Searching for Compact Radio Sources Associated with UCH\textsc{ii} Regions

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Abstract

Ultra-compact (UCH)\textsc{ii} regions represent a very early stage of massive star formation. The structure and evolution of these regions are not yet fully understood. Interferometric observations showed in recent years that compact sources of uncertain nature are associated with some UCH\textsc{ii} regions. To examine this, we carried out VLA 1.3 cm observations in the A configuration of selected UCH\textsc{ii} regions in order to report additional cases of compact sources embedded in UCH\textsc{ii} regions. With these observations, we find 13 compact sources that are associated with 9 UCH\textsc{ii} regions. Although we cannot establish an unambiguous nature for the newly detected sources, we assess some of their observational properties. According to the results, we can distinguish between two types of compact sources. One type corresponds to sources that are probably deeply embedded in the dense ionized gas of the UCH\textsc{ii} region. These sources are photoevaporated by the exciting star of the region and will last for $10^4$--$10^5$ years. They may play a crucial role in the evolution of the UCH\textsc{ii} region as the photoevaporated material could replenish the expanding plasma and might provide a solution to the so-called lifetime problem of these regions. The second type of compact sources is not associated with the densest ionized gas of the region. A few of these sources appear resolved and may be photoevaporating objects such as those of the first type, but with significantly lower mass depletion rates. The remaining sources of this second type appear unresolved, and their properties are varied. We speculate on the similarity between the sources of the second type and those of the Orion population of radio sources.

Key words: H\textsc{ii} regions – radio continuum: ISM

1. Introduction

In their early stages, massive stars produce compact photo-ionized regions with small sizes ($\lesssim$0.1 pc) and high electron densities and emission measures ($\gtrsim 10^6$ cm$^{-3}$, and $\gtrsim 10^7$ pc cm$^{-6}$, respectively), which are known as ultra-compact (UCH) H\textsc{ii} regions (see Churchwell 1990 and Kurtz 2002). These regions are believed to represent a very early stage of massive star formation as they are deeply embedded in molecular clouds and still retain high-density (ionized) gas. The high pressure contrast between the ionized gas and the neutral surrounding medium leads to the common assumption that UCH\textsc{ii} regions are freely expanding at the sound speed of ionized gas ($\sim 10$ km s$^{-1}$, Spitzer 1978). If this is true, their material should disperse very fast and become significantly more extended in $\sim 10^4$ years. However, Wood & Churchwell (1989) carried out a survey of selected sources in the Galactic plane and detected a much larger number of UCH\textsc{ii} regions than expected for their short lifetime.

Various models have been proposed to explain this paradox. Some of them describe mechanisms to confine the ionized region (e.g., van Buren et al. 1990; Xie et al. 1996), while others are based on the continuous replenishment of the ionized gas (e.g., Tenorio-Tagle 1979; Hollenbach et al. 1994). The prime mechanism for the confining models is the presence of an ionized accreting flow that quenches the expansion of the ionized gas (e.g., Galván-Madrid et al. 2011). Observationally, a variable ionized accretion flow can produce flux density variations, as recently reported in some UCH\textsc{ii} regions (Franco-Hernández & Rodríguez 2004; Galván-Madrid et al. 2008; De Pree et al. 2015). However, other authors attribute these flux variations to changes in the source of ionizing radiation (e.g., Franco-Hernández & Rodríguez 2004; Klassen et al. 2012a, 2012b). On the other hand, the replenishment models suggest substructure within UCH\textsc{ii} regions such as density gradients or photoevaporating disks (e.g., Yorke & Welz 1996). There is ample evidence that the homogeneous Strömgren sphere is an oversimplification not suitable to fully explaining the evolution of UCH\textsc{ii} regions. For this purpose, investigations of the small-scale structure of UCH\textsc{ii} regions are of paramount importance, as they may reveal the sources of gas replenishment required by some models to explain the lifetime of UCH\textsc{ii} regions.

In recent years, several compact sources possibly associated with UCH\textsc{ii} regions have been reported (Kawamura & Masson 1998; Dzib et al. 2013b; Carral et al. 2002; Rodríguez et al. 2014). A naive interpretation is that these sources are the so-called hyper-compact (HCH)\textsc{ii} regions surrounding even younger neighboring stars. However, very few of these sources have properties compatible with those of HCH\textsc{ii} regions. The studies mentioned above show that there is no unique explanation for the nature of these compact sources as they do not constitute a homogeneous class of objects. For example, W3(OH) harbors a compact source that exhibits time variability and a positive spectral index consistent with the presence of a fossil photoevaporating disk (Dzib et al. 2013b). On the other hand, the compact source found in NGC 6334A has a negative spectral index characteristic of optically thin

\textsuperscript{5} HCH\textsc{ii} regions constitute the smallest observed H\textsc{ii} regions, even though only a handful of this class of objects are known (e.g., Sánchez-Monge et al. 2011). They have extremely small sizes ($\gtrsim 0.03$ pc) and high emission measures ($\gtrsim 10^{16}$ pc cm$^{-6}$) and electron densities ($\gtrsim 10^6$ cm$^{-3}$, Kurtz 2005).
synchrotron emission, and it is also time variable (Rodríguez et al. 2014). The synchrotron emission implies the presence of mildly relativistic electrons. A negative spectral index can also indicate gyrosynchrotron emission. In this case, the electrons are accelerated in magnetic reconnection events near the surfaces of low-mass young stars. Alternatively, the electron acceleration can also occur in shocks of stellar winds between O companions forming a massive binary system that ionizes the H II region (e.g., Cyg OB2: Blomme et al. 2013). Additional examples where the flux of the source appears constant are found in G5.97-1.17 (Masqué et al. 2014). An interesting case is the Monoceros UCH II region, where two compact sources have been observed close to its center; one is related to a slightly resolved thermal source (Gómez et al. 2000), and the other to a magnetically active star (Dzib et al. 2016). This indicates that compact sources with different nature can coexist even in the same region.

