Extended emission associated with young H II regions

S. P. Ellingsen,1⋆ S. S. Shabala1 and S. E. Kurtz2
1School of Mathematics and Physics, University of Tasmania, Private Bag 21, Hobart, Tasmania 7001, Australia
2Centro de Radioastronomía y Astrofísica, UNAM-Morelia, Adpo. Postal 3–72, CP 58089, Morelia, Michoacán, México

Accepted 2004 December 3. Received 2004 October 13

ABSTRACT
We have used the Australia Telescope Compact Array (ATCA) to make observations of a sample of eight young ultra-compact H II regions, selected on the basis that they have associated class II methanol maser emission. We have made observations sensitive to both compact and extended structures and find both to be present in most sources. The scale of the extended emission in our sample is in general less than that observed towards samples based on IRAS properties, or large single-dish flux densities. Our observations are consistent with a scenario where extended and compact radio continuum emission co-exists within H II regions for a significant period of time.

We suggest that these observations are consistent with a model where H II evolution takes place within hierarchically structured molecular clouds. This model, which is the subject of an upcoming companion paper by Shabala et al., addresses both the association between compact and extended emission and the ultra-compact H II region lifetime problem.

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

1 INTRODUCTION
Ultra-compact H II regions (UCH II) arguably represent the earliest stage of high-mass star formation that can be reliably identified. As such they have been the focus of intensive investigation, particularly since the first large-scale interferometric survey of this class of sources by Wood & Churchwell (1989b). This survey detected compact radio continuum emission towards two-thirds of the sources searched, a much higher fraction than expected. Simple modelling of HII regions (e.g. Kahn 1954) suggests that the ultra-compact phase should be short lived and hence seen in only a small fraction of sources. This discrepancy (known as the UCH II lifetime problem), is thought to be due to the presence of an additional confinement mechanism that partly counteracts the expected pressure driven expansion. Numerous mechanisms have been suggested to reduce the expansion rate of HII regions, either through confinement due to infall (Reid et al. 1980), bow shocks (Van Buren et al. 1990), dense warm environments (De Pree, Rodríguez & Goss 1995), turbulent pressure (Xie et al. 1996), or other means such as photoevaporation of circumstellar discs (Hollenbach et al. 1994) and mass-loaded stellar winds (Dyson, Williams & Redman 1995). Champagne flows (Tenorio-Tagle 1979) have also been invoked as a means of extending the lifetime of the ultra-compact phase of H II regions. Although each model appears able to explain some objects, none seem to be universally valid. The UCH II lifetime issue has been most recently reviewed by Kurtz et al. (2000).

A second observational challenge related to UCH II regions has recently emerged from their apparent association with extended radio continuum emission. The majority of interferometric observations of UCH II regions have been sensitive to emission on angular scales of the order of 1–10 arcsec. However, surveys by Kurtz et al. (1999) and Kim & Koo (2001) have shown the presence of significant emission on larger scales towards the majority of the UCH II regions observed. Morphologically the extended emission appears to be directly associated with the UCH II regions (rather than a projection effect) and this is supported by observations of radio recombination lines (Kim & Koo 2001). The co-existence of a compact, high-emission measure region within a larger diffuse, lower-emission measure zone is not predicted by models which solve the lifetime problem through confinement. It may be broadly consistent with replenishment solutions, such as photoevaporation of circumstellar discs (Hollenbach et al. 1994), but no detailed work to predict H II region morphology has been undertaken for this model.

A scenario that addresses both the lifetime problem and the extended emission problem is as follows.

(i) A high-mass star commences nuclear fusion in the core and starts ionizing the surrounding neutral material, rapidly forming a UCH II region.
(ii) Soon after, a zone of more diffuse ionized gas begins to form surrounding the UCH II region. Over time the size of the diffuse region grows and the compact region begins to dissipate.
(iii) Eventually the compact region dissipates entirely and we are left with a classical H II region.

There may be some H II regions that do not follow this scenario, such as those associated with later-type stars that produce relatively few ionizing photons, where it is possible that no diffuse ionized region forms (Shabala et al. 2005). However, here we are interested

*E-mail: Simon.Ellingsen@utas.edu.au

© 2005 RAS
in the large fraction of H II regions that have been observed to exhibit both compact and more diffuse emission.

