Evolution of H II regions in hierarchically structured molecular clouds

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ABSTRACT
We present observations of the H91α recombination line emission towards a sample of nine H II regions associated with 6.7-GHz methanol masers, and report arcsecond-scale emission around compact cores. We derive physical parameters for our sources, and find that although simple hydrostatic models of region evolution reproduce the observed region sizes, they significantly underestimate emission measures. We argue that these findings are consistent with young ages in our sample, and can be explained by existence of density gradients in the ionized gas.

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

1 INTRODUCTION
Ultracompact (UC) H II regions are pockets of ionized hydrogen that form around massive stars in the earliest stages of their evolution. Together with massive bipolar outflows, strong far-infrared emission by dust, and the presence of molecular masers, they are indicative of massive star formation in its earliest stages. The simple model of H II region evolution (Spitzer 1978) does not explain many of their observed properties, such as the frequent occurrence of non-spherical morphologies and the lifetime paradox. This lifetime problem, first noted by Wood & Churchwell (1989), is that the number of observed UC HII regions exceeds that predicted from their dynamical expansion time-scales by two orders of magnitude, given the accepted massive star formation rate in the Galaxy. A number of modifications and enhancements to the basic model have been suggested, including the work of Dyson, Williams & Redman (1995), Hollenbach et al. (1994), Tenorio-Tagle (1979) and van Buren et al. (1990), Franco, Tenorio-Tagle & Bodenheimer (1990), Arthur & Lizano (1997) and Keto (2003). The thermal (De Pree et al. 1995a) and turbulent (Xie et al. 1996) pressure confinement models are appealing due to their dependence on the ambient conditions observed to commonly exist in molecular clouds.

De Pree et al. (1995a) suggested thermal pressure confinement as an explanation of the lifetime paradox. They noted that when Wood & Churchwell proposed the lifetime problem in 1989, the molecular medium surrounding the UC H II regions was thought to have temperatures $\sim 25$ K and densities $\sim 10^{5}$ cm$^{-3}$. More recent observations indicate $T \sim 100$ K and $n \sim 10^{7}$ cm$^{-3}$. The resulting 400 times increase in thermal pressure limits the expansion of the Strömgren sphere. A weakness of this model, noted by Xie et al. (1996), is the exceedingly high emission measures that it predicts ($\sim 10^{15}$ pc cm$^{-6}$), which are more than two orders of magnitude greater than the values typically observed.

Hierarchical density and temperature structures are known to exist within star-forming regions, with hot cores embedded in larger, less-dense molecular clumps which themselves are within still larger and less-dense molecular clouds. The densities decrease by approximately an order of magnitude in going from core to clump and again from clump to cloud (Cesaroni et al. 1994). In a seminal work, Franco et al. (1990) showed that these density inhomogeneities are important for H II region evolution. That the hierarchical structure of molecular clouds plays an important role in H II evolution is supported by the marked similarity in the ionized and neutral gas density structures observed within molecular clouds (Kim & Koo 1996, 2002; Koo & Kim 2003).

The large thermal molecular line and recombination linewidths observed towards many UC H II regions suggest that significant turbulent motions are present, probably of magnetic origin (García-Segura & Franco 1996). This led Xie et al. (1996) to suggest that turbulent pressure is the dominant mechanism to restrict the expansion of an H II region. In contrast to thermal pressure confinement, the assumed densities are lower, resulting also in lower emission measures. During much of the expansion phase, however, the turbulent pressure is expected to play a lesser role than thermal pressure in confining the H II region. This is discussed briefly in Section 4.1.1.

