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# Ultracompact H II regions with extended emission: the complete view

Eduardo de la Fuente<sup>1b</sup>, <sup>1</sup>★<sup>†‡</sup> Alicia Porras,<sup>2</sup> Miguel A. Trinidad,<sup>3</sup> Stanley E. Kurtz,<sup>4</sup> Simon N. Kemp,<sup>1</sup> Daniel Tafoya,<sup>5</sup> José Franco<sup>6</sup> and Carlos Rodríguez-Rico<sup>3</sup>

<sup>1</sup>Instituto de Astronomía y Meteorología, Dpto. de Física, CUCEI, Universidad de Guadalajara, Av. Vallarta 2602, 44130 Guadalajara, Jalisco, México

<sup>2</sup>Instituto Nacional de Astrofísica, Óptica y Electrónica, Luis E. Erro Número 1, 72840 Tonantzintla, San Andrés Cholula, Puebla, México

<sup>3</sup>Departamento de Astronomía, Universidad de Guanajuato, Apartado Postal 144, 36000 Guanajuato, México

<sup>4</sup>Instituto de Radioastronomía y Astrofísica, UNAM, Antigua Carretera a Pátzcuaro Número 8701, 58089 Morelia, Michoacán, México

<sup>5</sup>Department of Space, Earth and Environment, Chalmers University of Technology, Onsala Space Observatory, SE-439 92 Onsala, Sweden

<sup>6</sup>Instituto de Astronomía, UNAM, Apartado Postal 70-264, CDMX 04510, México

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## ABSTRACT

In this paper, we present the results of a morphological study performed on a sample of 28 ultracompact H II (UC H II) regions located near extended free–free emission, using radio continuum (RC) observations at 3.6 cm with the C and D Very Large Array (VLA) configurations, with the aim of determining a direct connection between them. By using previously published observations in B and D VLA configurations, we compiled a final catalogue of 21 UC H II regions directly connected with the surrounding extended emission (EE). The observed morphology of most of the UC H II regions in RC emission is irregular (single- or multi-peaked sources) and resembles a classical bubble structure in the Galactic plane with well-defined cometary arcs. RC images superimposed on colour composite *Spitzer* images reinforce the assignments of direct connection by the spatial coincidence between the UC components and regions of saturated 24  $\mu$ m emission. We also find that the presence of EE may be crucial to understand the observed infrared excess because an underestimation of ionizing Lyman photons was considered in previous works (e.g. Wood & Churchwell; Kurtz, Churchwell & Wood).

**Key words:** stars: pre-main-sequence – ISM: bubbles – H II regions – radio continuum: ISM.

## 1 INTRODUCTION

The ultracompact H II (UC H II) regions (term coined by Israel, Habing & de Jong 1973) are small (size  $\leq 0.1$  pc), dense ( $n_e \gtrsim 10^4$  cm $^{-3}$ ) regions with high emission measure (EM  $\geq 10^7$  pc cm $^{-6}$ ) and composed of photoionized hydrogen surrounding a recently formed ionizing OB-type star (e.g. Wood & Churchwell 1989; Kurtz, Churchwell & Wood 1994; Hoare et al. 2007). They were first studied via interferometric observations (e.g. Davidson & Harwit 1967; Mezger et al. 1967; Ryle & Downes 1967) and they are thought to represent an intermediate evolutionary state between hypercompact H II regions (an earlier phase, e.g. Sewilo 2006) and compact H II regions (a later phase, Churchwell 2002). The physical characteristics of the UC H II regions have been determined

observationally in surveys with the Very Large Array (VLA) performed by numerous authors (see review by Churchwell 2002).

Large-scale (arcminute) structures of ionized gas have been found that seem to be related to the UC H II regions (Mezger et al. 1967; Condon et al. 1998). Although these structures were discovered in the 1960s, only a few studies aiming to understand their origin have been conducted: Kurtz et al. (1999), using the VLA in configuration D at 3.6 cm; Kim & Koo (2001), using the VLA in configuration DnC at 21 cm; Ellingsen, Shabala & Kurtz (2005), using ATCA in configuration 750D at 3.5 cm, and de la Fuente (2007), using *Spitzer* IRAC data (see de la Fuente et al. 2009a,b, for a summary). Since all these works were complementary and addressed the problem from different points of view, none of them reached conclusive results to clarify the nature of the UC H II regions.

Kurtz et al. (1999) carried out an inspection of 3.6 cm VLA images taken in configurations B (Kurtz et al. 1994) and D, with maximum recoverable scales (MRS) of up to 10–20 arcsec and 3 arcmin, respectively, and 21 cm images from the NVSS survey (Condon et al. 1998) with MRS of up to 10–15 arcmin. This was the first attempt to establish a *direct connection* between the UC H II regions and the large-scale extended emission (EE), which appears as an arcminute scale common structure of ionized gas embracing

\* E-mail: edfuente@gmail.com

† Research Associated at ‘HAWC’ Gamma-Ray National Laboratory (CONACYT).

‡ Research stay at National Astronomical Observatory of Japan (NAOJ), Tokyo, Japan, (2018).

the UC H II region. By comparing the emission distributed over spatial scales of several arcminutes, they found a common structure in eight UC H II regions from a randomly selected sample of 15 sources ( $\sim 53$  per cent) from the Kurtz et al. (1994) survey. The confirmation of a direct connection between the UC emission and the EE may impact on UC H II region definition, modelling, lifetime problem, and energetics. As Kurtz et al. (1999) indicate, if this connection is demonstrated, the EE would require about 10–20 times more Lyman photons to keep its ionization than the UC emission would require.

For example, Wood & Churchwell (1989) and Kurtz et al. (1994) noted that the *IRAS* fluxes correspond to a stellar content producing more Lyman continuum photons than is suggested by the radio flux. They explained this disparity by assuming that some fraction of the ionizing photons is absorbed by dust, and/or by the possible presence of a cluster of later-type stars, contributing to the infrared (IR) luminosity but not to the Lyman continuum flux. If Wood & Churchwell (1989) and Kurtz et al. (1994) underestimated the Lyman photon flux as of result of their insensitivity to large-scale structures (i.e. EE) then the need for dust/clusters to explain the IR/radio disparity may have been substantially overestimated.

This work aims to compile a larger catalogue of UC H II regions + EE (UC H II + EE) and to determine the significance of the EE for our understanding of the energetics of these regions. Thus, in this paper we present a radio continuum (RC) morphological study using VLA observations of a sample of UC H II regions with EE in order to: (i) compare new 3.6 cm VLA images taken in the configuration D with a sample of sources from Kim & Koo (2001) to find (or confirm) the presence of UC H II + EE regions; (ii) compare new 3.6 cm VLA images taken in the configuration C with previously published images taken in configuration B and D to probe if the EE has a direct connection with the UC H II region. To do this, we use a multiresolution image (MRI) combination method, which we propose to be a technique that works better than the one used by Kurtz et al. (1999) to search for common and continuous structures at several scales; (iii) explain how the presence of EE can impact the IR excess problem; and (iv) enlarge the catalogue of UC H II + EE regions.

In Section 2, we describe the VLA observations, calibration, and data reduction process. The VLA low-resolution morphological study and *Spitzer* counterparts imagery discussion are presented in Section 3, while a short individual source description is given in Section 4. The discussion of how the presence of EE can resolve the problem of IR excess is presented in Section 5. Conclusions are given in Section 6.

## 2 OBSERVATIONS AND DATA REDUCTION

### 2.1 The sample

The sources targeted in our VLA observations were selected according to the following criteria: (i) following Wood & Churchwell (1989) and Kurtz et al. (1994), the sources must exhibit UC H II region colours with IR excess in their *IRAS* fluxes and (ii) the sources must have EE associated with the UC H II region in either Kurtz et al. (1999, 3.6 cm VLA configuration D) or Kim & Koo (2001, 21 cm VLA configuration DnC) observations. The resulting sample consists of 28 UC H II + EE regions and they are listed in Table 1. Additionally, most of the targeted sources have *Spitzer*-IRAC (Fazio et al. 2004) and MIPS (Rieke et al. 2004) 24  $\mu$ m data from GLIMPSE and MIPS GAL surveys (Churchwell et al. 2009). It is worth noting that two of the UC H II regions seemed not to show a direct connection with the observed EE, thus we propose two other

RC peaks to be those the associated with the UC H II regions: i.e. G23.44–0.21 instead of G23.46–0.20, and G25.71+0.04 instead of G25.72+0.05. The proposed new UC H II + EE regions are listed in Table 1 and they are discussed in more detail in Section 4.3.

### 2.2 Observations

Snapshot-mode interferometric observations were carried out with the VLA of the National Radio Astronomy Observatory (NRAO) in the C and D configurations. Continuum emission at 3.6 cm was observed in the C configuration (VLA-C) on 1998 December 1st and 13th, and in the D configuration (VLA-D) on 2005 April 3rd. The total on-source integration times were  $\sim 9.5$  min for the VLA-C observations and  $\sim 15$  min for the VLA-D observations. The total spectral bandwidth was  $\Delta\nu = 50$  MHz for all the observations. As mentioned above, a total of 28 regions were targeted, of which 15 were observed with the VLA-D, 12 with the VLA-C, and one source was observed in both configurations. The absolute flux calibrator 3C 286 (with an assumed flux of 5.23 Jy) was used for all the observations and the quasars J2322+509 (1.60 Jy), J2015+371 (2.95 Jy), J1922+155 (1 Jy), J1832–105 (1.28 Jy) were used as phase calibrators. The image noise level (rms), parameters of the resulting synthesized beams, and the integrated flux densities of the UC H II regions associated with EE are given in Table 2. In addition, for those sources observed with the VLA-C, images in the configurations B and D were produced using archival data from Kurtz et al. (1994) and Kurtz et al. (1999), respectively, which allowed us to perform MRI combination.<sup>1</sup>

### 2.3 Data reduction

The data were calibrated and reduced with the package aips of the NRAO following standard procedures. All the images were self-calibrated in phase in order to improve the signal-to-noise ratio. In order to optimize the compromise between angular resolution and sensitivity, we created the images setting the robust parameter robust = 0 (see Briggs 1995), resulting in an angular resolution ranging from  $\sim 2$  to 9 arcsec, which allowed us to detect emission distributed over angular scales up to  $\sim 3$  arcmin. Each observational run was calibrated independently and then combined using the aips task dbcon. Finally, the multiresolution clean algorithm (Wakker & Schwarz 1988) was used to obtain the final MRIs by combining the configuration C data with the data of configurations B (Kurtz et al. 1994) and D (Kurtz et al. 1999). The parameters of the synthesized beam and noise levels of the resulting images are listed in Table 3.

## 3 MORPHOLOGICAL STUDY

### 3.1 Relation between UC H II region and the extended emission

The RC images of the 15 regions taken in the VLA-D at 3.6 cm are shown in Fig. 1. A comparison between the VLA-D 3.6 cm images with those at 21 cm from Kim & Koo (2001) reveals that the emission has a similar morphology, albeit at a different angular scale (MRS of 3 and 15 arcmin, respectively). Therefore, as discussed in Kurtz et al. (1999) and Kim & Koo (2001), these sources are considered to be systems composed of an UC H II region and EE.

<sup>1</sup>For three sources, data from only one of those two configurations were available in the archive.

**Table 1.** The sample of 28 ultracompact H II regions with extended emission.

UC H II region	IRAS source	RA <sup>a</sup> (J2000)	Dec. (J2000)	Distance <sup>b</sup> (kpc)
G05.48–0.24	17559–2420	17 <sup>h</sup> 59 <sup>m</sup> 02 <sup>s</sup> .9	–24°20′54″.5	14.3 <sup>(1)</sup>
G05.97–1.17	18006–2422	18 03 40.51	–24 22 44.4	2.7 <sup>(2)</sup>
G10.30–0.15	18060–2005	18 08 56.11	–20 05 53.8	6.0 <sup>(3)</sup>
G12.21–0.10	18097–1825A	18 12 39.72	–18 24 20.5	13.5 <sup>(2)</sup>
G18.15–0.28	18222–1321	18 25 01.08	–13 15 39.3	4.2 <sup>(3)</sup>
G19.60–0.23	18248–1158	18 27 38.11	–11 56 39.5	3.5 <sup>(2)</sup>
G23.71+0.17	18311–0809	18 33 53.54	–08 07 13.8	8.9 <sup>(2)</sup>
G23.46–0.20 <sup>c</sup>	18319–0834	18 34 44.92	–08 31 07.4	9.0 <sup>(1)</sup>
G25.72+0.05 <sup>c</sup>	18353–0628	18 38 02.80	–06 23 47.4	9.3 <sup>(2)</sup>
G28.20–0.05	18402–0417	18 42 58.08	–04 14 04.6	9.1 <sup>(3)</sup>
G31.39–0.25	18469–0132	18 49 33.04	–01 29 03.7	8.9 <sup>(5)</sup>
G33.13–0.09	18496+0004	18 52 07.96	+00 08 11.6	7.1 <sup>(6)</sup>
G35.58–0.03	18538+0216	18 56 22.52	+02 20 27.0	3.6 <sup>(6)</sup>
G37.55–0.11	18577+0358	19 00 16.02	+04 03 15.1	9.9 <sup>(2)</sup>
G35.20–1.74	18592+0108	19 01 46.49	+01 13 24.7	3.3 <sup>(6)</sup>
G37.87+0.40	18593+0408	19 01 53.62	+04 12 49.0	9.3 <sup>(6)</sup>
G43.24–0.04	19081+0903	19 10 33.52	+09 08 25.1	11.7 <sup>(4)</sup>
G45.07+0.13	19110+1045	19 13 22.08	+10 50 53.4	6.0 <sup>(6)</sup>
G45.12+0.13	19111+1048	19 13 27.85	+10 53 36.7	6.0 <sup>(6)</sup>
G45.45+0.06	19120+1103	19 14 21.40	+11 09 14.1	6.0 <sup>(6)</sup>
G48.61+0.02	19181+1349	19 20 30.95	+13 55 26.7	9.8 <sup>(6)</sup>
G54.10–0.06	19294+1836	19 31 42.22	+18 42 51.6	7.9 <sup>(1)</sup>
G60.88–0.13	19442+2427	19 46 20.13	+24 35 29.4	2.2 <sup>(6)</sup>
G78.44+2.66	20178+4046	20 19 39.22	+40 56 36.6	3.3 <sup>(3)</sup>
G77.96–0.01	20277+3851	20 29 36.72	+39 01 21.9	4.4 <sup>(5)</sup>
G106.80+5.31	22176+6303	22 19 18.23	+63 18 47.5	0.9 <sup>(5)</sup>
G111.61+0.37	23133+6050	23 15 31.16	+61 07 12.9	5.2 <sup>(3)</sup>
G111.28–0.66	23138+5945	23 16 03.94	+60 02 00.9	2.5 <sup>(3)</sup>

<sup>a</sup>Right ascension (RA) and Declination (Dec.) were precessed from 1950 coordinates of Wood & Churchwell (1989) and Kurtz et al. (1994) papers. Sources are ordered by increasing RA.

