation process, the H\alpha luminosity is produced by the recombination of photoelectrons and the FIR luminosity is produced by the amount of stellar light absorbed by dust, the consideration of both 24 \(\mu\)m and 8 \(\mu\)m emissions as SFR tracers relies on the observational correlation between the integrated luminosity at these two wavelengths and the extinction-corrected H\alpha luminosity. The relation has been found to hold in a statistically significant number of H\textsc{ii} knots in different galaxies. Calzetti et al. (2005) found a correlation between the 24 \(\mu\)m and the extinction-corrected Pa\alpha luminosities for the central H\textsc{ii} emitting knots in M51, which holds over more than two orders of magnitude in luminosity. A similar correlation was found for the H\textsc{ii} regions in M81, but with higher dispersion in the low-luminosity range and a larger range of dust opacities in those objects (Pérez-González et al. 2006). These correlations were also confirmed for Luminous Infrared Galaxies (LIRGs) and Ultraluminous Infrared Galaxies (ULIRGs; Alonso-Herrero et al. 2006). The 8 \(\mu\)m emission was also studied as a star formation tracer in M51 and M81, but higher dispersion was found in the correlation of the 8 \(\mu\)mH\alpha luminosities of H\textsc{ii} regions in these galaxies. A more complete study by Calzetti et al. (2007) involving a large galaxy sample shows the ability of the 24 \(\mu\)m emission to trace the star formation in galaxies of different types and metallicities (see also Wu et al. 2005 and Relaño et al. 2007). These relations between dust emission and ionizing luminosity strictly hold only in very dusty H\textsc{ii} regions, where most of the stellar luminosity is reprocessed by dust. For H\textsc{ii} regions with a wider range of dust opacity, Kennicutt et al. (2007) show that a linear combination of the 24 \(\mu\)m emission, tracing the obscured star formation, and the observed H\alpha luminosity, which would trace the un-absorbed star formation, correlates better than other SFR tracers with the extinction-corrected H\alpha luminosity. This correlation has been confirmed in a large sample of H\textsc{ii} regions by Calzetti et al. (2007) and more recently for galaxies by Zhu et al. (2008).

The previously mentioned studies assume a direct correspondence between the 24 \(\mu\)m and H\alpha emissions. But although a considerable analysis has been carried out from a statistical point of view, little has been done to corroborate the spatial correlation of the emissions proposed as tracers of the star formation, and the geometries of the gas and dust relative to the position where the stars actually form within H\textsc{ii} emitting knots. Using spatially resolved observations we are able to test the assumptions upon which the previous studies rest. The study of the emission distribution within an H\textsc{ii} region at the wavelengths that trace the SFR and the relation with the classical components of the H\textsc{ii} regions (central OB stars, ionized gas, photodissociation region (PDR), and molecular gas) offer an opportunity to test the hypotheses that are assumed in the statistical studies. Such an analysis, carried out in a set of giant H\textsc{ii} regions at different evolutionary stages, can help to test the basis for the results derived from the previous statistical correlations.

M33 is an especially appropriate object because it offers a sample of giant H\textsc{ii} regions spanning wide ranges in luminosity and size. The distance of the galaxy (840 kpc; Freedman et al. 1991) allows an intermediate spatial resolution at the infrared wavelength range (at a distance of M33, the Multiband Imaging Photometer (MIPS) has a linear resolution of \(\sim20\) pc at 24 \(\mu\)m, which is \(\sim10\) times smaller than the typical sizes of giant H\textsc{ii}
regions). Among the brightest H II regions in M33 there is a wide range of properties which allows us to select a complete set of giant H II regions covering different luminosities and evolutionary stages. For example, IC131 containing a compact H II region, IC131-West, and NGC 604 is a more evolved and dispersed high-luminous H II region.

NGC 604 is of special interest. It is the brightest luminous H II region in M33 and the second most luminous nearby H II region after 30 Doradus in the Large Magellanic Cloud. Its ionized gas shows a complex morphology of cavities, shells, and filaments that testify to the large amount of kinetic energy involved in the interior of the region. Relevant to this paper, the stellar content has been analyzed with filter imaging (e.g., Hunter et al. 1996; Drissen et al. 1993) and spectroscopically (e.g., Pellerin 2006; Terlevich et al. 1996; González-Delgado & Pérez 2000); the ionized gas emission and dust extinction have been recently studied with Hubble Space Telescope (HST) images by Maíz-Apellániz et al. (2004). At longer wavelengths CO molecular gas has been observed by Wilson & Scoville (1992) and radio emission has been analyzed by Churchwell & Goss (1999). The size of the region and its evolutionary stage make it very suitable for analyzing the correspondence of the IR Spitzer emission and the location of knots of star formation within the H II region.

We study a set of luminous H II regions in the nearby galaxy M33 combining data at different wavelengths: 24 μm, 8 μm from Spitzer, ~154 nm, ~232 nm from GALEX, Hα and R-Band ground-based data and Hα and Hβ HST data. For two of the most luminous H II regions in the sample we analyze CO molecular data. We study the emission distribution at different wavelengths within the H II regions in the sample we analyze CO molecular data. We study the emission distribution at different wavelengths within the H II regions in order to better understand the empirical correlations of the new proposals of star formation tracers in local environments. The rest of the paper is organized as follows. In Section 2, we explain the set of observations we analyze here; in Section 3, we describe the emission distribution within our set of H II regions; Section 4 is devoted to obtain integrated fluxes for each H II region and to convert them into star formation measurements. We study NGC 604 in depth in Section 5; we summarize our conclusions and discuss the results in Section 6.

2. SAMPLE AND DATA

We have selected a sample of bright H II regions in M33: NGC 588, NGC 592, NGC 595 and NGC 604, IC131, and IC131-West (the western radio component of IC131, see Viallefond et al. 1983). All of them show high-Hα luminosity over the range 2 x 10^38 to 3 x 10^39 erg s^{-1}. We have chosen large H II regions whose sizes allow us to spatially resolve their structure at the wavelengths we study here (the spatial scale of the observations presented here ranges from ~1 pc for the HST data to ~32 pc for the CO observations). The H II regions of our sample are at different evolutionary stages—from the compact IC131-West to the more evolved NGC 604—and show different Hα morphologies from the open Hα shell structure of NGC 595 to a well defined complete Hα shell shown by NGC 588 or the multiple arcs and filaments of NGC 604 (see Figures 1 and 2). There are available data from UV to the IR for our set of H II regions and for two of them, NGC 604 and NGC 595, we are able to compare with CO intensity maps. Finally, for NGC 604 we also analyze Hα and Hβ images from the HST Data Archive. In this paper, we have used a data combination from Spitzer (Werner et al. 2004), GALEX (Martin et al. 2005), and ground-based Hα observations from the Local Group Galaxies Survey (LGGS; Massey et al. 2006, 2007). For NGC 604 and NGC 595 we have compared these data with CO intensity maps from Wilson & Scoville (1992).

2.1. IR Data: Spitzer

The Infrared Array Camera (IRAC, Fazio et al. 2004) on Spitzer is an imaging camera operating at four “channels” (3.6, 4.5, 5.8, and 8 μm). The field of view is 5.2 x 5.2 in the full array readout mode (256 x 256 pixels). The plate scale is 12 pixel^{-1}. M33 was observed six times using IRAC under Program ID 5 (P.I.: R. Gehrz). The Basic Calibrated Data (BCD) created by the Spitzer Data Center (SSC) pipeline version S14.0.0 were taken from the Spitzer Data Archive and assembled with MOPEX version 16.3.7. The images were oriented and aligned using common point sources and background subtraction in all the images was done before combining them together. Since the 8 μm image is dominated by the polycyclic aromatic hydrocarbon (PAH) emission and most of the 3.6 μm emission can be assumed to have a photospheric stellar origin (Helou et al. 2004), we have used the 3.6 μm image to estimate the stellar contribution of the 8 μm flux. We have followed the method described in Helou et al. (2004) (see also Calzetti et al. 2007) and generated scaled 3.6 μm images with scale factors within a range of 0.22–0.28. We found that the scale factor which gave least residuals after subtracting the stellar component from the 8 μm image was 0.24. We estimated an uncertainty of <1% in the integrated 8 μm fluxes of our H II region sample for a change in the scale factor of 0.04.

Observations of M33 at 24 μm were obtained with the MIPS in the Scan-Mode on Spitzer (Rieke et al. 2004). The field of view is 5' x 5' and the resolution is 5″. We retrieved the BCDs of Program ID 5 corresponding to position 2 (R.A.(2000) = 1h34m10.00s, decl.(2000) = decl.(2000) = 30d47m02.0s), and position 3 (R.A.(2000) = 1h33m30.00s, decl.(2000) = 30d32m11.0s), which cover the portion of the galaxy disk where our set of H II regions are located. The BCD data were created using the SSC pipeline software version S16.1.0 and the data were assembled using Mopex version 16.3.7, preserving the original pixel size of 2′′.45. For each pointing, the images were oriented and aligned using several point sources and a sky level was obtained and subtracted for each image. After the subtraction of a constant sky level, a small gradient in the background was still seen in all the images. Prior to combining the images, the background gradient was removed using the task insurfit in IRAF. Although MIPS provides observations at longer wavelengths (70 μm and 160 μm), the spatial resolution achieved at these wavelengths is low for the purposes of this study (~60 pc and ~150 pc for 70 μm and 160 μm, respectively). For this reason, we have not included them in the analysis presented here.