Icke (1979) investigated the formation of H II regions in non-homogeneous media and was able to explain some non-spherical morphologies. Observational evidence obtained in the last decade, however, suggests that many H II regions have compact cores within diffuse, arcminute-scale extended emission (Kurtz et al. 1999; Kim & Koo 2001). Other sources exhibit this to a smaller degree – the so-called core-halo morphology; see Wood & Churchwell (1989) and Kurtz, Churchwell & Wood (1994). A study of the compact and extended radio continuum emission and radio recombination
lines (RRLs) from eight H II regions known to be associated with 6.7-GHz methanol masers has been undertaken. The RRL analysis is presented here, while details of the continuum observations can be found in Ellingsen, Shabala & Kurtz (2005) (hereafter ESK05). In Section 2, we briefly outline our observations. The results are presented in Section 3, and these are compared with a simple model in Section 4. A discussion of our findings is presented in Section 5.

2 OBSERVATIONS

Eight UC H II regions with associated methanol maser emission were observed with the Australia Telescope Compact Array (ATCA) on 1999 July 10 and 11. Both continuum and recombination line emission were observed in the ATCA 750D array, with an angular resolution of 7 arcsec and largest detectable angular scale of ∼50 arcsec. Details of the continuum observations are found in ESK05.

The H91α recombination line (ν0 = 8.584 82 GHz) was observed with a 8-MHz bandwidth and 512 spectral channels, giving a frequency resolution of 15.625 kHz (0.529 km s⁻¹), and total velocity coverage of 270 km s⁻¹. The data were further smoothed by frequency averaging over four or eight channels. All sources were observed together with associated secondary calibrators immediately before and after each on-source observation. The primary calibrator PKS B1934−638 was observed each day to calibrate the flux density scale.

The observations were made with the array in the 750D configuration, with a minimum baseline of 31 m and maximum of 719 m. Because the primary aim of these observations was to look for extended emission associated with the sources, baselines to the 6-km antenna were not used in order to maximize sensitivity to large-scale structure. A summary of the fields observed is given in Table 1.

3 RESULTS

H91α emission was detected in six sources. The observed line profiles and Gaussian fits obtained after continuum subtraction are shown in Fig. 1. As we are only interested in emission around the RRL peak, non-zero baselines were used in some sources for a better fit in those regions. The flux densities per channel were obtained by integrating over the area of the UC H II region (typically around 5 × 5 arcsec²; see Table 2). No H91α emission was detected from G336.40−0.25, G339.88−1.26 or G345.01+1.79. These three regions have low-continuum brightness so the expected local thermodynamic equilibrium (LTE) line brightness is at or below the image noise level.

The fit parameters are given in Table 2. These were achieved using a standard non-linear least-squares fitting routine, and resulted in unrealistically low error estimates for the fit parameters. In order to determine a realistic uncertainty, we made Monte Carlo simulations, using the same routine to fit Gaussian profiles with known parameters, plus white noise of various amplitudes. Comparison of the methanol maser peak velocities from Table 1 with the H91α velocities from Table 2 shows approximate agreement (indicating an association between the masers and the star formation region) but sufficient difference in some cases to suggest that the masers may not be directly linked to the ionized gas. The detection is only marginal for G309.92+0.48 and thus no formal parameters were derived for this source.

3.1 Arcsecond-scale emission

3.1.1 Moment maps

Image cubes for the six sources that exhibited H91α emission were analysed for the presence of arcsecond-scale extended emission near the UC H II regions. Two complementary methods were employed for this analysis.

The first of these involved examining crosscuts through the image cubes in various position–velocity planes. Positional crosscuts were taken to run through the peak brightness position at a range of angles. Typically, the cuts were made at constant right ascension or declination or along a line joining the compact region to features of potential interest. Part a (left-hand plots) in Figs 2–5 show the position–velocity plots of integrated flux density for appropriate crosscuts in sources exhibiting significant arcsecond-scale extended emission. Position angle is calculated anticlockwise from a cut in constant declination. Position is defined as the offset from the plane passing through the point of maximum H91α emission. If both compact and extended components are present and physically associated, provided no strong shocks are present, their systemic velocities should be approximately equal or change smoothly between the two positions. Therefore, taking a cut along the line joining them would result in emission at the same peak velocity, but offset positionally by the distance between the two components.