<sup>b</sup>Distance values are from: (1) Wood & Churchwell (1989); (2) Churchwell, Walmsley & Cesaroni (1990); (3) Kurtz et al. (1994); (4) Watson et al. (1997); (5) Kurtz et al. (1999); (6) Araya et al. (2002).

<sup>c</sup>These sources were previously catalogued as UC H II regions (Kim & Koo 2001), but other peaks in our RC images (Fig. 1) seem to be associated with the EE: G23.44–0.21 instead of G23.46–0.20, and G25.69+0.03 instead of G25.72+0.05. See Section 4.2 for details.

Fig. 2 shows images at 3.6 cm taken in the VLA-C and their respective MRIs obtained after combining data from the available configurations (see Table 3 for details). If the multiconfiguration image shows that the UC emission is completely embedded within the EE, there is a strong indication that both emissions are directly connected. A good example of such a case is G35.20–1.74. The emission of this source exhibits an extended smoothly distributed morphology in the VLA-D image (Fig. 1), as well as in its VLA-C and VLA-(B + C + D) images (Fig. 2). This way of determining the direct connection between UC H II region and the EE is more robust than the simple inspection made by Kurtz et al. (1999) because if there is emission filtered out in the observation of one configuration, the MRIs can reveal the association. It is important to remark that Kurtz et al. (1999) and Kim & Koo (2001) discarded UC H II + EE candidates due to the emission not being continuous, our observations recovered the missing emission for those sources and the connection between UC H II region and the EE was revealed. Following this technique, we completely ruled out nine candidate sources, marked with ‘no’ or ‘unlikely’ labels by Kim & Koo (2001) and Kurtz et al. (1999) (see Table 4). The criterion to rule out these candidates was that they exhibit a clearly disconnected distribution between the UC emission and the EE. An example of this kind of

behaviour is G48.61+0.02; although it has continuous EE on its VLA-D image (see fig. 7 of Kurtz et al. 1999), this behaviour is not observed either on the VLA-C or on VLA-BCD images (Fig. 2), confirming the conclusions of Kurtz et al. (1999). All discarded sources are presented and commented in Section 4.3. Our results on direct connection between UC and EE emissions are summarized in Table 4.

We perform a morphological classification similar to that proposed by Wood & Churchwell (1989), based on shapes from RC emission. According to them, morphological types are: I = spherical (or unresolved), II = cometary (parabolic), III = core halo, IV = shell, V = irregular (or multiply peaked). Based on Figs 1 and 2 of VLA emission at 3.6 cm, we associate a morphological type to each source (see Table 4). We find that cometary type is dominant in our sample (43 per cent), morphological types spherical and irregular coincide in number (21.5 per cent), while the least favoured types are core halo (16 per cent) and shell (0 per cent).

The RC morphology presented in this work traces ionized gas and matches the observed IRAC morphology (see Section 3.2), where dust and Polycyclic aromatic hydrocarbons (PAHs) features on the cometary arcs are clearly observed and could be related to photodissociated regions (PDRs; Hollenbach & Tielens 1997). It



**Table 2.** VLA observational parameters and UC H II fluxes.

UC H II region	IRAS source	VLA <sup>a</sup> configuration	S <sub>v</sub> <sup>b</sup> Jy	Beam size (arcsec)	PA (deg)	rms (mJy beam <sup>-1</sup> )
G05.48−0.24	17559−2420	D	1.18	14.03 × 7.22	−13	0.07
G05.97−1.17	18006−2422	D	8.06	14.07 × 6.90	−12	0.47
G10.30−0.15	18060−2005	D	5.80	12.57 × 6.98	−12	0.35
G12.21−0.10	18097−1825A	D	1.30	12.50 × 7.30	−13	0.15
G18.15−0.28	18222−1321	D	4.20	11.52 × 7.80	−14	0.10
G19.60−0.23	18248−1158	B	2.84	1.05 × 0.76	9	0.40
		D	4.33	11.28 × 7.89	5	1.50
G23.71+0.17	18311−0809	D	1.49	10.61 × 7.72	−17	0.07
G23.44−0.21 <sup>c</sup>	18319−0834	D	1.16	10.70 × 8.22	−15	0.09
G25.71+0.04 <sup>c</sup>	18353−0628	D	0.68	10.93 × 7.80	−11	0.09
G28.20−0.05	18402−0417	D	0.48	9.60 × 7.87	−08	0.06
G31.39−0.25	18469−0132	B	0.04	0.98 × 0.73	−26	0.05
		C	0.65	3.05 × 2.36	−12	0.08
		D	0.65	9.81 × 7.83	13	0.15
G33.13−0.09	18496+0004	B	0.45	0.92 × 0.74	−29	0.15
		C	0.54	2.82 × 2.37	−14	0.15
		D	0.55	9.44 × 7.93	16	1.80
G35.20−1.74	18592+0108	B	2.57	0.87 × 0.83	17	0.90
		C	10.96	2.85 × 2.40	−19	0.70
		D	11.31	9.85 × 7.80	−2	2.00
G35.58−0.03	18538+0216	B	0.10	0.86 × 0.73	−20	0.07
		C	0.69	2.76 × 2.34	−13	0.14
		D	0.85	9.12 × 7.89	18	0.25
G37.55−0.11	18557+0358	D	0.93	8.79 × 7.79	−12	0.07
G37.87+0.40	18593+0408	B	2.85	0.95 × 0.79	34	0.47
		C	4.05	2.02 × 1.86	−14	0.30
		D	4.11	9.00 × 7.70	6	0.50
G43.24−0.04	19081+0903	B	0.18	0.78 × 0.69	7	0.15
		C	0.70	2.61 × 2.31	−14	0.28
		D	0.73	8.57 × 6.43	7	0.90
G45.07+0.13	19110+1045	D	0.73	8.36 × 7.67	−18	0.30
G45.12+0.13	19111+1048	D	1.80	8.36 × 7.67	−18	0.30
G45.45+0.06	19120+1103	D	4.50	8.23 × 7.63	−25	0.40
G48.61+0.02	19181+1349	B	0.05	0.90 × 0.76	48	0.05
		C	0.82	2.48 × 2.49	−10	0.20
		D	1.64	8.63 × 7.57	24	0.70
G54.10−0.06	19294+1836	D	0.52	8.78 × 7.77	−24	0.06
G60.88−0.13	19442+2427	B	0.09	0.74 × 0.68	−14	0.08
		C	0.49	2.42 × 2.26	4	0.06
G77.96−0.01	20277+3851	B	0.08	1.65 × 1.65	−45	0.07
		C	0.60	2.47 × 2.28	22	0.07
		D	0.95	7.71 × 7.42	21	0.10
G78.44+2.66	20178+4046	B	0.03	0.79 × 0.66	−58	0.05
		C	0.07	1.92 × 1.75	30	0.08
		D	0.07	7.77 × 7.39	−3	0.06
G106.80+5.31	22176+6303	B	0.03	0.86 × 0.61	−46	0.05
		C	0.02	9.15 × 7.28	53	0.05
G111.28−0.66	23138+5945	B	0.05	0.86 × 0.62	−46	0.05
		C	0.25	3.41 × 2.11	75	0.06
		D	0.30	9.33 × 7.34	61	0.06
G111.61+0.37	23133+6050	B	0.27	0.92 × 0.86	14	0.65
		C	0.93	3.32 × 2.11	70	0.07
		D	0.97	9.29 × 7.36	59	0.20

<sup>a</sup>For those sources observed with the VLA configuration C, VLA configurations B and D images were recreated using data from Kurtz et al. (1994) and Kurtz et al. (1999), respectively.

<sup>b</sup>UC H II integrated flux densities were obtained using suitable boxes covering the whole RC emission above 3 times the noise level.

<sup>c</sup>These sources are proposed to be related to the EE. See Section 4.2 for details.

is important to remark that the IRAC morphology at mesoscales, avoiding the spatial filter produced by interferometers at large scales, is in agreement with the RC morphology presented in this work; supporting results are shown in Tables 4 and 5.

Kim & Koo (2001, 2002, 2003) suggest a model to explain the origin of EE considering the hierarchical structure of molecular clouds and a champagne flow from one or more ionizing sources (see their fig. 8). The density gradient expansion that generates

**Table 3.** Combined multiconfiguration VLA image parameters.

UC H II region	<i>IRAS</i> <sup>a</sup> source	VLA configurations <sup>b</sup>	Beam size (arcsec)	PA (deg)	rms (mJy beam <sup>-1</sup> )
G19.60–0.23 <sup>c</sup>	18248–1158	BD	$1.05 \times 0.76$	9	0.360
G31.39–0.25	18469–0132	BCD	$0.98 \times 0.73$	–26	0.045
G33.13–0.09	18496+0004	BCD	$0.92 \times 0.74$	–29	0.065
G35.58–0.03	18538+0216	BCD	$0.86 \times 0.73$	–20	0.070
G35.20–1.74	18592+0108	BCD	$0.87 \times 0.83$	17	0.300
G37.87+0.40	18593+0408	BCD	$0.95 \times 0.79$	34	0.300
G43.24–0.04	19081+0903	BCD	$0.78 \times 0.69$	7	0.400
G48.61+0.02	19181+1349	BCD	$0.90 \times 0.76$	48	0.270
G60.88–0.13	19442+2427	BC	$0.74 \times 0.68$	–14	0.060
G78.44+2.66	20178+4046	BCD	$0.79 \times 0.66$	–58	0.055
G77.96–0.01	20277+3851	BCD	$1.65 \times 1.65$	–45	0.100
G106.80+5.31	22176+6303	BC	$0.86 \times 0.61$	–46	0.050
G111.61+0.37	23133+6050	BCD	$0.92 \times 0.86$	14	0.040
G111.28–0.66	23138+5945	BCD	$0.86 \times 0.62$	–46	0.060

<sup>a</sup>UC H II regions are ordered by *IRAS* name.<sup>b</sup>VLA configurations combined to produce the MRIs.<sup>c</sup>The MRI of G19.60–0.23 is not shown in Fig. 2 but is shown superimposed on the *Spitzer* image in Fig. 3.

EE in a natural way in compact regions is described by Franco, Tenorio-Tagle & Bodenheimer (1990). However, in most of the sources that we study in this work the IRAC 8  $\mu\text{m}$  emission seems to be surrounding the MIPS 24  $\mu\text{m}$  and RC emission, which can be more easily interpreted as originating in a bubble as described by Churchwell et al. (2006). Although, it is important to point out that without information of the kinematics of the ionized gas and density field of the ambient medium we cannot completely rule out the Kim & Koo’s champagne model, at least not for all the sources under study in this work. A champagne-like flow scenario could be tested source-by-source having the respective molecular and kinematical data.

For completeness and comparison to our sample, the sources with IRAC bubble structures from Churchwell et al. (2006) are indicated in Table 4. Three quarters of the bubbles in Churchwell et al. (2006) are associated with B4–B9 stars (too cool to produce detectable radio H II regions), while the others are produced by young OB3 stars with detectable radio H II regions. They suggest that bubbles that overlap known H II regions are produced by stellar winds and radiation pressure from young OB stars in massive star formation regions.