A more extensively studied case is the Orion Nebula Cluster (ONC), which shows a large number and variety of compact radio sources, as reported in the past three decades (Churchwell et al. 1987; Garay et al. 1987; Zapata et al. 2004; Kounkel et al. 2014; Forbrich et al. 2016). The large number of compact sources associated with the Orion Nebula might be partly due to its proximity to Earth and to the richness of the cluster. This enables the detection of weak sources (which would remain undetectable in more distant objects) and the resolution of these sources into individual compact components. In addition, most of the objects present IR, optical, or X-ray counterparts depending on their intrinsic nature or extinction. All these properties are indicative of the varied class of objects coexisting in the ONC, which clearly shows the striking stellar multiplicity intrinsic in the vicinity of massive stars.

Motivated by the possible high occurrence of UCH II regions with associated compact sources, we carried out high-resolution VLA observations of selected UCH II regions to search for additional cases of compact sources hidden in the bright free–free emission of the photoionized region. By inspecting these compact sources in very young environments such as UCH II regions, we are possibly studying the youngest objects of ONC-like radio source populations. The article is structured as follows: in Section 2 we describe the observations. In Section 3 we present the resulting maps and the newly discovered compact sources found in UCH II regions. In Section 4 we analyze some selected sources. Finally, in Section 5 we discuss the general results of the analyzed sources and draw conclusions.

2. Observations

The 1.3 cm Jansky Very Large Array observations were conducted in two observing blocks on 2014 May 16 and 28 with the A configuration. We observed 12 out of 17 proposed UCH II regions of the Wood & Churchwell (1989) and Kurtz et al. (1994) surveys in two observing blocks. These sources were selected because they showed evidence of compact structures in archival data. The 5 remaining sources correspond to a third observing block that was not observed due to time constraints. We observed half of the source set in each observing block. In the source selection, we also applied the following two criteria: (i) sources must be located at <4.5 kpc, and (ii) sources with irregular morphologies are discarded. The studied regions and observational parameters are listed in Table 1. We observed the frequency range 18–26 GHz with a spectral setup optimized for continuum observations. We used the three-bit samplers with full polarization mode and set 2 s as the integration time. The flux calibrator was 3C 286. Pointing corrections were applied for telescope slews larger than 10 degrees on the sky. To obtain a homogeneous uv coverage, the fields were observed with 1–1.5 minutes of time on-source preceded and followed by 30 seconds observing the gain calibrator. This sequence was applied to each field and was repeated until an observing block of two hours was completed. This arrangement gives on-source observing times between 4 and 6 minutes.

Data were calibrated with the Common Astronomical Software Applications (CASA) package through the pipeline provided by the National Radio Astronomy Observatory (NRAO). A first set of maps was made with the CLEAN task of CASA with natural weighting and fitting the frequency dependence across the bandwidth with two terms of the Taylor polynomial during the deconvolution.

### Table 1

| Source     | Pointing Center α (J2000) | Pointing Center δ (J2000) | Gain Calibrator | Bootstrapped Flux Density† (Jy) | Fitted Spectral Index |
|------------|----------------------------|---------------------------|-----------------|---------------------------------|----------------------|
| G5.89-0.39 | 18°00′30″387              | −24°04′00″12              | J1745-2900      | 0.99 ± 0.01                     | 0.011 ± 0.02         |
| G5.97-1.17 | 18°03′40″504              | −24°22′44″40              | J1832-1035      | 1.043 ± 0.005                   | −0.718 ± 0.002       |
| G19.61-0.23| 18°27′38″117              | −11°36′39″48              | J1851-0035      | 0.803 ± 0.004                   | −0.200 ± 0.006       |
| G20.08-0.14| 18°28′10″280              | −11°28′47″13              | J1931+2243      | 0.517 ± 0.004                   | −0.171 ± 0.001       |
| G28.29-0.36| 18°44′15″097              | −04°17′55″29              | J2015+3710      | 3.86 ± 0.01                     | −0.006 ± 0.001       |
| G35.20-1.74| 19°01′46″490              | 01°13′24″65               |                 |                                 |                      |
| G60.88+0.13| 19°46′39″202              | 25°12′48″05               |                 |                                 |                      |
| G61.48+0.09A| 19°46′39″202          | 25°12′48″05               |                 |                                 |                      |
| G76.18+0.13| 20°23′45″733              | 37°38′32″38               |                 |                                 |                      |
| G76.38-0.62| 20°27′26″773              | 37°22′48″01               |                 |                                 |                      |
| G78.44+2.66| 20°19′39″231              | 40°56′37″68               |                 |                                 |                      |
| G79.30+0.28| 20°32′29″479              | 40°16′04″64               |                 |                                 |                      |

Note.

† At 21.96 GHz.

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parameter set to 2). As we aimed to detect compact components associated with resolved UCH II regions, we obtained a second set of maps of selected sources using uniform weight and suppressing the bright extended free–free emission by removing the short spacings of the visibilities in most of the regions (between 200 and 800 kλ depending on the region). The parameters of both sets of maps are given in Table 2. The choice of the $\nu \lambda$ range was based on minimizing the extended emission without affecting the image quality significantly. The corresponding angular scale for which larger structures are suppressed is given in Column 4 of Table 2.

