A VERY LARGE ARRAY STUDY OF ULTRACOMPACT AND HYPERCOMPACT H II REGIONS FROM 0.7 TO 3.6 cm

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ABSTRACT

We report multi-frequency Very Large Array observations of three massive star formation regions (MSFRs) containing radio continuum components that were identified as broad radio recombination line (RRL) sources and hypercompact (HC) H II region candidates in our previous H92α and H76α study: G10.96 + 0.01 (component W), G28.20 − 0.04 (N), and G34.26 + 0.15 (B). An additional HC H II region candidate, G45.07 + 0.13, known to have broad H66α and H75α lines, small size, high electron density, and emission measure, was also included. We observed with high spatial resolution (0.′′9–2.′′3) the H53α, H66α, H76α, and H92α RRLs and the radio continuum at the corresponding wavelengths (0.7–3.6 cm). The motivation for these observations was to obtain RRLs over a range of principal quantum states to look for signatures of pressure broadening and macroscopic velocity structure. We find that pressure broadening contributes significantly to the linewidths, but it is not the sole cause of the broad lines. We compare radio continuum and dust emission distributions and find a good correspondence. We also discuss maser emission and multi-wavelength observations reported in the literature for these MSFRs.

Key words: H II regions – radio lines: ISM – stars: formation

1. INTRODUCTION

Hypercompact (HC) H II regions represent an earlier evolutionary state than compact and ultracompact (UC) H II regions. These very small (∼0.03 pc), high electron density (n_e ∼ 10^3−10^6 cm^{-3}) and high emission measure (EM ∼ 10^8 pc cm^{-6}) nebulae are ionized from within by O or B stars and usually are associated with maser emission. Many, but not all, have unusually broad radio recombination lines (RRLs) with full widths at half-maximum intensity (FWHM) ≥ 40 km s^{-1} (De Pree et al. 1996, 1997; Sewilo et al. 2004a). HC H II regions have rising spectral indices α (where S_λ ∝ λ^α) from centimeter to millimeter wavelengths with typical values of α ∼ 1, which suggests a range of densities and optical depths in the ionized gas. Broad RRLs (BRRRLs) and intermediate sloped (−0.1 < α < +2) power-law spectral indices may be associated with the age of HC H II regions, appearing only during a small fraction of the lifetime of the HC phase. There are very dense and compact H II regions, however, that do not have intermediate power-law spectral energy distributions or broad RRLs (e.g., G34.26 + 0.15 A, Avalos et al. 2006; Sewilo et al. 2004a).

Although possibly related to the age, the physical reason that some HC H II regions do not present BRRRLs is poorly understood. The broad linewidths suggest highly dynamic internal structures (e.g., bipolar outflows, expansion, stellar winds, accretion, disk rotation, shocks) as well as electron impact (pressure) broadening. High spatial resolution observations over a wide range of frequencies are required to distinguish the relative contributions from pressure broadening and bulk motion of the gas. Transitions with high principal quantum numbers, n, are significantly affected by pressure broadening, while low n transitions are mostly free of pressure broadening and are sensitive to large-scale motions. With high spatial resolution at a range of frequencies, it is possible to distinguish bulk motions from pressure broadening. Observations have shown that both pressure broadening and gas dynamics contribute to line broadening (Sewilo et al. 2008; Kato et al. 2008).

Theoretical progress has been made toward understanding the nature of HC H II regions. The model of hierarchical clumping of the nebular gas proposed by Ignace & Churchwell (2004) was able to reproduce the intermediate values of spectral indices seen in HC H II regions. Tan & McKee (2003) and Kato (2003) proposed models that predict both confinement of the ionized gas in HC H II and the BRRRL emission. The photoevaporating disk model, originally proposed by Hollenbach et al. (1994) and Lizano et al. (1996) to explain the most compact UC H II regions, has been recognized to be applicable to HC H II regions (Lugo et al. 2004).

Here, we report high spatial resolution, multi-frequency Very Large Array (VLA) observations of four candidate HC HII regions with the goal of determining their physical properties. Three sources, G10.96 + 0.01, G28.20 − 0.04, and G34.26 + 0.15, were selected based on an earlier H92α and H76α study (Sewilo et al. 2004a). We also observed the HC HII candidate G45.07 + 0.13 NE, which is known to have broad H66α and H76α lines (Garay et al. 1985, 1986), small size, and high electron density (i.e., high EM). Additional RRLs were observed to search for systematic broadening with increasing principal quantum number. A strong correlation of line width with principal quantum number would indicate pressure broadening as the main mechanism for line broadening, as opposed to large-scale motions (rotation, outflows, infall, etc.). The rms electron temperature and the rms electron density of the sources can be determined for each transition using the assumption of local thermodynamic equilibrium (LTE). RRLs also provide information on the velocity structure of the sources.

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Instrumental Parameters for the VLA Observations

| Parameter                              | 2003 Mar 20 | 2004 Mar 7, 8 |
|----------------------------------------|-------------|--------------|
| Program                                | AS753       | AS797        |
| Transitions observed                   |             |              |
| H53a                                   | (a) H66a    | (b) H76a     |
|                                       | (c) H92a    |              |
| Observed sources                       | G28.20−0.04 | G10.96+0.01 (ab) |
|                                       | G34.26+0.15 | G28.20−0.04 (b) |
|                                       |              | G45.07+0.13 (c) |
| Total observing time                   | 10 hr       |              |
|                                       | (a) 3 hr    |              |
|                                       | (b) 9 hr    |              |
|                                       | (c) 1 hr    |              |
| Configuration                          | D           | C            |
| Synthesized beam/FWHM (")              |             |              |
| P.A.(°)                                |             |              |
| G10.96+0.01                            | 1.4 × 0.8, −8 (a) |
|                                       | 2.0 × 1.2, −2 (b) |
| G28.20−0.04                            | 1.9 × 1.4, −10 |
| G34.26+0.15                            | 1.6 × 1.5, −4 |
| G45.07+0.13                            | 2.5 × 2.4, −31 (c) |
| Rest frequency of the H line           | 42951.97 MHz | (a) 22364.17 MHz |
|                                       |             | (b) 14689.99 MHz |
|                                       |             | (c) 8309.38 MHz |
| Observing mode                         | 1A          | 2AD          |
| Bandwidth                              | 25 MHz      | 12.5 MHz     |
| Number of channels                     | 31          | 31           |
| Channel separation                     | 781.25 kHz  | 390.625 kHz  |
| Velocity resolution (°°°)              |             |              |
|                                       | 6.5 km s⁻¹  | (a) 6.2 km s⁻¹ |
|                                       |             | (b) 9.6 km s⁻¹ |
|                                       |             | (c) 16.9 km s⁻¹ |
| Flux density calibrator (Jy):           |             |              |
| 3C 286 for G10.96+0.01                 | 2.53 (a), 3.50 (b) |
| G28.20−0.04                            | 1.47        | 3.50 (b)     |
| G34.26+0.15                            | 1.47        |              |
| G45.07+0.13                            | 5.27 (c)    |
| Phase calibrators (Jy):                |             |              |
| 1820–254 for G10.96+0.01               | 0.610 ± 0.004 (a) |
| 1851+005 for G28.20−0.04               | 0.692 ± 0.003 (b) |
| 1925+211 for G45.07+0.13               | 0.72 ± 0.02   |

Notes.

* a, b, and c indicate values for the H66a, H76a, and H92a lines, respectively.
* Primary beams are 1° for AS753; 2° for AS797 (a), (b), and (c), respectively.
* The observations were done with uniform spectral weighting, thus the velocity resolution is 1.2 times the channel separation.

We report detections of the H53α, H66α, H76α, and H92α RRLs and the 0.7, 1.3, 2.0, and 3.6 cm radio continuum emission with resolutions of 1°5, 0°9, 1°2, and 2°3, respectively, toward the MSFRs G10.96+0.01, G28.20−0.04, G34.26+0.15, and G45.07+0.13 (hereafter G10.96, G28.20, G34.26, and G45.07). The observations are described in Section 2. In Section 3, we derive physical properties of the nebulae based on continuum observations and investigate the change of line width with principal quantum number. In Section 4 we investigate the dust emission toward these sources using mid-infrared Spitzer Space Telescope GLIMPSE data. We compare the mid-infrared GLIMPSE and radio continuum images with previous maser emission and multiwavelength observations. We discuss the general results in Section 5 and summarize the main conclusions in Section 6.
use VLA morphology of G28.20 N at even higher resolution, here we created the high resolution (0.′′6) interferometric data from the literature. The relative positional uncertainty of 12 GHz H2O masers detected toward G45.07 NE is 0.′′1 (Hofner & Churchwell 1996). The distribution of masers is shown in Figures 1(b), 4, and 6 for G10.96 W, G28.20 N, and G45.07 NE, respectively.

