**SPITZER--IRAC IMAGERY AND PHOTOMETRY OF ULTRACOMPACT H II REGIONS WITH EXTENDED EMISSION**

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**ABSTRACT**

We present the results of a morphological study performed to a sample of Ultracompact (UC) H II regions with Extended Emission (EE) using Spitzer--IRAC imagery and 3.6 cm VLA radio-continuum (RC) maps. Some examples of the comparison between maps and images are presented. Usually there is a point source counterpart to the peak(s) of RC emission, at the position of the UC H II. Encontramos que la morfología predominante de la EE es cometary, y en la mayoría de los casos es coincidente con emisión IR a 8.0 µm. También presentamos resultados preliminares de la fotometría Spitzer--IRAC de una sub-muestra de 13 regiones UC H II con EE (UC H II + EE ) basada en datos del legado de GLIMPSE. Además, realizamos fotometría IRAC individual a 19 fuentes UC H II dentro de estas 13 regiones. Mostramos que las fuentes UC H II caen en lugares específicos, en ambos diagramas de diagnóstico, color-color de IRAC y del producto AM. Presentamos conteos de fuentes estelares jóvenes para cada región, y concluimos que una proporción de ~2%, ~10%, y ~88% de las fuentes en UC H II + EE son, en promedio, Clase I, II, y III, respectivamente.

**Key Words:** H II regions: Ultracompact — Stars: Pre-main sequence — Stars: High mass

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pact (UC) emission at arcsec scales, but if it is, there will be strong implications and changes in our understanding of these objects, such as definition, environment, energetics and excitation mechanism (F07; F09; Kurtz 2002; Kurtz et al. 1999). This association can be performed comparing VLA with IR observations (F07; F09). The former traces ionized gas and the latter dust and environment at large scales, where previous VLA radio-observations only detect sources smaller than 20″–30″ (e.g. Kurtz, et al. 1994; Wood & Churchwell 1989; using the conf. A and B), and extended emission at scales up to ∼3′ (Kurtz et al. 1999) and to ∼7–15′ (Condon et al. 1998; Kim & Koo 2001) using the conf. D.

The Spitzer legacy project GLIMPSE (Benjamin et al. 2003), via photometry and imaging, has provided excellent tools to study star formation regions, discover star clusters, and to characterize the YSO population (e.g. F07; F09; Chavarria et al. 2008; Kumar & Grave 2007, KG07 hereafter; Hartmann et al. 2005 and references therein).

A summary of the results reported in de la Fuente Ph. D. thesis (2007), regarding the comparison between IRAC imagery and VLA low resolution maps is presented in § 2 and § 3, while the IRAC photometry analysis and young stellar classification also for UC H II sources, are presented in § 4. Preliminary conclusions are given in § 5.

2. THE DE LA FUENTE 2007 SAMPLE AND OBSERVATIONS

29 UC H II regions with EE were studied by F07. The selection criteria was to include regions with both: a) EE and suggested candidates according to Kurtz et al. (1999) and Kim & Koo (2001), plus G35.20–1.74 (IRAS 18592+0108) and G19.60–0.23 (IRAS 18248–1158), and b) IR excess in the Wood & Churchwell (1989) and Kurtz et al. (1994) samples (see F09).

The Radio Continuum (RC) maps were obtained from VLA conf. D observations at 3.6 cm. These observations trace the ionized gas and have resolutions ∼9″ and are sensitive up to ∼3′ structures. In order to have VLA maps in conf. D at 3.6 cm from all sources, F07 combine several new observations with those presented in Kurtz et al. 1999. Nevertheless, although F07 made VLA multiresolution cleaning maps using conf. B, C, and D, here we will discuss only the conf. D maps.