Another way of determining whether any two components are likely to be associated is by plotting the first moment (a
flux-weighted velocity mean across the cube) distribution across the region of H91α emission. This is shown in grey-scale in part b (right-hand plots) of each figure. Superimposed are the continuum contours of observations also made in the 750D array configuration.

Clipping levels used in Figs 2–5 were set to 2σ, corresponding to 6–11 mJy beam⁻¹ depending on the source (see Table 1). Lower density gas outside the UCH II cores is indicated in the first moment plots by presence of more emission at velocities close to the peak H91α velocity of the source (given in Table 2). In position–velocity plots, this corresponds to ‘peaks’ and/or ‘troughs’ (depending on the location of extended emission) in position at the peak RRL velocity. Evidence of such emission is seen in G 318.95−0.20 (Fig. 2), G 328.81+0.63 (Fig. 3) and NGC 6334 E (Fig. 4) and F (Fig. 5) components. Less arcsecond-scale emission is observed around G 308.92+0.12, and almost none at all around G 309.92+0.48. These results are consistent with the continuum observations of ESK05, and in all cases suggest association between the compact and more extended components.

Although unlikely, line-of-sight effects cannot be ruled out, as illustrated by the star-forming complex NGC 6334. The E and F components of this complex are well known to be separate star-forming regions, separated by more than 1 arcmin on the sky. However, their systemic velocities are very similar, with the best fit to the E component RRL giving a peak velocity of −4.0 ± 1.0 km s⁻¹, compared with −5.3 ± 0.6 km s⁻¹ for the F component. For this reason, the two regions would have been extremely difficult to distinguish had...
they been superimposed along our line of sight, rather than clearly separated on the sky. This suggests that all moment analysis results should be treated with a degree of caution.

### 3.2 Derived source parameters

#### 3.2.1 Stellar ionizing flux and electron temperatures

Assuming LTE, the electron temperature $T_e$ is related to the continuum and recombination line brightness temperatures $T_C$ and $T_L$, and the line full width at half-maximum (FWHM) $\Delta V$ in km s$^{-1}$, by

$$
\frac{T_L \Delta V}{T_C} = \frac{6983 \nu_{1.1}^{1.1}}{7^{0.15} (1 + Y^+)} ,
$$

where $Y^+$ is the fractional abundance of He$^+$ by number (McGee & Newton 1981). Assuming $Y^+ = 0.1$ and rearranging yields

$$
T_e = \left( \frac{6348 \nu_1^{3/2} T_C}{T_L \Delta V} \right)^{0.87} ,
$$

(1)

The continuum and recombination line brightness temperatures are related to the peak flux density $S$ (in Jy) and beam solid angle $\Omega$ via

$$
T_{\text{Bright}} = \frac{S \times 10^{-26} c^2}{2 \nu^2 k_B \Omega} .
$$

(2)

The continuum observations were made at $\nu_C = 8.64$ GHz, while the H91$\alpha$ rest frequency is $\nu_{1} = 8.584$ GHz. $T_e$ can then be determined by combining equations (1) and (2). In general, optical depth, pressure broadening and stimulated emission must be accounted for in the RRL analysis (Roelfsema & Goss 1992). These non-LTE effects can be significant for the H91$\alpha$ line. For expected emission measures of $\sim 10^7$ pc cm$^{-6}$, we use a correction factor of $\frac{7^2}{2 \nu_{1}} \sim 1.3$ (Shaver et al. 1983). The values of $T_e$ derived above must be scaled by this factor to account for non-LTE effects. The resulting values for $T_e$ are shown in Table 2. They are somewhat higher than values obtained with single-dish observations (Caswell & Haynes 1987). The $T_e$ uncertainties for most sources are quite large due to uncertainties in the H91$\alpha$ fit parameters.