We will leave aside for the moment the question as to how this scenario occurs; this is addressed in more detail in Section 4 and Shabala et al. (2005). Our scenario is consistent with current observations, because any observation made with an interferometer at high resolution during stage (ii) will detect compact emission and observations made with lower resolution will detect extended emission. All we require to solve the dual observational challenges of lifetime and extended emission is that the time-scale over which compact and extended emission co-exist is long enough to explain the observed excess of UCH II regions on the basis of various arguments given by Kurtz et al. (2000) this is estimated to be approximately a factor of 5 (although uncertain by a factor of 2) and so, using $3 \times 10^4$ yr as an estimate for the lifetime of the UCH II phase (Wood & Churchwell 1989a), we estimate stage (ii) to be of the order of $10^5$ yr.

If the scenario outlined above is correct then the flux density and radius of the diffuse extended emission will increase with time. Very young H II regions will have little or no associated extended emission, while older regions will have a significant amount. Masers are thought to trace the early stages of high-mass star formation and so we predict that H II regions with associated masers should show little or no extended emission. Class II (e.g. 6.7-GHz) methanol masers are believed to trace exclusively the early stages of high-mass star formation (Minier et al. 2003). This contrasts with the other common masing molecules OH and water which are associated with more than one type of astrophysical object. Many 6.7-GHz methanol masers have no associated centimetre radio continuum emission (Phillips et al. 1998; Walsh et al. 1998), but are associated with millimetre and submillimetre continuum emission (Pestalozzi, Humphreys & Booth 2002; Walsh et al. 2003). This suggests that many class II methanol masers trace a pre-UCH II phase, and for those where there is an associated UCH II region it is young. Analysis of the scaleheight of 6.7-GHz methanol masers in the Galaxy shows that it is significantly smaller than any other extreme Population I object (van der Walt et al. 1996).

To test the scenario outlined above we have selected a sample of eight UCH II regions associated with 6.7-GHz methanol masers. Assuming that this criterion selects young H II regions then we predict they should exhibit relatively little extended emission compared with the regions observed by Kurtz et al. (1999) and Kim & Koo (2001).

2 OBSERVATIONS AND DATA PROCESSING

Eight UCH II regions associated with 6.7-GHz methanol masers were imaged with the Australia Telescope Compact Array (ATCA) in the 750D configuration. For the 750D array the minimum base-line length is 107 m and the maximum is 719 m. The observations were made on 1999 July 10 and 11, with all sources being observed on both days to improve the overall uv coverage. For each of the UCH II regions a 3-min scan was both preceded and followed by a 1-min scan of a phase calibrator. Over the two days sources were observed approximately 20 times, for a total onsource integration time of approximately 1 h. The correlator was configured to record a 128-MHz bandwidth, centred at a frequency of 8.64 GHz. The data were calibrated using the MIRIAD software package applying the standard techniques for ATCA continuum observations. The data for each day were calibrated separately and merged into a single data set for imaging. Table 1 lists the fields imaged, the rms level in the residual image and similar information for the related 6-km array observations (see below).

Imaging and self-calibration of the data was undertaken in DIFMAP. To identify all sources of emission within the primary beam a 2048 x 2048 arcsec$^2$ image, centred at the phase centre, was created and cleaned. The DIFMAP model was then discarded and the image re-cleaned and self-calibrated with a small loop gain and clean boxes around all emission regions. The amplitude corrections applied by self-calibration were typically small (a few per cent or less), indicating good basic calibration of the data. The only exceptions were the few sources that exhibited significant extended emission that was not well sampled with the 750D array. For the majority of the sources the resulting rms after imaging was 1 mJy beam$^{-1}$ or less.

High-resolution ATCA observations have been published in the literature for G318.91−0.16, G339.88−1.26, NGC 6334F (Ellingsen, Norris & McCulloch 1996) and G308.92+0.12, G309.92+0.48, G345.01+1.79 (Phillips et al. 1998). The imaging methodology used for the 750D observations was based on that of Phillips et al. (1998) and so for consistency the sources observed by Ellingsen et al. (1996) were reimaged using the same approach. The remaining two UCH II regions (G328.81+0.63 and G345.01+1.79) had not previously been imaged at high resolution and sensitivity. These sources were observed at 8.59 GHz with the ATCA in the 6A configuration on 1994 July 4 (G328.81+0.63) and July 5 (G345.01+1.79). These data were calibrated using the AIPS software package, applying the standard techniques for ATCA continuum observations. Imaging was undertaken in DIFMAP, using the same approach as for the 750D observations. PKS 1934−638 was used as the primary flux density calibrator for all observations; its flux density at 8.59 and 8.64 GHz was assumed to be 2.86 and 2.84 Jy, respectively.