We used VLA K-band spectral-line archival data for G28.20 N HC H II region (Program ID AP465) to supplement the single-dish water maser data available for this source in the literature. The observations were taken on 2008 April 4 with the VLA in C configuration. A 3.125 MHz bandwidth with 255 channels of 12.2 kHz each was used. We followed standard VLA data reduction procedures. The synthesized beam is 1.′′19 × 0.′′94 at position angle of −12.8. The typical rms of a line-free channel is 22 mJy beam −1 . We determined the positions and peak flux densities of the masers from Gaussian fits to the peak channel of each H2O maser data available for this source in the literature. The observations were taken on 2008 April 4 with the VLA in C configuration. A 3.125 MHz bandwidth with 255 channels of 12.2 kHz each was used. We followed standard VLA data reduction procedures. The synthesized beam is 1.′′19 × 0.′′94 at position angle of −12.8. The typical rms of a line-free channel is 22 mJy beam −1 . We determined the positions and peak flux densities of the masers from Gaussian fits to the peak channel of each maser. The H2O maser positions and observed parameters are listed in Table 4. The uncertainty of the H2O maser positions in G28.20 N is 0.′′1.

We also investigate dust emission for our sample using data from the Spitzer Space Telescope GLIMPSE survey ("Galactic Legacy Infrared Mid-Plane Survey Extraordinaire", Benjamin Ne is 0.′′6 (Kurtz et al. 2004). The relative positional accuracy of 22 GHz H2O masers detected toward G45.07 NE is 0.′′1 (Hofner & Churchwell 1996). The distribution of masers is shown in Figures 1(b), 4, and 6 for G10.96 W, G28.20 N, and G45.07 NE, respectively.

The 2 cm flux density from the region that encloses two compact components (9′′ × 12′′) is 3.9 mJy beam −1 . The 2 cm flux density from the region that encloses compact components (9′′ × 12′′) is 3.9 mJy beam −1 . The peak flux density is 2.78 Jy beam −1 . The faint S1 component emerging at 7 mm is partially blended with component S; the reported flux density is the total integrated flux density from both components. The flux density of the S1 component constitutes ∼15% of the total flux. The peak 7 mm flux density of S1 is 26.6 mJy beam −1 .

c The faint S1 component emerging at 7 mm is partially blended with component S; the reported flux density is the total integrated flux density from both components. The flux density of the S1 component constitutes ∼15% of the total flux. The peak 7 mm flux density of S1 is 26.6 mJy beam −1 .

d The A component is partially blended with component C; the integrated flux density should be considered the lower limit.

e The B component is not fully resolved from the cometary component C, thus we cannot give either its angular diameter or flux density. The position given in the table was determined from the 3.6 cm continuum map in Sewilo et al. (2004a).

f The integrated flux density was calculated using the AIPS task IMEAN from the area of ∼22′′ by ∼12′′ in R.A. and decl., respectively, that encloses all three components of the G34.26 H II region complex. The total flux density of the A component is ∼92 mJy, the remaining ∼908 Jy arise from components B and C. Only a small fraction of this flux density (< 3%) comes from the B component (see the text).

Notes.

a Source positions, deconvolved angular sizes, position angles, and integrated flux densities were determined by elliptical Gaussian fitting using the AIPS routine JMFIT. We estimate the positional uncertainty to be ∼0′′1. Uncertainties in source sizes depend on both the brightness and the intrinsic source extent; we estimate them to be accurate to within ∼10%. The flux density uncertainties are ∼10%—this value takes into account the error of the fit (JMFIT) and systematic effects (e.g., calibration errors, mismatches between the Gaussian model and the actual source shape, etc.).

b The E component of the MSFR G10.96 is overresolved at both 1.3 and 2 cm. Most of the flux is filtered out, thus we do not give either the total flux density or source size at these wavelengths. The 1.3 cm coordinates correspond to the maximum pixel. The peak flux density at 1.3 cm is 3.9 mJy beam −1 . The 2 cm flux density from the region that encloses two compact components (9′′ × 12′′) is 3.9 mJy beam −1 . The 2 cm flux density from the region that encloses two compact components (9′′ × 12′′) is 3.9 mJy beam −1 .

c The faint S1 component emerging at 7 mm is partially blended with component S; the reported flux density is the total integrated flux density from both components. The flux density of the S1 component constitutes ∼15% of the total flux. The peak 7 mm flux density of S1 is 26.6 mJy beam −1 .

d The A component is partially blended with component C; the integrated flux density should be considered the lower limit.

e The B component is not fully resolved from the cometary component C, thus we cannot give either its angular diameter or flux density. The position given in the table was determined from the 3.6 cm continuum map in Sewilo et al. (2004a).

f The integrated flux density was calculated using the AIPS task IMEAN from the area of ∼22′′ by ∼12′′ in R.A. and decl., respectively, that encloses all three components of the G34.26 H II region complex. The total flux density of the A component is ∼92 mJy, the remaining ∼908 Jy arise from components B and C. Only a small fraction of this flux density (< 3%) comes from the B component (see the text).

Table 3

| Source         | λ  | Comp. | Position (h m s) | δ(J2000) (′′) | Time on Source (hr) | Source Diameter (′′ × ′′) | Source P.A. (°) | Integrated Flux Density (mJy) | rms (mJy beam −1 ) |
|----------------|----|-------|------------------|---------------|---------------------|-------------------------|----------------|-------------------------------|-------------------|
| G10.96+0.01    | 1.3 cm | E    | 18 09 42.85 | −19 26 29.6 | 0.5                  | ...                     | ...            | ...                           | 0.4               |
| G28.20−0.04    | 0.7 cm | N    | 18 42 58.11  | −04 13 35.7  | 0.6                  | 0.7 × 0.5              | 159            | <108              | 1.4               |
| G34.26+0.15    | 0.7 cm | A    | 18 53 17.95  | +01 14 56.3  | 1.0                  | 0.3 × 0.2              | 54             | >86        | 2.8               |
| G45.07+0.13    | 3.6 cm | NE   | 19 13 22.08  | +10 50 53.2  | 0.6                  | 0.6 × 0.6              | 87             | 350            | 0.8               |

The coordinates correspond to the maximum pixel in the cometary component C. The peak flux density is 2.78 Jy beam −1 .

c The faint S1 component emerging at 7 mm is partially blended with component S; the reported flux density is the total integrated flux density from both components. The flux density of the S1 component constitutes ∼15% of the total flux. The peak 7 mm flux density of S1 is 26.6 mJy beam −1 .

d The A component is partially blended with component C; the integrated flux density should be considered the lower limit.

e The B component is not fully resolved from the cometary component C, thus we cannot give either its angular diameter or flux density. The position given in the table was determined from the 3.6 cm continuum map in Sewilo et al. (2004a).

The integrated flux density was calculated using the AIPS task IMEAN from the area of ∼22′′ by ∼12′′ in R.A. and decl., respectively, that encloses all three components of the G34.26 H II region complex. The total flux density of the A component is ∼92 mJy, the remaining ∼908 Jy arise from components B and C. Only a small fraction of this flux density (< 3%) comes from the B component (see the text).
Figure 1. 1.3 (a) and 2 cm (b) VLA continuum images and the H66α (c) and H76α (d) line profiles integrated over the central portion of the W continuum component of the MSFR G10.96. The positions of the two CH₃OH maser spots in G10.96 W are superimposed on the 2 cm image (b). Beam sizes are the same as in Figure 2.

Table 4

| Water  | α(J2000) (h m s) | δ(J2000) (° ′ ″) | V_{LSR}^a (km s^{-1}) | S_{peak}^b (Jy) |
|--------|-----------------|-----------------|-----------------------|-----------------|
| Maser  |                 |                 |                       |                 |
| 1      | 18 42 58.07     | -04 13 56.9     | 97.7                  | 1.2             |
| 2      | 18 42 58.12     | -04 13 57.8     | 95.6                  | 10.7            |
| 3      | 18 42 58.11     | -04 13 57.6     | 93.1                  | 1.6             |
| 4      | 18 42 58.06     | -04 13 57.0     | 91.0                  | 22.2            |

Notes.

^a The velocity of the peak channel.
^b The uncertainties of peak flux densities are dominated by systematic errors.

We adopt a standard 10% uncertainty for the VLA at K band.

et al. 2003; Churchwell et al. 2009). The inner Galactic plane was imaged at 3.6, 4.5, 5.8, and 8.0 μm using the IRAC camera (Fazio et al. 2004) on the Spitzer Space Telescope. The IRAC spatial resolution ranges from 1′.5 to 1′.9 between the 3.6 and 8.0 μm bands. The IRAC image mosaics were created by the GLIMPSE pipeline. The absolute accuracy of the GLIMPSE point-source positions is 0.3 (Meade et al. 2009).