We also calculate the ionizing flux and stellar spectral type for each source by using the observed continuum fluxes of ESK05 and...
derived electron temperatures via the standard Schraml & Mezger (1969) argument. These values are given in Table 3, together with the corresponding spectral types from Panagia (1973).

3.2.2 Emission measures

The continuum brightness temperature $T_C$ is related to electron temperature $T_e$ via the optical depth, $\tau$, 

$$T_C = T_e (1 - e^{-\tau}).$$

Rearranging this expression, the optical depth is given by

$$\tau = -\ln \left(1 - \frac{T_C}{T_e}\right).$$

From equation (2), $T_C$ and therefore $\tau$ can be evaluated for each source using the derived $S_C$ values and beam solid angles given in Table 2. From this, the peak emission measure for each source can be derived using

$$EM_{peak} = \frac{\tau}{8.235 \times 10^{-3} \alpha(v, T_e) T_e^{-1.35} v_c^{-2.7}}.$$
Figure 5. RRL H91α moment maps for NGC 6334F. The plots are as in Fig. 2. Position–velocity contours are at 20–90 per cent of maximum emission of 126.1 mJy beam\(^{-1}\) spaced by 10 per cent. The lowest contour of 25.2 mJy beam\(^{-1}\) corresponds to 4.5σ. Continuum contours are at 10–90 per cent of maximum emission of 2.13 Jy beam\(^{-1}\) spaced by 10 per cent. Arcsecond-scale emission around the core is seen to the east and south of the emission centre. The southern component appears at velocities consistent with the −5.33 km s\(^{-1}\) systemic velocity of the region and represents the tail of the cometary region. The eastern component, however, peaks at velocities of about +20 km s\(^{-1}\), which is significantly different from systemic region velocity and the maser velocities of approximately −10 km s\(^{-1}\). Therefore, it does not appear to be associated with the compact region. This result is corroborated by the lack of significant eastern extension in the superimposed continuum contours, or the high-resolution continuum maps of ESK05. This emission is in fact known to be coincident with a massive, poorly collimated bipolar outflow (Jackson, Ho & Haschick 1988; Bachiller & Cernicharo 1990; De Pree et al. 1995b).

Table 3. UC component sizes derived from calculated emission measures and continuum contours of ESK05, and kinematic distances to the sources. Also given are the ionizing flux for each source, derived from electron temperatures and continuum flux densities (Schraml & Mezger 1969) of Table 2, and the corresponding spectral type (Panagia 1973). The distances to sources are from Panagia et al. (1998); Caswell & Haynes (1987) and Mezger & Henderson (1967). Optical depths and peak emission measures are also given where appropriate. In the case of source G309.92+0.48, Caswell & Haynes (1987) electron temperature scaled for non-LTE effects is used to derive EM\(_{\text{peak}}\). A scaled Caswell & Haynes (1987) electron temperature is also quoted for source G339.88−1.26. Continuum temperatures for sources G328.81+0.63 and NGC 6334F are comparable with their electron temperatures, and we therefore adopt a lower limit of τ = 1 for these sources. Correction factors are interpolated from Mezger & Henderson (1967) values, and range from 0.9762 to 0.9940. The cut-off fractions have been determined by comparing the derived peak emission measures with the canonical UC H\ II region value of \(10^7\) pc cm\(^{-6}\). Large uncertainties associated with calculated \(T_\alpha\) and EM\(_{\text{peak}}\) values arise due to propagation of smaller uncertainties through calculations. Peak emission measures predicted by the model outlined in Section 4 are also given; these should be treated as order-of-magnitude estimates.