2.2. UV Data: GALEX

The Nearby Galaxies Survey (NGS) includes observations of nearby galaxies of different types and environments, M33 among others (Bianchi et al. 2003a, 2003b). The far-ultraviolet (FUV) (1344–1786 Å, λ_{eff} = 1539 Å) and near-ultraviolet (NUV) (1771–2831 Å, λ_{eff} = 2316 Å) data of M33 were taken from the GR2 data release of the GALEX-Nearby Galaxies Survey, which is available to the public via the Multimission

1. [http://ssc.spitzer.caltech.edu/postbcd/mopex.html](http://ssc.spitzer.caltech.edu/postbcd/mopex.html)
2. IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.
Figure 1. Continuum-subtracted Hα images of our set of H II regions in M33: NGC 595 (upper left), NGC 588 (upper right), IC131 and IC131-West (lower left), and NGC 592 (lower right) with 24 μm emission contours overlaid. The intensity contours are at (2, 5, 10, 20, 40, 60, 80, 95)% of the 24 μm maximum intensity in each region. A 2% contour level corresponds to a range of (2–6)σ, depending on the region (3σ = 2.0 × 10^{-17} erg s^{-1} cm^{-2} for the 24 μm image). A 3σ value in the continuum-subtracted Hα image corresponds to 2.0 × 10^{-17} erg s^{-1} cm^{-2}.

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

2.3. Ground-based Hα Imaging

We use Hα emission observations provided by the KPNO/CTIO LGGS Collaboration, which has already published UBVRJ catalogs of stars in M31 and M33 (Massey et al. 2006), and also provides images at Hα, [S ii], and [O iii] (Massey et al. 2007). The M33 data were taken with the Mosaic CCD camera at the prime focus of the 4 m Mayall Telescope, the observations have a plate scale of 0.27 pixel^{-1} and a spatial resolution of 0.8. We have retrieved two images of M33 from the final reduced data available at the National Optical Astronomy Observatory (NOAO) Science Archive; one obtained with the narrow-band Hα- k1009 (6575/81 Å) filter and the other with the broadband filter R Harris k1004 (6514/1511 Å) used for continuum subtraction. The Hα and continuum images were aligned using the positions of several field stars and aperture photometry of these stars was used to derive a scale factor of 0.41 ± 0.05. We generated continuum-subtracted Hα images with scale factors in the range of 0.36–0.46. A scale factor of 0.44 was finally chosen after careful inspection of the residuals in the continuum subtraction process. An uncertainty of 1%–3% in the integrated Hα fluxes was estimated for a change in the

3 http://galex.stsci.edu/GR2/
Figure 2. Upper: NGC 604 continuum-subtracted Hα image at high resolution with 8 μm (left) and UV (right) emission contours overlaid. The intensity contours are at (2, 5, 10, 20, 40, 60, 80, 95)% of the maximum intensity at each wavelength (2% contour level corresponds to $3\sigma \left(9.6 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}\right)$ and $20\sigma \left(1.0 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}\right)$) at 8 μm and UV, respectively). A 3σ value in the continuum-subtracted Hα image of NGC 604 corresponds to $4.2 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$. Lower left: observed Hα luminosity of NGC 604 at 6″ resolution with 24 μm emission contours overlaid. Lower right: absorbed Hα luminosity for NGC 604 derived using the Balmer extinction map in Figure 10 (left) with 24 μm emission contours overlaid. The intensity contours are at (2, 5, 10, 20, 40, 60, 80, 95)% of the maximum 24 μm intensity (2% contour level corresponding to 10σ).

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

scale factor of 0.05. Contributions of [N II]λ6548,6584 emission lines to the integrated fluxes were obtained using the transmission curve of the Hα-k1009 filter and the expected [NII]/Hα emission line ratios for each H II region in our sample (Bosch et al. 2002 and Vílchez et al. 1988). We applied a calibration factor of $1.79 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ given in Table 2 in Massey
et al. (2007)\(^4\) for the Hα emission-line sources. This calibration was checked by comparing the integrated fluxes with previously reported Hα fluxes (see Section 4).

### 2.4. Hubble Space Telescope Wide-Field Planetary Camera 2 Imaging of NGC 604

We retrieved Hα and Hβ observations of NGC 604 from ID Programs 5773 and 9134 from the HST MAST Data Archive. We selected images at three different filters: F656N and F487N to isolate the Hα and Hβ emissions and F547M for continuum subtraction. The observations for the F656N, F487N, and F547M filters consist of 2 × 1100 s, 3 × 2700 s, and 2 × 500 s, respectively. The images were aligned and cosmic rays were rejected using STSDAS package *coadd* in IRAF. Wide-Field Planetary Camera 2 (WFPC2) mosaic images were then obtained using the task *wmosaic* in the STSDAS package. The resulting Hα, Hβ, and continuum (F547M) images were aligned using positions of stars in the images. Using aperture photometry for field stars, we obtained scale factors of 0.11 ± 0.04 and 0.18 ± 0.05 for Hα and Hβ, respectively. A detailed inspection of the images showed that the best scale factors were 0.14 and 0.16 for the Hα and Hβ images, respectively. Changes in the scale factors of 0.04 and 0.05 give flux uncertainties of 3% and 7% for Hα and Hβ, respectively. The final resolution of the Hα and Hβ images is ~0″2. We used the absolute photometric calibrations of the WFPC2 nebular filters to measure the integrated flux of the region. Corrections for the contamination of the [N II] λ6548,6584 emission lines were performed for the Hα image and the final integrated flux was compared with previously reported fluxes from the literature (see Section 4).

### 2.5. Data from Literature

We also make use of data available in the literature at other wavelengths. We use interferometric CO observations of NGC 604 and NGC 595 with a synthesized beam of ~7″×8″ as published by Wilson & Scoville (1992). We also analyze the results of the stellar photometry of NGC 604 previously published by Hunter et al. (1996) and use the F555W image of this H II region for a comparison with the CO data.

### 3. EMISSION DISTRIBUTION WITHIN THE H II REGIONS

The study of the components of the interstellar dust is improving considerably since the launch of *Spitzer* (e.g., Draine & Li 2007; Lebouteiller et al. 2007). The general model of the interstellar dust suggests the existence of three different components: large grains (emitting at wavelengths λ > 50 μm), very small grains (VSG; emitting at λ > 10 μm), and PAH molecules with emission at concentrated features in the 3–15 μm region (Désert et al. 1990; Draine 2003). In this general picture we would expect that the emission corresponding to the 24 μm MIPS band will be related to the emission of the VSG, while the 8 μm IRAC band will include part of the PAH emission features. The relation of the dust model components and the infrared (IR) emission in the IRAC and MIPS bands has been recently studied by Draine & Li (2007). While the VSG are heated by single photons from the stellar radiation field producing a broad temperature distribution and are believed to be located close to the central stellar cluster in star-forming regions (Cesarsky et al. 1996; Lebouteiller et al. 2007); the PAH grains can be of various sizes emitting at different bands (Draine & Li 2001) and their emission is seen to peak in the interfaces between the H II regions and the molecular clouds and PDRs (Cesarsky et al. 1996).

In this section, we analyze the emission at 8 μm and 24 μm in the interior of a set of H II regions (NGC 604, NGC 595, NGC 588, NGC 592, and IC131) and relate them to the UV and Hα emission observed in the H II regions. NGC 604 and NGC 595, which are more extensively studied objects than the rest, will be discussed separately below (see Section 5).

#### 3.1. 24 μm and Hα Emission

We first analyze the spatial correspondence between the 24 μm and Hα emissions. In Figure 1, we show continuum-subtracted Hα images for the selected H II regions with 24 μm contours overlaid. There is a clear spatial correlation between Hα and 24 μm emissions in all H II regions of our sample. The most luminous Hα knots correspond spatially to the most luminous ones at 24 μm and the Hα morphology is perfectly traced by the 24 μm emission at lower resolution: the most luminous knots at 24 μm and Hα are located at the same position within NGC 588, the same is seen in NGC 592, and IC131-West, a very concentrated Hα knot, shows the same highly concentrated morphology at 24 μm. The same spatial correspondence is seen for NGC 604 in Figure 2 (lower left panel), where the Hα emission at 6″ resolution is compared to the 24 μm emission. In NGC 595 the agreement is not so good: the 24 μm emission peaks in between the two central Hα maxima, which could be due to a higher extinction at this particular position within the region (see Figure 18 in Bosch et al. 2002), but in general the 24 μm emission follows the same shell-like distribution as Hα in this region. The strong correspondence between the emission at both wavelengths confirms the general trend observed in other galaxies (e.g., Calzetti et al. 2000; Pérez-González et al. 2006; Alonso-Herrero et al. 2006; Prescott et al. 2007) and in nearby H II regions (Churchwell et al. 2006; Watson et al. 2008; see also Tabatabaei et al. 2007).