3. RESULTS

3.1. Physical Properties of the Sources

Physical properties of the sources were derived from the observed continuum parameters reported in Table 3 using the equations of Mezger & Henderson (1967) and Panagia & Walmsley (1978) for spherical, optically thin, homogeneous, and ionization-bounded H II regions. Panagia & Walmsley (1978) presented modified versions of the Mezger & Henderson (1967) equations for geometry-dependent physical parameters such as the rms electron density \( n_{e,\text{rms}} \), the emission measure \( \text{EM} \), and the mass of ionized gas \( M_{\text{H}^0} \). The excitation parameter \( U \) and the Lyman continuum photon flux required
to maintain ionization of the nebula \(N_e\) do not depend on the source size or its morphology and were derived using the formulae from Mezger & Henderson (1967). The continuum optical depth \(\tau_c\) was calculated from the Oster (1961) formula in a form presented by Mezger & Henderson (1967), using EM derived based on the results of Panagia & Walmsley (1978). The derived physical parameters for each source are presented in Table 5. The linear diameter of a sphere listed in Table 5 is the diameter of the spherical model for the source, rather than the apparent Gaussian half-power width of the source reported in Table 3. An optically thin homogeneous sphere has the same peak EM and total flux density as the observed source. The calculations take into account the dependence on the beam size as described in Panagia & Walmsley (1978).

The \(N_e\) values were used to estimate a lower limit to the spectral type of the exciting star given in the last column of Table 5. The classification is based on the non-LTE, spherically expanding (owing to the stellar wind), line-blanketed (to account for the effects of metals on the atmospheric structure and emerging ionizing flux) model atmospheres derived by Smith et al. (2002) under the assumption that a single star ionizes a dust-free, ionization bounded \(H\) region. The assignment of a given spectral type with \(N_e\) depends strongly on assignment of effective temperature with spectral type and how accurately stellar atmosphere models reflect reality. For these reasons, spectral types listed in Table 5 are approximations. The stellar spectral type corresponds to the value of radio flux density at the highest frequency observed.

A second set of physical properties of the nebulae was derived based on their peak brightness temperature; these are “peak physical properties” (Wood & Churchwell 1989). These quantities depend only on the peak brightness, not the measured...
Figure 3. (a) The 7 mm VLA continuum image and the integrated H53α line profiles from the N (c) and S (e) components of MSFR G28.20. (b) The 2 cm VLA continuum image and the integrated H76α line profiles from G28.20 N (d) and S (f). The beam sizes shown in the lower left corners in (a) and (b) are \( \sim 1.5\) and \( \sim 1.4\), respectively (see Table 1).
3.2. Radio Recombination Line Analysis

The Gaussian fit parameters of the line profiles are given in Table 7. $V_{LSR}$ is the central line velocity relative to the local standard of rest, FWHM is the line full width at half-

Figure 4. Distribution of OH and CH$_3$OH masers in G28.20 N superimposed on: the 7 mm VLA image (a and b: b is a magnification of the central portion of the image shown in a; this paper), the 1.3 cm VLA image (c; VLA archival data, project AZ168), and the CH$_3$CN SMA image (d; Qin et al. 2008). The synthesized beams of the VLA shown in the lower left insets in (a) and (c) are $\sim 1''6$ and $0''09$, respectively (see Table 1). The synthesized beam of the SMA is $\sim 1''5$ (see Section 4.2) and is shown in the lower left corner in (d).

The peak optical depth was estimated from $T_B = T_e(1 - e^{-\tau_c})$ assuming a kinetic temperature of $T_e = 10^4$ K that is constant over the synthesized beam. The peak EM was calculated using the optical depth equation from Mezger & Henderson (1967). The relation $n_e = \langle n_e^2 \rangle^{1/2} = (EM/\Delta s)^{1/2}$ was used to calculate the rms electron density ($n_e,\text{rms}$) averaged over the beam. The quantity $\Delta s$ is the source size along the line of sight through the peak position. We assume that the sources in our sample have spherical geometry based on their projected circular symmetry; for $\Delta s$ we adopt their geometrical mean angular diameters (half-power widths, or “source size” in Table 3) assuming that the extent of the source along the line of sight is the same as its extent in the plane of the sky. The peak physical properties are given in Table 6.

Thus, they can be derived for all the sources from our sample including the blended components B and C in the G34.26 complex and the overresolved component E of G10.96. The brightness temperature $T_B$ is given by the Rayleigh–Jeans approximation.
The measured line widths given in Table 7 are broadened because of the finite velocity resolution of the observations. To determine the intrinsic line widths, the instrumental spectral resolution was deconvolved from the observed lines. The convolution function in the spectral frequency domain was assumed to be a Gaussian function with FWHM of 1.2 times the channel width (or twice the channel width if the spectrum was Hanning-smoothed off-line) and deconvolved from the observed line widths. The deconvolved line widths (FWHM$_{\text{deconv}}$) are given in Table 8.

We calculated the LTE electron temperatures $T_e^*$ for all the sources with reliable RRL measurements using the formula from Rohlfs & Wilson (1986):

$$T_e^* = \left[ \frac{6.985 \times 10^5}{a(\nu, T_e)} \right] \cdot (\frac{S_L/S_C}{\text{peak}})^{-1} \cdot \frac{1}{\text{FWHM}_{\text{deconv}}} \cdot \left( \frac{1 + Y^+}{1 + Y^+} \right)^{0.87},$$

(1)

where $\nu$ is in GHz, FWHM$_{\text{deconv}}$ is in km s$^{-1}$, and $T_e^*$ in K. $Y^+ = N(\text{He}^+)/N(\text{H}^+)$ is the ratio of ionized He to H atoms and is assumed to be 0.1. The factor $a(\nu, T_e)$ is approximately 1 (Altenhoff et al. 1960). This equation was derived under...
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Cont peak flux = 3.2828E-01 JY/BEAM
Levs = 7.690E-04 * (-3, 3, 6, 10, 20, 40, 80, 160, 300, 400)

DECLINATION (J2000)
RIGHT ASCENSION (J2000)
19 13 22.8
22.6
22.4
22.2
22.0
21.8
21.6
21.4
21.2
10 51 00
50 55
50
45
40
0.1 pc
(a)

Table 5
Source Averaged Physical Parameters based on Continuum Observations

| Source             | λ (cm) | Diameter of Sphere (mpc) | τc | n(cm)/τc,10^4 (cm^-3) | EM/10^7 (pc cm^-6) | U (pc cm^-2) | M_HII (M☉) | log N'(c) | Spectral Type |
|--------------------|--------|--------------------------|----|-------------|-----------------|-------------|------------|-----------|--------------|
| G10.96 + 0.01c     | W      | 1.3                      | 121 | 0.02       | 2.9             | 5.3         | 57.6       | 0.6       | 48.8         | O7.5V        |
|                    | ...    | 2                        | 124 | 0.06       | 2.7             | 5.3         | 56.4       | 0.6       | 48.8...      | ...          |
| G28.20−0.04        | N      | 0.7                      | 28  | 0.04       | 17              | 36          | 43.9       | 0.05      | 48.4         | O8V          |
|                    | ...    | 2                        | 35  | 0.2        | 9.8             | 19          | 37.1       | 0.05      | 48.2...      | ...          |
| G34.26 + 0.15d     | A      | 0.7                      | 8   | 0.03       | 27              | 24          | 16.3       | 0.002     | 47.1         | B0.5V        |
| G45.07 + 0.13 NE   | NE     | 3.6                      | 32  | 0.7        | 9.4             | 19          | 33.4       | 0.04      | 48.1         | O8.5V        |
| G45.07 + 0.13 SW   | SW     | 3.6                      | 65  | 0.03       | 1.4             | 0.8         | 18.7       | 0.05      | 47.3         | B0V          |

Notes. The physical parameters are the linear diameter of a spherical H II region (assumed model), the continuum optical depth (τc), the rms electron density (n(cm)), the emission measure (EM), the excitation parameter (U), the mass of ionized gas (M_HII), and the Lyman continuum photon flux required to maintain ionization of the nebula (N'(c)).

a We estimate an uncertainty of the derived physical parameters to be up to 20%. These parameters depend on the different combinations of the integrated flux density, observed source size, and assumed distance. All of these quantities have uncertainties of ~10%.

b Lower limits to the spectral types of the exciting stars are derived from N'(c) using the model stellar atmosphere results of Smith et al. (2002). See the text for details.

c We do not report the physical parameters for component E of G10.96 + 0.01, because most of the emission from this source is filtered out. See footnote to Table 3.

d We do not report the physical parameters for components B and C of G34.26 + 0.15. They are blended at our spatial resolution, hence we cannot determine their angular sizes or flux densities.

several assumptions about H II regions: (1) the structure is plane-parallel, homogeneous and isothermal, (2) all optical depths are small: |τl + τc| ≪ 1 and τc ≪ 1, and (3) the lines can be treated in the LTE approximation.