| Source          | Spectral type | log\(\sigma_\alpha\) | Kin. dist. (kpc) | \(T_\alpha\) (K) | \(\tau\) | EM\(_{\text{peak}}\)/10\(^7\) (pc cm\(^{-6}\)) | Cut-off | UC size (arcsec) | UC size (pc) | Predicted EM\(_{\text{peak}}\)/10\(^7\) (pc cm\(^{-6}\)) |
|-----------------|---------------|----------------------|------------------|-----------------|---------|-----------------------------------------------|---------|-----------------|-------------|-----------------------------------------------|
| G308.92+0.12    | B0            | 47.01                | 5.2\(^a\)        | 8200 ± 1400     | 0.65 ± 0.12 | 41 ± 17                                       | 0.024   | 9               | 0.21       | 3.1                                           |
| G309.92+0.48    | O7.5          | 48.52                | 5.3\(^e\)        | 12,200          | 1.54 ± 0.40 | 56 ± 34                                       | 0.018   | 3               | 0.078      | 5.3                                           |
| G318.95−0.20    | B0            | 47.72                | 2.0\(^c\)        | 12,600 ± 800    | 1.44 ± 0.10 | 56 ± 18                                       | 0.018   | 13              | 0.126      | 2.6                                           |
| G328.81+0.63    | O8            | 48.39                | 3.0\(^d\)        | 12,900 ± 500    | >1           | 41 ± 4                                        | 0.024   | 6 × 11           | 0.087 × 0.156 | 4.3                                           |
| G336.40−0.25    | B0.5          | 46.74                | 5.2\(^e\)        | 4800            |             | −                                             | −       | −               | −          | −                                              |
| G339.88−1.26    | B0.5          | 45.99                | 3.0\(^c\)        | 10,000          |             | −                                             | −       | −               | −          | −                                              |
| G345.01+1.79    | B0            | 47.11                | 1.7\(^c\)        | 10,000          | −           | −                                             | −       | −               | −          | −                                              |
| NGC 6334F      | O9            | 48.00                | 1.7\(^d\)        | 10,100 ± 500    | >1           | 30 ± 7                                        | 0.034   | 5 × 8           | 0.041 × 0.066 | 4.4                                           |
| NGC 6334E      | B0\(^f\)      | 47.13                | 1.7\(^d\)        | 7500 ± 600      | 0.65 ± 0.07  | 13 ± 3                                        | 0.079   | −               | −          | 3.3                                           |

Here, \(\alpha(\nu, T_\alpha)\) is a correction factor of the order of 1 adopted from Mezger & Henderson (1967). Values of \(\tau\) and peak emission measure calculated for each source are shown in Table 3.

The peak emission measures thus derived were used to estimate the angular and physical sizes of the UC components of the regions. Taking UC regions to have emission measures in excess of \(10^7\) pc cm\(^{-6}\), the cut-off emission measure fraction was determined for each source. This was defined as the lowest contour level for which emission measure exceeds \(10^7\) pc cm\(^{-6}\), and is given by cut-off = \(10^7 / \text{EM}_{\text{peak}}\). The location of the closest contour in the 6-km continuum images of ESK05 then determined the size of the observed UC region, given in Table 3. For the purposes of comparison with our models, the sources G308.91+0.12, G309.92+0.48 and G318.95−0.20 were considered to be spherical, while cometary sources G328.81+0.63 and NGC 6334F were modelled with the star offset from the centre of the spherical density distribution.

4 MODELLING

Detailed numerical modelling will certainly be required to address the nature of extended emission associated with UC H\ II regions. In this section, we present a simple, semiquantitative model, Franco et al. (2000a,b) and Kim & Koo (2001) suggest that the ambient density structure is the primary factor determining H\ II region sizes and morphologies, thereby implying the need for more realistic ambient density representation; e.g. Franco et al. (1990). However, in the
present work our focus is on the apparent association between the UC components and more diffuse arcsecond-scale extended emission (Wood & Churchwell 1989; Kurtz et al. 1994), and we show that this can be explained in an order of magnitude argument by a hierarchical density model.