### 3. Observational Results

The 1.3 cm continuum emission of the observed regions is shown in Figures 1 and 2. Owing to the lack of short baselines of the A configuration of the VLA, the extended emission of these regions is poorly imaged. This limitation is not important for our study, which focuses on the most compact components of the regions. By comparing our 1.3 cm maps with those obtained at 2 cm with the VLA in the B configuration of Wood & Churchwell (1989) and Kurtz et al. (1994), we assess that in many regions, only the brightest part of the emission is recovered. The G78.44+2.66 and G79.30+0.28 regions show the most extreme cases of filtering where practically the entire emission disappears. On the other hand, G60.88+0.13 and G61.48+0.09 present angular sizes $\lesssim$1 arcsec and can be fully mapped, while G76.18+0.13 and G76.38-0.62 lack any extended structure.

We report compact sources associated with UCH II regions, in most of the cases for the first time, whose positions are indicated in Figures 1 and 2. Since our observations filter out most of the extended emission, the compact sources appear visible at first glance. In some maps, however, the extended emission produces artifacts that reduce the dynamic range and limit our ability to detect compact sources. To suppress the extended emission of the ionized gas around the compact source, we removed the short baselines of the visibility data set for selected regions (see Section 2). A close-up view of the detected compact sources from this new set of maps can be seen in Figures 3 and 4.

Given the small field of view presented in these figures, the probability that a background compact source is seen in the same direction as the UCH II regions is extremely small: following expression A1 of Anglada et al. (1998) for a 10$''$ field of view (the largest field of view of all the maps shown in Figures 1 and 2) and adopting three times the rms noise of 50 $\mu$Jy (typical rms noise as seen in Column 6 of Table 2) as the detection threshold, we obtain $1 \times 10^{-4}$ expected background sources to be detected at 1.3 cm. The position of the compact source does not necessarily coincide with the brightest part or with the centroid of the UCH II region, as can be inferred from a comparison with larger scale maps found in the literature. To ensure that these compact sources are not merely the peaks of more extended emission, we compared their fluxes and sizes in maps obtained with several $\nu \lambda$ ranges. In all the maps of a set corresponding to a specific region, the properties of the compact source barely changed, indicating that they are distinct compact structures. There is the case of G28.29-0.36, however, where the compact source appears coincident with the brightest UCH II peak and is marginally resolved, making its independent nature from the extended free–free emission questionable.

The observational parameters of the compact sources derived from Gaussian fits are shown in Table 3. Their measured flux densities are typically a few mJy, and some of them appear marginally resolved with a typical deconvolved size of a few hundred au. However, because some of our observations have limited $\nu \lambda$ coverage, some of the deconvolved sizes must be taken with caution. We attempted to derive spectral indices using the 8 GHz bandwidth, but except for G76.38-0.62 and G76.18+0.13, the signal-to-noise ratio of the sources was insufficient for obtaining trustworthy results.

From the physical size and flux density, we can under certain assumptions derive several physical parameters listed in Table 4. The assumptions and the formulas used are explained in the footnotes of the table. We considered only the physics of the most likely scenario to explain the nature of the compact sources.
sources. Regions G76.18+0.13 and G76.38-0.62 were discarded from the table because they have brightness temperatures of 25,000 ± 11,000 and 15,000 ± 300 K, possibly indicative of a hot optically thick HCHII region. However, the spectral indices of these sources (see below) do rule out an optically thick free–free nature. We briefly discuss these sources below.

Figure 1. Continuum 1.3 cm emission maps with natural weighting of the observed regions in the observing block executed on 2014 May 28 (color scale and contours). For all panels, levels are $C$ times $-2^{n}, 2^{n}, 2^{n/2}, 2^{n/2}, 2^{n/2}, 2^{n/2}, 2^{n/2}, 2^{n/2}$, and $2^{n}$, where $C$ is given by 2.5 times the rms noise shown in Column 3 of Table 2, except for G5.89-0.39, G19.61-0.23, and G35.20-1.74, which were constructed with a Gaussian taper of 0.25, 0.2, and 0.35 arcsec, giving rms noise levels of 8.5, 1.5, and 2 mJy beam$^{-1}$, respectively. The field of view depends on the panel. The synthesized beam is shown in the bottom right corner. The blue circles indicate the compact sources reported in Table 3 found after removing the short spacings of the visibility data set. The red triangles indicate the 2MASS (PSC) positions.
4. Analysis of Selected Sources

By inspecting Figures 1 and 2, we find that the compact sources follow two main trends according to their location with respect to the whole UCH II region. On one hand, there are sources coincident with or close to the centimeter emission peak of the UCH II region (hereafter, Type I sources). Despite...
the lack of extended emission of the G76.18+0.13 and G76.38-0.62 regions, we include their associated compact sources in this group as they are coincident with the peak emission of the maps of Kurtz et al. (1994). On the other hand, there are sources that appear scattered around the UCH II region (hereafter, Type II sources).

4.1. Type I sources

Type I sources (i.e., those that are located within the boundaries of the radio emission from the UCH II region) are related to the exciting star of the region based on their association with the dense ionized gas. Below we give some individual remarks on Type I sources and provide a tentative interpretation for the nature of the compact sources belonging to this group.

1. G28.29-0.36. This region is embedded in a dusty massive cloud, as indicated by millimeter and submillimeter observations (Hill et al. 2005; Rathborne et al. 2006; Walsh et al. 2003). The cloud is coincident with the source IRAS 18416–0420 and has extended mid-IR emission that implies the presence of warm dust (Walsh et al. 2003; Rathborne et al. 2006). Moreover, the association of bright radio emission suggests ongoing massive star formation in this region (Helfand et al. 2006). The centimeter continuum maps of Kurtz et al. (1994) resolve G28.29-0.36 into two peaks, aligned north-south, surrounded by diffuse emission. As seen in Figure 5, within the astrometric uncertainties of the VLA, the G28.29-VLA1 source is coincident with the northern and brightest peak of the Kurtz et al. (1994) map.