However, several of the observed sources have relatively high optical depths (τc from 0.02 to 0.2), causing attenuation of the line-to-continuum ratio. In these cases, the LTE electron temperatures have been calculated using the line-to-continuum ratios corrected for opacity rather than the measured values:

\[(S_L/S_C)_{corr} = (S_L/S_C)_{peak} \cdot (e^{τ_c} - 1)/τ_c.\]

The corrected line-to-continuum ratios and the LTE electron temperatures are listed in Table 8. The uncertainties in T′ were estimated by a linear propagation of errors.

3.3. Spitzer/IRAC Mid-infrared Emission

High-spatial resolution mosaics from GLIMPSE (Churchwell et al. 2009) are a unique tool for the study of massive star formation regions (MSFRs). The IRAC 3.6, 5.8, and 8.0 μm bands contain strong polycyclic aromatic hydrocarbon (PAH) features that probe conditions in photodissociation regions...
surrounding molecular gas (e.g., Tielens et al. 1993). PAHs Lyman ultraviolet photons but are destroyed in H(PDRs) that separate the ionized gas in H\textsc{ii} regions.

The spectrum was Hanning smoothed. The GLIMPSE Catalog is more reliable but less complete than the Archive.8 The GLIMPSE Point Source Catalog (green circles) and Archive8 sources (red circles) are overlaid on the 3.6 \textmu m bands. G45.07 is saturated in all bands. G45.07 is saturated in all bands.

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reported in Sewiło et al. (2008) based on the same data: 39.7 \, G_{34.26} + 0.15 \, A_{H53} 

The deconvolved linewidths of the H76\(\alpha\) lines are slightly smaller than those reported in Sewiło et al. (2008) based on the same data: 39.7 \pm 1.3 \, km \, s^{-1} and 57.6 \pm 2.2 \, km \, s^{-1} for H53\(\alpha\) and H76\(\alpha\) lines, respectively. The difference in linewidths is due to different integration areas used in both papers. While Sewiło et al. (2008) integrated the lines over the entire source, the lines reported in this paper were integrated over the area enclosed by the 50% contour.

c The line-to-continuum ratios corrected for opacity for this source was derived from the peak optical depths listed in Table 6. The bright IRAC sources suffer from the “electronic band-width effect,” this instrumental effect is exhibited only in the 8.0 and 5.8 \, \mu m IRAC bands for saturated or bright sources; it produces artifacts appearing as a sequence of sources of decreasing intensity. This effect is seen in the 8.0 \, \mu m image of G28.20\,N, and 5.8 \, \mu m and 8.0 \, \mu m images of G34.26 and G45.07 NE. As an example, the source appearing to be blended with G28.20\,N slightly to the south in the 8.0 \, \mu m image of Figure 8 is not the S component, but rather is an image artifact produced by this effect.

A discussion of the IR emission from individual sources is presented in Section 4.

4. COMMENTS ON INDIVIDUAL SOURCES

In this section, we present the results of our RRL and mid-IR study for the individual sources. We also summarize the previous work on radio, IR, maser, and molecular line (where available) emission from each source.

4.1. G10.96 + 0.01

The G10.96 MSFR consists of two compact radio continuum components G10.96 E and G10.96 W surrounded by more diffuse ionized gas. They have been detected in radio continuum between 1.4 GHz and 8.6 GHz (Becker et al. 1994; Walsh et al. 1998; Paper I). In Paper I, we reported the detection of a broad H92\(\alpha\) line with an FWHM of 43.8 \pm 1.5 \, km \, s^{-1} toward the W component. The E component has a linewidth of 33.6 \pm 4.9 \, km \, s^{-1} toward the E component. The E component has a linewidth of 33.6 \pm 4.9 \, km \, s^{-1} toward the W component. The E component has a linewidth of 33.6 \pm 4.9 \, km \, s^{-1} toward the W component. The E component has a linewidth of 33.6 \pm 4.9 \, km \, s^{-1} toward the W component. The E component has a linewidth of 33.6 \pm 4.9 \, km \, s^{-1} toward the W component. The E component has a linewidth of 33.6 \pm 4.9 \, km \, s^{-1} toward the W component. The E component has a linewidth of 33.6 \pm 4.9 \, km \, s^{-1} toward the W component. The E component has a linewidth of 33.6 \pm 4.9 \, km \, s^{-1} toward the W component. The E component has a linewidth of 33.6 \pm 4.9 \, km \, s^{-1} toward the W component. The E component has a linewidth of 33.6 \pm 4.9 \, km \, s^{-1} toward the W component.

The deconvolved linewidths of the H76\(\alpha\) and H66\(\alpha\) lines from G10.96 W reported in Table 8 are 28.4 \pm 1.5 and 28.0 \pm 0.6 \, km \, s^{-1}, respectively (see Figure 1). These results indicate that the H92\(\alpha\) line is strongly affected by pressure broadening (see the discussion in Section 5.1). For G10.96 E, both H76\(\alpha\) and H66\(\alpha\) lines are narrow with FWHMs of 19.4 \pm 0.3 and 15.0 \pm 4.9 \, km \, s^{-1}, respectively (see Figure 2). These lines are narrower than their H92\(\alpha\) counterpart by over 10 \, km \, s^{-1}, even if the 30% uncertainty in the FWHMs of the higher frequency...
Figure 8. IRAC 8.0 $\mu$m (left) and 3.6 $\mu$m (right) images of G28.20. The 8.0 $\mu$m image shows that G28.20 is located toward an infrared dark cloud (see the text). The 3.6 $\mu$m image is zoomed in on the source; 7 mm radio contours indicate the positions of radio sources (see Figure 3(a)). The point sources from GLIMPSE are marked. The source appearing to be blended with G28.20 N slightly to the south in the 8 $\mu$m image is an image artifact produced by the “electronic bandwidth effect” (see Section 2.2). The intensity ranges from 0.5 mJy to 51.2 mJy for the 8 $\mu$m image, and from $\sim$7 $\mu$Jy to 25.4 mJy for the 3.6 $\mu$m image. One arcmin and 10 arcsec are equal to $\sim$1.7 pc and $\sim$0.3 pc, respectively, assuming a distance of 5.7 kpc (Table 2).

Figure 9. Left: the three color composite image of G34.26. Red, green, and blue correspond to IRAC 8.0 $\mu$m, 4.5 $\mu$m, and 3.6 $\mu$m, respectively. The 7 mm 3$\sigma$ radio contour (see Figure 5) is overlaid to indicate the radio positions. A striking feature of the image is a massive outflow detected at 4.5 $\mu$m (see Section 4.3.2). An incomplete ring of emission dominating the central and lower parts of the image corresponds to radio component D. Right: the IRAC 3.6 $\mu$m image of G34.26 with the high-resolution 2 cm radio contours (Sewilo et al. 2004a) overlaid. Mid-IR components E and F from Campbell et al. (2000) and the peak of radio D component (Fey et al. 1994) are marked with blue circles and labeled. The GLIMPSE point sources are marked. The 8.0 $\mu$m image suffers from the “electronic bandwidth effect” (see Section 2.2). The intensity ranges are ($\sim$1 $\mu$Jy, 20.7 mJy), ($\sim$1 $\mu$Jy, 23.4 mJy), and (0.3 mJy, 55.9 mJy) for 3.6, 4.5, and 8.0 $\mu$m image, respectively. One arcmin and 10 arcsec are equal to $\sim$1.1 pc and $\sim$0.2 pc, respectively, assuming a distance of 3.7 kpc (see Table 2).

Several maser species have been detected toward G10.96. Methanol (CH$_3$OH) 6.67 GHz masers were first reported by Schutte et al. (1993) and later confirmed by Walsh et al. (1997), both based on single-dish observations. The high resolution interferometric survey of Walsh et al. (1998) revealed two CH$_3$OH maser spots in the W component, near the continuum emission peak (see Figure 1(b)). Water masers and CS(2-1) emission are reported by Codella et al. (1995) and
Bronfman et al. (1996), respectively, based on single-dish observations. In Figure 7 we present 3.6 and 8.0 µm images of the G10.96 MSFR. These images indicate a close correspondence between the distribution and morphology of dust and ionized gas. The diffuse dust emission from G10.96 E is filamentary, with a size of ~60′′×40′′ (~4.1×2.7 pc at a distance of 14 kpc; Table 2) in R.A. and decl., respectively. This filamentary structure is more prominent at 24 µm (MIPSGAL survey; Carey et al. 2009), but is also noticeable at shorter wavelengths. In the 3.6 µm image a possible central ionizing source (high-mass (proto)star) is prominent in the W component. The 3.6, 4.5, 5.8, and 8.0 µm flux densities of the IRAC source (GLIMPSE Archive ID: SSTGLMA G010.9584+00.0219) are 9.7 ± 0.9 mJy, 58.7 ± 7.5 mJy, 174.2 ± 12.1 mJy, and 395.3 ± 30.7 mJy, respectively.