The density structure of star-forming cores is an important modelling parameter. Numerous studies have shown that in low-mass star-forming clouds the density structure on large scales (>1 pc) is well fit by power-law distributions $n \propto r^{-p}$. In high-mass star formation regions, the exponent of the density power law flattens significantly for more evolved objects, such as H II regions (van der Tak et al. 2000; Beuther et al. 2002; Hatchell & van der Tak 2003). High-mass cores are less well fit by single power laws, and show a tendency towards clumpy substructure, possibly with the clumps embedded within overall gradients (Evans 1999; Beuther et al. 2002). Given the observational uncertainty regarding the magnitude of the density gradients and the scales over which they apply, we have ignored them in our modelling in favour of a simple approximation of a series of concentric spherical gas clumps.

We assume that the star forms within a hot core ($R = 0.1$ pc, $T_o = 200$ K, $n_0 = 10^5$ cm$^{-3}$), that is located within a molecular clump of radius $R = 0.3$ pc, having molecular gas temperature $T_o = 50$ K and density $n_0 = 10^6$ cm$^{-3}$, which itself lies within a molecular cloud ($R > 0.3$ pc, $T_o = 25$ K, $n_0 = 10^5$ cm$^{-3}$). The physical characteristics for the interior hot core are taken from Churchwell (2002), while those for the intermediate molecular clump are given by Cesaroni et al. (1991) and Garay & Lizano (1999), and for the exterior molecular cloud we used the parameters given by Churchwell (1999). We note that the values we use to define hot cores and molecular clumps are indicative only and differ slightly from those used by Kim & Koo (2001).

In the simple model of H II region evolution, the radius of the expanding region is given as a function of time in terms of the initial Str"omgren radius $R_s$ and sound speed in the ionized gas $a_i$ by (Dyson & Williams 1980)

$$\frac{dR(t)}{dt} = a_i \left(\frac{R(t)}{R_s}\right)^{-3/4}. \tag{5}$$

The Str"omgren radius is given as

$$R_s = \left(\frac{3}{4\pi} \frac{S_c}{n_0^2 R_s^2}\right)^{1/3}$$

and assuming the strong-shock limit for the expansion following the (instantaneous) formation of the Str"omgren sphere, we have

$$R(t) = R_s \left(1 + \frac{7a_i}{4R_s}t\right)^{4/7}.$$

### 4.1 Model characteristics

#### 4.1.1 Thermal and turbulent pressure

Given the higher thermal pressures that we now know to exist in molecular cores, H II regions produced by O9 or later stars may still be UC when they reach pressure equilibrium with their surroundings (De Pree et al. 1995a). The non-thermal broadening of molecular lines in high-mass star-forming regions suggests that turbulence is present, with velocities of the order of 2 km s$^{-1}$ (Xie et al. 1996). The resulting additional turbulent pressure $p_{\text{turb}} = n_0 m_{H_2} V_{\text{turb}}^2$ given in terms of the molecular hydrogen mass $m_{H_2}$ and the turbulent velocity $V_{\text{turb}}$ in the surrounding medium, may act to restrict H II region expansion.

Using equation (5), we can compare the relative contributions of the expanding ionization front (IF) and turbulence in the ambient medium to the energy balance,

$$\frac{E_{\text{photo}}}{E_{\text{turb}}} = \left(\frac{\frac{dR}{dt}}{V_{\text{turb}}}\right)^2 = \left(\frac{a_i^2}{V_{\text{turb}}^2} \left(\frac{R}{R_s}\right)^{-3/2}\right).$$

The sound speed in the ionized gas is $a_i = \sqrt{2kT_i/m_i} \sim 12.9$ km s$^{-1}$ for an electron temperature of 10 000 K. Taking an initial Str"omgren radius of 0.02 pc, and UC region radius of 0.1 pc, we have $R = 5 R_s$, and $E_{\text{photo}}/E_{\text{turb}} \sim 3.7$. Thus, photoionization energy nominally dominates (for $R \approx R_s$) but is of the same order as the turbulent energy. Turbulent velocities greater than 2 km s$^{-1}$ could shift the balance in favour of turbulence. Moreover, as the expansion proceeds, the IF energy dominance will die off, as $R$ grows well beyond $R_s$.