3 RESULTS

Figs 1–8 show contour plots of radio continuum images for each of the eight fields (containing a total of 11 H II regions). In each figure

Table 1. The fields imaged in the 750D array with the ATCA. The listed IRAS sources are all within 30 arcsec of the 6.7-GHz methanol maser position except for G318.95−0.20, where the separation is 144 arcsec.

<table>
<thead>
<tr>
<th>Field name</th>
<th>Right ascension (J2000)</th>
<th>Declination (J2000)</th>
<th>rms in resid. image (mJy beam$^{-1}$)</th>
<th>6-km obs. reference</th>
<th>rms in 6-km resid. image (mJy beam$^{-1}$)</th>
<th>Associated IRAS source</th>
</tr>
</thead>
<tbody>
<tr>
<td>G308.92+0.12</td>
<td>13:43:02</td>
<td>−62:08:51</td>
<td>0.1</td>
<td>Phillips et al. (1998)</td>
<td>0.2</td>
<td>13395−6153</td>
</tr>
<tr>
<td>G309.92+0.48</td>
<td>13:50:42</td>
<td>−61:35:10</td>
<td>0.2</td>
<td>Phillips et al. (1998)</td>
<td>0.3</td>
<td>13471−6120</td>
</tr>
<tr>
<td>G318.95−0.20</td>
<td>15:00:55</td>
<td>−58:58:42</td>
<td>1.0</td>
<td>this work</td>
<td>0.2</td>
<td>14567−5846</td>
</tr>
<tr>
<td>G328.81+0.63</td>
<td>15:55:48</td>
<td>−52:43:07</td>
<td>0.5</td>
<td>this work</td>
<td>0.5</td>
<td>15520−5234</td>
</tr>
<tr>
<td>G336.40−0.25</td>
<td>16:34:11</td>
<td>−48:06:26</td>
<td>0.2</td>
<td>Phillips et al. (1998)</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>G339.88−1.26</td>
<td>16:52:05</td>
<td>−46:08:34</td>
<td>0.08</td>
<td>Ellingsen, Norris &amp; McCulloch (1996)</td>
<td>0.15</td>
<td>16484−4603</td>
</tr>
<tr>
<td>G345.01+1.79</td>
<td>16:56:48</td>
<td>−40:14:26</td>
<td>0.2</td>
<td>this work</td>
<td>0.5</td>
<td>16533−4009</td>
</tr>
<tr>
<td>NGC 6334F</td>
<td>17:20:53</td>
<td>−35:47:01</td>
<td>2.2</td>
<td>Ellingsen et al. (1996)</td>
<td>59.0</td>
<td>17175−3544</td>
</tr>
</tbody>
</table>
Figure 1. Radio continuum images of G308.92+0.12: (a) 8.59-GHz ATCA 6-km image of the compact emission (Phillips et al. 1998); (b) 8.64-GHz ATCA 750-m image of the extended emission; (c) 843-MHz MOST image of the large-scale continuum emission (Green et al. 1999). The location of the 6.7-GHz methanol maser cluster is marked with a plus symbol. The squares in (b) and (c) show the area covered in (a) and (b), respectively.

Figure 2. Radio continuum images of G309.92+0.48: (a) 8.64-GHz ATCA 6-km image of the compact emission (Phillips et al. 1998); (b) 8.64-GHz ATCA 750-m image of the extended emission; (c) 843-MHz MOST image of the large-scale radio continuum emission (Green et al. 1999). The location of the 6.7-GHz methanol maser cluster is marked with a plus symbol. The squares in (b) and (c) show the area covered in (a) and (b), respectively.
Figure 3. Radio continuum images of G318.91−0.16: (a) 8.59-GHz ATCA 6-km image of the compact emission; (b) 8.64-GHz ATCA 750-m image of the extended emission; (c) 843-MHz MOST image of the large-scale radio continuum emission (Green et al. 1999). The squares in (b) and (c) show the area covered in (a) and (b), respectively.

Figure 4. Radio continuum images of G328.81+0.63: (a) 8.59-GHz ATCA 6-km image of the compact emission; (b) 8.64-GHz ATCA 750-m image of the extended emission; (c) 843-MHz MOST image of the large-scale radio continuum emission (Green et al. 1999). The location of the 6.7-GHz methanol maser cluster is marked with a plus symbol. The squares in (b) and (c) show the area covered in (a) and (b), respectively.