The IRAC images also reveal a cluster of sources around the radio emission peak in component E (see Figure 7). Some of these objects may be ionization sources; however, we cannot rule out that some may be background objects. The multiplicity of ionizing (proto)stars may give rise to the multiple-peak morphology of the UC H II region shown in Figure 2. The mid-IR source located near the 3.6 cm peak of G10.96 E in Figure 7 corresponds to one of the two peaks (E2 to the southwest) of the 2 cm emission (Figure 2(b)). The GLIMPSE Archive provides the 3.6, 4.5, and 5.8 µm flux densities for this source (SSTGLMA G010.9646+00.0098) of 8.2 ± 2.7 mJy, 13.1 ± 4.0 mJy, and 58.9 ± 7.6 mJy, respectively.

4.2. G28.20—0.04

The G28.20—0.04 MSFR hosts two radio continuum components: N and S. Both components were detected in previous radio continuum (0.7 cm–6 cm, e.g., Kurtz et al. 1994; Walsh et al. 1998; Sewilo et al. 2004a, 2008) and RRL (H92α and H53α; Sewilo et al. 2004a, 2008) observations. The N component has been identified as the HC H II region candidate by Sewilo et al. (2004a) based on the 3.6 cm continuum and H92α RRL observations. The H92α lines reported in Paper I have FWHMs of 74 ± 3 and 35 ± 1 km s⁻¹ for components N and S, respectively. Higher-frequency RRLs from G28.20 N (H53α, Sewilo et al. 2008; H30α, Kato et al. 2008) are significantly narrower than the H92α line, with line widths of 39.8 ± 1.7 km s⁻¹ and 20.9 ± 0.6 km s⁻¹, respectively.

In Figure 3, we present a 2 cm and a new 7 mm continuum image of G28.20, along with the corresponding H76α and H53α line profiles. Both RRLs are narrower than the H92α line reported in Paper I for both the N and S components. The H76α and H53α FWHMs are 55 ± 3 and 38 ± 1 km s⁻¹ for component N, and 24 ± 4 km and 19 ± 2 s⁻¹ for component S, respectively. The significant increase in line width with increasing quantum number for G28.20 N indicates that pressure broadening is an important (possibly dominant) line broadening mechanism for the H92α line detected from this source.

Although not evident in Figure 3, we detect marginal evidence for 7 mm continuum emission at the southeast border of G28.20 N. The emission is slightly more evident in the 6 cm CORNISH image (C. Purcell 2010, private communication). We do not report parameters for this marginal detection, but note the possible presence of a non-thermal source at this position. In addition, our continuum images—at both 7 mm and 2 cm—show evidence for a new source, with a rising spectral index, just to the east of G28.20 S. We refer to this source as G28.20 S1 (see Figure 3(a)) and report approximate values for its parameters in Table 3.

However, Sewilo et al. (2008) showed that gas dynamics also contributes to line broadening in G28.20 N. The morphology and velocity structure of G28.20 N was resolved in their high resolution (~0′′.15) 7 mm continuum and H53α VLA observations. The source appears as a shell-like structure with an inner radius of 1100 AU and an outer radius of 2500 AU. They detected a velocity gradient of 10³ km s⁻¹ pc⁻¹ along the minor axis of the continuum source, from which they inferred a rotating torus around an ~30 M☉ central object. Based on line broadening and splitting along the major axis, they also suggested the presence of an outflow.

4.2.1. Molecular Gas Kinematics

G28.20 N has also been the target of high resolution molecular line observations by Qin et al. (2008), who proposed the existence of a hot core in G28.20 N. They used the Submillimeter Array (SMA) to image transitions in CH₃CN, CO, ¹³CO, SO₂,
et al. (2008) based on the 13CO distribution and line profile, Qin et al. (2008) argued that 13CO emission originates outside of the HMC, since the excitation temperature and H$_2$ density are lower than those derived from the CH$_3$CN line. The 13CO spectrum shows blueshifted absorption and redshifted emission with the absorption and emission peaks aligned with the source rotational axis (i.e., the SE–NW direction; Sewiło et al. 2008). Based on the 13CO distribution and line profile, Qin et al. (2008) concluded that 13CO traces an outflow from the source, detected in G28.20 N shows two velocity peaks (95 and 97 km s$^{-1}$) separated by 0.7 km s$^{-1}$. This velocity difference corresponds to a NE–SW velocity gradient of $\sim$400 km s$^{-1}$ pc$^{-1}$ (Qin et al. 2008). A similar velocity pattern was observed in the $K = 5$ component of the CH$_3$CN ($J = 12$–11) transition detected toward G28.20 N (S.-L. Qin 2010, private communication). The infall and outflow were previously reported by Sollins et al. (2005), based on VLA observations of ammonia (HPBW from $\sim$0.3′ to $\sim$3′).

Based on the same SMA data previously used by Qin et al. (2008), Klaassen et al. (2009) reported a detection of the SO$_3$ and OCS velocity gradient of $\sim$150 km s$^{-1}$ pc$^{-1}$ in a roughly N–S direction (as opposed to the NE–SW direction suggested by Qin et al. 2008). Klaassen et al. (2009) also suggested the presence of a CO outflow in the NE–SW direction. Qin et al. (2008) found that the CO data are inconclusive due to the contamination from the infall; as mentioned above, they suggested an outflow in the SE–NW direction based on the 13CO data. The detection of the H53$\alpha$ velocity gradient in the NE–SW direction by Sewiło et al. (2008) supports the Qin et al. (2008) interpretation.

4.2.2. Maser Emission

Numerous masers have been detected toward the G28.20 MSFR: 1665 and 1667 MHz OH (Argon et al. 2000), 22 GHz H$_2$O (Han et al. 1998; Kurtz & Hofner 2005; this paper), and 6.67 GHz CH$_3$OH (Walsh et al. 1998). G28.20 was also observed with arcmminute resolution in the excited OH transitions at 6035 MHz (Caswell & Vaile 1995; Caswell 2003) and 6030 MHz (Caswell 2003). The OH, H$_2$O, and CH$_3$OH maser emission is associated with component N (see Figure 4).

4.2.3. Dust Emission

Spitzer IRAC images of G28.20 at 8.0 and 3.6 $\mu$m are shown in Figure 8. The 8.0 $\mu$m image shows that G28.20 is located toward an elongated region of high extinction (infrared dark cloud, IRDC) stretching over at least 2′ ($\sim$3.3 pc at 5.7 kpc) in a roughly NE–SW direction. This IRDC is probably the natal molecular cloud from which the protostars in G28.20 are forming. Figure 8(b) shows the 3.6 $\mu$m image of G28.20 MSFR. The contours of the 2 cm radio emission indicate the position of the N and S components. The mid-IR sources from the GLIMPSE Catalog/Archive are indicated by circles. A bright source, detected in $K_s$ band and all four IRAC bands, coincides with G28.20 N. A much weaker source, detected at 3.6 and 4.5 $\mu$m, coincides with G28.20 S. Midway between the two radio components, a third IR source is a near-IR (JHK$_s$) source (also detected at 3.6 $\mu$m). This source does not have a radio counterpart and may be a foreground object or a less deeply embedded object.

Both G28.20 N and G28.20 S have counterparts in the GLIMPSE Archive: SSTGLMA G028.203-00.0493 and SSTGLMAG028.1984-00.0501, respectively. The mid-IR source corresponding to G28.20 N is significantly brighter than the sources that matches G28.20 S. The 3.6 and 4.5 $\mu$m flux densities are 358.4 $\pm$ 18.9 mJy and 2123.0 $\pm$ 99.3 mJy for component N, and 2.1 $\pm$ 0.3 mJy and 8.9 $\pm$ 1.2 mJy for component S. The 5.8 $\mu$m flux density of G28.20 N is 3892.0 $\pm$ 98.6 mJy.

4.3. G34.26 + 0.15

Four radio continuum components (A–D) and two infrared sources (E and F; Campbell et al. 2000) have been identified in the G34.26 MSFR. Component C is a prototypical cometary UC H II region with a compact head toward the east and a diffuse tail to the west (e.g., Reid & Ho 1985; Garay et al. 1986; Sewiło et al. 2004a). Components A and B, located to the east of component C, are UC H II region candidates. A more evolved component (D), located southeast of components A–C, is thought to be an H II shell with a diameter $\sim$1′, expanding within an ambient density gradient (Fey et al. 1994).

We detected H53$\alpha$ emission toward G34.26 components A, B, and C. The line parameters are presented in Tables 7 and 8; line profiles and the 7 mm continuum image are shown in Figure 5.