The good spatial correlation between 24 μm and Hα emissions shows that the dust emitting at 24 μm would be predominantly heated by the emission coming from the OB stars within the H II regions. In this situation, the 24 μm emission radiated by the dust, that has previously absorbed the light coming from the stars, would be more related to the absorbed Hα luminosity than to the observed Hα luminosity in the region. In order to test this hypothesis we have produced a map of absorbed Hα luminosity of NGC 604 (Figure 2, right panel) using the following method. We have obtained a map of the gas extinction using *HST* continuum-subtracted Hα and Hβ images (the derivation of this map will be explained below in Section 5), then the extinction map was used to derive an extinction-corrected Hα luminosity map of the region. Assuming a color excess of E(B−V) = 0.07 mag (van den Bergh 2000) and Cardelli et al. (1989) extinction law with RV = 3.1, we derive a contribution of A(Hα) = 0.17 for the foreground Galactic extinction. The Hα luminosity absorbed in the H II region will be the difference between the total extinction-corrected Hα luminosity and the Hα luminosity corrected for the foreground Galactic extinction. The result is shown in the right panel in Figure 2 with 24 μm emission contours overlaid. In spite of the relatively low extinction in NGC 604, we can clearly see that the

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\(^4\) There is an error in the units of the Hα calibration factor listed in Table 2 of Massey et al. (2007) that we have checked with the authors of this paper (P. Massey 2008, private communication).
absorbed Hα luminosity (right panel) correlates better with the 24 μm emission than the observed Hα luminosity (left panel). This result qualitatively confirms previous results showing that the 24 μm is directly linked to the extincted star formation (Kennicutt et al. 2007; Calzetti et al. 2007; Pérez-González et al. 2006). We further quantitatively investigate this relationship in Section 4.3.

3.2. 8 μm Emission

The 8 μm emission shows differences from the 24 μm emission distribution in the interiors of our set of H II regions. In Figure 3, we show the continuum-subtracted Hα images with 8 μm emission contours overlaid. In the outskirts of the H II regions the 8 μm emission traces the filamentary structure, delineating in some cases the Hα filaments and shells (e.g., in NGC 595 and NGC 588 and NGC 604 in Figure 2, upper left panel). In the central part of the H II regions the 8 μm maxima is in general displaced from the Hα maxima (e.g., NGC 595 and the western part of NGC 604), while the maxima at 24 μm coincides with Hα maxima. The morphology suggests that the 8 μm emission is more related to the PDR than to the location of the ionizing stars or the ionized gas. Differences between 24 μm and 8 μm emissions within extragalactic H II regions were also suggested by Helou et al. (2004) for NGC 300, but the linear resolution of their data (a factor of 2.5 lower than ours) did not allow them to make a firm statement about this. Similar results related to the distribution of the 24 μm, 8 μm, and Hα emission as these shown here for our set of H II regions have been reported for Galactic H II regions (e.g., Churchwell et al. 2006; Watson et al. 2008).

Figure 3. Continuum-subtracted Hα images of our set of H II regions in M33: NGC 595 (upper left), NGC 588 (upper right), IC131 and IC131-West (lower left), and NGC 592 (lower right) with 8 μm emission contours overlaid. The intensity contours are at (2, 5, 10, 20, 40, 60, 80, 95)% of the maximum intensity. A 2% contour level corresponds to a range of (2–6)σ, depending on the region. (A color version of this figure is available in the online journal.)
3.3. UV Emission

As one would expect, the UV stellar emission follows a different distribution from the dust emission at the 24 μm and 8 μm Spitzer bands, and from the emission of the ionized gas at Hα. The UV stellar radiation is generally absorbed by the dust, thus we would not expect to observe UV emission from the stars and dust emission in the same positions within the star-forming regions. In Figure 4, we show the continuum-subtracted Hα images for our set of H II regions with FUV contours overlaid. The Hα emission, in general, surrounds the FUV emission in all H II regions of our sample. This effect is much better appreciated in the shell-like H II regions such as NGC 595, IC 131, NGC 588, and in NGC 604 (Figure 2, upper right panel). The exception to the trend is IC131-West. This knot shows very highly concentrated emission at all wavelengths; it is probably a compact H II region but the extinction derived from different methods (see Table 2) reveals a low dust content in the knot. The existence of UV emission in the center of the shell-like H II regions was also observed by Calzetti et al. (2005) for M51 and Thilker et al. (2005) for M33 in a general study of the UV emission across the galaxy.

The trend observed in all these figures, with the exception of IC131-West, seems to be a stratification of the different emissions. From inside to the outer border of the region: FUV emission is located at the center, then Hα and 24 μm emissions spatially correlate, and both of them are surrounded by the low-intensity filamentary 8 μm emission structure. The best representative cases of the stratification are NGC 595 and NGC 604. For these regions we have also analyzed CO molecular emission and we will comment on the results later.
studied by Calzetti et al. (2005) in M51 and by Pérez-González et al. (2013) in NGC 4038. 

The observed Hα luminosities are given in Column 9 of Table 1. Based on the noise of the Hα image and the aperture size for each Hα region, the uncertainties of our photometry are in the range of 4%–12%. We have checked the Hα luminosities to be in the range of 4%–12%. We have checked our photometry with previously reported results provided by Hodge et al. (2002). We find differences in the Hα luminosities to be in the range of 3%–15%, which are within the range of the uncertainties of our photometry.

### 4. INTEGRATED FLUX MEASUREMENTS

We have obtained aperture fluxes for our set of H II regions in all the wavelengths available in this study. The apertures used to extract the fluxes in each H II region (Column 4 in Table 1) were selected to include the total Hα emission in our images. Background contamination was eliminated using concentric annuli of 25″–35″ width and internal radii of 25″–45″, depending on the aperture size selected for each H II region. The observed Hα luminosities are given in Column 9 of Table 1.

The 8′′ aperture fluxes, the aperture corrections related to changes in the Hα region (Column 4 in Table 1) are given in Column 9 of Table 1. The errors correspond to the uncertainties in the flux estimations due to the noise of the image. For the extinction-corrected Hα luminosity, the error is the combination of the flux uncertainty and the error in the extinction (Column 2 in Table 2).

### 4.1. Ionization Requirements

The observed Hα luminosity of NGC 604, the most intense H II region in our sample, is given in Column 9 of Table 1. It is close to that of 30 Doradus (L(Hα) = 5.13×10^9 erg s⁻¹; Kennicutt & Hodge 1986) and corresponds to a stellar content of ~135 equivalent O5(V) stars (using the ionizing photons for an O5(V) star given in Martins et al. 2005). The other H II regions (except NGC 595) have Hα luminosities one order of magnitude lower than the luminosity of 30 Doradus. Our set of H II regions is therefore 20–300 times more luminous than the well studied Orion nebula. The Hα luminosities of our set of H II regions overlap with the range of luminosities for the H II knots studied by Calzetti et al. (2005) in M51 and by Pérez-González et al. (2006) in M81, which allows us to compare our results for individual H II regions with those presented in statistical studies.

The 8 μm and 24 μm integrated luminosities for the H II regions are given in Table 1 (Columns 7 and 8, respectively). Aperture corrections were applied to the 8 μm fluxes using the photometric corrections for extended sources given in the SSC Web site. For the 24 μm fluxes, the aperture corrections were derived from the theoretical point spread function (PSF) of MIPS at 24 μm. The errors in the 8 μm and 24 μm fluxes for each H II region are given in Table 1, and we estimate flux uncertainties within a range of 3%–20%.

### 4.2. Extinction Measurements

Table 2 is devoted to the global extinction measurements for our set of H II regions, which shows the extinction for each region derived from four different methods: A_{Hα}(Hα) is the extinction derived using the Hα/β emission line ratio (Caplan & Deharveng 1986), A_{24}(Hα) is the extinction derived from the ratio between Hα and 24 μm emissions, A_{07}(Hα) is obtained from the ratio between the thermal radio and the Hα emission.

### Notes

The extinction uncertainties referred to uncertainties in the measured fluxes (see Table 1 and the text).

1. A_{Hα}(Hα) is the value adopted here to correct the observed Hα luminosities. For each H II region, the extinction is the mean value of the extinctions reported in the references listed in the last Column. The errors in the magnitudes are the standard deviations of the different values given in the literature. For NGC 595, we take the value obtained from the Balmer decrement using PMAS observations (M. Relaño et al. 2009, in preparation) and for NGC 604 the value derived in this paper. The extinctions reported here are total extinctions, assuming the Cardelli (1989) extinction law with RV = 3.1.

5. The extinction uncertainties referred to uncertainties in the measured fluxes (see Table 1 and the text).

6. The extinction errors are a combination of the errors in the measured Hα and radio fluxes and an uncertainty in the estimated aperture radio of 20%, except for IC131 where an uncertainty of 10% is considered due to the extended Hα shell structure not related to radio emission. The uncertainties for the radio fluxes are those given in Gordon et al. (1999). An additional uncertainty in A_{Hα}(Hα) is related to changes in the H II region temperature: A_{Hα}(Hα) will decrease by 0.1 mag when the temperature increases by ~1500 K.

7. The ratio between the thermal radio and the Hα emission.

8. The extinction uncertainties referred to uncertainties in the measured fluxes (see Table 1 and the text).

9. A_{Hα}(Hα) is the value adopted here to correct the observed Hα luminosities. For each H II region, the extinction is the mean value of the extinctions reported in the references listed in the last Column. The errors in the magnitudes are the standard deviations of the different values given in the literature. For NGC 595, we take the value obtained from the Balmer decrement using PMAS observations (M. Relaño et al. 2009, in preparation) and for NGC 604 the value derived in this paper. The extinctions reported here are total extinctions, assuming the Cardelli (1989) extinction law with RV = 3.1.

10. The extinction uncertainties referred to uncertainties in the measured fluxes (see Table 1 and the text).

11. A_{Hα}(Hα) is the value adopted here to correct the observed Hα luminosities. For each H II region, the extinction is the mean value of the extinctions reported in the references listed in the last Column. The errors in the magnitudes are the standard deviations of the different values given in the literature. For NGC 595, we take the value obtained from the Balmer decrement using PMAS observations (M. Relaño et al. 2009, in preparation) and for NGC 604 the value derived in this paper. The extinctions reported here are total extinctions, assuming the Cardelli (1989) extinction law with RV = 3.1.
(Churchwell & Goss 1999), and $A$ (FUV) is the FUV extinction that will be studied in the next section.