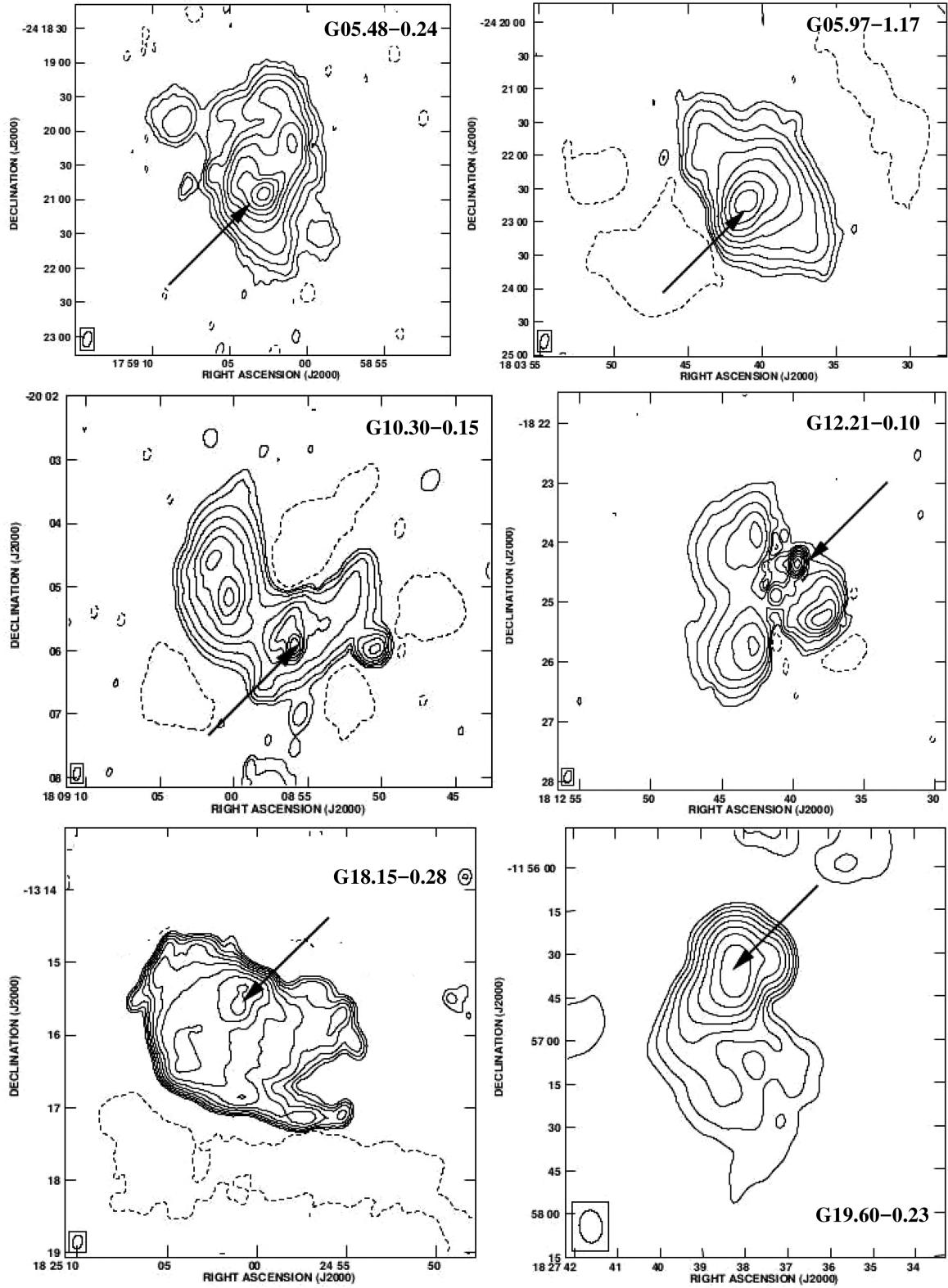
In summary, based on the morphology of RC emission images at 3.6 cm, for the 28 objects in the original sample (Table 1), 9 are discarded as UC H II + EE regions (‘N’ at fourth column in Table 4) resulting in 19 sources confirmed plus 2 new sources (G23.44–0.21 and G25.69+0.03) giving a final catalogue of 21 UC H II + EE regions listed in Table 5. This table also includes observed EE sizes and the number of RC emission peaks. The average EE size in these sources is  $4.9 \pm 3.1 \text{ arcmin}^2$ . The RC peaks could be associated with independent UC H II regions or IR sources, and the EE related to cometary-like shapes at large scales can be the bubble-like structures described by Churchwell et al. (2006), de La Fuente et al. (2009a), and Phillips & Ramos-Larios (2008) with PDRs on the cometary arcs and where dust, ionized gas, and a possible stellar cluster coexist.

### 3.2 *Spitzer* IRAC and 24 $\mu\text{m}$ (MIPS) emissions

Churchwell et al. (2006, 2007) looking at the IRAC 3.6, 4.5, 5.8, and 8.0  $\mu\text{m}$  bands (Benjamin et al. 2003; Fazio et al. 2004)

from the GLIMPSE *Spitzer* and Ancillary Data (Benjamin et al. 2003; Churchwell et al. 2009), found and catalogued nearly 600 IR ‘bubbles’ around OB stars in the galaxy. Later, using 24  $\mu\text{m}$  diffuse emission sources from MIPS GAL, Carey et al. (2009) and Bania et al. (2010) found similar structures with spatially coincident 21 cm continuum emission. They discovered several hundreds of new Galactic H II regions, including those associated with Churchwell et al. (2006) bubbles.

IRAC images are dominated by PAHs at 3.3, 6.2, and 7.7  $\mu\text{m}$  (Li & Draine 2001), where the strongest emission is observed at 8.0  $\mu\text{m}$  (Churchwell et al. 2006). This band traces knots-like sources that could be either star clusters or externally illuminated condensations. The 5.8  $\mu\text{m}$  band is considered a good dust tracer (Churchwell et al. 2004) while the 4.5  $\mu\text{m}$  band, free of dust and PAHs emission, traces ionized gas from Br  $\alpha$  and shocked emission (Cyganowski et al. 2008). The 3.6  $\mu\text{m}$  band also shows the presence of stellar clusters and both ionized and reflection nebulosities (Flagey et al. 2006; Smith et al. 2006). Therefore, GLIMPSE images are particularly helpful in identifying bubbles as emission from PAHs at 8.0  $\mu\text{m}$ , and to detect bubble rims (Simpson et al. 2012). The MIPS 24  $\mu\text{m}$  emission associated with warm dust is commonly observed located within the bubble and with the morphology that closely traces the RC emission (Churchwell et al. 2006; Watson et al. 2008; Watson, Hanspal & Mengistu 2010; Simpson et al. 2012). Such bright 24  $\mu\text{m}$  and RC emissions are frequently surrounded by shells traced by intense 8.0  $\mu\text{m}$  emission in giant Galactic H II regions and extragalactic star-forming regions (e.g. Povich et al. 2007; Bendo et al. 2008; Relaño & Kennicutt 2009; Flagey et al. 2011). Considering the latter, Simpson et al. (2012) catalogued 5106 bubbles using RGB images (red = 24  $\mu\text{m}$ , green = 8.0  $\mu\text{m}$ , and blue = 4.5  $\mu\text{m}$ ) finding red emission surrounded by green rims or spherical-type shapes. Phillips & Ramos-Larios (2008) imaged 58 compact H II regions using only IRAC bands. They show these sources as isolated entities within larger star-forming regions, many of them with similar structures consisting of spheroidal shells with narrow emission rims, and in many cases, attached to filaments and haloes, that are particularly evident within the 5.8 and 8.0  $\mu\text{m}$  bands. In this direction, an IRAC-*Spitzer* study of several UC H II + EE regions (many of them listed in Table 1), including IRAC photometry, is reported by de La Fuente et al. (2009b). In



**Figure 1.** Images at 3.6 cm of the 15 UC H II + EE regions observed in the VLA-D. The contour values are integer multiples of  $-3$  and  $3$  times the image noise level ( $\text{mJy beam}^{-1}$ ), which is listed in Table 2. The solid arrows indicate the position of the UC H II region associated with the EE from previous works. For two regions (G23.46 $-0.20$  and G25.72 $+0.05$ ), a dashed arrow indicates the position of the new UC H II region proposed in this work to be associated with the EE. See Section 4.2 for details.

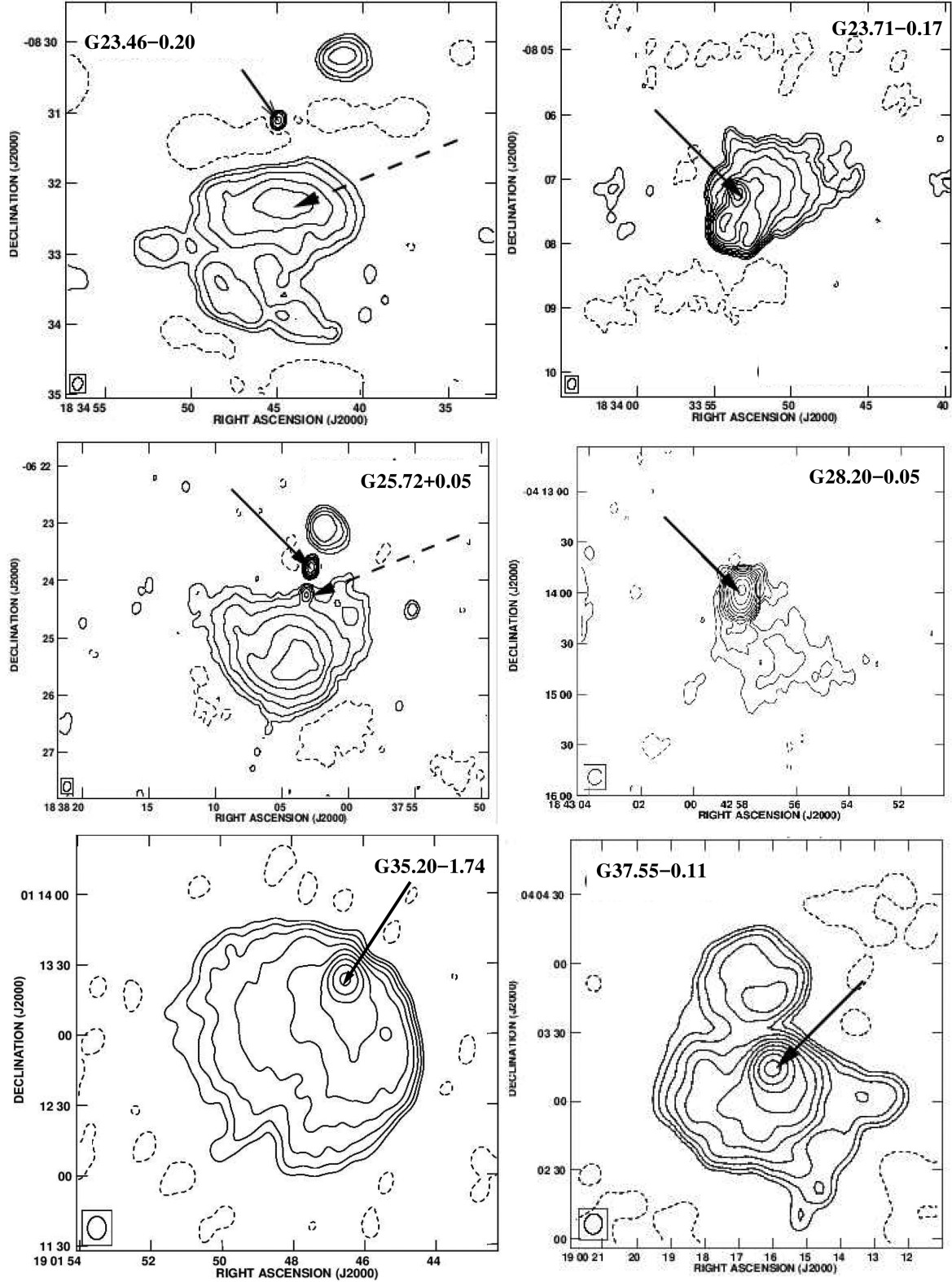


Figure 1 – continued

this study, it was found that the observed EE looks similar to the ‘bubbles’ detected by Churchwell et al. (2006), and heated dust (traced by 5.8 and 8.0  $\mu\text{m}$  bands, Flagey et al. 2006; Smith et al. 2006; Kumar & Grave 2007) coexists with ionized gas (traced by

4.5  $\mu\text{m}$  band, Cyganowski et al. 2008) and star clusters (traced by 3.6  $\mu\text{m}$  band, Flagey et al. 2006; Smith et al. 2006).

The morphology of the studied sources in all IRAC bands is similar but increasing in intensity from 3.6 to 8.0  $\mu\text{m}$ . Also, a visual



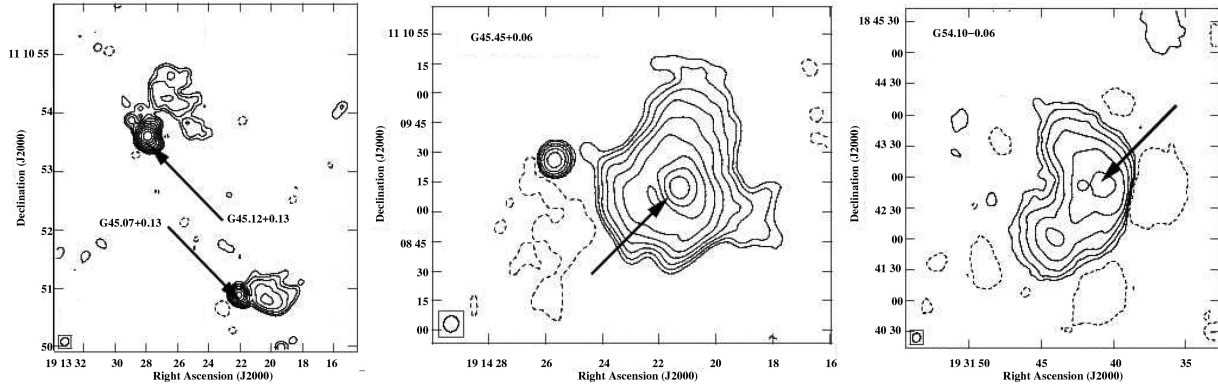


Figure 1 – continued

Table 4. Results from morphological study of extended emission.