22 of the 29 UC H II regions have infrared images available in all IRAC (Fazio et al. 2004) bands

| IRAS Source | α(2000) | δ(2000) | Distance |
|-------------|---------|---------|----------|
| 17559–2420  | 17 59 03| −24 20 49| 14.31 |
| 18060–2005  | 18 08 58| −20 05 15| 6.02  |
| 18097–1825A | 18 12 40| −18 24 21| 13.52 |
| 18222–1321  | 18 25 01| −13 15 40| 4.23  |
| 18248–1158  | 18 27 38| −11 56 42| 3.52  |
| 18319–0834  | 18 34 45| −08 31 07| 9.01  |
| 18311–0809  | 18 33 53| −08 07 26| 8.92  |
| 18353–0628  | 18 38 03| −06 23 47| 9.32  |
| 18402–0417  | 18 42 58| −04 14 05| 9.13  |
| 18469–0132  | 18 49 32| −01 29 04| 8.96  |
| 18496+0004  | 18 52 08| +00 08 12| 7.14  |
| 18538+0216  | 18 56 24| +02 20 38| 3.64  |
| 18557+0358  | 19 00 16| +04 03 13| 9.92  |
| 18593+0408  | 19 01 54| +04 12 49| 9.34  |
| 19081+0903  | 19 10 35| +09 08 31| 11.75 |
| 19110+1045  | 19 13 22| +10 50 53| 6.04  |
| 19111+1048  | 19 13 28| +10 53 37| 6.04  |
| 19120+0917  | 19 14 26| +09 22 34| 8.04  |
| 19120+1103  | 19 14 21| +11 09 04| 6.04  |
| 19181+1349  | 19 20 31| +13 55 24| 9.84  |
| 19294+1836  | 19 31 43| +18 42 52| 7.91  |
| 19442+2427  | 19 44 14| +24 27 50| 2.24  |

*From the F07 sample of 29 UC H II regions with EE

bTaked from: (1) Wood & Churchwell (1989); (2) Churchwell et al. (1990); (3) Kurtz et al. (1994); (4) Araya et al. (2002); (5) Watson et al. (1997); (6) Kurtz et al. (1999).

at 3.6, 4.5, 5.8, and 8.0 μm. They are listed in Table 1. Dust and PAH features (at 3.3, 6.2, 7.7, and 8.6 μm) can be detected in the 3.6, 5.8 and 8.0 μm bands. The 8.0 μm band is strongly dominated by PAH emission (predominant at 7.7 μm). Shocked emission is observed at 4.5 μm band (Cyganowski et al. 2008). The 3.6 μm band also shows the presence of stellar clusters and nebulosities (ionized or reflection nebula), and can be used as a tracer of photodissociation regions (PDRs) via PAH emission (e.g. Sloan et al. 1996).

3. MAPS AND IMAGES

Figures 1 and 2 show all IRAC images of the UC H II regions with EE IRAS 18060–2005 (G10.30–0.15) and IRAS 18222–1321 (G18.15–0.28), respectively, with a four-band gray scale image. Figure 3

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9http://isc.astro.cornell.edu/~sloan/library/1996/pahim96a.html
Fig. 1. The UC H II region with EE IRAS 18060–2005 (G10.30–0.15). Left: Gray scale IRAC 4–bands combined image. North is up and East to the left. Right: IRAC images at a) 8.0 µm, b) 5.8 µm, c) 4.5 µm, and d) 3.6 µm with the VLA conf. D map (F07) superposed as contours (the EE). The crosses show the position of the UC H II region.

Fig. 2. Same as Figure 1 for the UC H II region with EE IRAS 18222-1321 (G18.15–0.28) shows the four-band combined IRAC image of IRAS 18577+0358 (G37.55–0.11). In these figures, the respective VLA conf. D maps are superposed as contours.

The IR emission (IRE) has similar morphology in all bands suggesting that in these regions, both gas and dust coexist. As was expected, dust has a strong presence in these massive star formation regions (e.g., Wood & Churchwell 1989; Kurtz et al. 1994), and plays a fundamental role in several physical processes related with UC H II regions with EE like their energetics (F07; F09). The IRE is brightest in the 8 µm band and decreases at lower wavelengths becoming sometimes undetectable in the 3.6 µm band.