© 2005 RAS, MNRAS 357, 1003–1012
Extended emission from young HII regions

Figure 5. Radio continuum images of G336.41−0.26: (a) 8.64-GHz ATCA 6-km image of the compact emission (Phillips et al. 1998); (b) 8.64-GHz ATCA 750-m image of the extended emission; (c) 843-MHz MOST image of the large-scale continuum emission (Green et al. 1999). The location of the 6.7-GHz methanol maser clusters are marked with plus symbols. The squares in (b) and (c) show the area covered in (a) and (b), respectively.

Figure 6. Radio continuum images of G339.88−1.26: (a) 8.59-GHz ATCA 6-km image of the compact emission (Ellingsen et al. 1996); (b) 8.64-GHz ATCA 750-m image of the extended emission; (c) 843-MHz MOST image of the large-scale continuum emission (Green et al. 1999). The location of the 6.7-GHz methanol maser cluster is marked with a plus symbol. The squares in (b) and (c) show the area covered in (a) and (b), respectively.
Figure 7. Radio continuum images of G345.01+1.79: (a) 8.59-GHz ATCA 6-km image of the compact emission; (b) 8.59-GHz ATCA 6-km image of the compact emission from the H II region G345.01+1.82; (c) 8.64-GHz ATCA image of the extended emission from the G345.01+1.79 region. The location of the 6.7-GHz methanol maser clusters are marked with plus symbols. The square in (c) shows the area covered in (a).

Figure 8. Radio continuum images of NGC 6334F: (a) 8.59-GHz ATCA 6-km image of the compact emission (Ellingsen et al. 1996); (b) 8.64-GHz ATCA 750-m image of the extended emission; (c) 843-MHz MOST image of the large-scale emission (Green et al. 1999). The location of the 6.7-GHz methanol maser clusters are marked with plus symbols. The squares in (b) and (c) show the area covered in (a) and (b), respectively.
(except Fig. 7) panel (a) shows a $50 \times 50$ arcsec$^2$ 8.6-GHz image made using a 6-km array, panel (b) shows a $5 \times 5$ arcmin$^2$ 8.6-GHz image obtained using a 750-m array and panel (c) shows a $10 \times 10$ arcmin$^2$ 843-MHz MOST image from the Molonglo Galactic Plane Survey (MGPS1) (Green et al. 1999) for sources where they are available. The location of 6.7-GHz methanol maser clusters is marked with a plus symbol. The maximum angular resolution of the 6-km array observations is approximately 1 arcsec and the largest angular scales that can reliably be imaged are approximately 15 arcsec. For the 750-m array observations the angular resolution is approximately 7 arcsec and the largest angular scale that can be detected is of the order of 50 arcsec. The MGPS1 images have an angular resolution of 43 arcsec and the rms noise is typically 1–2 mJy beam$^{-1}$. The peak and integrated flux density for the ATCA observations are listed in Table 2. These observations are at the same frequency and have comparable angular scales and sensitivities to the VLA B- and D-array observations of Kurtz et al. (1999).

In contrast to the IRAS selected H II regions of Kurtz et al. (1999), where many of the D-array images (equivalent to the 750-m array images) show significant extended emission, for our sample that is not the case. The only source that shows significant large-scale structure is G336.41$+$0.26 and in this source the compact region lies at the edge of the diffuse emission and so is probably not directly associated.

Our sample was selected on the basis of having a detected UCH II region with an associated 6.7-GHz methanol maser site, the only exception being G318.95$-$0.20 for which Ellingsen et al. (1996) detected no radio continuum emission at the maser site, but did detect an H II (G318.91$-$0.16) region associated with IRAS 14567$-$5846, which is 2 arcmin away. Our 750-m array observations are consistent with the higher-resolution observations of Ellingsen et al. (1996), detecting radio continuum emission only at the IRAS site and not at the maser location. Three additional regions of radio continuum were detected that are not associated with methanol maser emission. G345.00$+$1.79 and G345.01$+$1.82 can clearly be seen in Fig. 7 and NGC 6334E is present to the north-west of NGC 6334F in Fig. 8(b) and dominates the emission in Fig. 8(c).

### 3.1 Individual sources

(i) G308.92$+$0.12. This H II region has a core–halo morphology and in terms of the size of the emission region seen in the 6-km array image (Fig. 1a) it is one of the largest associated with a maser in this sample. Phillips et al. (1998) found that the 6.7-GHz methanol masers are located near the northern tip of the region, offset by approximately 5 arcsec from the peak of the radio continuum emission and suggest that it is likely there is more than one ionizing source present. This is supported by mid-infrared observations, which detected a strong 11.5-µm point source associated with the maser location, but nothing at the H II region peak (Phillips et al. 2005). The 750-m array image (Fig. 1b) shows that the true extent of the H II region is significantly larger than suggested by the observations of Phillips et al. (1998) and slight extensions are present to the north-west, east and south. The 750D observations show that the flux density is increasing with decreasing baseline length, suggesting there may be more flux density present on still larger scales. The MOST image (Fig. 1c) lends some support to this showing possible extension to the north-west.