UC H II	EE <sup>a</sup>	Direct connection <sup>a</sup>		EE size <sup>b</sup> approx (arcmin <sup>2</sup> )	RC	Morphological	Spitzer bubble		
region		previous	this work		peaks	type <sup>c</sup>	Ch06/Ch07 <sup>d</sup>	Simp12 <sup>e</sup>	this work
G05.48–0.24	Y	Y (1)	Y	3.0 × 2.0	5	III	Y	Y	Y
G05.97–1.17	Y	Y (3)	Y	3.5 × 2.0	1	II	N	N	Y
G10.30–0.15	Y	Y (3)	Y	4.0 × 1.5	5	V	Y	Y	Y
G12.21–0.10	Y	Y (3)	Y	4.0 × 3.0	5	V	N	Y	Y
G18.15–0.28	Y	–	Y	2.0 × 4.0	2	II	Y	N	Y
G19.60–0.23	Y	–	Y	0.8 × 2.0	5	II	N	Y	Y
G23.44–0.21	Y	–	Y	2.0 × 2.0	1	II	N	Y	Y
G23.71+0.17	Y	Y (3)	Y	2.0 × 2.0	1	II	Y	Y	Y
G25.69+0.03	Y	–	Y	3.0 × 4.0	2	II	Y	N	Y
G28.20–0.05	Y	–	N	1.5 × 1.0	1	III	Y	N	Y
G31.39–0.25	Y	P (2)	Y	2.5 × 1.5	2	V	Y	Y	P
G33.13–0.09	Y	U (2)	N	0.5 × 0.5	1	I	Y	N	N
G35.20–1.74	Y	–	Y	2.0 × 2.0	1	II	N	N	N
G35.58–0.03	Y	U (2)	N	2.0 × 2.0	1	I	Y	N	Y
G37.55–0.11	Y	Y (3)	Y	2.0 × 2.0	2	III	N	Y	Y
G37.87+0.40	Y	P (2)	Y	2.0 × 0.5	1	II	Y	N	N
G43.24–0.04	N	N (2)	N	0.5 × 0.5	1	II	N	N	N
G45.07+0.13	Y	–	Y	1.0 × 1.0	1	I	Y	Y	Y
G45.12+0.13	Y	–	P	1.5 × 1.5	1	I	N	Y	Y
G45.45+0.06	Y	–	Y	2.0 × 2.0	1	III	N	N	Y
G48.61+0.02	Y	P (2)	N	2.0 × 1.5	3	V	Y	Y	N
G54.10–0.06	Y	–	Y	3.0 × 2.0	2	II	Y	Y	Y
G60.88–0.13	Y	P (2)	Y	1.0 × 3.0	1	II	Y	Y	Y
G77.96–0.01	Y	P (2)	Y	2.0 × 3.0	2	V	N	N	N
G78.44+2.66	Y	U (2)	N	0.3 × 0.3	1	I	N	N	N
G106.80+5.31	Y	U (2)	N	1.0 × 1.0	2	V	N	N	N
G111.28–0.66	Y	P (2)	Y	2.5 × 2.5	2	II	N	N	N
G111.61+0.37	N	N (2)	N	2.5 × 2.5	2	I	N	N	N

<sup>a</sup>Y = yes, N = no, P = possible, U = unlikely, in previous works according to: (1) Koo et al. (1996), (2) Kurtz et al. (1999), and (3) Kim & Koo (2001).

<sup>b</sup>Presence of EE considering continuum images at arcmin scales with VLA-D configuration. EE size was obtained fitting a box to the contour of lower value on 3.6 cm maps.

<sup>c</sup>Morphological type according Wood & Churchwell (1989): I = spherical (or unresolved), II = cometary (parabolic), III = core halo, IV = shell, V = irregular (or multiply peaked).

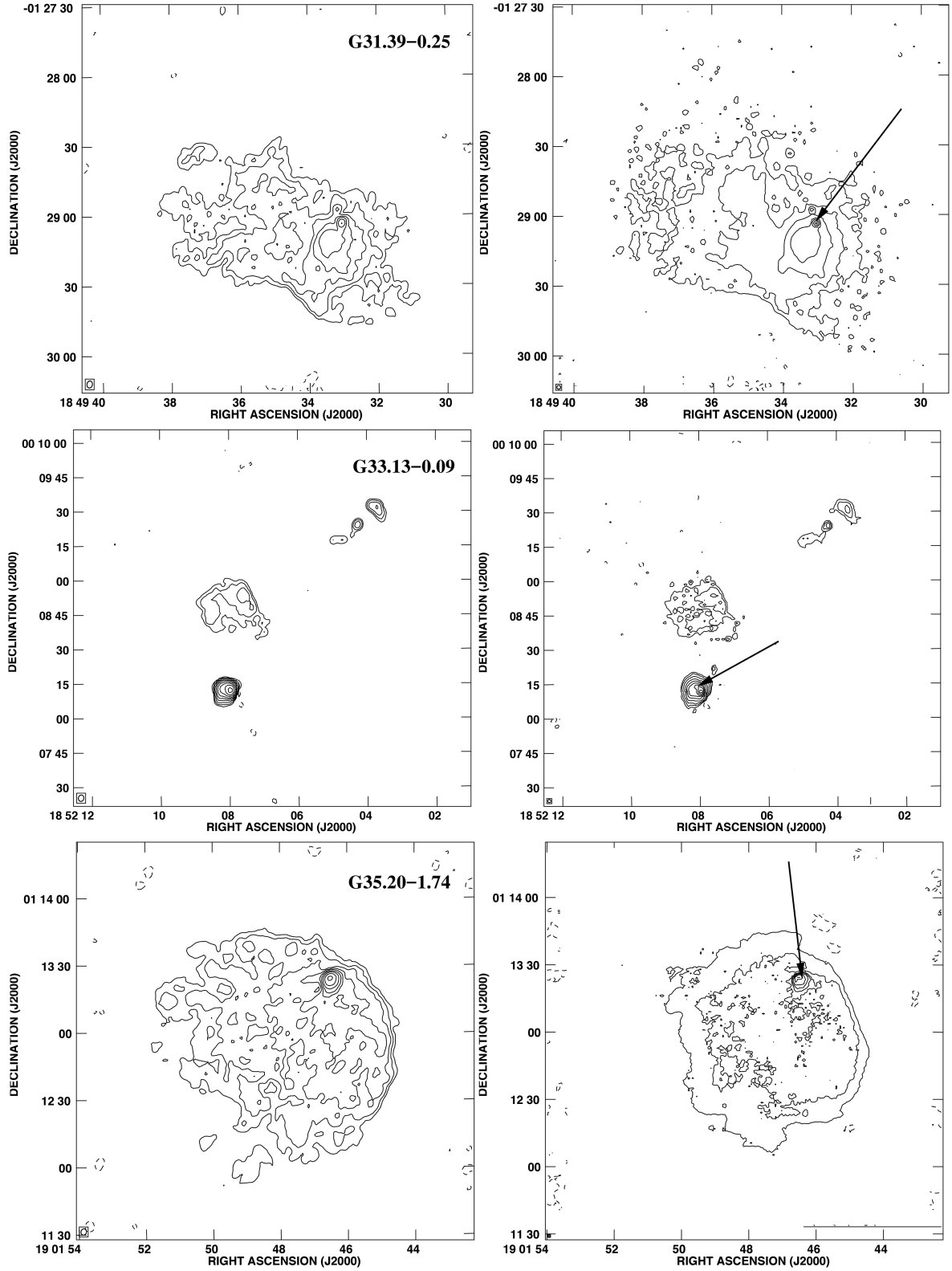
<sup>d</sup>Presence of Bubble-like structures from IRAC images according to Churchwell et al. (2006, 2007).

<sup>e</sup>Presence of Bubble-like structures from IRAC and MIPS images according to Simpson et al. (2012).

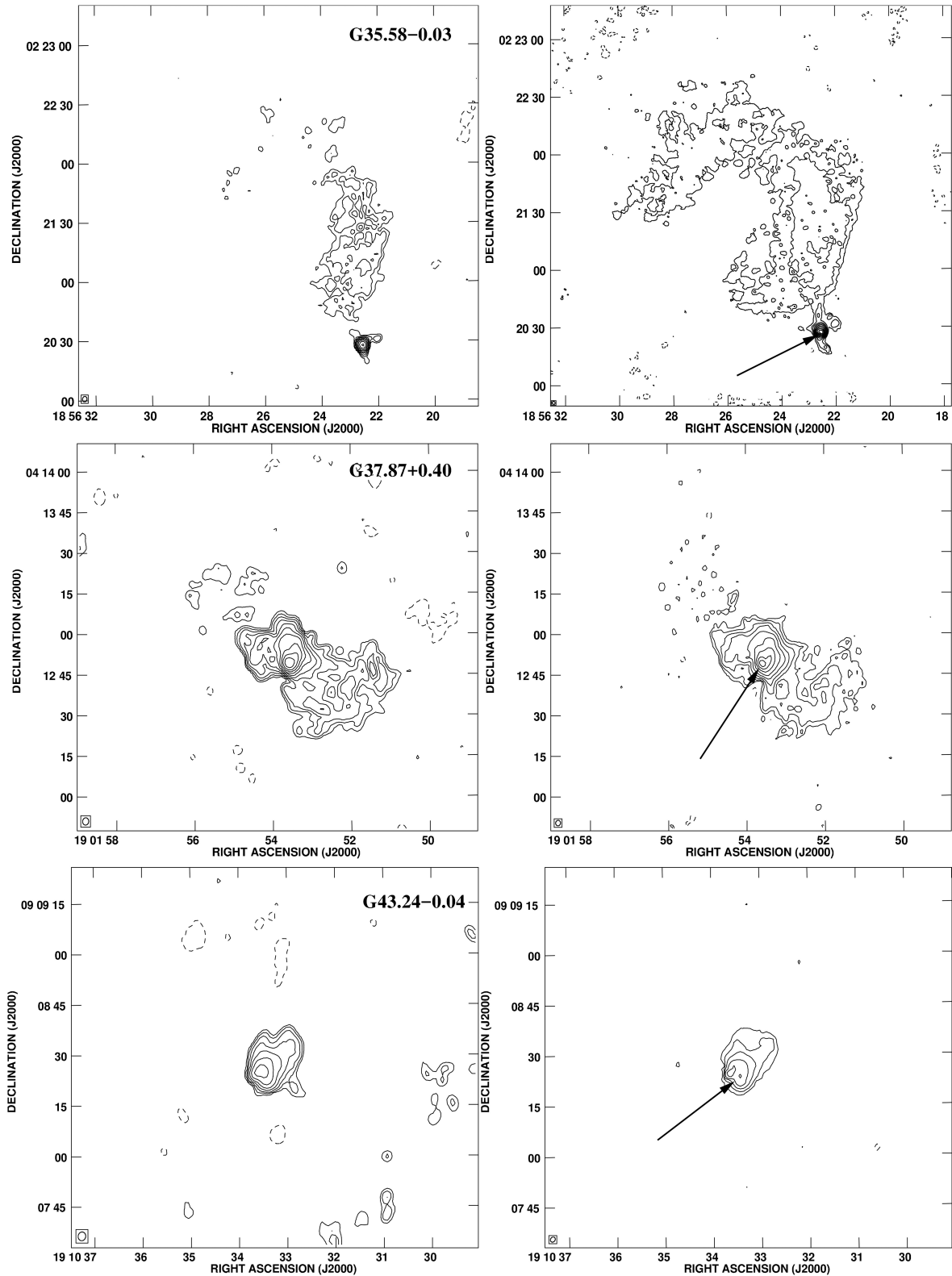
inspection of these sources in the 24  $\mu$ m band shows saturation at the position of all the UC H II peaks, except for G12.21–0.10, suggesting that this MIPS band is useful to locate candidate UC H II + EE regions. In these UC H II + EE regions, the 24  $\mu$ m emission is more intense than in the brightest IRAC band (8.0  $\mu$ m) indicating the presence of relatively cool dust.

Spitzer RGB images (red = 24  $\mu$ m, green = 8.0  $\mu$ m, and blue = 4.5  $\mu$ m) of all UC H II + EE regions in our catalogue are shown in Fig. 3. These images show a similar behaviour to that noted by Simpson et al. (2012, and references therein): the MIPS emission clearly coincides with the VLA RC emission and green (8.0  $\mu$ m) rims surround them. The 8.0  $\mu$ m emission traces very





**Figure 2.** New VLA-C configuration images at 3.6 cm (*left*) and the MRIs combining available B, C, and D VLA configuration images at 3.6 cm (*right*), as specified in Table 3. The contour values are integer multiples of  $-3$  and  $3$  times the image noise level ( $\text{mJy beam}^{-1}$ ) listed in Table 2 and Table 3, respectively. The solid arrows show the position of the UC H II regions.