The 2MASS point source catalog (PSC) reports two IR sources that might be associated with the northern and southern peaks (see Figure 5). This coincidence suggests that the G28.29-0.36 UCH II region is composed of at least two subregions, each one photoionized by its own star, detected at IR wavelengths. A close inspection of the corresponding panel of Figure 3 reveals that the IR source falls 0’’25 south of G28.29-VLA1. Given the 2MASS PSC astrometric accuracy of ≤0’’1, similar to the
accuracy of the VLA data, the separation between G28.29-VLA1 and the IR source corresponds to more than twice the $\sigma_{\text{rms}}$ error in the determination of positions with our observations. In addition, G28.29-VLA1 is the largest Type I source ($\sim 300$ au, see Table 4) and shows some evidence of being extended.

2. G35.20-1.74. The G35.20-1.74 region belongs to the W 48 complex found at the edge of a molecular cloud (Zeilik & Lada 1978). The region presents strong maser activity (Genzel & Downes 1977; Evans et al. 1979; Caswell et al. 1995) that led Zhang et al. (2009) to derive a parallax distance of $3.27 \pm 0.49$ kpc based on maser observations. The complexity of the region is revealed by interferometric radio observations that show that the molecular cloud contains a PDR region (Rosie et al. 2005) with five H II regions, of which G35.20-1.74 is the brightest (Onello et al. 1994). In addition, observations with higher angular resolution reveal a cometary morphology for G35.20-1.74 with the tip pointing to the northeast (Wood & Churchwell 1989; Kurtz et al. 1994). Strikingly, low-resolution maps of this region at centimeter wavelengths show large-scale emission oriented to the northwest (Roshi et al. 2005).

Figure 6 shows that our observations recover the northeastern tip of the region and for the first time show the compact source G35.20-VLA1. This source is located near the center of the UCH II region and $\lesssim 1''$ southwest of the brightest emitting region. This means that the source is clearly detached from this part of the UCH II region, but is still embedded in the extended cometary emission. In our sample of compact sources, G35.20-VLA1 has the largest emission measure and ionized gas density ($\sim 3 \times 10^9$ cm$^{-6}$ pc$^{-1}$ and $\sim 2 \times 10^5$ cm$^{-3}$, respectively, see Table 4).

3. G76.18$+$0.13. The UCH II region appears unresolved in the maps presented by Kurtz et al. (1994) with an angular resolution of $\lesssim 1''$. We derive a spectral index of $-0.45 \pm 0.05$ using the 8 GHz bandwidth of our observations, which is indicative of nonthermal emission. We found no evidence of circular polarization. With our higher resolution data we can obtain a very small and uncertain size. Given the poor $uv$ coverage of our observations, we do not attribute significance to this deconvolved size. Therefore, we cannot discard a stellar corona origin for the emission of this source. This
emission may be associated with a low-mass stellar companion of the exciting star of the region.

4. **G76.38-0.62.** This region belongs to the S106 H II region located at a distance of 1 kpc (Eiroa et al. 1979; Churchwell & Bieging 1982). The region shows a bipolar morphology, possibly indicative of a powerful wind (Felli et al. 1984). There is some controversy about the exciting object of the region, but most of the studies point to an early B-type star (e.g., Bally et al. 1983; Kurtz et al. 1994). Despite the complexity of the region, Kurtz et al. (1994) only detected the compact core that is probably associated with the exciting star. Our higher angular resolution observations show similar results with a deconvolved compact core size of ~100 × 50 au.

Because of the high signal-to-noise ratio of our detection for this source, we could derive the spectral index within the 8 GHz of bandwidth of our observations. Our result, 0.75 ± 0.08, is consistent with an ionized
outflow. In addition, our data show marginal circular polarization over the source at a level of 0.5 ± 0.1%. In order to confirm or reject this result, we analyzed the data from project AF362 taken on 1999 July 6 at X-band and set an upper limit of \(1.1\%\) (3\(\sigma\) upper limit) for the circular polarization. We conclude that there is no clear evidence of circular polarization for this source.

4.1.1. The Nature of Type I Sources

The close association with the centimeter emission peak and with a possible IR counterpart suggests that Type I sources are associated with the exciting star of the region. However, for G28.29-0.36 and G35.20-1.74, Kurtz et al. (1994) estimated a spectral type of O9 for the ionizing star. Such a star delivers \(\sim 5 \times 10^{38} \text{ s}^{-1}\) ionizing photons (Panagia 1973), and as seen in Column 7 of Table 4, the ionizing flux required to maintain the free–free emission of G28.29-VLA1 and G35.20-VLA1 is \(\sim 5 \times 10^{45} \text{ s}^{-1}\). Therefore, these compact sources probably do not harbor the exciting star of the region unless a considerable leakage of the UV photon flux occurs in the source (see the analysis of G35.20-VLA1 below).

The scenario where these sources are very compact H\ II regions surrounding an early-B-type star embedded in the UCH\ II region is unlikely: such a region would be dynamically unstable and expand away with a lifetime too short to be observed. However, a mechanism to maintain these very compact photoionized regions observable for a longer time might be at work. Given their small size, one possibility is that they are confined within the region where the material is gravitationally trapped. This could be the case of G35.20-VLA1 and G76.38-VLA1, whose sizes are smaller than twice the gravitational radius for an O9 (\(\sim 150\) au) and B1 (\(\sim 125\) au) stars, which are ionizing G35.20-1.74 and G76.38-0.62, respectively. If these sources were to harbor the exciting source of the region, they could therefore retain a significant amount of ionized material, especially G35.20-VLA1, whose electron density and emission measure are an order of magnitude above those derived for the rest of the compact sources. Moreover, G76.38-VLA1 and the 2MASS source positions are an excellent match, and in addition, the required ionizing photon flux for this source is consistent with a B1 star.