#### 4.1.2 Density structure in ionized regions

Low-density extended emission on arcminute scales is observed near many UC H II regions (Kurtz et al. 1999; Kim & Koo 2001; ESK05). By comparison, as shown in Section 3.1.1, we observe emission on arcsecond scales around the UC cores, consistent with other observations (e.g. Wood & Churchwell 1989; Kurtz et al. 1994). Inhomogeneous ambient density structure can explain this (Li, MacLow & Abel 2004). Non-uniformity within the ionized region can also arise if the expansion velocity of the ionization and shock fronts is much greater than the sound speed, a condition that occurs early in the H II region expansion phase.

The expansion velocity of an H II region slows with time, and is of the order of the sound speed when the region reaches pressure equilibrium. The diffusion time-scale as the region expands into a molecular clump is of the order of the sound-crossing time $t_{\text{clump}} = R_{\text{clump}}/a_i$. Taking $t_{\text{clump}} \sim 0.15$ pc and $a_i \sim 12.9$ km s$^{-1}$ as before gives $t \sim 1.5 \times 10^4$ yr. This is a significant fraction of an UC H II region lifetime of $\sim 10^5$ yr, and hence the ionized gas density cannot be considered uniform in all cases. This situation is further amplified by the presence of density inhomogeneities. Clearly, to model H II regions properly, a full hydrodynamical treatment of the problem is required. Such modelling is beyond the scope of this paper, which purports only to offer a semiquantitative plausibility argument.

### 4.2 Comparison with observations

Apart from NGC 6334E which happened to be in the same field of view as NGC 6334F, the nine regions presented here were selected for the presence of 6.7-GHz methanol maser emission. These masers are thought to correspond to a relatively short evolutionary phase that ends soon after the formation of the UC H II region (see ESK05). The recombination line analysis of extended emission around the majority of our sample shows that it is associated with the compact emission and thus the two must be considered together. We have compared the predictions from our model (compiled in Table 3) with the data for spherical (G 308.92+0.12, G 309.92+0.48 and G 318.95−0.20) and cometary (G 328.81+0.63) sources. The cometary source G 328.81+0.63 was modelled by positioning the ionizing star 0.096 pc from the hot core centre. In all cases, observed region sizes agree within a factor of a few with predicted pressure equilibrium values. However, the predicted peak emission measures are consistently more than an order of magnitude less than the observed values (see Table 3). This discrepancy can be explained by...
the presence of significant amounts of ionized gas around the UC region on arcsecond scales, consistent with observational results of Section 3.1.1 and discussed in more detail below. The remaining sources in our sample, particularly those with complex morphologies, will require more detailed modelling than is considered here.

For a spherical H II region, the distance of a site line from the centre of the region is \( d = r \cos \theta \). The emission measure at this distance is obtained by traversing a length \( 2r \sin \theta \). For uniform electron density, we then have \( EM(d)/EM_{\text{peak}} = (2 n_e^2 r \sin \theta)/(2n_e^2r) = \sin \theta \). Thus

\[
\frac{d}{r} = \sqrt{1 - \left(\frac{EM(d)}{EM_{\text{peak}}}\right)^2}.
\]  

(6)

The resultant theoretical contours can then be compared with observations. The UC components of sources G 308.92+0.12, G 309.92+0.48 and G 318.95−0.20 were largely unresolved in the 750D array results presented in ESK05, and high-resolution images made with the 6-km array (also presented in ESK05) were used instead. The synthesized beam FWHM was taken as 1.2 arcsec for all three sources. For each source, the resulting beam was then convolved with theoretical contours using the Table 3 UC region sizes.