Figure 2 – *continued*

well the cometary arcs observed in RC. The cometary arcs could be PDRs with PAHs (Hollenbach & Tielens 1997; Díaz-Miller, Franco & Shore 1998; Tielens et al. 2004; Peeters et al. 2005, and references therein), but H I observations are needed to confirm

their PDR nature. It is clear that *Spitzer* images are good to find structures at mesoscales with better resolution than RC, and the saturated position of the UC H II regions is in agreement with the idea that UC H II regions are the brightest objects in the Galaxy

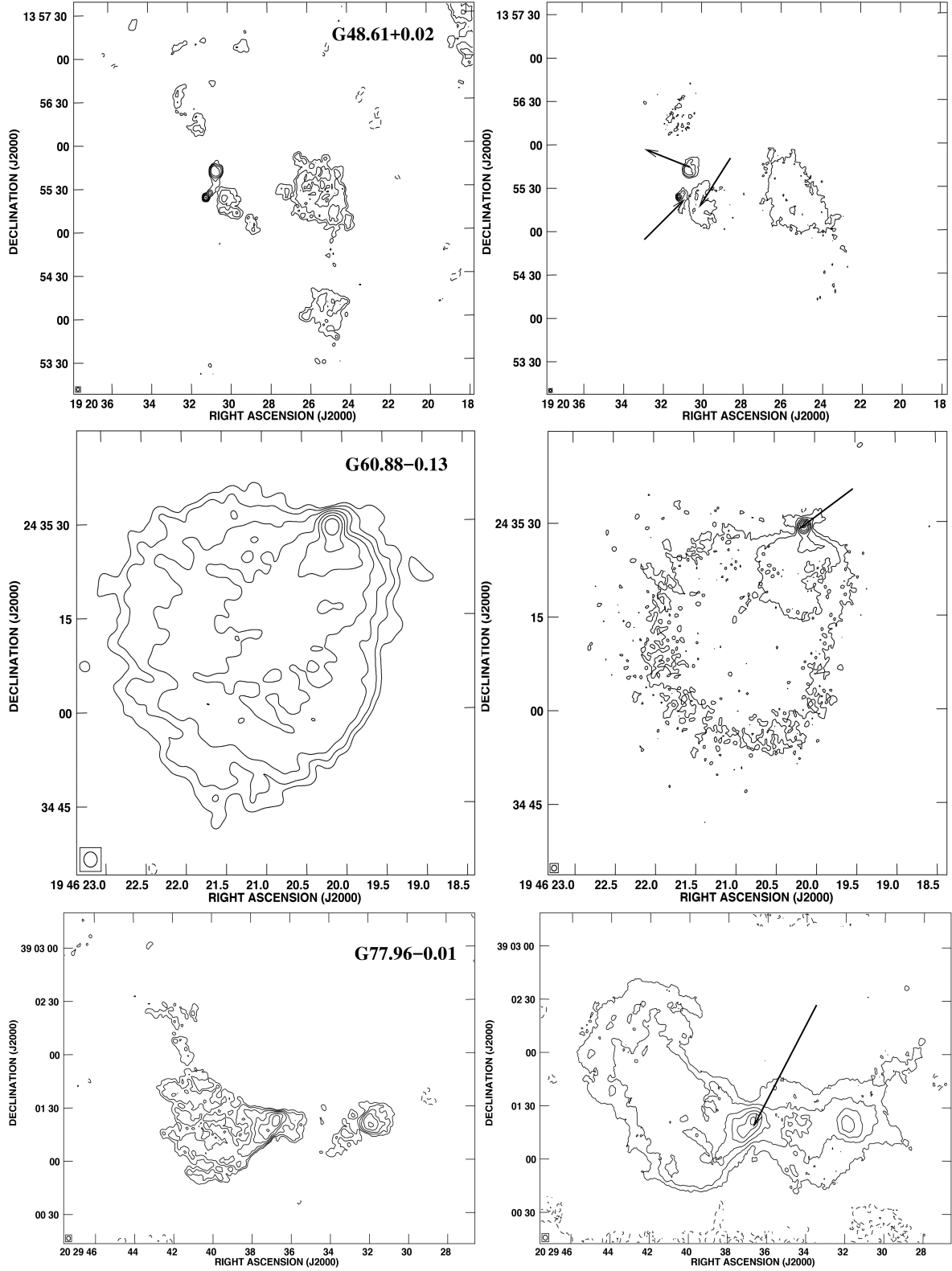
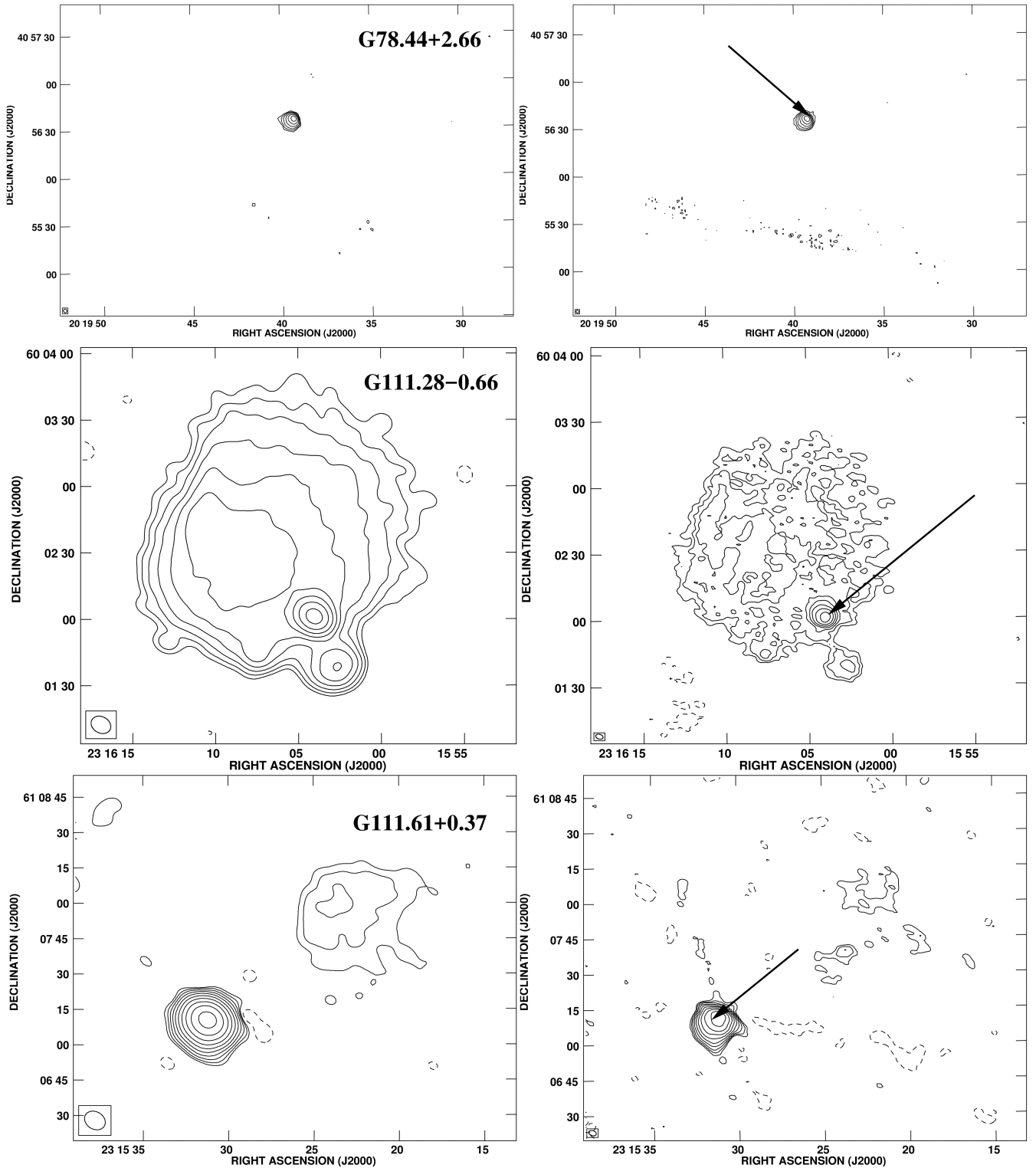


Figure 2 – continued

at MIR/FIR wavelengths (Churchwell 2002). For example, in the G25.7+0.0 complex, the position of the saturated 24  $\mu$ m emission confirms our suggestion that the observed EE initially associated with G25.72+0.05 is instead related to G25.69+0.03, a possible

compact H II region, and G25.71+0.04 which seems to be an UC H II region embedded at the edge of this EE (see Fig. 3).

The literature shows that all the UC H II + EE regions are related with star-forming regions, with young stellar objects (YSOs) and

Figure 2 – *continued*

other related phenomena such as maser emission. Also, many of them were catalogued by Churchwell et al. (2006, 2007) and Simpson et al. (2012). The last columns in Table 4 summarize a search of the sources in our catalogue of 28 UC H II + EE regions in other IR surveys. Several sources have not had an UC H II + EE classification before.

Combining the *Spitzer* view with our RC results, it can be seen that the UC H II + EE regions of our catalogue are arcmin scale star-forming regions. In some cases they are part of larger (degree size) structures, and composed of a collection of arcmin scale ionized gas bubbles similar to those found by Churchwell et al. (2006) and Simpson et al. (2012). Alternatively, they may

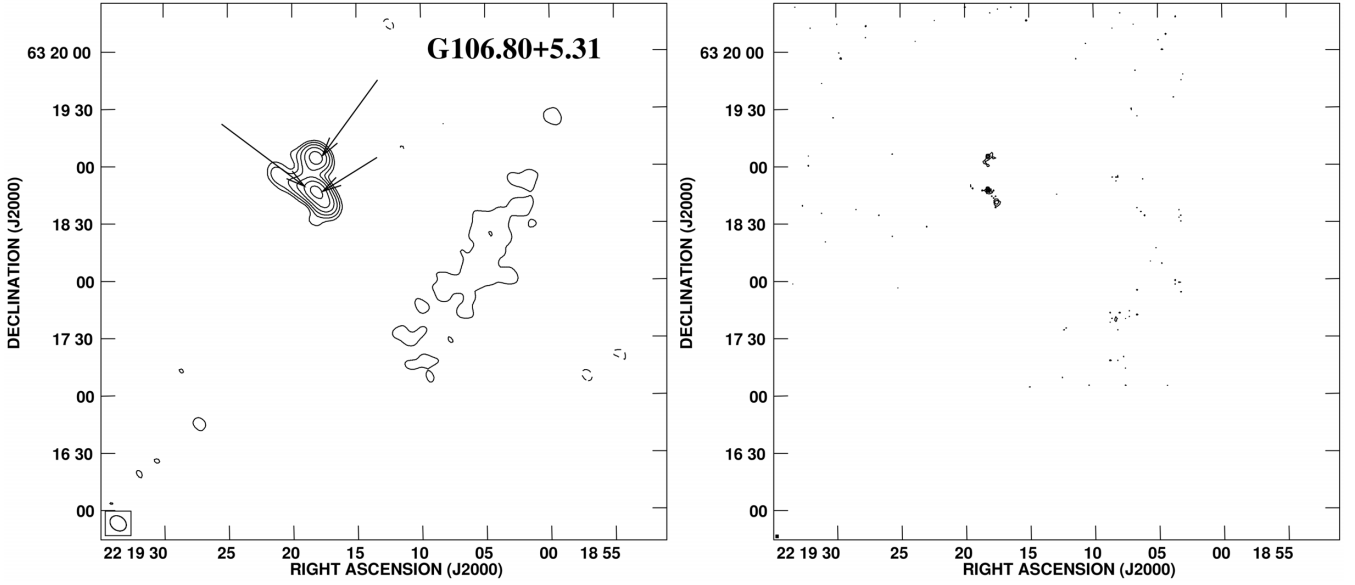


Figure 2 – continued

Table 5. The final catalogue of UC H II + EE.

UC H II + EE	IRAS	RA	Dec.	Distance <sup>a</sup>	Size	Spitzer	RC
region	source	(J2000)	(J2000)	(kpc)	approx (arcmin <sup>2</sup> )	bubble <sup>b</sup>	peaks
G05.48–0.24	17559–2420	17 <sup>h</sup> 59 <sup>m</sup> 02 <sup>s</sup> .9	–24°20′54″.5	14.3 <sup>(1)</sup>	3.0 × 2.0	Y	5
G05.97–1.17	18006–2422	18 03 40.5	–24 22 44.7	2.7 <sup>(2)</sup>	3.5 × 2.0	Y	1
G10.30–0.15	18060–2005	18 08 56.1	–20 05 53.4	6.0 <sup>(3)</sup>	4.0 × 1.5	Y	5
G12.21–0.10 <sup>c</sup>	18097–1825A	18 12 39.7	–18 24 20.1	13.5 <sup>(2)</sup>	4.0 × 3.0	Y	5
G18.15–0.28	18222–1321	18 25 01.2	–13 15 40.0	4.2 <sup>(3)</sup>	2.0 × 4.0	Y	2
G19.60–0.23	18248–1158	18 27 37.7	–11 56 42.0	3.5 <sup>(2)</sup>	0.8 × 2.0	Y	5
G23.44–0.21	18319–0834	18 34 44.4	–08 32 22.5	9.0 <sup>(1)</sup>	2.0 × 2.0	Y	1
G23.71+0.17	18311–0809	18 33 53.5	–08 07 14.2	8.9 <sup>(2)</sup>	2.0 × 2.0	Y	1
G25.69+0.03	18353–0628	18 38 05.1	–06 25 31.9	9.3 <sup>(2)</sup>	3.0 × 4.0	Y	2
G28.20–0.05	18402–0417	18 42 58.2	–04 14 05.0	9.1 <sup>(3)</sup>	1.5 × 1.5	Y	1
G31.39–0.25	18469–0132	18 49 32.9	–01 29 03.7	8.9 <sup>(5)</sup>	2.5 × 1.5	Y	2
G35.20–1.74	18592+0108	19 01 46.9	+01 13 08.0	3.3 <sup>(4)</sup>	2.0 × 2.0	P	1
G37.55–0.11	18577+0358	19 00 16.0	+04 03 10.3	9.9 <sup>(2)</sup>	2.0 × 2.0	Y	2
G37.87+0.40	18593+0408	19 01 53.6	+04 12 48.9	9.3 <sup>(4)</sup>	2.0 × 0.5	Y	1
G45.07+0.13	19110+1045	19 13 22.0	+10 50 53.9	6.0 <sup>(4)</sup>	1.0 × 1.0	Y	1
G45.12+0.13	19111+1048	19 13 27.8	+10 53 36.7	6.0 <sup>(4)</sup>	1.5 × 1.5	Y	1
G45.45+0.06	19120+1103	19 14 21.3	+11 09 12.9	6.0 <sup>(4)</sup>	2.0 × 2.0	Y	1
G54.10–0.06	19294+1836	19 31 43.1	+18 42 52.0	7.9 <sup>(1)</sup>	3.0 × 2.0	Y	2
G60.88–0.13 <sup>d</sup>	19442+2427	19 46 20.1	+24 35 29.4	2.2 <sup>(4)</sup>	1.0 × 3.0	Y	1
G77.96–0.01	20277+3851	20 29 36.7	+39 01 21.9	4.4 <sup>(5)</sup>	2.0 × 3.0	P	2
G111.28–0.66	23138 + 5945	23 16 03.9	+60 02 00.8	2.5 <sup>(3)</sup>	2.5 × 2.5	P	2

<sup>a</sup>From: (1) Wood & Churchwell (1989), (2) Churchwell et al. (1990), (3) Kurtz et al. (1994), (4) Araya et al. (2002), and (5) Kurtz et al. (1999).