(ii) G309.92$+$0.48. This H II region (IRAS 13471$-$6120) is the most compact in the sample with Table 2 showing only 8 per cent more integrated flux density in the 750-m array observations than in the 6-km, the lowest ratio observed. The 6-km array image (Fig. 2a) of Phillips et al. (1998) shows slight low-level extension of the main feature with a second region with a peak flux density of 5.4 mJy beam$^{-1}$ to the north-east. Observations at 10.8 and 18.2 µm by De Buizer, Piña & Telesco (2000) detect strong emission associated with the H II region and a weaker more deeply embedded source associated with the weak radio continuum emission to the north-east. Phillips et al. (1998) found the 6.7-GHz methanol masers to be located close to the peak of the H II region. The 750-m array image (Fig. 2b) also shows small deviations from a point source with lower-level contours slightly extended to the north-east, south-east and west.

(iii) G318.91$-$0.16. The H II region shown in Fig. 3 (IRAS 14567$-$5846) has a shell morphology at the highest resolutions. There is no compact radio continuum emission associated with the masers to a 5σ level of 0.82 mJy beam$^{-1}$ (Ellingsen et al. 1996) and we did not detect any diffuse emission with a 5σ limit of 5 mJy beam$^{-1}$. The H II region is quite symmetrical in the 750-m array image (Fig. 3b), but shows increasing flux density with decreasing baseline length. This, combined with low-level extension to the south-west (also present in the MOST image Fig. 3c) suggests further extended emission is present on still larger scales.

### Table 2.

The peak flux density, integrated flux and rms noise level in the residual image for 11 H II regions. Sources indicated with an asterisk do not have an associated 6.7-GHz methanol maser. There is no emission sufficiently compact to be imaged in the 6-km array associated with NGC 6334E.

<table>
<thead>
<tr>
<th>Source</th>
<th>6-km array observations</th>
<th>750-m array observations</th>
<th>Ratio of 750-m int. to 750-m peak</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak flux density (mJy beam$^{-1}$)</td>
<td>Integrated flux (mJy)</td>
<td>Peak flux density (mJy beam$^{-1}$)</td>
</tr>
<tr>
<td>G308.92$+$0.12</td>
<td>25.0</td>
<td>363</td>
<td>263</td>
</tr>
<tr>
<td>G309.92$+$0.48</td>
<td>320.9</td>
<td>679</td>
<td>671</td>
</tr>
<tr>
<td>G318.91$-$0.16*</td>
<td>40.8</td>
<td>1078</td>
<td>725</td>
</tr>
<tr>
<td>G328.81$+$0.63</td>
<td>239.2</td>
<td>1680</td>
<td>1461</td>
</tr>
<tr>
<td>G336.41$-$0.26</td>
<td>7.4</td>
<td>35</td>
<td>28</td>
</tr>
<tr>
<td>G339.88$-$1.26</td>
<td>7.6</td>
<td>10</td>
<td>6.6</td>
</tr>
<tr>
<td>G345.01$+$1.79</td>
<td>232.1</td>
<td>273</td>
<td>286</td>
</tr>
<tr>
<td>G345.00$+$1.79*</td>
<td>7.3</td>
<td>62</td>
<td>60</td>
</tr>
<tr>
<td>G345.01$+$1.82*</td>
<td>54.6</td>
<td>139</td>
<td>145</td>
</tr>
<tr>
<td>NGC 6334F</td>
<td>479.6</td>
<td>2694</td>
<td>2130</td>
</tr>
<tr>
<td>NGC 634E*</td>
<td>417</td>
<td>5100</td>
<td>12.23</td>
</tr>
</tbody>
</table>
The H II region (IRAS 15520−5234) shown in Fig. 4(a) appears to be a partial superposition of two nearby sources, a point source and a cometary H II region. Our image is consistent with that of Walsh et al. (1998), but our higher dynamic range better reveals the cometary morphology. Walsh et al. found the majority of 6.7-GHz methanol masers to be located near the peak of the cometary region, but offset slightly in the direction of the unresolved peak. There is a single maser spot offset by approximately 3 arcsec from the others, close to the peak of the unresolved continuum emission (Norris et al. 1993; Dodson, Ojha & Ellingsen 2004). Mid-infrared observations by De Buizer et al. (2000) detect at least six sources in this region and morphological comparison with the radio continuum emission suggests that the masers are coincident with the peak of the infrared emission. The 6-km image shows continuous low-level extensions to the north and south, and regions of emission further north and south are suggestive of large-scale extensions not satisfactorily imaged with this array configuration. The 750-m array image shows slightly resolved, nearly symmetrical emission with the flux density near constant on baselines shorter than 30 kλ.