Coincidence between radio and IR morphologies is observed, confirming the presence of heated dust within the ionized gas. Morphologies are
similar to those defined for UC H II regions (e.g., Wood & Churchwell 1989; Kurtz et al. 1994): cometary (IRAS 18353–0628), core–halo (e.g. IRAS 19120+1103), bipolar (e.g. IRAS 18593+0408), and irregular or multipeaked. Nevertheless, the cometary morphology appears to dominate in our sample. The strongest IRAC emission is observed in the RC peaks, and in the cometary arcs.

The PAH emission is a good tracer of the “radiation temperature” and the IRAC 8.0 μm band is dominated by this emission. The striking comparison between the IRAC images and the VLA RC maps (Figures 1 to 3) suggests that the EE is due to ionizing radiation. However, soft UV radiation which may not significantly contribute to the overall H II region could be an important ionization source for the EE. In the 8.0 μm image, several knot–like sources are observed. They could be either star clusters or externally illuminated condensations. Furthermore, the 8.0 μm band can effectively trace weak structures and has proven useful in unveiling the underlying physical structure of the dense core/cloud (e. g., Heitsch et al. 2007).

Churchwell et al. (2006) using GLIMPSE images, identified and studied “bubbles around OB stars in the galaxy. Three-quarters of the bubbles in their sample are due to B4–B9 stars (too cool to produce detectable radio H II regions), while the other ones are produced by young O–B3 stars with detectable radio H II regions. They suggest that bubbles overlapping known H II regions appear to be produced by stellar winds and radiation pressure from young OB stars in massive star formation regions. Furthermore, they found that the 8.0 μm emission is weak at the center, but strong in the shells that define the bubbles and often extends outside the bubbles (see Figure 1). They support the idea that PAHs are destroyed in the vicinity of hot stars and instead trace the Photodissociation regions (PDRs) in the neighborhood of hot stars or star-clusters.

In our sample, the UC H II regions with EE seem to be part of larger structures (parsecs) that by size could be classified as classical H II regions (parsecs–scale) and could be the “bubbles identified by Churchwell et al. (2006). Indeed our regions resemble the morphologies described by these authors (contrast their Figure 2 with our Figures 1 to 3), and the cometary arcs observed at RC could be related with PDRs.

In the color images, black filaments due to a higher density gas/dust component of IR dark clouds (IRDCs; e.g., Rathborne et al. 2006 and references therein) are observed. Because the IRDCs appear

in silhouette against the bright Galactic background at mid-IR wavelengths, in Figures 1 to 3 these objects appear as white filaments. There is not a good correlation between the IR and RC morphology of IRDC’s, nevertheless IRDC’s are related with massive star formation regions, and several of them (e.g. IRAS 18222+1321) clearly cross through the center of the UC H II regions.

Images show the presence of dark patches in several UC H II + EE, which we suspect are IRDCs. It has been suggested that IRDCs could be the initial stage of massive star formation (similar to the pre-stellar cores of low mass star formation) and star clusters (e.g., Rathborne et al. 2006). If some IRDCs are forming high-mass stars and star clusters, and if the massive stars form in clusters with many lower-mass stars, then our imagery favors the idea that the IRDCs are related with the initial stages of both high and low–mass star formation, although because IRDCs are distant, the observations have so far lacked the sensitivity to detect lower-mass protostars.

4. IRAC PHOTOMETRY

From the list of UC H II + EE with available IRAC observations presented in Table 4, a subsample of 13 UC H II + EE was selected to be studied in more detail. These regions lie on the galactic plane in the interval 20°≤ l ≤50°of galactic longitude.
TABLE 2