<sup>b</sup>In this work, Y = Yes and P = Probably, based on the availability of *Spitzer* data. However, for those marked with P and without MIPS data, the 2MASS *K<sub>s</sub>* image suggests that gas emission matches the morphology of RC data (see Fig. 4).

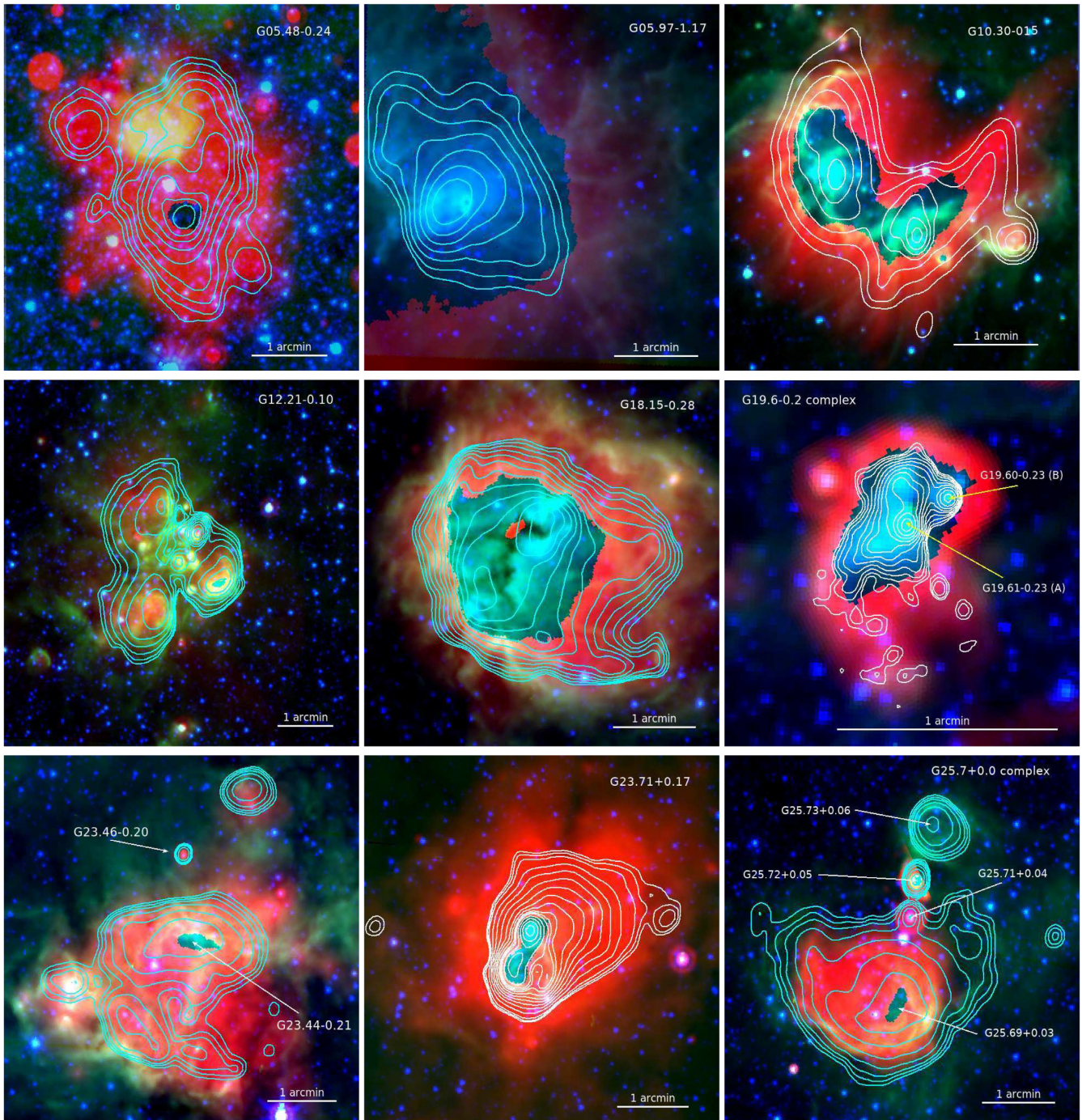
<sup>c</sup>This source was studied in detail and confirmed to host a hot core by de la Fuente et al. (2018).

<sup>d</sup>The source G60.87–0.11, located ~1.5 arcmin to the West of this source, is proposed as a new UC H II + EE, but more data are needed to confirm this.

be compact H II regions (Phillips & Ramos-Larios 2008) with well defined cometary arcs, where low-mass and high-mass YSOs, ionized gas, star clusters, dust, and PAHs coexist. This result is more realistic than the idea of a single ionizing source producing the EE involving or not a density gradient from a champagne flow

model. In addition, it is very likely that the difference between an UC H II + EE and a compact H II region is more an effect of scale size of the emission than an evolutionary trend from the UC H II region defined by Wood & Churchwell (1989) and Kurtz et al. (1994).





**Figure 3.** RGB images (red = 24  $\mu\text{m}$ , green = 8.0  $\mu\text{m}$ , and blue = 4.5  $\mu\text{m}$ ) of the UC H II + EE regions with MIPS data available. Contours at 3.6 cm are from VLA D configuration (see Table 2), except for G19.60–0.23 (BD), G31.39–0.25 (BCD), G37.87+0.40 (BCD), and G60.88–0.13 (BC) where MRIs are superimposed (see Table 3). All these sources are catalogued as UC H II + EE regions except G35.58–0.03 and G48.61+0.02. These images show that in these regions, the red emission (dust) matches very well with the whole RC emission, the green emission (PAHs) delineates the RC cometary arcs, and the UC H II position is saturated at 24  $\mu\text{m}$ . See text in Section 4 for individual details.

#### 4 COMMENTS ON INDIVIDUAL SOURCES

Based on the analysis of RC and IR images (Figs 1–3), a confirmation, addition, or elimination to a final catalogue of UC H II + EE regions was performed. As a result, 68 per cent of the original sample (19/28 regions) were confirmed to be UC H II + EE regions, 7 per cent (2/28) were reassigned a new RC peak or UC source(s) with the EE, and 25 per cent (7/28) were not defined as UC H II +

EE regions. A total of 21 UC H II + EE regions are reported in Table 5. Below, we provide the IRAC-MIPS RGB images in Fig. 3, and comment on individual regions.

##### 4.1 Sources confirmed as UC H II + EE (19 regions)

G05.48–0.24: This source was already classified by Koo et al. (1996) as an UC H II + EE. They presented VLA AnB and BnC



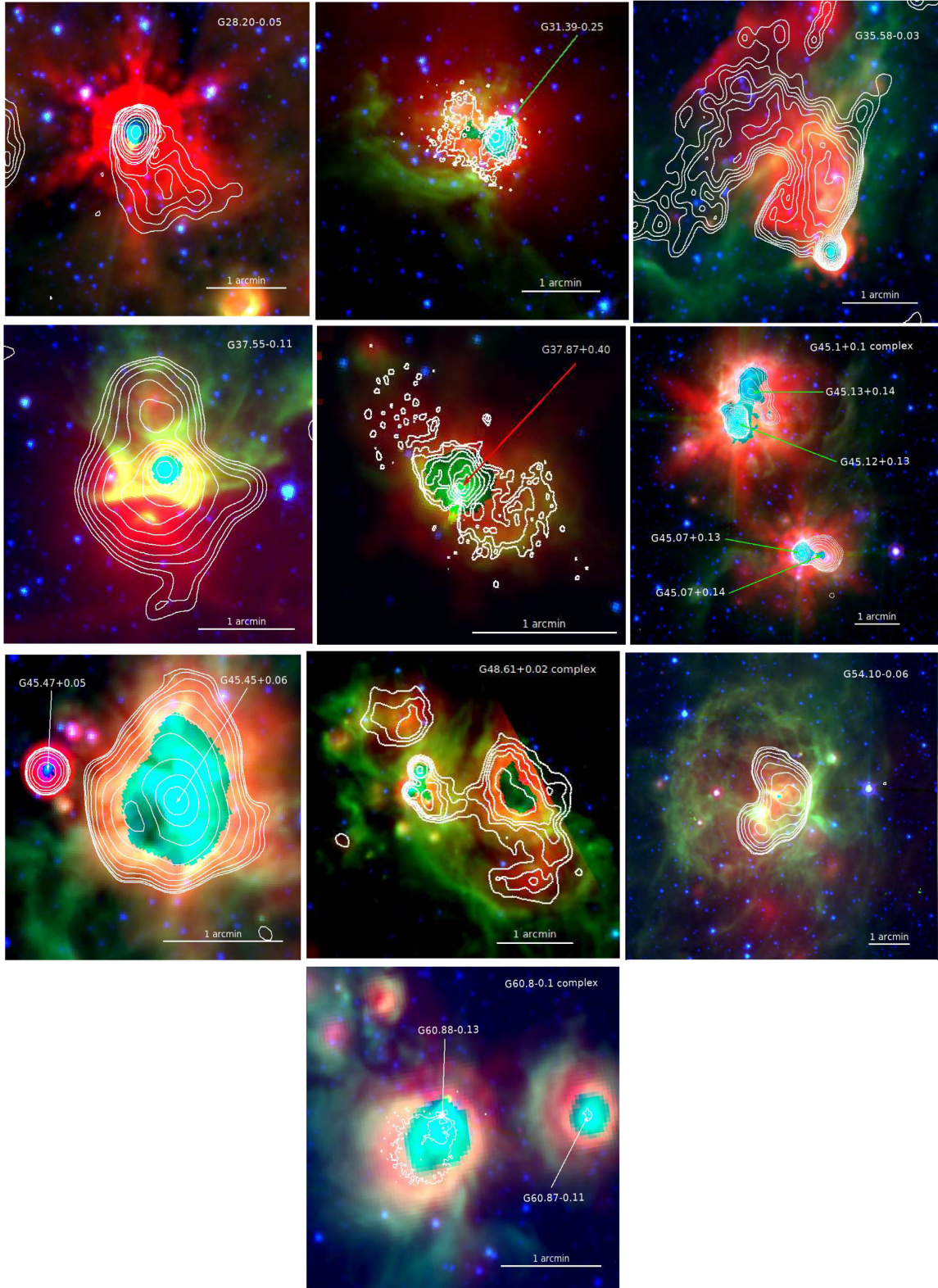


Figure 3 – continued

RC data as well as VLA D data at 21 cm, indicating that the UC H II region is immersed in extended arcmin scale diffuse emission. In addition, they also presented H I and  $^{13}\text{CO}$  line data. Our VLA-D image (Fig. 1) confirms that this source can be classified as UC

H II + EE. The MIPS image in Fig. 3 shows saturation on the UC H II position and the EE matches very well with the MIPS emission.

G05.97–1.17: Stecklum et al. (1998) argued that the nature of this UC source should not be considered as an UC H II region, ionized

by an embedded B0 star, but rather as a young star surrounded by a circumstellar disc that is being photoevaporated by Her 36. On the other hand, Kim & Koo (2001) described this source as a single compact component, probably Her 36, surrounded by EE of  $14 \times 10.7$  arcmin<sup>2</sup> size. Furthermore, it can be seen from Fig. 3 that all the EE presented in Fig. 1 is located within the region where the MIPS emission is saturated, which supports the description given by Kim & Koo (2001). In addition, since the EE resembles the *Spitzer* IR bubbles, we decided to include this source in our catalogue.

G10.30–0.15: The image in Fig. 3 shows saturated MIPS emission on the UC component described by Kim & Koo (2001, 2002) confirming its nature as UC H II + EE region. MIPS 24  $\mu$ m emission coincides with the VLA emission presented in Fig. 1.

G12.21–0.10: This source was also included in studies by Kim & Koo (2001, 2003). They observe VLA DnC 21 cm on RC and radio recombination lines, as well as with the NRAO 12 m CO and CS molecular tracers. de la Fuente et al. (2018) confirm the presence of a new hot molecular core and provide its characterization. Its RGB image in Fig. 3 shows a collection of compact H II regions with cometary arcs well defined by the 8.0  $\mu$ m emission.

G18.15–0.28: Before this work, no VLA low angular resolution images of this object were published. Wood & Churchwell (1989) and Kurtz et al. (1994) classified this source as cometary. Our 3.6 cm VLA-D image shows EE around the UC component labelled with an arrow in Fig. 1. The MIPS emission is saturated at arcmin scales, suggesting that several UC H II regions might be in this zone.

G19.60–0.23: This source was studied in detail by Garay et al. (1998) but never classified as UC H II + EE. Our VLA-D image at 3.6 cm (Fig. 1), and the MRI combining this data with the 3.6 cm VLA-B from Kurtz et al. (1994) confirm this classification. The MIPS image in Fig. 3 shows saturation in the UC H II regions G19.61–0.23 and G19.60–0.23 as well as on the EE ( $\sim 30$  arcsec). This image not only confirms the nature as an UC H II + EE region of the G19.60–0.2 complex, but also that the EE defines an IR bubble.