The H76$\alpha$ (Paper I) and H53$\alpha$ (this paper) lines from G34.26 A are narrow, with FWHMs of $\sim$22 km s$^{-1}$, consistent with a combination of thermal and turbulent broadening. The H53$\alpha$ linewidth of component C is 50.2 $\pm$ 6.4 km s$^{-1}$, in good agreement with the H76$\alpha$ linewidth of 55.5 $\pm$ 1.9 km s$^{-1}$ reported by Garay et al. (1986). These authors demonstrate that this relatively broad linewidth probably results from microturbulent motions having a velocity of $\sim$30 km s$^{-1}$, Component B has a broad H76$\alpha$ line of FWHM 48.4 $\pm$ 4.4 km s$^{-1}$ (Paper I); however the H53$\alpha$ line is $\sim$15 km s$^{-1}$ narrower (see Table 8) indicating that the H76$\alpha$ line has a substantial contribution from pressure broadening. Also notable is the higher H53$\alpha$ line center velocity for component B; the velocity is more than 15 km s$^{-1}$ higher than for either component A or C. It is unclear if this velocity difference is important to understand the nature of component B. Hatchell et al. (2001) considered component B as a strong candidate for the driving source of the SiO outflow; if this is the case, there may be a dynamic explanation for the higher H53$\alpha$ velocity.

If we assume no contribution to the component A and B line widths from large scale motions and a non-thermal (turbulent) contribution of 5 km s$^{-1}$ (FWHHM; Cesaroni et al. 1991; Plume et al. 1997; Sewiło et al. 2008), then we can determine an upper limit for pressure broadening from the H76$\alpha$ line. The electron temperatures for the A and B components are 5700 K and 5300 K, respectively (Paper I). Thus, the thermal plus turbulent contribution to the line width is $\sim$17 and $\sim$16 km s$^{-1}$ for components A and B, respectively. The resulting upper limits for the pressure broadening contribution to the H76$\alpha$ line (calculated as described in Sewiło et al. 2008) are $\sim$10 km s$^{-1}$ and $\sim$43 km s$^{-1}$ for the A and B components, respectively.

Components A and B meet the criteria for UC H II regions (Paper I; Avalos et al. 2006; this paper). The diameters, electron densities, and EMs derived in Paper I based on high-resolution ($\sim$0′.5) 2 cm observations are 0.008 pc and 0.006 pc (assuming a...
distance of 3.7 kpc; 1.4 \times 10^5 \text{ cm}^{-3} and 2.2 \times 10^5 \text{ cm}^{-3}; 2.2 \times 10^6 \text{ pc cm}^{-6} and 4.3 \times 10^6 \text{ pc cm}^{-6}, respectively. However, both components A and B have a relatively low turnover frequency of \sim 10 \text{ GHz} (Avalos et al. 2006). The physical parameters derived in this paper (see Table 5) for component A agree with the Paper I results. No physical parameters for component B can be derived because this source is partially blended with component C at the resolution of 1.5\arcsec.

Avalos et al. (2009) resolved G34.26 A and B with 0.05 resolution VLA observations and detected possible limb brightening in both sources. They used spherical shell models with power-law density gradients \( n \propto r^{-\alpha} \) to explain their observations. They showed that the 7 mm intensity profiles, radio continuum spectra, and angular sizes of both G34.26 A and B can be reproduced by a shell of inner and outer radii \sim 400 \text{ AU} and \sim 1000 \text{ AU}, respectively, and a density gradient \( \alpha \sim 0.3\text{--}1.0 \). This physical picture is quite similar to what has been proposed for G24.78 + 0.08 A1 (Beltrán et al. 2007) and G28.20 -- 0.4 N (Sewilo et al. 2008).

4.3.1. Maser Emission

Maser emission is detected in G34.26 including H$_2$O (Hofner & Churchwell 1996), OH at 1665 and 1667 MHz (Garay et al. 1985; Gaume & Mutel 1987; Gasiprong et al. 2002), OH at 6 GHz (Caswell & Vaile 1995), and CH$_3$OH at 6.67 GHz (Menten 1991) and 44 GHz (Kurtz et al. 2004). The H$_2$O maser spots are distributed ahead of and projected onto the cometary arc of component C, while most of the OH masers are more tightly confined to a parabolic arc along the eastern edge of component C (e.g., Gasiprong et al. 2002). A cluster of OH 1665 MHz masers is associated with component B. No OH, H$_2$O, or CH$_3$OH maser emission is detected toward component A. Several of the authors cited above provide detailed discussions of the relation between the masers and other physical phenomena within the MSFR.

High angular resolution molecular line observations (Keto et al. 1992; Garay & Rodríguez 1990; Heaton et al. 1989; Hofner & Churchwell 1996; Mookerjea et al. 2007) indicate that the molecular gas lies roughly between components A, B, and C (hot core). In particular, there is no evidence for localized molecular peaks coincident with components A or B.

4.3.2. Dust Emission

Mid-IR emission from components A, C, and D of G34.26 was detected at wavelengths from 8 to 20.6 \mu m with resolutions \sim 2\arcsec by Keto et al. (1992) and Campbell et al. (2000). Their observations failed to detect component B suggesting that this source is more deeply embedded. They also showed that component C does not have a cometary morphology in the mid-IR; the general discrepancy between mid-IR and radio morphologies is discussed by Hoare et al. (2007). Campbell et al. (2000) detected two additional sources, which they designated E and F. Component F is located about 17\arcsec south of component C in the 20.6 \mu m image; component E is located 2\arcsec south of and is blended with component C (Campbell et al. 2000). Mid-IR sources C and E coincide with the arc of the cometary H \alpha region (see Figure 9) and were resolved into four individual sources in the subarcsecond resolution 10.5 \mu m and 18.1 \mu m images of De Buizer et al. (2003).

The IRAC images of G34.26 illustrate how active and dynamic this MSFR is. Figure 9 shows the 4.5 \mu m and 3.6 \mu m images. The 8.0 and 5.8 \mu m emission is similar to that shown in Figure 9 except that the outflow is only detected at 4.5 \mu m (see below). The IR counterparts of radio components A and C cannot be distinguished from one another, owing to very bright, diffuse emission in the IRAC bands. Also, IR components E and C are blended. IR component F was detected in all bands.

The large ring of emission southeast of components A--C (see left panel of Figure 9) corresponds to the D radio component of the G34.26 complex. Comparison of the 2 cm image of Fey et al. (1994) with the IRAC images shows that this IR ring has roughly the same angular extent (\sim 1\arcmin radius) and brightness distribution (75\% complete ring of emission with an opening to the NE) as at radio wavelengths.

The IRAC images reveal multiple IR sources that were not detected by earlier infrared observations. Nevertheless, component B remains undetected, even in the IRAC images. The point sources listed in the GLIMPSE Catalog and Archive are shown in Figure 9. The high-resolution 2 cm radio contours (Paper I) are overlaid on the 3.6 \mu m image to indicate the positions of the A--C radio components; IR sources E and F are also marked. Only G34.26 C has a counterpart in the GLIMPSE Archive (SSTGLMA G034.2572+00.1533) with flux densities of 4857 \pm 278 mJy and 4481 \pm 155 mJy at 4.5 and 5.8 \mu m, respectively.

One of the most prominent features in the color composite image of G34.26 (Figure 9) is an outflow detected as an Extended Green Object (EGO; Cyganowski et al. 2009). Molecular outflows are particularly strong in the IRAC 4.5 \mu m band because of shocked H$_2$ and/or CO line emission (Cyganowski et al. 2008). The source of the outflow is unknown. Moreover, other outflows appear in SiO (Hatchell et al. 2001) and 13CO (Matthews et al. 1987). The latter two outflows are not well aligned with the EGO, suggesting that they are different outflows arising from different driving sources.

4.4. G45.07 + 0.13

G45.07 consists of a bright NE component (S$_{2cm}$ = 620 mJy) and a much fainter SW component (S$_{2cm}$ = 40 mJy), separated by \sim 6\arcsec (see Figure 6). The SW component was first detected by Garay et al. (1986) at 2 cm and designated G45.07 A. Both NE and SW components are unresolved in our radio continuum maps. High resolution (HPBW \sim 0.1\arcsec) observations by Turner & Matthews (1984) of the NE component revealed a clumpy ring with a gap to the west which they integrated as a shell with an inner cavity produced by a stellar wind from a hot central star. However, Garay et al. (1986) suggested that the ring-like structure may be the ionized inner wall of an accretion disk. They further suggest that the ring is expanding at \sim 10 km s$^{-1}$ (owing to a hot stellar wind) and is inclined by \sim 75\degree to the line of sight. The H76\alpha RRL integrated over the whole NE component is broad with an FWHM of 48.1 \pm 0.9 km s$^{-1}$ (Garay et al. 1986). Garay et al. (1985) also detected broad H66\alpha emission with an FWHM of 42.3 \pm 2.3 km s$^{-1}$. Keto et al. (2008) reported a detection of the H30\alpha line toward the NE component with FWHM of 33.2 \pm 4.2 km s$^{-1}$.