SUMMARY OF SPITZER–IRAC PHOTOMETRY OF UC H II SOURCES

| UC H II Number | IRAS name   | RA2000       | DEC2000       | [3.6]–[4.5] | [5.8]–[8.0] | αIRAC |
|----------------|-------------|--------------|---------------|-------------|-------------|-------|
| 1              | 18097–1825A | 273.16498    | -18.40563     | -0.04       | 2.23        | 0.18  |
| 2              | 18222–1321  | 276.25469    | -13.26131     | 0.88        | 1.66        | 2.01  |
| 3              | 18248–1158  | 276.90905    | -11.94459     | 1.49        | 2.44        | 3.83  |
| 4              | 18248–1158  | 276.90557    | -11.94238     | 1.52        | 1.84        | 3.21  |
| 5              | 276.91150   | -11.94552    | 0.56          | 1.82        | 1.85        |       |
| 6              | 276.90965   | -11.94083    | 1.29          | 1.64        | 3.32        |       |
| 7              | 18311–0809  | 278.47304    | -8.12053      | 1.03        | 1.74        | 2.61  |
| 8              | 18311–0809  | 278.47186    | -8.11929      | 0.75        | 1.89        | 3.18  |
| 9              | 18353–0628  | 279.51210    | -6.39700      | 0.79        | 1.81        | 2.82  |
| 10             | 18402–0417  | 280.74260    | -4.23288      | 1.72        | 0.67        | 2.65  |
| 11             | 18469–0132  | 285.06682    | 4.05381       | 1.09        | 1.67        | 3.16  |
| 12             | 18538+0216  | 284.09413    | 2.34090       | 1.31        | 1.60        | 2.59  |
| 13             | 18577+0358  | 285.06682    | 4.05381       | 1.09        | 1.67        | 3.16  |
| 14             | 18593+0408  | 285.47342    | 4.21320       | 1.76        | 1.50        | 3.55  |
| 15             | 19120–0017  | 288.60926    | 9.37569       | 1.28        | 1.83        | 3.46  |
| 16             | 19120–1103  | 288.58885    | 11.15436      | 1.62        | 0.37        | -0.61 |
| 17             | 19181+1349  | 290.12751    | 13.92710      | 1.72        | 1.79        | 3.05  |
| 18             | 19181+1349  | 290.12751    | 13.92710      | 1.72        | 1.79        | 3.05  |
| 19             | 19181+1349  | 290.12751    | 13.92710      | 1.72        | 1.79        | 3.05  |

aIRAC sources coincident with the radio-continuum peak(s) of UC H II regions with extended emission (UC H II + EE).

RC maps of this sub-sample show –in some cases– more than one peak. Thus we identify 19 UC H II s within these 13 regions.

IRAC photometry available on-line[10] for these 13 regions was downloaded, searching for sources within a radius of 5′ around the EE and embracing the UC H II source(s). Although the photometry of a number of IR sources is obtained (see Table 3), no data were available for the IR counterpart of UC H II source(s), found –by visual inspection– to be within a tolerance separation of ~ 3″ from the radio-continuum emission peaks (see Figures 1 to 3).

Following the standard procedure[11] we used IRAF/qphot package on the 19 UC H II s to obtain individual point source photometry in all four IRAC bands. This process was performed on the pipeline mosaic images with 1.22″ of pixel size.

10http://irsa.ipac.caltech.edu/applications/Gator/ and then follow links to the highly reliable GLIMPSE I and GLIMPSE II catalogs of the Spitzer Space Telescope Legacy Science Programs.

11described at http://ssc.spitzer.caltech.edu/irac/iracphot.html

The source radius and the sky annulus were typically chosen to be 5–7 pix and 5–10/10–20 pix respectively. The greatest sky annulus value was used for radius greater than 5 pix and to avoid the flux contribution by nearby sources. Zero points were set to 17.30, 16.82, 16.33 and 15.69, while photons per ADU (epadu IRAF/qphot keyword) were set to 3.3, 3.7, 3.8, and 3.8, both for IRAC bands (channels) 1 to 4, respectively. Since this measurements were made source by source, only in some of them an aperture correction was necessary to apply. Photometrical errors are estimated to be ~0.2 mag. A summary of IRAC colors produced by these measurements is provided in Table 2.