G23.71+0.17: Fig. 3 shows MIPS saturated emission at the UC H II position reported by Kim & Koo (2001) and at the SE component marginally detected in the Kim & Koo (2001) image. This image suggests that at least two UC H II regions might be present.

G28.20–0.05: It was classified as hypercompact H II by Sewilo et al. (2008). A visual inspection on the 8  $\mu$ m image at large scale suggests this object as an UC H II + EE into an infrared dark cloud (IRDC), where IRAC emission does not trace the RC emission but covers all the region in a continuous structure of 15 arcmin in size. On the other hand, the MIPS image shown in Fig. 3 clearly shows that the 24  $\mu$ m emission dominates and coincides with the RC EE, and it is saturated at the UC position.

G31.39–0.25: Kurtz et al. (1999) suggested this source as an UC H II + EE and reported two sources, G31.396–0.257 (marked with an arrow in Fig. 2) and a component slightly to the North, G31.397–0.257. Besides, our map also shows a third RC peak located at  $18^{\text{h}}:49^{\text{m}}:33^{\text{s}}.4, -01^{\text{d}}:29^{\text{m}}:11^{\text{s}}.4$  which corresponds to the YSO MSX6CG031.3948–00.2585 reported by Urquhart et al. (2009). Part of this bubble is delineated by the southern arc of about 2 arcmin in length shown in 8  $\mu$ m emission (Fig. 3).

G35.20–1.74: The new VLA images at 3.6 cm taken with configurations D and C are shown in Figs 1 and 2, respectively. Since a density gradient  $n_e \propto r^{-2}$  was reported by Franco et al. (2000) and the RC morphology resembles a champagne flow, this source could be considered as a candidate to test the Kim & Koo (2001, 2003) model. Unfortunately, no *Spitzer* data are available. Nevertheless,

the  $K_s$  2MASS image shows diffuse gas that matches with the RC EE (see Fig. 4). On the other hand, if the  $K_s$  2MASS emission turned out to be similar to that observed at *Spitzer* wavelengths, then this EE could be an IR bubble in the style of Churchwell et al. However, further observations would be required to confirm this hypothesis.

G37.55–0.11: This source was catalogued as UC H II + EE by Kim & Koo (2001). The IRAC bands image shows a remarkable lack of IRAC emission at the South part of the UC H II region, i.e. there is no IRAC emission tracing this part of the EE. On the other hand, MIPS emission is observed to trace very well the ionized gas (Fig. 3). This behaviour can be explained in terms of colder dust present in this region of the UC H II + EE that is clearly bounded to the north by emission by PAHs (yellow and green colours). Furthermore, the UC H II position is saturated. The MIPS emission is a good tracer of UC H II regions and extended ionized gas (Fig. 1).

G37.87+0.40: This source has bipolar morphology on the VLA-D image at 3.6 cm (Kurtz et al. 1999). However, on the configuration C and MRI (Fig. 2), the NE lobe is weak and almost disappears while the SW lobe emission is more intense. Although the bipolar morphology of this source could be due to a bipolar flow, there is no direct evidence of its existence. An analysis of the CO line emission could shed light on the origin of the bipolar morphology. Based on our morphological study and the fact that both UC and EE in central contours coincide with the saturated region in 24  $\mu$ m MIPS emission (see Fig 3), we suggest that G37.87+0.40 is an UC H II + EE.

G45.07+0.13 and G45.12+0.13: These two objects are located in a 5 arcmin field, and both present EE as shown in Fig. 1. The MIPS image shows saturation on the UC H II region and the EE confirming that this complex has at least four UC H II regions: G45.12+0.13 and G45.13+0.14 to the North, and G45.07+0.13 and G45.07+0.14 to the South.

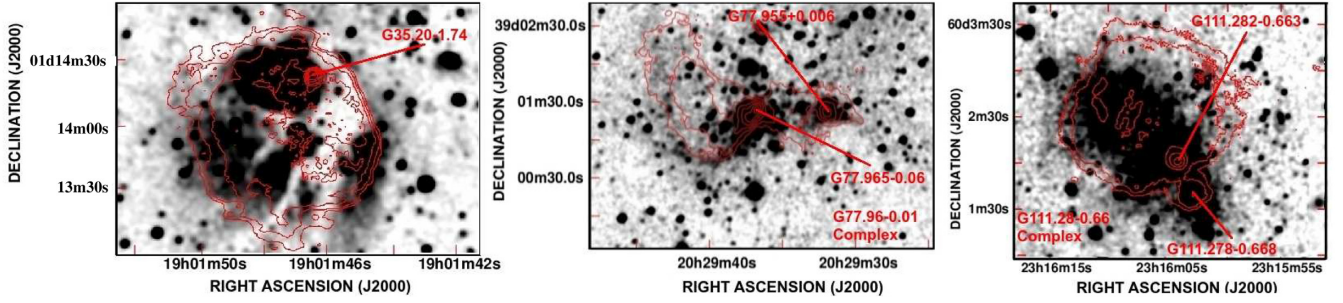
G45.45+0.06 and G45.47+0.05: In the VLA-D image at 3.6 cm, two UC H II regions are observed in the field. One corresponds to G45.45+0.06 (marked with an arrow in Fig. 1), and the other, more compact, to the East is G45.47+0.05. In the NRAO VLA Sky Survey image at 21 cm (Condon et al. 1998), both UC H II regions are surrounded by the same RC emission. Our image, shown in Fig. 1, confirms that G45.45+0.06 can be classified as UC H II + EE. The MIPS image in Fig. 3 confirms this result indicating that for G45.45+0.06 more than one UC H II region can be included, since the shape of saturation is not circular and some point-like sources can be seen at 4.5  $\mu$ m.

G54.10–0.06: Before this work, no low-resolution VLA images of this source were reported. Our VLA-D image at 3.6 cm shows EE surrounding two RC peaks, the most prominent marked with an arrow in Fig. 1 (G54.10–0.06), and a second source to the SE. The MIPS emission is saturated on the UC H II position and the EE resembles two bubbles with PAHs emitting filaments or a PDR that clearly separates them.

G60.88–0.13: This source is the only one with *Spitzer* emission and RC morphology that may be explained under the scenario of a central ionizing source, producing an ionization front propagated in a density gradient medium, and producing a champagne flow (Franco et al. 1990; Kim & Koo 2001, 2003). Further molecular observations are needed to confirm if this model applies. However, since the *Spitzer* emission coincides completely with the RC emission, the associated EE has the bubble morphology discussed by Churchwell et al. (2006) and Simpson et al. (2012).

G77.96–0.01: In Fig. 2, this source presents two UC H II regions; one at the centre (G77.965–0.006), and the other  $\sim 1$  arcmin to the





**Figure 4.** 2MASS  $K_s$  band images for the three sources classified as P = Probably in column 7 of Table 5. Contours at 3.6 cm are from multiresolution maps (Fig. 2). These regions do not have MIPS data.

West (G77.955+0.006). Both are located inside the EE in a ‘double-lobe’ structure. On the configuration C image (Fig. 2, left-hand panel), the emission in the West lobe from G77.965–0.006 towards G77.955+0.006 tends to disappear but surrounds G77.955+0.006. Unfortunately, no *Spitzer* data are available for this source, but the 2MASS  $K_s$  image shows gas and several point sources, see Fig. 4. The observed gas matches with the RC EE but it is very weak in the zone where the two lobes become very faint. Both lobes may be part of different bubbles, with G77.965–0.006 being the object that can be classified as UC H II + EE, but better studies, kinematics, and IR images are needed to confirm this.

G111.28–0.66: This object was catalogued as UC H II + EE by Kurtz et al. (1994). Two UC H II regions are clearly observed in Fig. 2: G111.278–0.668 and G111.282–0.663, this last identified with an arrow. Unfortunately, the MIPS image is not available. However, the  $K_s$  2MASS nebulosity resembles the EE observed in the SW–NE direction (see Fig. 4). Still, mid-IR images are needed to confirm if the EE can be considered as an IR bubble, but there is no reason to discard this object as an UC H II + EE, following Kurtz et al. (1994, 1999).

#### 4.2 Sources with UC H II region reassigned (two regions)

G23.46–0.20: Kim & Koo (2001) showed a multipeak image where the main source is marked with a solid arrow in Fig. 1. Our VLA-D 3.6 cm image shows three independent sources discarding the possible association of G23.46–0.20 with the EE. Although G23.46–0.20 can be discarded as an UC H II + EE, the EE is more related to the source labelled as A by Kim & Koo (2001) and shown with a dashed arrow in Fig. 1. This new source is designated as G23.44–0.21 in this work (see Table 5). This reassignment is also confirmed with the MIPS image (Fig. 3), where G23.46–0.20 appears as a single UC H II region while G23.44–0.21 appears saturated, and the EE coincides with the dust. The shape of saturation appears elongated in the E–W direction and two–three point-like counterpart sources are seen in 4.5  $\mu$ m. Since one or more of these sources might be UC H II regions, we decided to keep it as an UC H II + EE rather than consider it as one compact H II region. Observations with higher angular resolution that resolve out the EE could single out the more compact emission from the UC H II regions.

G25.72+0.05: Kim & Koo (2001) do not classify this source as UC H II + EE because the LSR velocities, which were obtained from radio recombination lines, were different for the UC emission and the EE. Our VLA-D 3.6 cm image has better resolution than their data and three aligned but independent point sources are clearly observed (see Fig. 1). The EE includes more to G25.71+0.04

(dashed arrow in Fig. 1) than to G25.72+0.05 (solid arrow in the same figure). The source G25.73+0.06, to the North of G25.72+0.05 does not have MIPS counterpart data, thus we do not know if its 24  $\mu$ m emission is saturated, but it could be another H II region, maybe compact. Nevertheless, this source appears not to be related to the EE. The MIPS image of the G25.7+0.0 complex in Fig. 3 confirms these results and strongly suggests that the EE is not only associated with G25.71+0.04 but mostly related to G25.69+0.03. As in the case of G23.44–0.21, G25.69+0.03 might contain a set of UC H II regions in the NW–SE direction as shown by the saturated region.

#### 4.3 Sources discarded as UC H II + EE (seven regions)

G33.13–0.09: was classified as an ‘unlikely’ UC H II + EE by Kurtz et al. (1999). Our VLA MRI confirms this interpretation showing that the UC H II region and the EE are independent of one another (see Fig. 2).

G35.58–0.03: was classified as an ‘unlikely’ UC H II + EE by Kurtz et al. (1999). Our VLA MRI (see Fig. 2) confirms this assumption showing that the EE is more related to another structure, like a complex elongated SE–NW structure. The MIPS image (Fig. 3) shows saturation at the position of the UC H II region and the EE coincides with two regions separated by a PAHs filament or a PDR (green and yellow emission).

G43.24–0.04: Our VLA MRI is presented in Fig. 2. It is totally discarded as UC H II + EE as was suggested by Kurtz et al. (1999).

G48.61+0.02: Kurtz et al. (1994) report three UC components in this field; G48.606+0.023 (to the SE), G48.606+0.024 (at the middle), and G48.609+0.027 (to the North). These sources are marked with arrows in Fig. 2. Although Kurtz et al. (1999) classify this region as a ‘possible’ UC H II + EE, our images discard this idea. In Fig. 3, two saturated zones are seen. MIPS saturated zone to the East coincides with the three sources reported by Kurtz et al. (1994), and a star cluster is known (Morales et al. 2013), [MCM2005b] 21. Saturated zone to the West coincides with the radio source GB6 B1918+1349 (Gregory et al. 1996) and about 10 IR sources in the 2MASS catalogue (Skrutskie et al. 2006) in a radius of about 20 arcsec.

G78.44+2.66: Kurtz et al. (1999) argued for an ‘unlikely’ connection between the EE and the UC H II region. Our images confirm this idea (see Fig. 2) and no *Spitzer* data are available.