We detected H92\alpha emission toward both the NE and SW components of G45.07; however, we were not able to determine reliable line parameters and physical properties of the sources based on these data. The H92\alpha line observed toward the SW component is very narrow relative to the channel width (16.9 km s$^{-1}$) preventing a reliable Gaussian analysis. We estimate that the peak line-to-continuum ratio of this line is \sim 0.07. For the NE component, the H92\alpha line has a very poor signal-to-noise ratio, likely the result of the high optical
depth which attenuates the line. The peak line-to-continuum ratio for this line is $\sim 0.03$ and the deconvolved FWHM of $40 \pm 9$ km s$^{-1}$.

Hunter et al. (1997) reported a molecular outflow centered on G45.07 NE based on observations at millimeter and submillimeter wavelengths and in the CO(6–5) and CS(2–1) molecular lines. Infall was also detected by redshifted CS(2–1) absorption, confirming the young age of this source. The outflow axis is aligned spatially and kinematically with the H$_2$O maser spots in G45.07 NE (Hofner & Churchwell 1996), suggesting that the masers form in warm and dense shocked gas at the inner edges of the outflow lobes (Hunter et al. 1997).

Several masers have been detected in the NE component of G45.07, while no maser emission is associated with the SW component (see Figure 6(b)). Hofner & Churchwell (1996) detected four clusters of water masers in the area, three of which are closely associated with the centimeter continuum emission from the NE component. The fourth group is located about 2$^{\prime\prime}$ north of the NE component and is not coincident (in high resolution images) with any radio continuum emission. The H$_2$O masers are intermixed with 1665 and 1667 MHz OH masers at these two locations (Garay et al. 1985; Argon et al. 2000). A 44 GHz CH$_3$OH maser was detected $\sim 6$ north of the NE component by Kurtz et al. (2004). Single-dish observations by Menten (1991) and Caswell et al. (1995) revealed methanol 6.67 GHz masers.

4.4.1. Mid-infrared Emission

High-resolution observations (from 1.2 to 1.7; De Buizer et al. 2003, 2005; Kraemer et al. 2003) at mid-IR wavelengths from 10.5 $\mu$m to 20.6 $\mu$m revealed three mid-IR components associated with the G45.07 MSFR, designated KJK 1, 2, and 3 by Kraemer et al. (2003). The brightest component, KJK 1, is coincident with G45.07 NE and contributes roughly half of the total (KJK 1–3) flux at 12.5 $\mu$m and 20.6 $\mu$m (Kraemer et al. 2003). The second brightest component, KJK 2, lies 2$^{\prime\prime}$ north of KJK 1, coincident with the water maser group 2$^{\prime\prime}$ north of the NE component (Hofner & Churchwell 1996, see discussion above); this source is a good candidate for an HMC. The third mid-IR component, KJK 3, corresponds to the SW component of G45.07.

GLIMPSE images of the G45.07 MSFR are presented in Figure 10. At IRAC bands, G45.07 is a bright source. The KJK 1 and 2 sources are not well resolved in these images but are clearly apparent in Figure 10. KJK 3 is very faint at shorter IRAC bands, but is bright at 8 $\mu$m where PAH emission dominates.

The GLIMPSE Catalog and Archive sources shown in Figure 10 reveal the positions of (proto)stars that may be responsible for exciting PAH emission. In general there is a good correspondence between the distribution of dust and gas in G45.07; however the dust emission extends beyond the region of ionized gas emission at 3.6 cm because the PAH contribution to this band traces the PDR that surrounds the nebula. The correspondence in projected emission does not necessarily imply that ionized gas and dust are well mixed. Additionally, the VLA filters out extended emission and much of the extended IR emission is instrumental (sidelobes of the Spitzer point-spread function), making the interpretation of the data more difficult.

5. DISCUSSION

5.1. Radio Recombination Lines

We detected RRLs from all four sources in our sample (see Table 2 for details on the observed transitions). Figure 11 shows the relation between the widths (FWHMs) of the RRLs and frequency for these sources. Regions classified as HC HII candidates and UC HII regions are plotted separately in Figures 11(a) and (b), respectively. The dashed vertical lines indicate the rest frequencies of the observed transitions.

The change of observed Gaussian line widths with frequency (or principal quantum number) presented in Figure 11 clearly illustrates the effects of pressure broadening based on our data. The limited sensitivity that is typical of very high spatial resolution RRL observations rarely permits the Voigt profile to be seen (Roelfsema & Goss 1992). Very broad bandwidths and good signal-to-noise ratios in the weak RRL wings are a prerequisite to fit Voigt profiles; our data are not adequate for such a fitting procedure.

Figure 11(a) shows that the lines from HC HII regions (except G34.26 A), particularly the lower-frequency transitions, are too broad to be the result of a combination of thermal and turbulent broadening only. If an electron temperature of 10,000 K and turbulent velocity of 5 km s$^{-1}$ are assumed, the contribution from thermal and turbulent motions to the line widths would be only $\sim 22$ km s$^{-1}$. The change in line width with transition apparent in Figure 11(a) strongly suggests that pressure broadening is a dominant broadening mechanism. Owing to the rapid change of pressure broadening with principal quantum number $n$ (FWHM of pressure broadening $\propto n^{7.4}$; Brocklehurst & Seaton 1972), the lower-frequency lines are affected much more strongly by pressure broadening than the higher-frequency lines. At high frequencies, pressure broadening becomes negligible, thus line widths should be dominated by thermal, turbulent, and bulk motions. Even though pressure broadening depends so strongly on $n$, accurate adherence to the $n^{7.4}$ dependence is not expected because of other dependences on electron density and electron temperature, which vary within HII regions (e.g., Roelfsema & Goss 1992).

Pressure broadening is less strongly dependent on electron density than on the principal quantum number (FWHM $\propto n_{e,true}$, where $n_{e,true}$ is the local true electron density; Brocklehurst & Seaton 1972). The true electron density traced by line widths is higher than the rms electron density measured from the continuum data. The difference depends on the filling factor $f$ of the HII region ($f = n^2_{e,rms}/n^2_{e,true}$). The filling factor is the fraction of the total volume that is occupied by dense gas; thus it is a measure of clumpiness in the HII region. The higher electron density results in more pressure broadening, thus this effect may explain the observed increase in line width for the relatively low rms electron density UC HII regions G10.96 E and G28.20 S (see Figure 11(b)).

Sources G28.20 N, G28.20 S, G34.26 B, and G34.26 C have been observed in high frequency RRLs: H30$\alpha$ for G28.20 N and H53$\alpha$ for the remaining three sources. By comparing these high frequency lines with lower frequency (and hence pressure-broadened) lines, we can determine $n_{e,true}$. Comparing these densities with the rms values from the continuum observations then provides an estimate of the filling factor. Sources showing the steepest slopes in the FWHM versus frequency plot of Figure 11 will have $n_{e,true}$ much greater than $n_{e,rms}$, and hence have the smallest filling factors.
The largest change of linewidth with frequency of the RRL is obtained for G28.20 N. Sewilo et al. (2008) obtained an  for G28.20 N, on the other hand, shows only a 4 km s$^{-1}$ change in linewidth between the H76$\alpha$ and H53$\alpha$ lines. We determine an  of (1.2 ± 0.7) × 10$^5$ cm$^{-3}$ compared to the continuum value of 8 × 10$^3$ cm$^{-3}$, thus yielding a filling factor of 5 × 10$^{-3}$.

For G34.26 components B and C we calculate true electron densities of (4.2 ± 0.9) × 10$^5$ cm$^{-3}$ and (4 ± 2) × 10$^5$ cm$^{-3}$, respectively, resulting in filling factors of 0.3 and 0.06.

We note that the true electron densities and hence the filling factors are calculated under the assumption that the H53$\alpha$ line results from microturbulent motions and the true filling factors will be smaller.

The broad linewidths (FWHM ≥ 40 km s$^{-1}$) detected toward the HC H$\alpha$ candidates (Figure 11(a)) probably have a contribution from bulk motions; G28.28 N has been related to rotation and possible outflow; G34.26 B to an outflow; and G45.07 NE to expansion (see Section 4.4). All these phenomena may contribute to line broadening. For the UC H$\alpha$ region G34.26 C (Figure 11(b)), Garay et al. (1986) proposed that the relatively broad H76$\alpha$ line results from microturbulent motions of ∼30 km s$^{-1}$ (see Section 4.3).