We have derived $A_{\text{rad}}(\text{H}\alpha)$ for NGC 604, using the integrated $\text{H}\alpha$ and $\text{H}\beta$ fluxes from the HST images, assuming a temperature of $T_e = 8500$ K (Esteban et al. 2002), and applying Equation (A.10) in Caplan & Deharveng (1986) for the case of a screen of homogeneously distributed interstellar dust:

$$A_{\text{rad}}(\text{H}\alpha) = 5.25 \log \left( \frac{L(\text{H}\alpha)}{2.859 \times (T_e/10^4)^{-0.07}} \right),$$

(1)

We obtain $A_{\text{rad}}(\text{H}\alpha) = 0.37 \pm 0.16$, which agrees with the values reported by Maíz-Apellániz et al. (2004; 0.24 mag), Viallefond & Goss (1986; 0.28 mag), and Melnick et al. (1987; 0.39 mag) for the extinctions derived using $\text{H}\alpha$ and $\text{H}\beta$ integrated fluxes. In Column 2 of Table 2, we give the mean value of the extinctions reported in the literature for our set of H II regions. We take into account only the extinctions derived from integrated $\text{H}\alpha$ and $\text{H}\beta$ fluxes. The extinction errors correspond to the standard deviations of the values reported from different authors. For NGC 588, Melnick (1979) obtained 0.46 mag, Viallefond & Goss (1986) 0.81 mag, and Melnick et al. (1987) 0.40 mag; for NGC 592, 0.16 mag and 0.53 mag are reported by Viallefond & Goss (1986) and Melnick et al. (1987), respectively; for IC131 and IC131-West, there are no Balmer extinction values derived from integrated flux measurements; thus we assumed the value given by Vílchez et al. (1988) from long-slit observations for these H II regions. For NGC 595, we have assumed a value of 0.27 for the integrated extinction derived from integral-field spectroscopic observations (M. Relaño et al. 2009, in preparation).

We have been able to calculate $A_{\text{rad}}(\text{H}\alpha)$ using the radio continuum fluxes at 6 and 20 cm (4.84 GHz and 1.42 GHz) reported by Gordon et al. (1999). These authors estimate the radio spectral index for each H II region: NGC 588, NGC 595, and NGC 604 show a radio spectral index of $\alpha = 0.1$ ($S \propto \nu^{-\alpha}$) and NGC 592, IC131, and IC131-West show spectral indices of $\alpha = 0.2 \pm 0.1$, $\alpha = 0.2 \pm 0.2$, and $\alpha = 0.2 \pm 0.1$, respectively. Using these values, consistent with previously reported values (Tabatabaei et al. 2007), we assume that our set of H II regions has $\alpha \sim 0.1$ and use the 4.84 GHz fluxes in Gordon et al. (1999) to estimate the extinction using the $\text{H}\alpha$ luminosities derived in this paper. We have estimated the aperture sizes from the 4.84 GHz image, which is published in Duric et al. (1993), since they are not specified in Gordon et al. (1999). We have then obtained the observed $\text{H}\alpha$ fluxes for the same apertures and derived $A_{\text{rad}}(\text{H}\alpha)$ using Equation (2) of Churchwell & Goss (1999). We assumed a temperature of $10^4$ K for all the H II regions except for NGC 604 that we used $T_e = 8500$ K. The values for $A_{\text{rad}}(\text{H}\alpha)$ are given in Column 4 of Table 2, except for NGC 588 for which we are not able to obtain an accurate value for the extinction. The errors quoted for the extinctions are a combination of the photometric errors and the extinction uncertainties for a change of 20% in the estimated aperture radii. For NGC 592 and NGC 604, we find values within the range reported in the literature (Israel & Kennicutt 1980, Viallefond & Goss 1986, and Churchwell & Goss 1999). For IC131-West, we find an extinction of 0.5 mag lower than the value given by Viallefond & Goss (1986); this is due to the different aperture of the $\text{H}\alpha$ and radio fluxes used by Viallefond & Goss (1986) to derive the extinction for this region. Taking into account the uncertainties, the extinction given for NGC 595 is close (a difference of 0.14 mag) to the value reported by Viallefond et al. (1983) for a similar aperture.

$A_{\text{rad}}(\text{H}\alpha)$ is the extinction derived assuming that the absorbed $\text{H}\alpha$ luminosity scales with the 24 $\mu$m luminosity (Kennicutt et al. 2007). In this case, the corrected $\text{H}\alpha$ luminosity will be a combination of the observed $\text{H}\alpha$ luminosity and the 24 $\mu$m luminosity, and the extinction can be derived in the usual way:

$$A_{24}(\text{H}\alpha) = -2.5 \log \left( \frac{L_{\text{obs}}(\text{H}\alpha)}{L_{\text{obs}}(\text{H}\alpha) + a \times L(24 \mu \text{m})} \right),$$

(2)

where $a = (0.031 \pm 0.006)$ is a scale factor that is empirically obtained from flux measurements of H II knots in different galaxies (Calzetti et al. 2007). We have obtained $A_{24}(\text{H}\alpha)$ using the luminosities given in Table 1. With the exception of NGC 604 and NGC 592, the extinctions derived using the 24 $\mu$m and $\text{H}\alpha$ emissions and those derived from the radio continuum and $\text{H}\alpha$ fluxes agree within the uncertainties. For NGC 604 and NGC 592, increasing the $\text{H}\alpha$ region temperature by 1500 K would decrease $A_{\text{rad}}(\text{H}\alpha)$ by 0.1 mag, reducing the discrepancy between $A_{\text{rad}}(\text{H}\alpha)$ and $A_{24}(\text{H}\alpha)$.

4.3. Stellar Masses

The excellent spatial correlation between the 24 $\mu$m and the absorbed $\text{H}\alpha$ emission in NGC 604 (see Figure 2, lower right panel), which was derived using the Balmer extinction map shown in Figure 10, supports the hypothesis that the 24 $\mu$m emission is a good tracer for the extincted star formation (Calzetti et al. 2007; Pérez-González et al. 2006). The linear relation between these two luminosities implies that the dust emitting at 24 $\mu$m is dominated by the light arising from the star clusters that also produce most of the ionizing luminosity. Here, we show that even at small spatial scales the 24 $\mu$m luminosity traces the current star formation that ionizes the interstellar gas. The correlation is not as good for 8 $\mu$m and the UV; 8 $\mu$m emission has a more extended filamentary structure than $\text{H}\alpha$ emission and UV is more concentrated in the interior of the H II shells where there is no apparent ionized gas (see Figures 3 and 4).

In order to analyze more deeply these observed trends, we have quantified the star formation (SF) in each individual H II region using FUV, 24 $\mu$m, and 8 $\mu$m emissions, and compared the results with those derived from the extinction-corrected $\text{H}\alpha$ luminosities. We will then be able to compare our predictions of SF measurements for H II regions with the results derived from statistical studies applied to regions in different galaxies. The SFR calibrations widely used to quantify the SF are derived assuming a constant SFR over a time scale of 100 Myr (Kennicutt 1998, Calzetti et al. 2007, Iglesias-Páramo et al. 2006), but the typical ages for the H II regions are much smaller ($\sim 2$–8 Myr, Bresolin & Kennicutt 1997, Copetti et al. 1985) and the observable parameters suggest in general an instantaneous burst of star formation (e.g., González-Delgado & Pérez 2000, Malamuth et al. 1996). These properties are also shown in Figure 5, where we compare the extinction-corrected $\text{H}\alpha$ and FUV luminosities derived for our H II regions with a set of instantaneous SF bursts of different stellar masses obtained using Starburst99 (Leitherer et al. 1999). The extinction-corrected luminosities correspond to models of H II regions having stellar masses $\sim 10^4$–$10^5 M_\odot$ and ages of 3–6 Myr. Although we cannot rule out the possibility that H II regions might have non-coeval star clusters (e.g., 30 Doradus among other H II regions shows evidence of a new stellar generation, see Brandner et al. 2001), we assume as approximation an instantaneous burst of SF to describe our H II
regions, which furthermore allows us to define their ages. In the instantaneous SF burst approximation, the SFR is finite at the beginning of the burst ($t = 0$), and remains zero after this time. In order to study the amount of SF within the H II regions, the classical calibrations of the SFR valid for galaxies with continuous SF (Kennicutt 1998) are not applicable here, as we will explain further in this section. Thus, we will derive new calibrations that allow us to quantify the SF from the extinction-corrected Hα and FUV luminosities.

With the exception of IC131, there are independent estimates of the age and the initial mass function (IMF) exponent for the H II regions of our sample (e.g., Hunter et al. 1996; Drissen et al. 1993; Terlevich et al. 1996; González-Delgado & Pérez 2000 for NGC 604; Malamuth et al. 1996 for NGC 595; Jamet et al. 2004 for NGC 588; and Pellerin 2006 for NGC 592). Based on these estimates we can assume that our H II regions are $\tau \sim 4$ Myr old and have Salpeter IMFs ($\alpha = 2.35$) with mass limits 0.1–100 $M_\odot$. From our Figure 5 it is clear that our H II regions span an age range of 3–6 Myr; the assumed age of 4 Myr is an approximation that is supported by the ages estimated in the literature for some of our H II regions: González-Delgado & Pérez (2000) predict an age of 3 Myr for NGC 604 using photoionization models; Malamuth et al. (1996) give an age of 4.5 Myr for NGC 595; and Jamet et al. (2004) an age of 4.2 Myr for NGC 588, both studies used color–magnitude diagrams (CMDs) to predict the ages. Pellerin (2006) predicts an age of 4 Myr for NGC 592 based on FUV spectral synthesis analysis and finds consistent ages for the rest of the H II regions. There are no estimated ages for IC131 and IC131-West in the literature but from Figure 5 we can assume that 4 Myr could also be a reasonable estimated age for them.