These objects may not be fully ionized, but instead may have an inner neutral component. This neutral component would be continuously photoevaporated, either internally or externally, by the ionizing star of the region. Such a scenario for a photoevaporating accretion disk was proposed by Hollenbach et al. (1994). Otherwise, they could be dense neutral globules surrounded by an externally ionized envelope (Garay et al. 1987). These objects are probably small-scale structures inherent of molecular clouds (e.g., Pauls et al. 1983; Morata et al. 2003) that were engulfed by the ionizing front.

We propose that G28.29-VLA1 is externally ionized by the O-type star exciting the region because its size is larger than twice the gravitational radius of the exciting star. In this case,
the number of ionizing photons causing the ionization is set by the stellar type and the solid angle of G28.20-VLA1 as seen from the exciting star. As discussed above, the required UV photon flux necessary to ionize G28.29-VLA1 is $4.6 \times 10^{45}$ s$^{-1}$. This means that the number of ionizing photons impinging G28.20-VLA1 is a factor of $10^3$ lower than the total provided by the exciting star. When we take the distance of G28.29-0.36 ($3.3$ kpc, Solomon et al. 1987) and the size of G28.29-VLA1 (300 au) into account, the exciting star must therefore be located at 2600 au from the compact source in order to obtain a geometrical dilution of $10^3$. Considering that the dust opacity affects the UV photons in the region, the separation between G28.29-VLA1 and the ionizing star must be taken as an upper limit. Similarly, considering possible projection effects in the map, the observed angular distance can be smaller than that corresponding to the separation between the exciting source and G28.29-VLA1. According to this, our estimated value for the angular separation, $\lesssim 0.8$ arcsec, is in good agreement with the separation of the IR and radio sources, as seen in the corresponding panel of Figure 3.

Since G35.20-VLA1 and G76.38-VLA1 possibly harbor the exciting source of the region, we propose that they are internally ionized. Judging from their deconvolution, these sources appear to be elongated with a shape reminiscent of a partially edge-on disk-like morphology. In this scenario, the non-detection of any IR counterpart of the exciting star in G35.20-VLA1 could be explained if it is surrounded by the edge-on disk and efficiently obscured. Moreover, in the case of G76.38-VLA1, the source is elongated perpendicular to the outflow found by Felli et al. (1984). This invokes the photoevaporating disk picture around a massive star proposed by Hollenbach et al. (1994). In this picture, the ionized material forms a static atmosphere above the disk for radii smaller than the gravitational radius. If the stellar wind is not excessively strong, the static atmosphere is preserved and produces the observed free–free emission. Since HCHII regions are considered to harbor only a single star or a small multiple system, the true nature of these regions could be explained as static (or blowing) ionized atmospheres of these photoevaporating disks around massive stars. However, the shape and extension of these static atmospheres depends on the stellar wind properties, which for the exciting star of these regions are poorly constrained. The study of these sources based on a possible photoevaporating disk is beyond the scope of this paper, and we propose this interpretation as tentative.

4.2. Type II sources

Type II sources are not located within the boundaries of their associated UCHII region. Although the sources of this category probably belong to the main region, their location suggests that they are unrelated with the dense gas of the UCHII region. Below we comment on individual sources and offer a
speculative discussion on the possible nature of Type II sources.

1. G5.97-1.17. This region lies in the core of an extended H II region, the Lagoon Nebula or M8, located at a distance of 1.3 kpc (Arias et al. 2006). The region is ionized by the UV photons of an O7 star named Herschel 36 (Woolf 1961, hereafter, Her 36). About 4000 au southeast from Her 36, there is a radio source identified with G5.97-1.17, which was first associated with an UCHII region. More recently, however, Stecklum et al. (1998) interpreted this source as a proplyd (hereafter G5.97). Moreover, Goto et al. (2006) reported the presence of a close intermediate-mass stellar companion of Her 36 traced by 2 cm emission (Her 36 SE). Using data of the present paper, Masqué et al. (2014) confirmed the proplyd nature of G5.97, finding hints of nonthermal emission from this object, and at the same time, detecting radio emission toward the Her 36 multiple system.

The map of Figure 1 shows three compact sources in the G5.97-1.17 region. The eastern source corresponds to the G5.97 proplyd and is the largest object in angular size of the list of compact sources in Table 3. Its proplyd nature is suggested by its cometary shape with the tip pointing to Her 36 (see Figure 4). We derived an emitting size of 330 × 160 au that is in good agreement with the radius of 160 au derived in Stecklum et al. (1998). The radio emission of Her 36 appears 27″ northwest of the G5.97 proplyd as an unresolved source. Masqué et al. (2014) associated this radio emission with a region where the winds of Her 36 and Her 36 SE collide and based this on the position of the radio peak between the two stellar components. The 2MASS position seen in the G5.97-Her 36 SE panel of Figure 4 is slightly displaced to the northwest of the radio emission and may be coincident with the Her 36 main component.

North of Her 36 there is another unresolved radio source with a flux density of 1 mJy (which we call Her 36N). Consulting the literature, we find that Allen (1986) reported a northern IR companion (Her 36B) located 3.6 arcsec from the Her 36 main component. Although the association of the radio source with Her 36B is tempting, there is a small but significant offset of ~0.8 arcsec between the position of these sources. Instead, the Her 36N position has an excellent match with a 2.2 μm source seen close to Her 36B in the Figure 1 of Goto et al. (2006).