5.2. Continuum Emission

The continuum observations of MSFRs G10.96 and G28.20 at two wavelengths (Table 3) allow a determination of the spectral index for the individual sources in these regions, provided that the reliable flux density measurements can be made (G10.96 W, G28.20 N). For consistency, the two continuum images for each region (1.3 cm and 2 cm for G10.96; 7 mm and 2 cm for G28.20) were convolved to a common resolution before measuring the flux densities. For G10.96 W, the 1.3 cm and 2 cm flux densities of 296 ± 15 mJy and 288 ± 15 mJy, respectively, give a spectral index of +(0.07 ± 0.17), indicating that this source is in the optically thin regime. The 7 mm and 2 cm flux densities of G28.20 N are 723 ± 37 mJy and 490 ± 25 mJy, respectively, indicating a spectral index of +(0.4 ± 0.1). This value suggests that the H$\alpha$ region has a turnover wavelength in the 2 cm–7 mm range. The flux density distribution for G28.20 N, based on high-resolution interferometric observations covering the wavelength range from 6 cm to 1.3 mm (Table 9), is shown in Figure 12.
The plot shows the spectrum becoming optically thin in the 20–50 GHz range.

We found that G28.20 N is very similar to the well-studied HC H II region G24.78+0.08 A1 (Beltrán et al. 2007) in terms of physical properties, kinematics (rotation, infall, outflow), morphology (shell-like), and association with masers. The flux density distributions of these sources are similar in terms of the shape and the turn-over frequency (Beltrán et al. 2007; Figure 12). Neither of these HC H II regions has a rising spectrum to millimeter wavelengths (as do G9.62+0.19 E and G75.78+0.34 (H2O); see Franco et al. 2000). The shell-like morphology appears to be a common feature of the HC H II region complexes: G10.96 W, G28.20 N, G34.26 B and C, and G45.07 NE; Garay et al. 1985) based on the maser and radio continuum emission in those regions. This interpretation can also apply to G10.96 W from our sample, where the two CH3OH maser spots are near the continuum emission peak and have velocities (~25 km s⁻¹; Walsh et al. 1998) redshifted by ~14 km s⁻¹ relative to the H66α velocity (see Table 7).

The OH maser velocities in G28.20 N appear to be inconsistent with the velocity gradient reported for the H53α line by Sewiło et al. (2008). In particular, the H53α velocity gradient, when extrapolated to the position of the arc of maser emission, gives velocities of 115–120 km s⁻¹, significantly higher than the OH maser velocities of 93–101 km s⁻¹. The differing direction and magnitude of the H53α and the OH velocity gradients suggests that dynamics of the ionized and molecular gas trace different phenomena.

The orientation of the H2O masers (SE–NW) in G28.20 N is consistent with the outflow suggested by Sewiło et al. (2008) and Qin et al. (2008). However, the velocity structure of the masers is ambiguous and does not provide strong evidence for the outflow.

In G45.07 NE, the H2O maser spots are aligned spatially and kinematically with the outflow axis detected in CO(6–5) and CS(2–1) molecular lines (Hofner & Churchwell 1996; see Section 4.4), suggesting that the masers form in warm and dense shocked gas at the inner edges of the outflow lobes (Hunter et al. 1997).

### 5.4. Spitzer/IRAC Mid-IR Emission

We find that all the radio components have point-source counterparts in the GLIMPSE Archive except G34.26 A and B, and G45.07 SW. A faint mid-IR source was detected at the position of G45.07 SW; however, it was not included in the GLIMPSE catalog due to the close proximity of a much brighter source (G45.07 NE) that prevented an accurate photometric measurement. G34.26 A does not have a clear counterpart in the IRAC image; this source was detected in the mid-IR by earlier studies, unlike component B which is undetected in the mid-IR.

In Table 10, we list GLIMPSE counterparts to the radio sources (the closest neighbors). The distance between the mid-IR and radio positions ranges from 0.2 for G45.07 NE to 2.4 for G28.20 S (see Table 10). The proximity of the mid-IR sources to the radio peaks of HC H II regions suggests that these sources probably are the ionizing (protostars). The relatively low density of stars nearby to G10.96 E and G28.20 relative to more distant parts of these fields suggests extinction of background stars in these regions. The majority of IR sources shown in Figures 7–10 are probably background stars; however, we expect to find a number of young stellar objects (YSOs) in these MSFRs. The YSOs can be identified by their mid-IR colors and by fitting their spectral energy distributions with YSO models. This would be particularly
interesting for G28.20, which is located in an IRDC (see Figure 8).

The Spitzer images of the sources from our sample suggest that generally the large-scale spatial distribution of gas and dust in these regions are similar; G34.26 C being the principal exception in our sample. Higher resolution infrared observations would be worthwhile, however, to separate diffuse emission from the mid-IR emission from outflows and disks (e.g., NGC 7538 IRS 1; De Buizer & Minier 2005).

6. SUMMARY

We present high spatial resolution (0.09 to 2.3") multi-transition (H53α to H92α) VLA observations of four MSFRs hosting HC H ii region candidates identified in earlier studies. G10.96, G28.20, and G34.26 contain HC H ii region candidates with broad H92α (G10.96 W, G28.20 N) or H76α (G34.26 B) lines (Sewiło et al. 2004a). An additional HC H ii region candidate (G45.07 NE), known to have broad H66α and H76α lines, small size, high electron density and EM, was also included in this survey. We observed up to two additional transitions per source to investigate the change of line width with frequency. We found a strong correlation of line width with principal quantum number, i.e., higher frequency lines of sources with broad H92α or H76α lines have narrower linewidths (<40 km s⁻¹) indicating that pressure broadening is the main line broadening mechanism at lower frequencies. This result is not surprising because of the high electron density in HC H ii regions. However, large scale dynamics is also an important contributor to line broadening (Sewiło et al. 2008). We determined physical properties of the H ii regions based on both the continuum and line data. Multi-frequency RRLs reported in this paper are well separated in principal quantum number and will provide good constraints for non-LTE models of these regions. We also present a comparison of the radio continuum and mid-IR emission in HC H ii regions from our sample. Based on the Spitzer GLIMPSE survey, covering a wavelength range from 3.6 to 8.0 μm, we find a generally good correspondence between the radio continuum and dust distributions for the sources in our sample. The mid-IR images, however, show more complex features and reveal multiple sources that do not correspond so well to the radio continuum.

We report the distribution of H2O, OH, and CH3OH masers with respect to the radio continuum. We also present high-resolution VLA archival data for the water masers in G28.20 N for the first time. We compile information from the literature on maser emission in G10.96, G28.20, and G45.07. A detailed discussion of the maser distribution in G34.26 can be found elsewhere (e.g., Hofner & Churchwell 1996; Gaspergou et al. 2002). As expected, all of the MSFRs studied in this paper are associated with maser emission; however, the masers are not coincident with all the radio components in these regions. In G10.96, G28.20, and G45.07 the masers are associated only with the HC H ii regions (G10.96 W, G28.20 N, G45.07 NE). In G34.26 the masers are coincident with both the HC H ii region G34.26 B and also with the cometary UC H ii region G34.26 C. All of the sources associated with masers have broad RRLs.

The question of the origin of BRRLs is not fully answered, although our observations show that pressure broadening is an important mechanism. To distinguish the effects of pressure broadening from large scale motions of the gas and at the same time resolve the structures of HC H ii regions will require high-resolution observations of millimeter RRLs such as H42α and H30α. With its high spatial resolution and sensitivity, ALMA will be the instrument to address this issue.

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Table 10

| Source    | GLIMPSE ID | α (°) | δ (°) | K 3.6 μm | K 4.5 μm | K 5.8 μm | K 8.0 μm |
|-----------|------------|------|------|---------|---------|---------|---------|
| G10.96 W  | SSTGLMA G10.9584+00.0219 | 2.7 | 136 | ... | 9.7 ± 0.9 | 59 ± 8 | 174 ± 12 | 395 ± 31 |
| G10.96 E  | SSTGLMA G10.9646+00.0098 | 0.3 | 20 | ... | 8 ± 3 | 13 ± 4 | 59 ± 8 | ... |
| G28.20 N  | SSTGLMA G028.2003-00.0493 | 2.2 | 61 | 9.0 ± 0.4 | 358 ± 19 | 2123 ± 99 | 3892 ± 99 | ... |
| G28.20 S  | SSTGLMAG028.1984-00.0501 | 2.4 | 66 | ... | 2.1 ± 0.3 | 9 ± 1 | ... | ... |
| G34.26 C  | SSTGLMA G304.2572+00.1533 | 0.7 | 13 | ... | ... | 4857 ± 278 | 4481 ± 155 | ... |
| G45.07 NE | SSTGLMA G045.0712+00.1321 | 0.2 | 6 | 40 ± 1 | 2240 ± 184 | ... | ... | ... |

Notes.
1. The Galactic coordinates of the Spitzer sources are part of the GLIMPSE IDs.
2. The distance between the radio continuum source and the nearest mid-IR GLIMPSE point source; kinematic distances to MSFRs listed in Table 2 were used to calculate distances in mpc.
3. None of the sources have J and H fluxes available in the 2MASS Point Source Catalog.