(v) G336.41−0.26. There is a large amount of extended emission in the vicinity of this H II region and this is responsible for the poor dynamic range of both the 6-km and 750-m array images. Phillips et al. (1998) report four sites of 6.7-GHz methanol maser emission in this field, but none are directly associated with the strongest compact radio continuum emission in the region. Single featured, weak masers are associated with the continuum emission in Fig. 5(a) immediately to the west (G336.409−0.257) and north-west (G336.410−0.256) of the H II region. Figs 5(b) and (c) show a ridge of extended emission running south-west to north-east with the four maser sites lying along a line with the same position angle as the southern edge of the ridge. Interestingly there is no compact emission associated with the other two maser sites (G336.404−0.254 and G336.433−0.262) each of which contains multiple components. De Buizer et al. (2000) did not detect any mid-infrared emission associated with the G336.433−0.262 masers, but the other masers and compact radio continuum peak were not within the field of view of their observations. For this source it would appear that the extended emission is not directly associated with the UCH II region, as it lies at the edge, rather than near the centre. MSX images of the same region in the E-band (21 μm) show a similar morphology to the MOST image. We suggest that something has triggered a new epoch of star formation that we see projected along the southern edge of radio continuum emission associated with a previous episode. If this is the case then there are likely to be a number of millimetre continuum sources along this southern ridge (corresponding to the maser locations) that will in time produce detectable H II regions.

(vi) G339.88−1.26. This H II region (IRAS 16484−4603) is relatively weak and the 6-km image (Fig. 6a) shows signs of low-level extended emission, particularly to the north-east and north-west. The image in Fig. 6(a) is based on the same calibrated data set as that presented by Ellingsen et al. (1996), but has been cleaned and self-calibrated using DIFMAP for consistency with the treatment applied to the other sources in the sample. Ellingsen et al. (1996) estimate G339.88−1.26 to be produced by a B0.5 star. High-resolution mid-infrared observations by De Buizer et al. (2002b) show three sources near the H II region, elongated perpendicular to the radio continuum emission. The relative alignment of radio and mid-infrared emission is not certain, with that proposed by De Buizer et al. (2002b) being predicated on the argument that the H II region is associated with a star visible at optical and near-infrared wavelengths located in front of the mid-infrared source. A counter argument to this is that there should be no compact radio continuum emission, nor 6.7-GHz methanol masers remaining if the exciting star is optically visible. The 750-m array image (Fig. 6b) shows significant extended emission and the additional low-level features surrounding the main region suggests that there is additional flux on still larger scales.

(vii) G345.01+1.79. This H II region (IRAS 16533−4009) is very compact with less than 10 per cent more integrated flux density in the 750-m array observations than for the 6-km. Walsh et al. (1998) found that the 6.7-GHz methanol masers are offset to the west of the centre of the H II region. G345.01+1.79 holds the distinction of exhibiting methanol maser emission in more transitions than any other known source (Val’tts 1998; Val’tts et al. 1999; Cragg et al. 2001). The mid-infrared emission is also compact, being perhaps marginally resolved at 18.2 μm (De Buizer et al. 2000). There are two additional radio continuum sources in the same field of view, a lower surface brightness region to the south-west of about 12 arcsec in size (G345.00+1.79) and a compact region to the north-west (G345.01+1.82) shown in Fig. 7b. There is no MGPS1 image for this source as it lies more than 1.5 from the Galactic plane.

(viii) NGC 6334F. This cometary H II region (IRAS 17175−3544) lies in a star formation region that has been extensively studied at radio (Rodríguez, Cantó & Moran 1982), submillimetre (Sandell 2000), near-infrared (Straw, Hyland & McGregor 1989), mid-infrared (Kraemer et al. 1999) and X-ray (Sekimoto et al. 2000) wavelengths and in molecular lines (Kraemer & Jackson 1999; McCutcheon et al. 2000). There are six H II regions in the NGC 6334 region of which F (Fig. 8a) is the most compact (Rodríguez et al. 1982). The confusion of sources in, and the large number of observations of, the NGC 6334 region has led to a complex and confusing nomenclature, which is detailed in the appendix of Kraemer & Jackson (1999). The NGC 6334F H II region is referred to as NGC 6334F in infrared observations and here we have used the nomenclature appropriate to each wavelength.