2. G20.08-0.14. The G20.08-0.14 region is embedded in a molecular cloud (Turner 1979; Plume et al. 1992) where massive stars are forming, as confirmed by maser observations (Ho et al. 1983; Hofner & Churchwell 1996; Walsh et al. 1998). Galván-Madrid et al. (2009) carried out a detailed study of the kinematics of the region through molecular and recombination line observations and found that an accretion flow occurs at multiple scales. Using the new Bayesian distance calculator from Reid et al. (2016) and a vlsr ≈ 45 km s⁻¹ (Argon et al. 2000), we obtained that the near and far kinematic distances to G20.08-0.14 are 3.36 ± 0.18 kpc and 12.30 ± 0.20 kpc, with probabilities of 0.85 and 0.15, respectively. Given that the probability of the nearest kinematic distance is so much higher, we adopt this.

The region is composed of three components labeled A, B, and C, where region A is the brightest and region C is the most extended (Wood & Churchwell 1989). Our observations show regions A and B and resolve out region C. Region A is the brightest, as expected, and region B shows a ring-like morphology, maybe representing a signpost of an expanding bubble that interacts with the medium. As we are interested in small components, however, we focus on the compact source that is blended to the western side of region A (G20.08-VLA1). Some properties of G20.08-VLA1 differ from the rest of the compact sources. First, this source has a significantly larger size (~500 × 200 au), even though its determination is uncertain because it appears blended with region A. Second, G20.08-VLA1 can be associated with hot-core molecular emission (OCS and CH3CN) mapped by Galván-Madrid et al. (2009).

3. G60.88+0.13. This region, also known as Sh 87, is an active star-forming region located at a distance of 2.1 kpc (Clemens 1985). This region, cataloged as an optical H II nebula, is also associated with the infrared source IRAS 19442+2427 and has been studied by several authors at different wavelengths (e.g., Barsoum 1989; Xue & Wu 2008). In particular, a UCH II region was detected at 2 cm and 3.6 cm by Kurtz et al. (1994), with an embedded B0.5 ZAMS star. In addition, Sh 87 is one of the few examples where the proposed mechanism for triggering star formation as a cloud–cloud collision appears to be observed (Xue & Wu 2008).

G60.88-VLA1 is located 2° west of the UCH II region and appears unresolved. This source is coincident within 1.5 arcsec with a YSO reported by Campbell et al. (1989). According to the position accuracy of their observations (2 arcsec), these two objects may be associated. Moreover, there are several IR sources in the field, suggesting a cluster of young objects. All these features suggest a pre-main sequence stellar nature for G60.88-VLA1.

4. G61.48+0.09A. This object is an active star-forming region, located in the emission nebula Sh 2-88B. Its distance is controversial, but assuming 2.5 kpc, Evans et al. (1981) estimated a far-infrared luminosity of 2.8 × 10⁵ L☉. However, we here use the distance adopted in Kurtz et al. (1994) of 2.0 kpc. G61.48+0.09A is composed of an extended cometary (B1) and an UC (B2) H II regions (Felli & Harten 1981). Deharveng et al. (2000) associated B1 with a cluster of high-mass stars, with an O8.5V-O9.5V star as the dominant exciting source, while B2 appears as an UCH II region with an exciting star of spectral type later than B0.5V.

Furthermore, in Wood & Churchwell (1989), G61.48+0.09A appears as a compact northern source with some extended emission to the south. Our observations reveal the northern source as a bow-shock structure pointing to the southwest and two additional compact sources embedded in the diffuse southern emission (see the map of the region in Wood & Churchwell 1989). One of them is clearly resolved (G61.48-VLA1), while for the other the deconvolved size is poorly determined (G61.48-VLA2), implying a physical size of ≤100 au. None of the compact sources have known counterparts at other wavelengths, which is possibly due to obscuration, as the region is embedded in a large dense cloud.
5. G78.44+2.66. The G78.44+2.66 region is associated with IRAS 20178+4046 and harbors a cluster of young stars detected at IR wavelengths (Tej et al. 2007). Interferometric radio observations show that the UCHII region has a cometary morphology with the tip pointing to the northwest (Kurtz et al. 1994). Our A configuration observations, however, miss all the extended emission, and only two compact sources appear in the map. One of these sources, G78.44-VLA4, can be associated with an IR source previously detected by Tej et al. (2007, their source 2) and with a compact radio source (Neria et al. 2010, their VLA4; we adopt the same name). These latter authors detected a group of compact radio sources that they attributed to the presence of a cluster of pre-main sequence stars.

G78.44-VLA1 is unresolved and has no known counterparts. We failed to observe circular polarization toward this source. In contrast to G78.44-VLA4, G78.44-VLA1 appears to be located far away from the extended centimeter emission.

### 4.2.1. The Nature of Type II Sources

Only three out of the nine Type II sources are resolved (G5.97-Proplyd, G20.08-VLA1, and G61.48-VLA1). G20.08-VLA1 is the largest source of our sample and seems to have a well-defined nature: it probably corresponds to a hot core with an embedded massive object that has begun to ionize the internal part of the core. The molecular emission would come from a neutral shell surrounding the ionized region, where the centimeter emission is produced. The ionized region is expected to expand at the speed of sound, which for the derived size of G20.08-VLA1 (~500 au) yields an estimated age of about 200 years. Similarly, the measured size in the map for the bubble corresponding to region C (~3000 au) yields a lifetime of ~10^3 years. The youth of both objects makes it unlikely that they are observed, but it is not impossible given the crowded region in which they are situated. The fact that G20.08-VLA1 appears attached to other ionized regions of G20.08-0.14 but is not embedded within any of them suggests that it is part of a cluster of UC (or HCHII) regions. In this case, the improvement of our data with respect to previous observations allows us to detect lower mass and/or younger members of the cluster.