4.1. IRAC color-color diagram

Once we completed the photometry for the UC H II sources within the EE regions we can plot both, these sources and the ones lying into the extended emission area obtained from GLIMPSE catalogs. Figure 4 shows the [3.6]–[4.5] vs. [5.8]–[8.0] diagram of the 13 regions. Different symbols are used to mark the nature of the sources.
in Classes I, II, and III, following the classification scheme introduced by Lada (1987), but applied to IRAC wavelengths. In this case, the SED slope ($\alpha_{\text{IRAC}} = d \log(\lambda F_{\lambda}) / d \log(\lambda)$) is calculated from 3.6 to 8.0 μm, and the classification criteria are: Class I for sources with $\alpha > 0$, Class II for $-2 \leq \alpha \leq 0$, and Class III for $\alpha < -2$ (Lada et al. 2006, Chavarria et al. 2008). Although this classification was initially done for low/intermediate-mass young sources, an extension to the high-mass (up to 50 $M_\odot$) regime has been theoretically studied by Robitaille et al. (2006, Rea06 hereafter) and a similar definition of Stages I, II, and III has been introduced.

One of the goals of our study is to define the observational locus of high-mass pre-main sequence stars into IRAC diagnostic diagrams. Thus, we have estimated $\alpha_{\text{IRAC}}$ also for the UC H II sources, their values are given in Table 2, and according to the previous classification, all except one (UC H II 17), would be Class I.

Note that in Figure 4 there is a zone where $\sim 75\%$ of the ultra-compact sources (denoted with triangles) are grouped, that locus is around $[5.8]-[8.0] \approx 1.7$ and $0.5 \leq [3.6]-[4.5] \leq 2.0$. They are lying towards the upper-right extreme of the Stage I sources and downwards into the region where all Stages I, II, and III can meet (see, Figure 23 in Rea06). And this locus spans more or less in the direction of extinction vectors.

Fig. 4. Color-color diagram of all the sources in the sample of 13 UC H II + EE regions, and with complete IRAC photometry. Dashed lines show the locus of Class II sources as defined by Allen et al. 2004, the two lines outwards from this square mark the lower limit of the locus of Class I sources, the upper one also shows the direction of interstellar extinction (Megeath et al. 2004, and references therein). Continuous lines show the Stages I, II, III, and the region where Stages meet, defined by Rea06 based on a best grid of theoretical models. Reddening vector of $A_V=20$ mag is also shown (Indebetouw et al. 2005).
Fig. 5. AM-product diagram. It is similar to those presented in KG07 for 381 high-mass protostellar candidates regions with GLIMPSE data available. Note that in this diagram, UC H II sources are lying on the edge of the “extreme” Class I sources.

4.2. AM product diagram

Following KG07, a definition of the 8.0 µm magnitude and $\alpha_{IRAC}$ product is given by $AM = -M_{8\mu m} \times (\alpha_{IRAC} + 6)/10$, and is called “AM product” (alpha-magnitude product). This definition, and then a plot of absolute magnitude in 8 µm vs. AM product, help to separate effectively the luminous sources and to compare between sources at different distances. Photometric 8 µm magnitudes of this sub-sample are between ~1.5–7 mag, and distances between 3.5 and 13.5 kpc. A plot of IRAC sources is shown in Figure 5. Vertical lines at AM product values of 6 and 10, mark the approximate position of theoretical models by Rea06 for Class I objects at 8 and 20 $M_\odot$, respectively (see, Fig. 3 in KG07).

A linear fit to the UC H II sources, and Classes I, II, and III, give the slopes -0.96, -0.97, -2.02, and -2.71, respectively. This values are close to 1, 2, and 3, as might be expected from the definition of AM product, for Classes I, II, and III, respectively. Negative values of the slopes come from the nature of the absolute magnitude values in y axis. The small difference in slope between UC H II sources and other Class I sources can be seen in Figure 5 with the triangles lying on the edge of the “extreme” Class I sources. This AM product plot suggests that some of the UC H II sources might be Class 0 candidates.

4.3. IRAC sources by class

The total number of sources by class in the sample of 13 UC H II + EE regions are: 8172 Class III, 902 Class II, 196 Class I, and 19 UC H II source. Source counts in each region by Class are listed in Table 3. Relative percentages to the number of IR sources by Class in each region are given in parenthesis.