NGC 6334 provides a nice demonstration as to why class II methanol masers are thought to trace only the early stages of high-mass star formation. There are four sites of 6.7-GHz methanol masers in the NGC 6334 region; two are close to NGC 6334F (Fig. 8a), with one projected against the leading edge of the H II region and the second offset to the north-west 6 arcsec (Ellingsen et al. 1996). The third 6.7-GHz methanol maser G351.54+0.66 (Fig. 8b) is associated with the high-mass class 0 candidate NGC 6334(N), although offset from the peak of the dust continuum emission (Sandell 2000). The final 6.7-GHz methanol maser G351.16+0.70 is associated with the NGC 6334V region, which also has water and ammonia maser emission. The NGC 6334 region also contains three sites of OH maser emission (Brooks & Whiteoak 2001). The strongest of these is coincident with the methanol masers in NGC 6334F, while NGC 6334V and the more evolved region NGC 6334A also has OH masers. The two class II methanol maser sites without associated OH maser emission both appear to be young star forming regions. NGC 6334(N) is cold, dense, optically thick at wavelengths shorter than 130 μm and has associated class I methanol masers (Cheung et al. 1978; Kuiper et al. 1995; Kogan & Slysh 1998). NGC 6334F:IRS 12 is a deeply embedded mid-infrared source approximately 6 arcsec to the northwest of NGC 6334/NGC 6334F. It is much stronger at 18 than 10 μm with a dust temperature of about 110 K (De Buizer et al. 1996). The astrometry of De Buizer et al. (2002a) find the methanol masers to be projected against mid-infrared emission, but offset by more than an arcsec from the...
peak. They suggest that the methanol masers may instead be associated with a secondary peak in the NH$_3$(3, 3) emission (Kuiper et al. 1995). In either scenario the methanol masers are associated with a very young source.

NGC 6334F is the brightest H II region in our sample and Fig. 8 shows significant extension in both the 6-km and 750-m array images. The dynamic range of images of this region are limited by the presence of nearby more extended H II regions. NGC 6334E can be seen in Fig. 8b offset to the north-west and there are signs of NGC 6334B to the south-west, which is clearly seen in the MOST image (Fig. 8c). Fig. 8b shows that NGC 6334E has an angular size of approximately 50 arcsec, significantly more than the 20 arcsec estimate of Rodriguez et al. (1982) and demonstrates that as expected our 750-m array observations are able to image emission on this scale. The location and size of E are well matched to a void in the dust and molecular emission in the NGC 6334 region (McCutcheon et al. 2000; Sandell 2000); these have presumably been destroyed and driven away by UV photons and stellar winds.

4 DISCUSSION

Comparison of Figs 1–8 with comparable figures in Kurtz et al. (1999) qualitatively shows that the degree of extended emission in our sample is in general much less. The 6-km and 750-m ATCA observations were made at the same frequency and have comparable sensitivity in both scale size and intensity to the B- and D-array VLA observations of Kurtz et al. (1999) and so the differences cannot be attributed to observational effects. Good quantitative measures of the degree of extended emission are difficult, due to the often complex morphology of the extended emission. One simple means is to compare the peak and integrated intensity and the relative intensity between observations made in different array configurations. For a point source the peak flux measured in mJy beam$^{-1}$ will be equal to the integrated flux density measured in mJy. So the amount by which the integrated flux density exceeds the peak flux is a measure of the percentage of emission present on scales larger than the synthesised beam of the observations. Similarly, a comparison of the integrated intensity of the 6-km and 750-m array observations gives a direct measure of the percentage of emission resolved out by the higher-resolution observations. These quantities are summarized in Table 2. The integrated flux reported in the table is from a boxed region that encompasses the emission to the level of the lowest contour shown in the figures.