We have then used Starburst99 to derive the star formation calibrations for our H II regions in the instantaneous burst approximation using models with Salpeter IMF, mass limits of 0.1–100 $M_\odot$ and metallicity $Z = 0.02$. At $\tau \sim 4$ Myr the relation between the total stellar mass and the Hα luminosity will give

$$\text{SF}(H\alpha)(M_\odot) = 1.29 \times 10^{-34} L(H\alpha) \text{ (erg s}^{-1}\text{).}$$

and for the luminosity at $\lambda 1516$ Å we obtain the following relation:

$$\text{SF}(\text{FUV})(M_\odot) = 1.64 \times 10^{-21} L_{\text{FUV}} \text{ (erg s}^{-1}\text{ Hz}^{-1}).$$

We have applied these calibrations to obtain the SFs for our H II regions using the set of wavelengths we are considering in this paper. The observed Hα luminosities were corrected for extinction using a mean value of $A_{\text{Bal}}(H\alpha)$ derived from the literature (listed in Column 2 of Table 2). This method gives uncertainties in the corrected Hα luminosities of $\sim 25\%$. For the case of NGC 604, we use the value derived here, $A_{\text{Bal}}(H\alpha) = 0.37$ to obtain the extinction-corrected Hα luminosity. The extinction-corrected Hα luminosities are given in the last Column of Table 1 and the SFs derived from them are given in Column 4 of Table 3. A further uncertainty in quantifying the SF is the possible error in the age of the H II region. We estimate the error to be $\sim 20\%$ for the FUV calibration and $\sim 60\%$ for the Hα calibration in our case, because the ages of the H II regions have been estimated by different methods to lie between 3 and 4 Myr.

We use the empirical correlations between the 24 $\mu$m and extinction-corrected Hα luminosity found by Calzetti et al. (2007) for their high-metallicity data points—the metallicity for most of our H II regions are in the higher range defined by these authors (see Magrini et al. 2007; Vílcich et al. 1988)—to derive the SF from the 24 $\mu$m luminosity, SF(24 $\mu$m). The SFs derived in this way are given in Column 3 of Table 3. These are lower by a factor of 0.1–0.6 (see Column 7 in Table 3) than SF(Heαcorr). This result supports the suggestion of Pérez-González et al. (2006) that the 24 $\mu$m emission does not trace the total SF but only traces the ionizing photons absorbed by dust, a suggestion that is based on the better correlation they find between the 24 $\mu$m and the absorbed (extincted) Hα luminosity than to the extinction-corrected Hα luminosity (see Figure 8 in Pérez-González et al. 2006) for the H II emission knots in M81.

Following these ideas, Kennicutt et al. (2007) proposed a combination of Hα and 24 $\mu$m luminosities as a better tracer of the total SF. They proposed that the observed Hα luminosity traces the unobscured star formation, while the 24 $\mu$m emission represents the star formation reprocessed by dust. Thus, the extinction-corrected Hα luminosity is then expressed as a linear combination of these two luminosities:

$$L_{\text{cont}}(H\alpha) = L_{\text{obs}}(H\alpha) + a \times L(24 \mu m),$$

where we have used $a = (0.031 \pm 0.006)$ (Calzetti et al. 2007) to obtain the linear combination of both luminosities and to derive the total SF, SF(com). The results are given in Column 5 of Table 3 and the comparison with the SF(Heαcorr) is given in Column 8 of this table. The star formation derived from the combined luminosities represents 60%–100% of the SF(Heαcorr). For NGC 588, SF(com) represents only 63% of the SF(Heαcorr), for this H II region we have derived a value of $A_{\text{Zal}}(H\alpha)$ which is 0.5 mag lower than the Balmer extinction derived from the literature (see Table 2).

Calzetti et al. (2005) and Pérez-González et al. (2006) did not find as good correlation between the integrated 8 $\mu$m and Hα luminosities for the H II regions in M51 and M81 as they found for 24 $\mu$m and Hα luminosities. They suggested some mechanisms that can affect the relation between the 8 $\mu$m and Hα luminosities (contamination of diffuse emission from the general galactic radiation field and/or destruction of the PAH

Figure 5. Temporal evolution of the logarithmic Hα luminosity versus logarithmic FUV luminosity for a set of instantaneous star formation burst of different stellar masses (full lines). The models were obtained with Starburst99 (Leitherer et al. 1999) using a Salpeter IMF with mass limit 0.1–100 $M_\odot$, and metallicity $Z = 0.02$. The dashed lines show the luminosities at 3, 4, and 10 Myr after the start of the burst. Black points are observed luminosities and red points are the extinction-corrected luminosities for the set of H II regions. The models describe the ranges of masses and ages for our sets of H II regions; for NGC 604, the most luminous H II region, we find agreement with previously reported ages (e.g., $\tau \sim 3$ Myr for NGC 604; González-Delgado & Pérez 2000). (A color version of this figure is available in the online journal.)
Table 3

| Region       | SF(8 μm) 10^6 M_⊙ | SF(24 μm) 10^6 M_⊙ | SF(Heα corr) 10^6 M_⊙ | SF(Com) 10^6 M_⊙ | SF(FUV corr) 10^6 M_⊙ | SF(24 μm)/SF(Heα corr) | SF(Com)/SF(Heα corr) | SF(Heα corr)/SF(FUV corr) |
|--------------|---------------------|--------------------|------------------------|------------------|-----------------------|-------------------------|------------------------|--------------------------|
| NGC 588      | 0.07 ± 0.01         | 0.97 ± 0.11        | 10.85 ± 2.24           | 6.86 ± 0.26      | 4.92 ± 3.36           | 0.09 ± 0.02              | 0.63 ± 0.13             | 2.20 ± 1.58               |
| NGC 592      | 0.19 ± 0.04         | 1.49 ± 0.32        | 4.63 ± 1.24            | 3.98 ± 0.44      | 9.82 ± 6.71           | 0.32 ± 0.11              | 0.86 ± 0.25             | 0.47 ± 0.36               |
| IC131        | 0.16 ± 0.05         | 0.73 ± 0.11        | 4.29 ± 0.50            | 3.94 ± 0.43      | 1.54 ± 1.33           | 0.17 ± 0.03              | 0.92 ± 0.15             | 2.79 ± 2.43               |
| IC131-West   | 0.18 ± 0.01         | 1.86 ± 0.08        | 3.31 ± 0.11            | 3.63 ± 0.18      | 2.15 ± 1.46           | 0.56 ± 0.03              | 1.10 ± 0.07             | 1.53 ± 1.05               |
| NGC 595      | 1.78 ± 0.41         | 11.16 ± 0.94       | 21.00 ± 1.06           | 22.42 ± 1.51     | 6.86 ± 4.72           | 0.53 ± 0.05              | 1.07 ± 0.09             | 3.06 ± 2.11               |
| NGC 604      | 7.16 ± 0.90         | 28.43 ± 0.82       | 55.55 ± 8.34           | 56.87 ± 3.60     | 24.78 ± 16.59         | 0.51 ± 0.08              | 1.02 ± 0.17             | 2.24 ± 1.54               |

Notes.

1. Using the 8 μm–Hα relation fitted by Calzetti et al. (2005) and then applying the calibration for an instantaneous burst of SF: SF(Heα) (M⊙)=1.29×10^{-34}(L_{Hα}/erg s^{-1}), see Equation (3). All the SFs are given in 10^6 M_⊙. The errors given here account for the photometric errors and the errors for the extinctions quoted in Table 2.

2. Using the empirical relation between L_24(erg s^{-1}) and L_{corr}(Hα) (erg s^{-1}) given by Calzetti et al. (2007).

3. Using SF calibration for an instantaneous burst of SF (see Equation (3)).

4. Assuming L_{corr}(Hα) = L_{24}(Hα) + 0.031 × L_24 and then applying Equation (3).

5. Applying the SF calibration for the FUV emission for an instantaneous burst of SF at τ = 4 Myr derived in this paper: SF(FUV) (M⊙)=1.64 × 10^{-21}L_{FUV}(erg s^{-1} Hα^{-1}).