G5.97-Proplyd and G61.48-VLA1 have sizes slightly larger than the resolved Type I sources. Their emission measure and density are below those typical for an HCHII region. In external photoevaporation, the photon flux incident on the neutral condensation, \(J_0 = N_{\text{star}}/4\pi d^2\), with \(d\) being the projected distance to the exciting source that produces \(N_{\text{star}}\) ionizing photons, is reduced as \(J = 2J_0/[1 + \sqrt{1 + \alpha N_{\text{star}} R/3\pi\alpha^2 c^2}]\) (Spitzer 1978), where \(J\) is the photon flux at the ionization front of the condensation, \(c\) is the speed of sound in the medium (~10^4 cm s^-1), \(\alpha\) is the recombination coefficient (\(3 \times 10^{-13}\) cm^-3 s^-1), and \(R\) is the condensation radius. Then, equating the rate at which gas is ionized at the ionization front with the change of neutral mass per unit time, we obtain \(M = \pi R^2 J \mu m_H\), where \(\mu\) is the mean mass of a hydrogen atom.
molecular weight per particle, adopted to be 2.3, and $m_H$ is the hydrogen mass.

In the likely scenario where the structure of these photoevaporating objects is composed of a neutral component with a thin ionized envelope, we can study the case of G28.29-VLA1, which is a Type I source that is externally photoionized. Adopting half the derived size of the compact source as the radius of the object (150 au, see Table 4) and a distance of 825 au to the ionizing source estimated from the maps, we obtain a mass depletion rate due to photoevaporation of $3 \times 10^{-6} M_\odot \, \text{yr}^{-1}$. This rate is about an order of magnitude higher than those derived for the photoevaporating objects in the ONC ($10^{-6} - 10^{-7} M_\odot \, \text{yr}^{-1}$, Garay et al. 1987; Churchwell et al. 1987). An amount of photoevaporating material like this could create a region around G28.29-VLA1 with an emission measure large enough to be observable as an UCH II region.

Assuming a steady photoionization rate, a lifetime can be estimated from $M/M_*$, where $M$ is the mass of the condensation. Churchwell et al. (1987), Garay et al. (1987) estimated masses for the Orion photoevaporating objects of the order of $0.1 M_\odot$. Given the slightly larger size of G28.29-VLA1 with respect to the Orion sources ($\sim 300$ au versus $100-200$ au, see Table 5 of Churchwell et al. 1987) and the fact that the former is embedded in a higher ambient pressure, we can adopt this mass as a lower limit for the mass of G28.29-VLA1. Our derived lifetime of $\gtrsim 3 \times 10^5$ years is longer than the typical lifetime of UCH II regions estimated from free expansion.

Similarly, a photoevaporating disk around the exciting star, as proposed for G35.20-VLA1 and G76.38-VLA1, could provide enough ionized material to replenish the UCH II region. Hollenbach et al. (1994) estimated that disk masses of a few $M_\odot$ can considerably expand the lifetime of the region. Although from the present data we cannot infer the mass of the disks, their estimated radii (50–120 au) are somewhat smaller but on the order of other disks found around massive stars (e.g., IRAS 18162–2048: 200 au, Carrasco-González et al. 2012) that are known to have at least a few solar masses (Fernández-López et al. 2011; Carrasco-González et al. 2012). According to Hollenbach et al. (1994), such a disk would supply ionized material to the region for $\gtrsim 10^5$ years.

The same calculation of a mass depletion rate as shown above can be applied to photoevaporating objects representative of Type II, such as G5.97 Proplyd or G61.48-VLA1. For G5.97 Proplyd, which is photoionized by a star of O7 spectral type (Her 36) situated 3500 au away in projection, we derive a depletion rate of $\sim 10^{-6} M_\odot$ for a radius of 150 au (see Column 8 of Table 4). This value is higher than the value derived by Stecklum et al. (1998, $7 \times 10^{-7} M_\odot$), possibly because they adopted a larger distance to the region (1.8 kpc). Performing the same analysis for G61.48-VLA1, which has a radius of 150 au and is separated by 1000 au from its assumed ionizing star (G61.48-VLA2), we obtain a mass depletion rate of $\lesssim 10^{-6} M_\odot \, \text{yr}^{-1}$ if we assume that the latter object is a B-type star ($N_{\text{ion}} \lesssim 10^{48} \text{s}^{-1}$). These rates are similar to those found for photoevaporating objects in the ONC and lower than those of Type I sources. The similarity between G5.97 Proplyd and G61.48-VLA1 with the Orion photoevaporating objects suggests similar lifetimes ($10^5$ years). Therefore, the photoevaporating Type I sources are statistically younger than the photoevaporating Type II sources since the latter have lower mass depletion rates ($10^{-6} - 10^{-7} M_\odot \, \text{yr}^{-1}$) and can last an order of magnitude longer ($\sim 10^6$ versus $\sim 10^5$ years).

5. Discussion and Conclusions

From the last column of Table 3 we can assess the high occurrence of UCH II regions with associated compact components: 9 out of the 12 UCH II regions we surveyed have associated compact sources. In total, we detected 13 such sources. Nevertheless, the expected number of compact sources associated with a given UCH II region is low: we normally find one compact source per UCH II region, and only in three cases did we find additional compact sources associated with the same region. Invoking the statistical arguments discussed in Section 3, the likelihood of detecting background sources in our field of view is very low, and we consider that these compact sources are indeed associated with the corresponding UCH II region. In addition, most of them present free–free emission, indicating that they are (at least partially) ionized. This may add evidence that they are physically related to the region.