A direct quantitative comparison of the amount of extended emission in H II regions with and without associated class II methanol masers is shown in Fig. 9. A sample of 22 sources has been compiled, the 11 reported in the current work and the 11 from Kurtz et al. (1999) for which emission was detected in the D-array observations. We have not included the observations of Kim & Koo (2001) in this analysis as they are significantly different from those we report here and those of Kurtz et al. (1999). For the current observations we have calculated the ratio of the integrated to the peak flux density for each source detected in the 750-m array observations, while for Kurtz et al. (1999) we have taken the ratio of the integrated flux density within a 50 arcsec square at the centre of the field to the peak flux density for the D-array observations (columns 5 and 4 of their table 4). There is a total of eight sources in the sample with associated methanol masers, the seven from the current work, plus IRAS 18496+0004 from Kurtz et al. (1999). IRAS 22543+6145/Cep A from the Kurtz et al. (1999) list also has an associated 6.7-GHz methanol maser, but no emission is reported in their D-array observations. There are 14 sources in the sample without associated methanol masers, the 10 sources for which Kurtz et al. (1999) list D-array observations and four sources from the current work (marked with an asterisk in Table 2). Although the sample size is small, there is a clear tendency for sources with associated methanol masers to have quantitatively less extended emission. Three of the eight sources (38 per cent) with associated 6.7-GHz methanol masers have a ratio of integrated-to-peak flux density greater than 1.5 (G308.92+0.12, G339.88−1.26 and NGC 6334F). In contrast, 11 of the 14 sources without an associated 6.7-GHz methanol maser (79 per cent) have a radio greater than 1.5. High-mass stars form in clusters and so we expect that for some regions the observed radio continuum emission will be due to more than one ionizing source, possibly at different evolutionary stages. Considering that this will confuse the simple scenario we have outlined and dilute the difference between the two samples, the difference we find is striking.

A fundamental issue relating to H II regions with both compact components and extended emission is whether they are truly associated, that is are they both produced by a single exciting star? Kurtz et al. (1999) argued on the basis of morphology that in the majority of cases where they see extended emission it is associated with the compact component. Kim & Koo (2001) made single dish recombination line observations towards their sample and found that in all but one case both the compact and extended components have the same approximate velocity. For our sample of H II regions associated with methanol masers the limited degree and morphology of the extended emission observed in most cases strongly suggests that it is associated with the compact region. This is confirmed by Shabala et al. (2005), who used the ATCA in the 750D array to make recombination line observations of the same sample of H II regions. Recombination lines were detected towards five of the eight sources and in each case the moment maps demonstrate that the compact and extended emission are associated.

Our results and those of Shabala et al. (2005) and Kurtz et al. (1999) appear to be consistent with the scenario outlined in the introduction. This scenario is appealing as it explains both the lifetime problem and the association between compact and extended...
emission. It is also consistent with the observation that the majority of IRAS sources with colours consistent with UCH II do not have associated 6.7-GHz methanol masers (Szymczak & Kus 2000). Our observations suggest that those H II regions with associated 6.7-GHz masers are the young ones, while those without are likely to exhibit significant extended radio continuum emission in addition to any compact components. The remaining hurdle for our scenario is a plausible mechanism through which it can occur. Kim & Koo (2001) suggested that the association between compact and extended radio continuum emission in H II regions may be due to champagne flows in a hierarchically structured molecular cloud. Shabala et al. (2005) have used recombination line observations and information from the literature to derive a number of physical parameters for the H II regions in this sample. They have modelled the evolution of H II regions in a hierarchical molecular cloud formation and find good agreement between the observed and predicted radii and emission measures.

There is a well-known tendency for the stellar type as estimated from the IR luminosity (typically IRAS observations) to exceed that obtained using the radio flux density. A variety of explanations has been proposed for this, including that at the spatial resolution of IRAS the IR luminosity measured is that for the cluster, rather than for an individual star, and that dust absorbs some of the UV flux from the star, hence reducing the radio flux density. Our observations and those of Kurtz et al. (1999) and Kim & Koo (2001) suggest that another factor in the discrepancy between IR and radio determined spectral types is that most high-resolution interferometry observations significantly underestimate the total radio flux density from the H II regions owing to their insensitivity to the extended component. This effect will be greatest for older H II regions where the fraction of the total flux density in the extended state becomes significant.

5 CONCLUSIONS

Observations of eight H II regions associated with 6.7-GHz methanol masers find a significantly lower degree of extended emission associated with these sources than in other samples. We suggest that this is consistent with a scenario where both compact and diffuse ionized structures co-exist for a significant fraction of H II region lifetimes. Modelling by Shabala et al. (2005) of high-mass stars forming in hierarchically structured molecular clouds is consistent with our observations and appears to provide a consistent solution for the lifetime problem.

ACKNOWLEDGMENTS

We thank Marco Costa for his assistance with some of the observations presented in this paper. This research has made use of NASA’s Astrophysics Data System Abstract Service. Financial support for this work was provided by the Australian Research Council. This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES


This paper has been typeset from a TeX/PS file prepared by the author.