6. The SFs derived from the 8 μm emission are clearly much lower than the SF(Heα corr).

Ultraviolet emission is strongly affected by dust attenuation. In order to use it as a SF tracer, the UV emission has to be corrected using a reliable estimation of the extinction in this wavelength range. Generally, the attenuation has been estimated from the slope of the spectrum in the UV, β, which correlates well with the ratio between the IR and UV emissions for starburst galaxies (Meurer et al. 1999), but shows significant dispersion for normal galaxies (Kong et al. 2004; Cortese et al. 2006; Buat et al. 2005). We have estimated here the extinction in the UV wavelength range using Starburst99 models in the instantaneous burst approximation to compute the intrinsic (FUV–NUV) color and comparing it with the observed (FUV–NUV) color for our H ii regions. Assuming a given age for the starburst, the difference of the observed and intrinsic (FUV–NUV) color allows us to estimate the color excess E(B–V) following the starburst reddening curve given in Equation (4) of Calzetti et al. (2000), and then to derive the FUV extinctions. The intrinsic (FUV–NUV) color varies slightly with age: for 2 < τ < 4 Myr the standard deviation of the intrinsic (FUV–NUV) color derived from our models is σ = 0.06 and for 4 < τ < 20 Myr, σ = 0.03. Assuming an age of τ = 4 Myr, we have derived from our models an intrinsic (FUV–NUV) color of −0.101 and then, using the observed (FUV–NUV) color for each H ii region, we have obtained the FUV extinctions. The results are listed in Column 5 of Table 2. The errors quoted in the table take into account the photometric errors and the uncertainties in the zero-point calibration, ±0.05 m_AB and ±0.03 m_AV for FUV and NUV, respectively (Morrissey et al. 2007). As a check, we have compared the color excess obtained from this method with the color excess derived from other techniques given for three H ii regions (NGC 588, NGC 595, and NGC 604) in the literature, we found good agreement within the uncertainties in all these regions. We also derived the extinction at Hα, assuming the same color excess E(B–V) for the nebular gas as for the stellar continuum, and we found good agreement within the uncertainties with the extinctions at Hα listed in Column 2 of Table 2. We expect an additional uncertainty in the derived FUV extinctions related to the extinction curve used here (see Calzetti (2001) for a comparison of different extinction curves). Assuming extinction curves for the 30 Doradus region in the Large Magellanic Cloud (Fitzpatrick 1985) and the Small Magellanic Cloud’s bar (Gordon & Clayton 1998), we expect deviations of the FUV extinctions reported here of ~10% and ~50%, respectively.

We have used the FUV extinctions to correct the observed FUV luminosities and then we have quantified the SF (SF(FUV corr)) for each H ii region using Equation (4). The result is listed in Column 6 of Table 3. We find consistent values within the uncertainties given here between the SF(Heα corr) (the SF derived from the observed Hα luminosity corrected for extinction using the Balmer extinction values derived from the literature (Column 2 of Table 2)) and SF(FUV corr) (see the last column in Table 3). This shows that the SF(Heα corr) and SF(FUV corr) agree well within the uncertainties assuming an age of 4 Myr for the H ii regions, which is quite reasonable given the ages reported for these H ii regions in the literature (see above). Applying the same method for an age of 3 Myr, which gives an intrinsic (FUV–NUV) color in our models of ~0.119, we obtain values for the SF(Heα corr)/SF(FUV corr) between 0.6 and 1.2 (except for NGC 595 where we obtained a value of 0.2).

We report here the SFs for our set of H ii regions using wavelengths from the UV to the IR and assuming the H ii regions are formed in an instantaneous burst of star formation and are ~4 Myr old. The SF derived using the 8 μm emission is much lower than the SF predicted using the extinction-corrected Hα luminosity. This result is not surprising because the 8 μm emission is indeed only poorly correlated with the Hα emission at the small scales that we are exploring here in our set of H ii regions (see Figure 3). The 24 μm emission also gives lower values of the SFs than the SF(Heα corr), which gives evidence of the low dust content within these H ii regions suggested by the low extinctions derived for them (see Table 2). The combination of 24 μm and observed Hα luminosities gives values of the SFs close to those derived from the extinction-corrected Hα luminosity. This result, which is valid for our set of H ii regions, agrees with the results reported for other galaxies (Calzetti et al. 2007; Zhu et al. 2008) and is supported by the very good spatial correlation between the Hα and the 24 μm emission observed in our H ii regions (see Figure 1). Given the uncertainties in the SF derived from the UV emission we also find good agreement...
between SF(FUV\textsuperscript{corr}) and SF(H\alpha\textsuperscript{corr}) (see the last column in Table 3).

The application of the classical SFR calibrations valid for galaxies with continuous star formation over timescales of \(\sim 100\) Myr (Kennicutt 1998) gives however different results than those shown here. The FUV emission overpredicts the SFRs derived from the extinction-corrected H\alpha luminosities in the continuous SF approximation. This effect was also observed by Sullivan et al. (2000), who explained the difference by a series of starbursts superimposed on the galactic star formation history (see also Bell & Kennicutt 2001). We show here that the assumption of an instantaneous burst of SF is a better approximation in quantifying the SF for an H\alpha region than the assumption implied in the classical SFR calibrations. At 100 Myr, the H\alpha/FUV ratio drops by a factor of \(\sim 2\) (Starburst99, Leitherer et al. 1999), because at this time the ratio is dominated by the FUV emission coming from an older stellar population. Thus, the FUV emission will in general overestimate the actual SFR. As a test we have obtained Starburst99 models assuming a constant SFR and the same IMF as our previous models and applied the same method to derive the SFRs using the extinction-corrected H\alpha and FUV luminosities. We find consistent values (SFR(H\alpha\textsuperscript{corr})/SFR(FUV\textsuperscript{corr})\sim 1) at much later times (\(\tau \gtrsim 15\) Myr), which implies unphysical ages for the H\alpha regions. These results show that caution must be taken when applying the classical SFR calibrations to environments where the continuous SF approximation is not applicable, as in the case of the H\alpha regions.

5. NGC 604 AND NGC 595

NGC 604 is the most luminous and most studied H\alpha region in M33. It shows a very complex H\alpha morphology of shells and filaments revealing a complicated kinematic environment that has been studied by several authors (e.g., Rosa & Solf 1984; Sabaliscck et al. 1995; Yang et al. 1996; Medina-Tanco et al. 1997). Tenorio-Tagle et al. (2000) modeled the big cavities and show evidence of shells blowing out into the halo of M33. Stellar photometry of the region reveals a young population of 3–5 Myr (Hunter et al. 1996) and evidence of WR-stars has been found by several authors (Hunter et al. 1996; Drissen et al. 1993; D’Odorico & Rosa 1981; Rosa & D’Odorico 1982). Using radio observations and comparing them to the H\alpha emission, Churchwell & Goss (1999) obtained an optical depth map of NGC 604. The visual extinction varies across the face of the region, with the maxima located at the position of intense radio knots. This suggests the presence of dust embedded within the hot ionized gas in each radio component. The spatial distribution of ionized gas and dust using optical data has been exhaustively studied by Maíz-Apellániz et al. (2004) revealing differences between the extinction map derived from radio and H\alpha observations and the extinction map obtained from the Balmer decrement. Wilson & Scoville (1992) studied the distribution of the molecular gas in NGC 604 and identified four molecular clouds in the region, some of them showing a high CO(\(J = 3–2\))/CO(\(J = 1–0\)) ratio that would correspond to high temperature and density conditions of compressed gas where new stars could be forming (Tosaki et al. 2007).

The Spitzer observations of NGC 604 presented in this paper and the comparison with observations presented in previous studies allow us to perform a deeper study of NGC 604. We are able to compare the extinction maps derived from different methods with the dust emission within the H\alpha region, the location of the molecular gas and the position of the stars producing the UV and H\alpha emissions. The comparison will give a more complete picture of the structure of the H\alpha region and will allow us to suggest places where a new generation of stars could be located. In Figure 6 (left), we show a color illustration of the emission structure of NGC 604: the arcs and filaments in red corresponding to H\alpha emission are surrounded by the 8 \(\mu\)m emission in green. The 24 \(\mu\)m emission is restricted to the central part of the region and correlates with the position of the most intense central H\alpha knots. NGC 595, the second most luminous H\alpha region in M33 after NGC 604, is less well studied. We show in Figure 6 (right) a three-color image of the region. The emission distribution at H\alpha (red), 8 \(\mu\)m (green), and 24 \(\mu\)m (blue) is similar to that found for NGC 604. Unfortunately, we are not able to derive extinction maps for NGC 595 as for NGC 604, but we have CO molecular data available for this region from Wilson & Scoville (1992) that will be compared with observations at other wavelengths.
Figure 7. Comparison of CO observations with IR, Hα, and FUV emission distributions for NGC 604. In color, we show the 24 μm (top-left), 8 μm (bottom-left), Hα (top-right), and FUV (bottom-right) emission distributions. Contours correspond to the CO observations of Wilson & Scoville (1992). The capital letters correspond to the position of radio knots identified in Churchwell & Goss (1999). The CO observations only cover the southeast part of the H II region delineated by the black axis. We do not have information about the CO emission distribution for the northern part of the H II region.

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

5.1. Comparison to CO Emission

For NGC 604, we compare the location of the radio knots identified by Churchwell & Goss (1999) and the CO emission distribution from Wilson & Scoville (1992) with emission at 24 μm and 8 μm in the mid-infrared, FUV emission and ionized gas emitting at Hα (see Figure 7). The spatial distribution at these wavelengths shows a similar behavior as in the rest of
Figure 8. Comparison of CO with IR, Hα, and FUV emission distributions for NGC 595. Contours are the molecular emission, as shown in Wilson & Scoville (1992) and color images correspond to top-left: 24 μm emission, top-right: continuum-subtracted Hα emission, bottom-left: 8 μm emission, and bottom-right: FUV emission. In the top-right panel, we show the integration zone used to obtain the radial profiles in Figure 9. The location of the center and the dashed lines (±45° from the major axis of the ellipse) were chosen to include the Hα emission of the shell structure. The ellipticity was derived assuming an inclination angle of 56° for M33 (van den Bergh 2000).