Figure 6 shows the theoretical map thus obtained, together with a high-resolution image, for G 308.92+0.12. Table 4 shows the theoretical contour diameter and observed major and minor axes for each contour of each source. The final three columns give the observed/theoretical ratios for the two axes, as well as a geometric mean of the two for sources G 308.92+0.12 and G 309.92+0.48.

The non-spherical nature of G 318.95−0.20 (much more so than the other two sources) means that we have only given the major axis values for this source.

In all three sources, the observed/theoretical ratios decrease as we approach peak emission. Thus the observed contours are slightly denser near source core, implying the presence of density gradients in the ionized gas. For G 309.92+0.48 and especially G 308.92+0.12 the ratios are close to constant, suggesting almost uniform region density and thus that these sources are close to pressure equilibrium. This is again consistent with a lack of lower density gas observed around their UC cores. By comparison, the large spread of observed/theoretical ratios in G 318.95−0.20 suggests a much steeper ionized gas density gradient in this source, in keeping with observations of significant arcsecond-scale emission around its UC core. Accounting for this density gradient would raise the predicted peak emission measure and thus address the discrepancy between model and observations discussed in the previous section.

The ratios given in Table 4 are less than 1 for all three sources, indicating that the observed H II region sizes are smaller than model predictions. This could be due to the H II regions not being in pressure equilibrium with the ambient medium – an idea consistent with their young ages deduced from maser observations (Ellingsen, Norris & McCulloch 1996; Phillips et al. 1998; De Buizer et al. 2002), and also the fact that this ratio is closer to one for sources G 308.92+0.12 and G 309.92+0.48 which exhibit a more uniform density structure. G 309.92+0.48 is unresolved in the 750D array, and this is likely the main reason for the departure of observed contours from model predictions. Overestimates of stellar spectral types are another possible reason for the observed/predicted ratios being less than 1, although this is less likely as radio observations typically underestimate spectral types due to dust absorption. Other confinement mechanisms may also play a role. Evidence for non-thermal broadening in the Gaussian profiles of Fig. 1 lends further support to this scenario.

The above analysis is applicable to optically thin H II regions. If we instead had a constant continuum brightness temperature (as would be expected for an optically thick source), the theoretical emission measures would be more uniform around the source core, providing an even greater discrepancy between predictions and observations.

5 DISCUSSION

5.1 Emission measures

The fact that some fraction of ionizing photons is absorbed by dust suggests that our observed peak emission measures, which are already too high to be explained by constant density models, are underestimates. This effect can largely be ignored, however, as the attenuation factor is \((1 - f)^{1/3}\), where \(f\) is the fraction of photons absorbed by dust (Franco et al. 1990), which for \(f \sim 0.9\) results in
The fundamental difference between pressure confinement and other models is that it predicts that in many cases the observed H\textsc{ii} regions are already in equilibrium with their surroundings, rather than still undergoing expansion. Our modelling suggests pressure equilibrium may be reached very quickly, with expansion taking place for only a fraction of the observed lifetimes of H\textsc{ii} regions. The lower H\textsc{ii} region age limits thus derived are given in Table 5. These are consistent with methanol maser emission being associated with very young massive stars.

As discussed in Section 4.1.1, turbulence may provide an additional confinement mechanism. Any non-isotropic nature of the turbulence (e.g. if it is magnetohydrodynamic; García-Segura & Franco 1996) may also contribute to the non-spherical appearance of the resulting H\textsc{ii} region. Further investigation of this issue is warranted.

6 CONCLUSIONS

We have detected arcsecond-scale emission around UC H\textsc{ii} cores. Using region parameters derived from continuum and H\textsc{ii} recombination line data, we show that although simple models of expansion in hydrostatic equilibrium reproduce the observed region sizes, their emission measures are significantly underestimated. This discrepancy can be explained by the presence of density gradients in the ionized gas, consistent with young source ages and observations of the diffuse emission.

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