We classify these compact sources as Type I when they are located within the boundaries of their associated UCH II region, or Type II when they are associated with an UCH II region, but are not detected directly toward said region. As seen in the previous section, Type I sources include G28.29-VLA1, G35.20-VLA1, G76.38-VLA1, and G76.18-VLA1, even though the latter is too far away to properly determine its features. As seen in Column 4 of Table 3, these sources can be spatially resolved with sizes typically in the range $\sim 100-300$ au, discarding a stellar corona origin for their emission. Although our observations are insufficient to fully elucidate the intrinsic nature of these sources, they seem to be photoevaporating objects such as protostellar disks or globules with a neutral component. However, we infer important differences between them: while G28.29-VLA1 is probably externally photoionized, the remaining sources of this group appear to harbor the exciting star of the region. As seen in the previous section, the derived photoevaporating rates for Type I sources are clearly higher than that of photoevaporating proplyds and globules in the ONC. This might produce observational features such as UCH II regions, as a result of the considerable amount of ionized material flowing around the compact source.

On the other hand, Type II sources includes G5.97-Proplyd, G5.97-Her 36, G5.97-Her 36N, G20.08-VLA1, G60.88-VLA1, G61.48-VLA1, G61.48-VLA2, G78.44-VLA1, and G78.44-VLA4. A prime example is provided by G60.88+0.13, where G60.88-VLA1 is located far away from the cometary structure of the UCH II region. G20.08-VLA1 most likely has a distinct nature, and discussing it is beyond the scope of this paper. The high detection rate for these sources could be a consequence of the high population of objects associated with massive star-forming regions. In the most recent survey of radio sources in the ONC, 556 sources were detected (Forbrich et al. 2016). This high detection rate was due to the depth of the observations, which for a nearby region such as Orion provided an unprecedented threshold for radio source detection. Of the regions observed in this work, G5.97-1.17 has a distinctive extended diffuse appearance, and it is therefore the source that most resembles the ONC. If Orion were located at the distance of G5.97-1.17, the flux density of their compact sources would be roughly a factor of 10 lower than the values reported in Forbrich et al. (2016). Adopting the same detection threshold of a signal-to-noise ratio greater than 5, the rms value shown in Column 6 of Table 2 yields 0.25 mJy beam$^{-1}$. Only $\sim 10$ sources from the Forbrich et al. (2016) catalog would be above this level if their fluxes were scaled to that distance. The
difference of the field of view between their C-band observations and our Ku-band observations (the latter is about five times smaller) is approximately balanced by the difference in the distance between Orion and M8. In terms of lineal size, we therefore mapped a region similar to that of Forbrich et al. (2016). The number of radio sources in M8 we detected (three) is somewhat below the number expected for a ONC-like region (∼10). However, given the uncertainties of this analysis, we cannot discard that M8 has characteristics similar to the ONC in terms of radio source population. In this picture, many more compact sources remain to be discovered in M8; they are currently below our detection threshold. Very deep interferometric radio observations across the M8 region would assess the existence of a similar population of radio sources as in the ONC.

The remaining regions that have associated Type II sources might also harbor a variety of radio sources as rich as that of the ONC. Indeed, some compact Type II sources are unresolved, and some of them are related with already visible stellar objects such as PMS stars. This would correspond to a population of Type II sources detected here (G20.08-VLA1, G5.97 Proplyd, and G61.48-VLA1) are most likely of thermal nature, and with the exception of G20.08-VLA1, they are photo-evaporating objects similar to Type I sources. However, their photoionizing rate is about an order of magnitude lower than those of ONC sources. The flowing plasma from the photoevaporating objects of Type II is therefore expected to be more diffuse than that of Type I objects and to be possibly more extended because Type II sources are statistically older than Type I sources. Therefore, the associated centimeter emission of the photoevaporated material of Type II objects would be weaker and more extended than that of Type I objects, and thus easily filtered out by an interferometer.

With the present data we cannot establish an unambiguous nature for the newly detected compact sources. However, we assess some of their observational properties and their implications in the UCH II region evolution, which are listed below:

1. We found 13 compact sources among our observed 12 regions, indicating a high occurrence of such sources associated with UCH II regions or lying close to them. Based on this, we categorize the sources into two distinctive groups of compact sources (Type I and Type II).
2. Type I corresponds to sources coincident with the bright free–free emitting area, and they may be embedded in the UCH II region. They are probably photoevaporating objects with mass depletion rates of $10^{-5}$–$10^{-6} M_{\odot}$ yr$^{-1}$ and lifetimes of $10^{5}$–$10^{6}$ years. These objects would be extremely close to the ionizing massive stars and still would have some reservoir of mass because of their youth. They would show observational features such as UCH II regions lasting for $>10^{6}$ years as a result of the considerable amount of ionized material flowing around the compact source. This interpretation provides a solution to the so-called lifetime problem for UCH II regions.

3. Type II sources appear unrelated to the dense gas of the UCH II region. Some of these sources could be photo-evaporating objects with mass depletion rates of $\lesssim 10^{-6}$ $M_{\odot}$ yr$^{-1}$. This flowing material is too diffuse to create an observable UCH II region. Other Type II sources appear to be unresolved and possibly correspond to stellar objects. All these characteristics suggest that Type II sources correspond to a more evolved population than Type I sources.

4. There are some similarities between Type II sources and those of ONC radio sources. In particular, both populations have a rich variety of objects. Moreover, this variety includes photoevaporating objects, such as globules and proplyds, which have mass depletion rates similar to those of ONC photoevaporating objects. The compact sources detected here may be the tip of the iceberg of a larger and varied population of radio sources similar to that of the ONC.

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