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

The H II regions in our sample (see also Figure 2). The FUV emission, located within the larger Hα shells and probably tracing a moderate age stellar population, anticorrelates with the CO molecular emission (lower right panel in Figure 7). Except for the radio knot E, the faintest one, the radio components coincide with the location of maxima at 24 μm emission and have Hα emission associated with them (see top panels in Figure 7). The eastern high-intensity knots at 24 μm and 8 μm coincide with the position of the most intense central molecular cloud, but the maximum at 8 μm emission seems to be closer to the maximum of the molecular cloud than the maximum at 24 μm (upper and lower panels in Figure 7).

In NGC 595 (Figure 8), these patterns are even more clearly defined. The figure shows 24 μm, Hα, 8 μm, and FUV emission with CO contours overlaid. In this region, the CO emission follows perfectly the arched distribution of the 8 μm emission (the bottom left panel in Figure 8), while the 24 μm emission distribution shows its maximum slightly shifted from the CO maxima (upper left panel) and is spatially related to the shell-like Hα distribution. The FUV emission is clearly shown to be located in the inner part of the Hα-shell structure anticorrelating with the CO emission. The displacement between the different emission lines is better appreciated in Figure 9. In this figure, we show radial profiles extracted over elliptical rings of 2′ width covering the complete Hα shell structure of NGC 595 (see Figure 8 (top-right) where the integration zone is depicted). The integrated fluxes for each ring have been normalized to the maximum value in the corresponding ring. From the center
position to outer radii a layered structure emission is clearly seen: FUV is located at the inner part of the ellipse, then at larger radii there is emission at H\(\alpha\) and 24 \(\mu\)m, both following the same distribution, and slightly further out we find the 8 \(\mu\)m and CO emission distributions. The H\(\alpha\) and 24 \(\mu\)m emission distributions have coincident maxima, as well as the 8 \(\mu\)m and CO distributions. The geometry of the shell in NGC 595, defined as a semicircle in H\(\alpha\), reveals the same layered structure as the one observed in the southeast part of NGC 604, but with the 8 \(\mu\)m emission much more identified with the molecular cloud. This supports the idea that the 8 \(\mu\)m emission indeed traces the location of the PDR. The emission distribution in the interior of NGC 604 and NGC 595 at the wavelengths we are able to study here, from UV to CO emission, shows that the classical picture of the H\(\text{ii}\) region as seen in the Orion Nebula, with the molecular cloud located at the boundaries of the H\(\text{ii}\) region and delineating the PDR (O’dell 2001; Hollenbach & Tielens 1997), also holds for extragalactic H\(\text{ii}\) regions.

5.2. Extinction Maps of NGC 604

In order to compare the dust emission and extinction, we have derived extinction maps for NGC 604 following the two methods: one using the Balmer decrement and another based on the ratio between the 24 \(\mu\)m and H\(\alpha\) luminosities. The H\(\alpha\) and H\(\beta\) images were smoothed to 6′ resolution, and Equation (1) was applied with a temperature of 8500 K (Esteban et al. 2002) to derive the extinction map using the Balmer decrement. The result is shown in the left panel of Figure 10, overlaid with CO emission contours from Wilson & Scoville (1992) and the identified radio emission knots from Churchwell & Goss (1999). The Balmer extinction map is similar to the one derived in Bosch et al. (2002) at 2′ resolution from H\(\alpha\) and H\(\beta\) observations at the 1.0 m Jacobus Kapteyn Telescope and to the one derived by Maíz-Apellániz et al. (2004) at 4″ resolution. The second method applies Equation (2) and uses the 24 \(\mu\)m and H\(\alpha\) images of NGC 604. We convolved the H\(\alpha\) image to the resolution of the 24 \(\mu\)m image using the semiempirical PSF for a 75 K blackbody.6 Then, the smoothed H\(\alpha\) image was regridded to have the same pixel size as the 24 \(\mu\)m image and Equation (2) was applied to derive the extinction map shown in the right panel of Figure 10.

Both extinction maps show localized enhancements that are related to the position of radio knots (marked as capital letters in both figures) and the CO emission. Unfortunately, we only have CO observations of the southwest part of NGC 604 (marked as black axes in Figure 10); thus the comparison between both extinction maps and the CO emission can only be made for that part of the region. Although the range of values for the extinction derived from both methods is quite similar, the extinction distributions within the region are different. The comparison of both extinction maps is specially interesting at the position of the main molecular cloud in the region, MC-2 in Wilson and Scoville’s notation. At this position we find differences derived from both methods. The \(A_\text{24} (\text{H}\alpha)\) map shows a maximum that corresponds to the location of MC-2, while in the Balmer extinction map we can see an extinction gradient at this position. A similar phenomenology was observed by Maíz-Apellániz et al. (2004) comparing the Balmer extinction with the extinction derived using radio observations. They found a better correlation between the extinction map derived from radio observations and the position of the main molecular cloud identified by Engargiola et al. (2003) than between the Balmer extinction map and CO data. Maíz-Apellániz et al. (2004) explain the difference by proposing a scenario in which “H\(\text{ii}\) gas is located along the surface of the main molecular cloud but this cloud creates a high obscuration ‘flap’ that absorbs most of the Balmer photons located behind, letting only radio continuum photons traverse it.” We observe here the same effect, the 24 \(\mu\)m emission at the position of the MC-2 is produced by the absorption of the ionizing radiation coming from the stars located behind the flap. The extinction produced by this flap in the molecular cloud can be studied using radio or 24 \(\mu\)m emission, as shown in the right panel of Figure 10. The extinction predicted by the Balmer decrement will only account for the extinction suffered by the radiation coming from stars located at the surface of the molecular cloud facing toward us.

The picture described above agrees well with the results from kinematic studies (Yang et al. 1996). These authors described five H\(\alpha\) shells with different sizes and velocities in NGC 604. Their shells identified as 4 and 5 lie next to the position of the MC-2, with part of their surfaces bordering the molecular cloud (see top right panel in Figure 7 in this paper and Figure 2(c) in Yang et al. 1996). The authors found asymmetric expansion velocities for these shells, as opposed to the symmetric velocities observed in the rest of the shells located away from the molecular cloud. They argue that the expansion of these shells into the molecular clouds would cause the asymmetries, and that the shells are “blisters” located on the surface of the molecular cloud. If the surface of the molecular cloud has indeed a shell morphology, this geometry is consistent with the existence of a high obscuration flap that explains the difference between both extinction maps shown in Figure 10.

5.3. Embedded Star Formation in NGC 604?

The difference between the extinction maps explained in the previous section gives clues about the possibility of having an amount of dust along the line of sight that cannot be detected when only the Balmer extinction is considered. At the location

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6 http://dirty.as.arizona.edu/~kgordon/mips/conv_psfs/conv_psfs.html
of radio knots A and B Tosaki et al. (2007) found a high CO($J = 3–2)/CO(J = 1–0)$ ratio, which reflects conditions of high temperature and density. Using [S ii] $\lambda 6717/\lambda 6731$, Maíz-Apellániz et al. (2004) found high-density peaks at the positions of radio knots A and B suggesting the existence of two compact H ii regions. These locations could be sites where new embedded star formation takes place.

In order to check this hypothesis we have reanalyzed the stellar photometry presented by Hunter et al. (1996) in a rectangular area shown in Figure 12 that includes the bright radio knots A and B and most of the molecular cloud MC-2. We have used the HST WFPC2 stellar photometry performed by Hunter et al. (1996), which is available through ADC\(^7\) and created a CMD (Figure 11) of the central star cluster of NGC 604 (Cluster A in Hunter et al.’s notation). The diagram is the same as the one shown in Figure 5(a) (left panel) in Hunter et al. (1996). Neither reddening nor distance corrections have been applied. We recognize in the diagram the red giant branch at low F555W luminosity (identified by Hunter et al. (1996) as background stars) and the main sequence for the most luminous stars in the H ii region. We also show the reddening vector corresponding to $A_V = 1.5$ mag for an O3(V) star in the main sequence ($M_B = -5.79$, Martins et al. 2005 and $V - I = -0.322$, Bessell et al. 1998), following the extinction curve of Cardelli et al. (1989) with $R_V = 3.1$ and applying it to the WFPC2 filters (see Holtzman et al. 1995). $A_V = 1.5$ mag ($E(B-V) \sim 0.5$) is a reasonable upper limit of the mean extinction suffered by the stars in NGC 604; it corresponds to the maximum extinction observed in NGC 604 (see Figure 10) and Churchwell & Goss (1999) found an overall extinction of $A_V \sim 0.5$ mag for the region. Other studies show lower values for the overall extinction: $E(B-V) = 0.08$ (Hunter et al. 1996), $E(B-V) = 0.03$ (Pellerin 2006), $E(B-V) = 0.13$ (González-Delgado & Pérez 2000), corresponding to $A_V = 0.25$, $A_V = 0.09$, and $A_V = 0.40$, respectively; and here we obtain $A_{\text{Bal}}(\text{H}\alpha) = 0.37$, which corresponds to $A_V = 0.30$.

The blue points in Figure 11 represent stars located in a rectangular area including radio knots A and B which are bright (F555W $\leq 22.5$) and have higher F555W-F814W color (F555W-F814W $\geq 0$) than those corresponding to main sequence stars. We have excluded from this selection eight stars with F555W–F814W errors higher than 0.2 mag, which is the

\(^7\) Astronomical Data Center: http://adc.astro.umd.edu/adc.html

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Figure 10. Left: extinction map at 6′′ resolution obtained from the Hα/Hβ emission line ratio with CO emission contours overlaid. Right: extinction map derived from the 24 μm and Hα emission line ratio with CO contours. The Hα image has been convolved and regridded to have the same resolution and pixel scale as the 24 μm image from MIPS, only pixels with S/N > 15 in the 24 μm image were considered. The capital letters correspond to the position of radio knots identified in Churchwell & Goss (1999; see Figure 7). The black axes inside the plot show the field of view of the CO observations from Wilson & Scoville (1992). Unfortunately, we are not able to compare both extinction maps with the CO emission for the total H ii region, only for the region within the axes.