G106.80+5.31: This field contains three UC components (Kurtz et al. 1999) marked with arrows in Fig. 2; G106.795+5.311 (to the southwest), G106.797+5.312 (in the middle), and G106.800+5.316 (to the north). Kurtz et al. (1999) argued a connection was unlikely between the EE and the UC H II region. Our images (see Fig. 2)

**Table 6.** Results on the energetics for the initial sample.

UC H II region	$L_{\text{IRAS}}$ ( $10^4 L_{\odot}$ )	$\log N_{*c}$ ( $s^{-1}$ )	Spectral type (IRAS)	VLA (configuration)	$\log N'_{*c}$ ( $s^{-1}$ )	Spectral type (radio)	$f_d(\text{C,D})/f_d(\text{B max})^a$	EE level <sup>b</sup> Explain
G05.97–1.17	15.5	48.82	O6.5	D	48.75	O6.5	0.16/0.90 <sup>(1)</sup>	1
G19.60–0.23	14.0	48.82	O6.5	D	48.70	O7	0.24/0.50 <sup>(2)</sup>	1
G33.13–0.09	10.3	48.62	O7	D	48.42	O8	0.37/0.48 <sup>(2)</sup>	1
				C	48.41	O8	0.38/ –	
G35.20–1.74	26.9	49.08	O6	D	49.07	O6	0.03/0.79 <sup>(2)</sup>	1
				C	49.05	O6	0.06/ –	
G35.58–0.03	4.7	48.08	O9	D	48.02	O9	0.13/0.90 <sup>(2)</sup>	1
				C	47.93	O9.5	0.29/ –	
G37.55–0.11	28.1	49.08	O6	D	48.94	O6.5	0.13/0.90 <sup>(1)</sup>	1
G37.87+0.40	65.1	49.62	O5	D	48.98	O6.5	0.19/0.44 <sup>(2)</sup>	1
				C	48.96	O6.5	0.20/ –	
G43.24–0.04	31.7	49.08	O6	D	48.98	O6.5	0.21/0.81 <sup>(2)</sup>	1
				C	48.96	O6.5	0.24/ –	
G45.45+0.06	49.2	49.36	O5.5	D	49.19	O6	0.33/0.96 <sup>(2)</sup>	1
G111.28–0.66	2.7	47.36	B0	D	47.25	B0	0.22/0.87 <sup>(2)</sup>	1
				C	47.17	B0	0.35/ –	
G05.48–0.24	66.5	49.62	O5	D	49.36	O5.5	0.45/0.95 <sup>(1)</sup>	2
G10.30–0.15	65.7	49.62	O5	D	49.30	O5.5	0.52/0.96 <sup>(1)</sup>	2
G18.15–0.28	21.6	49.08	O6	D	48.85	O6.5	0.42/0.99 <sup>(2)</sup>	2
G23.71+0.17	34.2	49.36	O5.5	D	49.05	O6	0.51/0.95 <sup>(1)</sup>	2
G25.69+0.03	22.1	49.08	O6	D	48.75	O6.5	0.54/0.99 <sup>(1)</sup>	2
G28.20–0.05	20.5	49.08	O6	D	48.58	O7	0.69/0.93 <sup>(2)</sup>	2
G48.61+0.02	74.5	49.62	O5	D	49.17	O6	0.64/0.99 <sup>(2)</sup>	2
				C	48.87	O6.5	0.82/ –	
G54.10–0.06	14.9	48.82	O6.5	D	48.49	O7.5	0.53/0.99 <sup>(1)</sup>	2
G77.96–0.01	10.2	48.62	O7	D	48.24	O8.5	0.58/0.96 <sup>(2)</sup>	2
				C	48.04	O9	0.74/ –	
G111.61+0.37	16.6	48.82	O6.5	D	48.40	O8	0.62/0.90 <sup>(2)</sup>	2
				C	48.38	O8	0.64/ –	
G12.21–0.10	86.8	49.93	O4	D	49.36	O5.5	0.73/0.94 <sup>(1)</sup>	3
G23.44–0.21	73.9	49.62	O5	D	48.95	O6.5	0.79/0.99 <sup>(1)</sup>	3
G31.39–0.25	38.9	49.36	O5.5	D	48.69	O7	0.79/0.99 <sup>(2)</sup>	3
				C	48.69	O7	0.79/ –	
G45.07+0.13	49.3	49.36	O5.5	D	48.40	O8	0.89/0.94 <sup>(2)</sup>	3
G45.12+0.13	62.6	49.62	O5	D	48.79	O6.5	0.85/0.71 <sup>(2)</sup>	3
G60.88–0.13	4.3	48.08	O9	C	47.35	B0	0.81/0.97 <sup>(2)</sup>	3
G78.44+2.66	6.1	48.35	O8	D	46.86	B0.5	0.90/0.99 <sup>(2)</sup>	3
				C	46.86	B0.5	0.97/ –	
G106.80+5.31	2.3	47.36	B0	D	45.19	B1	0.90/0.99 <sup>(2)</sup>	3

<sup>a</sup>Values of  $f_d$  based on VLA C or D configuration to compare with  $f_d$  based on VLA B configuration data. For the latter, upper numbers denote values from: (1) Wood & Churchwell (1989) and (2) Kurtz et al. (1994).

<sup>b</sup>Different levels at which EE reduces the values of  $f_d$  explaining the IR excess: (1) Low, (2) Intermediate, (3) High. (see Section 5 for details).

confirm this idea. No *Spitzer* image is available and we cannot classify it as a bubble.

G111.61+0.37: This case is quite similar to G106.80+5.31 and G78.44+2.66. We confirm the result of Kurtz et al. (1999) of not classifying this source as UC H II + EE, and no *Spitzer* image is available.

## 5 ENERGETICS IN UC H II + EE

Following Kurtz et al. (1999), a way to quantify the energetics of an UC H II + EE is comparing the total ionizing flux of the exciting star calculated from RC and far-IR (FIR) observations. The ionizing photon rate,  $N'_{*c}$ , is estimated from the 3.6 cm observations in the D configuration using equation (1) of Kurtz et al. (1994),

$$\left(\frac{N'_{*c}}{s^{-1}}\right) \geq 8.04 \times 10^{46} \left(\frac{T_e}{K}\right)^{-0.85} \left(\frac{r}{pc}\right)^3 \left(\frac{n_e}{cm^{-3}}\right)^2, \quad (1)$$

considering a homogeneous sphere of radius  $r$ , electron density  $n_e$ , and electronic temperature  $T_e$ .

On the other hand, the total luminosity measured via *IRAS* fluxes can be converted into an ionizing photon rate,  $N^*_{*c}$ , using model stellar atmospheres (e.g. Panagia 1973; Casoli et al. 1986; Wood & Churchwell 1989; Kurtz et al. 1994).  $N'_{*c}$  and  $N^*_{*c}$  are considered limit values because an ionization-bounded and dust-free nebula is assumed;  $N'_{*c}$  represents a lower limit to the spectral type, while  $N^*_{*c}$  an upper limit (Kurtz et al. 1994; de La Fuente et al. 2009a).

Thus, we are interested in estimate the fraction of UV photons absorbed by dust – and hence without causing ionization –,  $f_d$ , defined as (Kurtz et al. 1994)

$$f_d = 1 - \frac{N'_{*c}}{N^*_{*c}}, \quad (2)$$

which we also assumed to produce all the *IRAS* FIR luminosity by dust within the UC H II + EE.



**Table 7.** Energetics results for the final catalogue.

UC H II region	$L_{\text{IRAS}}^a$ ( $10^4 L_{\odot}$ )	$\text{Log } N_{*c}^a$ ( $s^{-1}$ )	Spectral type <sup>a</sup> (IRAS)	VLA <sup>b</sup> (configuration)	$\text{Log } N_c^b$ ( $s^{-1}$ )	Spectral type <sup>b</sup> (radio)	$f_d(\text{B max})^c$	$f_d(\text{C,D})^b$
G05.48–0.24	66.5	49.62	O5	D	49.36	O5.5	0.95 <sup>(1)</sup>	0.45
G05.97–1.17	15.5	48.82	O6.5	D	48.75	O6.5	0.90 <sup>(1)</sup>	0.16
G10.30–0.15	65.7	49.62	O5	D	49.30	O5.5	0.96 <sup>(1)</sup>	0.52
G12.21–0.10	86.8	49.93	O4	D	49.36	O5.5	0.94 <sup>(1)</sup>	0.73
G18.15–0.28	21.6	49.08	O6	D	48.85	O6.5	0.99 <sup>(2)</sup>	0.42
G19.60–0.23	14.0	48.82	O6.5	D	48.70	O7	0.50 <sup>(2)</sup>	0.24
G23.44–0.21	73.9	49.62	O5	D	48.95	O6.5	NA	0.24
G23.71+0.17	34.3	49.36	O5.5	D	49.05	O6	0.95 <sup>(1)</sup>	0.51
G25.69+0.03	22.1	49.08	O6	D	48.75	O6.5	NA	0.54
G28.20–0.05	20.5	49.08	O6	D	48.58	O7	0.93 <sup>(2)</sup>	0.69
G31.39–0.25	38.9	49.36	O5.5	D	48.69	O7	0.99 <sup>(2)</sup>	0.79
G35.20–1.74	26.9	49.08	O6	C	48.69	O7		0.79
				D	49.07	O6	0.79 <sup>(2)</sup>	0.03
				C	49.05	O6		0.06
G37.55–0.11	28.1	49.08	O6	D	48.94	O6.5	0.90 <sup>(1)</sup>	0.13
G37.87+0.40	65.1	49.62	O5	D	48.98	O6.5	0.44 <sup>(2)</sup>	0.19
				C	48.96	O6.5		0.20
G45.07+0.13	49.3	49.36	O5.5	D	48.40	O8	0.94 <sup>(2)</sup>	0.89
G45.12+0.13	62.6	49.62	O5	D	48.79	O6.5	0.71 <sup>(2)</sup>	0.85
G45.45+0.06	49.2	49.36	O5.5	D	49.19	O6	0.96 <sup>(2)</sup>	0.33
G54.10–0.06	14.9	48.82	O6.5	D	48.49	O7.5	0.99 <sup>(1)</sup>	0.53
G60.88–0.13	4.3	48.08	O9	C	47.35	B0	0.97 <sup>(2)</sup>	0.81
G77.96–0.01	10.2	48.62	O7	D	48.24	O8.5	0.96 <sup>(2)</sup>	0.58
				C	48.04	O9		0.74
G111.28–0.66	2.7	47.36	B0	D	47.25	B0	0.87 <sup>(2)</sup>	0.22
				C	47.17	B0		0.35

<sup>a</sup>FIR data were recalculated using the IRAS flux and distances shown in Table 1. Also a single ionizing star and Panagia (1973) model were considered.

<sup>b</sup>This work.

<sup>c</sup>Taken from: (1) Wood & Churchwell (1989) or (2) Kurtz et al. (1994).

As mentioned in Section 1, the IR excess is quantified by  $f_d$ . Values of  $f_d \sim 1$  indicate a large IR excess. Values of  $0.42 < f_d < 0.99$  were found by the surveys of Wood & Churchwell (1989) and Kurtz et al. (1994).

A comparison between  $f_d$  (configuration D; Kurtz et al. 1999 and this paper) and  $f_d$  (configuration B; Wood & Churchwell 1989 and Kurtz et al. 1994) was performed. We use configuration D data because this configuration has an MRS of up to 3 arcmin, and  $f_d$  (configuration D) is slightly smaller than  $f_d$  (configuration C). Both configuration B and configuration D values are reported in Table 6. In order to determine the respective  $N_c'$ , we use the flux taken from a box that covers all the RC emission observed.

For 28 sources, the presence of EE reduces the values of  $f_d$ , but at different levels (see Table 6). According to the  $f_d$  (configuration D) value reduction, we define these levels as: (1) *Low*;  $f_d$  (configuration D)  $< 0.42$ , (2) *Intermediate*;  $0.42 < f_d$  (configuration D)  $< 0.7$ , and (3) *High*;  $f_d$  (configuration D)  $> 0.7$ . The  $f_d$  (configuration D) value of 0.42 was chosen because it is the lowest value reported by Wood & Churchwell (1989) and Kurtz et al. (1994), while values from  $f_d = 0.7$  to 0.99 were the most typical reported by them.

In summary, 10 regions (level 1) have  $f_d$  (configuration D)  $\sim 0.21$ , 10 regions (level 2)  $\sim 0.55$ , and the other 8 (level 3),  $\sim 0.78$ . The EE increases the  $N_c'$  value, raises the  $\xi = N_c'/N_c^*$  value and reduces  $f_d$ . Hence, an underestimation in the  $N_c'$  determination by Wood & Churchwell (1989) and Kurtz et al. (1994) was inferred. Table 7 shows the energetic results for the final catalogue. The presence of EE in UC H II regions could help to explain the IR excess observed as reported and discussed by Wood & Churchwell (1989) and Kurtz et al. (1994), because the  $N_c'$  in these surveys

with high-resolution VLA observations underestimated the ionizing Lyman photons from the EE. The observed EE is part of a bigger structure, so, if we consider the total  $N_c'$  of the whole region,  $f_d$  must drop significantly. Nevertheless, the overestimation of dust in these regions is not realistic as it is observed in *Spitzer* data (Churchwell et al. 2006; Phillips & Ramos-Larios 2008; de La Fuente et al. 2009a,b). Moreover, the presence of stellar clusters in these regions, indicated by both the UC emission and at large scales by the EE, is in agreement with the Kurtz et al. (1994) conclusion.

## 6 SUMMARY AND CONCLUSIONS

(i) We observed EE in a sample of 28 UC H II regions. Nine of them were discarded (no EE) and two new sources were added, giving a final catalogue of 21 UC H II + EE regions. This catalogue complements the works of Kim & Koo (2001), Kurtz et al. (1999), and Ellingsen et al. (2005) and is the largest sample so far. The EE seems to be common in UC H II regions and deserves special attention in forthcoming studies and analyses. We show that multiconfiguration VLA images are critical to confirm the direct connection between UC H II regions and their associated EE.

(ii) Following the Wood & Churchwell (1989) morphological classification, we conclude that cometary is the dominant type in our sample (43 per cent). However, we note in general that cometary arcs, spherical (21.5 per cent) and irregular with multi-peaked structure (21.5 per cent) morphologies are common and match with the *Spitzer* emission. MIPS 24  $\mu\text{m}$  and RC emissions match very well, and better than the other IRAC bands with the RC.

(iii) The observed EE in all sources appears to be arcmin scale complex bubbles, where gas, dust, and both low-mass and high-mass star(s) coexist, as a result of their star formation process. Our morphological study favours the bubbling Universe described by Churchwell et al. (2006, 2007) and Simpson et al. (2012, and references therein). Alternatively, a detailed comparison of molecular, IR, and radio emission on each source is needed to compare with the predictions of Kim & Koo (2001, 2003) model. The observed RC peaks in most cases are coincident with luminous IR counterparts or can be other UC H II regions (saturated at 24  $\mu$ m), while the cometary shape can trace PDRs.

(iv) The EE helps to explain the IR excess observed in these regions, because the  $N_c'$  calculated in Wood & Churchwell (1989) and Kurtz et al. (1994) underestimated the ionizing Lyman photons rate, no matter if they come from a single or several ionizing sources. The assumptions of a single ionizing star and dust-free nebula are not valid in the studies of energetics of UC H II regions.

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