Although the range of these sources varies form about 400 to 1000, the percentages are more or less consistent from region to region, and in average, ~88% are Class III sources, ~10% are Class II, and ~2% are Class I. These regions where selected...
TABLE 3
COUNTS OF IRAC SOURCES

| IRAS name         | N\(^b\) | Class I\(^c\) | Class II\(^c\) | Class III\(^c\) |
|-------------------|---------|---------------|----------------|-----------------|
| 18097–1825A       | 1100    | 19 (2)        | 80 (7)         | 1001 (91)       |
| 1822–1321         | 531     | 18 (3)        | 101 (19)       | 412 (78)        |
| 18248–1158        | 1028 (4)| 21 (2)        | 57 (6)         | 950 (92)        |
| 18311–0809        | 846 (2) | 7 (1)         | 100 (12)       | 739 (87)        |
| 18353–0628        | 810 (2) | 7 (1)         | 80 (10)        | 723 (89)        |
| 18402–0417        | 743     | 17 (2)        | 117 (16)       | 609 (82)        |
| 18469–0132        | 724     | 10 (1)        | 47 (6)         | 667 (92)        |
| 18538+0216        | 681     | 24 (4)        | 78 (11)        | 579 (85)        |
| 18577+0358        | 535     | 10 (2)        | 62 (12)        | 463 (86)        |
| 18593+0408        | 583     | 12 (2)        | 63 (11)        | 508 (87)        |
| 19120+0917        | 858     | 9 (1)         | 34 (4)         | 815 (95)        |
| 19120+1103        | 437 (2) | 26 (6)        | 50 (11)        | 361 (83)        |
| 19181+1349        | 394     | 16 (4)        | 33 (8)         | 345 (88)        |

\(^a\)Without including UC H\(^II\) sources, but see note\(^b\).

\(^b\)Number of sources with all four IRAC-bands data within a 5’ radius. In parenthesis, the number of UC H\(^II\) sources is given, when there are more than one in the region.

\(^c\)Numbers in parenthesis show the relative percentage.

because they embrace at least one young massive star evidenced by the radio-continuum peaks at 3.6 cm emission. And, it is interesting to note that the percentage averages for regions with more than one UC H\(^II\) source (IRAS 18248–1158, IRAS 18311–0809, IRAS 18353–0628, and IRAS 19120+1103) keep roughly the same values.

This numbers give an statistical base for a further study of the stellar evolutionary stage in these UC H\(^II\) + EE regions, and its relation with the observed stellar mass function. The photometry of the larger sample of 22 UC H\(^II\) + EE (listed in Table 1) will provide a more robust conclusion on these counts.

5. CONCLUSIONS

Because this is a work in progress, we list our preliminary conclusions.

1. Based on a comparison between RC maps at 3.6 cm (VLA conf. D) and GLIMP–IRAC images of a sample of UC H\(^II\) + EE, a coincidence of morphologies is observed. This indicate that heated dust coexists with ionized gas in the EE areas.

2. The peaks of RC emission are in most cases coincident with luminous IR counterparts. We identify broad (FWHM \(\sim\)8") IR point sources in the UC H\(^II\) position in several cases.

3. We perform Spitzer–IRAC photometry of 19 UC H\(^II\) sources in 13 UC H\(^II\) + EE regions (a subsample of F07), that are not available at GLIMPSE photometry catalogs.

4. This 19 UC H\(^II\) sources lie in a region located (locus) at \([5.8]–[8.0]\)\(\approx\)1.7 and \([0.5]–[3.6]\)\(\approx\)2.0, in the “classic” IRAC color-color diagram.

5. UC H\(^II\) sources also lie at the extreme border of Class I objects in the AM product diagram (KG07), suggesting that at least some of them might be Class 0 candidates.

6. Following an \(\alpha\)IRAC classification, we find that in average, the population of sources are: \(\sim\)2% of Class I (proto-stars), \(\sim\)10% of Class II (stars with disks), and \(\sim\)88% of Class III (stellar photospheres), in UC H\(^II\) + EE regions.

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