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

Figure 11. CMD for Cluster A defined in Hunter et al. (1996). The red line shows the extinction correction corresponding to $A_V = 1.5$ mag (see text). The stars marked with blue asterisks are stars located within the molecular cloud MC-2 that have F555W $\leq 22.5$ and F555W–F814W $\geq 0$. These stars, located to the right of the main sequence, would show an IR-excess and could be classified as young stellar objects.

(A color version of this figure is available in the online journal.)
spread seen for the main sequence in this diagram. The stars selected in this way are bright enough not to belong to the red giant branch and they cannot be supergiants (for an O9.5(I) $M_V = -6.28$, Martins et al. 2005, corresponding to an apparent magnitude of $m_V = 18.34$). Thus, the stars marked as blue asterisks in Figure 11 could be stars showing a redder excess that are probably forming in dense knots of dust and molecular gas. The location of these stars in NGC 604 is shown in Figure 12 on the HST F555W image from Hunter et al. (1996).

Another possible reason for the displacement of the stars to the right of the main sequence in the CMD could be the extinction produced by the molecular cloud MC-2, which can cause higher localized extinction than the lower overall extinction in the region. In order to test this possibility, we have derived the extinction required to locate the reddened stars on the main sequence, using the reddening vector shown in the CMD (Figure 10). We find that the stars need to be extinction corrected by $A_V \sim 0.1$--8.0 mag to be located in the main sequence.

A crude estimation of the extinction caused by the molecular cloud can be estimated using the conversion of the CO intensity into molecular mass ($N$(H$_2$)/$I_{CO} = 2 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$, Dickman et al. 1986) and the dust-to-gas mass ratio of $A_V/N$(H) $\sim 5.3 \times 10^{-22}$ mag cm$^2$ (Bohlin et al. 1978). The extinction value range derived in this way is $A_V \sim 1.5$--9.0 mag, similar to the extinction range required to locate the stars on the main sequence. In Figure 12, we plot the reddened stars and the extinction contours derived using the molecular emission on the F555W image, blue points are stars which required $A_V < 2.0$ mag to be located on the main sequence and red points stars requiring $A_V > 2.0$. Although the extinction estimates from the CO intensity map are quite crude, they show evidence that the CO molecular cloud could be producing an extra reddening in the H$\text{\textsc{ii}}$ region that lead us to confuse the redder stars with stars having an intrinsic IR-excess.

The reddened stars shown in the CMD could be explained by the existence of a foreground molecular cloud but we cannot rule out the possibility that the radio knots A and B are embedded star-forming regions that we cannot detect with our observations. The classical JHK infrared color–color diagram used to detect young stellar objects (Lada & Adams 1992) could be useful here to search for evidence of embedded star formation. The principal problem in using JHK photometry for NGC 604 is the detection limit; young stellar objects such as T Tauri stars, Herbig AeBe stars, and Class I sources can be very difficult to see at the distance of M33, because their apparent magnitudes range between $m_J \sim 26$ for T Tauri stars to $m_J \sim 22$ for Class I sources (see Figure 3 in Brandner et al. 2001).

Although we are not able to confirm the existence of embedded star formation in NGC 604 using the observations presented in this paper, we show here results that reinforce this hypothesis. First, the locations of the reddened stars coincide with high CO and 8 $\mu$m emission, second, we need to assume that there is ionized gas completely hidden by dust to explain the differences between the extinctions derived from the Balmer decrement and the extinction derived using 24 $\mu$m (Figure 10). Third, the high CO($J = 3$–2)/CO($J = 1$–0) ratio found by Tosaki et al. (2007) at the position of the radio knots A and B. All these results suggest that there should be embedded star formation in the surroundings of the molecular cloud MC-2.

6. SUMMARY AND DISCUSSION

We present observations to study the dust and gas emission distribution within a set of the most luminous H$\text{\textsc{ii}}$ regions in M33. The linear resolution of the observations allows us to make a comparison of the 24 $\mu$m, 8 $\mu$m, H$\alpha$, and UV emissions in the interior of the H$\text{\textsc{ii}}$ region sample and quantify the star formation for each individual H$\text{\textsc{ii}}$ region using different wavelengths. We find the following results.

1. The general picture assumed in previous extragalactic studies, which suggests a correspondence between the 24 $\mu$m emission and the nebular H$\alpha$ emission line, is found here at the small local scales where the stars form in the H$\text{\textsc{ii}}$ regions. The 24 $\mu$m emission structure suggests that the emitted dust is mixed with the ionized gas in the interior of the H$\text{\textsc{ii}}$ regions, while the 8 $\mu$m emission is associated with the H$\text{\textsc{ii}}$ region boundaries and neutral material. The UV emission is in general not associated with 24 $\mu$m and 8 $\mu$m emissions, and it is clearly surrounded by the emission of the ionized gas at H$\alpha$.

2. We quantify the SFs for our sample of H$\text{\textsc{ii}}$ regions using a set of available wavelengths and assuming an instantaneous burst of SF. The SFs derived from the 24 $\mu$m emission are up to a factor of 10 lower than that derived from the extinction-corrected H$\alpha$ luminosity, while the SFs derived using a linear combination of 24 $\mu$m and observed H$\alpha$ emission give better estimations of the total SFs in the regions than the estimations from the 24 $\mu$m or 8 $\mu$m emissions by themselves.

3. The 8 $\mu$m emission fails to reproduce the SFs values derived using the extinction-corrected H$\alpha$ luminosity, which is not surprising since 8 $\mu$m is more associated with the boundaries of the H$\text{\textsc{ii}}$ regions and shows larger systematic
uncertainties and a larger scatter when it is calibrated as an SFR tracer.

4. We show that the observed UV and Hα luminosities are consistent with young stellar populations (τ ∼ 3–4 Myr) and that the SFRs predicted from extinction-corrected FUV fluxes are similar to the values derived from Hα when the instantaneous SF approximation is taken into account.

5. We have derived extinction maps for NGC 604, the most luminous H II region in our sample. We see that although global extinction is modest (A_V = 0.30), we do find localized regions within NGC 604 with much higher extinction. The extinction values estimated from the 24 μm and Hα luminosity ratio are higher than those derived using the Balmer decrement at the location of MC-2. The underestimated extinction values using the Balmer method are probably related to geometrical effects at the surface of the main molecular cloud in NGC 604. In spite of these differences, the extinction variations seem to have little effect on global extinction derivations and thus on the SF measurements presented here.

6. The SFR derived from the 24 μm emission better traces the extincted SF in the H II regions. This is supported by the good spatial correlation between the absorbed Hα luminosity of NGC 604, derived using a Balmer extinction map of the region, and the emission at 24 μm. This is expected if the dust emitting at 24 μm reprocesses the light coming from the ionizing stars.

The results shown in this paper have important implications for the study of the star formation in galaxies. Our sample of H II regions are typical of star-forming regions in normal galaxies; therefore we expect the conclusions derived here at local scales to hold when studying statistically the SF in big galaxy samples. We see that (1) since dust reprocesses only a fraction of the UV stellar emission, the SFR derived using IR emission (24 μm, 8 μm, and IR) will underestimate the SF. (2) Although at small scales there are differences in the extinction derived from the Balmer decrement and from the 24 μm-to-Hα luminosity ratio for NGC 604, the integrated values for the extinction derived from both methods agree within the uncertainties (A_Bal(Hα) = 0.37 ± 0.16, A_24(Hα) = 0.40 ± 0.07). This supports the hypothesis of using 24 μm emission to correct the Hα luminosity for extinction. The local differences in extinction can be used to find places where there can be a higher dust content than the one derived only from the extinction of optical emission lines. (3) We do not see a similar correspondence between 24 μm and UV emission, which shows the inability of using the 24 μm emission to correct UV fluxes for extinction. (4) We also note here that the SFR calibrations derived assuming continuous SF approximation, generally applied to galaxies, are not applicable in H II regions. We show that an instantaneous burst of SF is a better approximation for our objects and we present the corresponding SFR calibrations for a burst of age 4 Myr.

The detailed study presented here using high-resolution data allows us to disentangle the spatial correspondence between the 24 μm and 8 μm emissions, which have been recently proposed as tracers of the SFR, and the location where the stars form. This study shows that the assumptions on which the statistical studies rely are valid and that the conclusions inferred from them also hold at small galactic scales. In spite of this, absolute SFR calibrations generally used for galaxies have to be treated with extreme care when applying to local star-forming regions such as individual H II regions.

It would be useful to extend the approach presented here to a larger sample of H II regions in M33 and the Magellanic Clouds. We would also like to study the dust emission at longer wavelengths using the same method as presented here, especially to compare the 24 μm emission associated with the ionizing stars with cooler dust emitting at 70 μm and 160 μm, but the resolutions of MIPS is insufficient to carry out this project in our sample of H II regions. Our limited comparison with CO observations illustrates the power of understanding the nebular geometry of the H II region (see also Ercolano et al. 2007) and the general structure of the interior of the H II regions, but more data (e.g., Herschel and HI observations) would be helpful to extend the conclusions reached here.

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