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Reliable Galaxy-wide identification of ultracompact H II regions

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ABSTRACT

We examine the problem of reliably identifying ultracompact (UC) H II regions from Galaxy-wide data bases. It is shown that there is significant contamination in the sample of potential UC H II regions, selected from the *IRAS* PSC using the two-colour criterion of Wood & Churchwell, due to cloud cores with lower mass stars. We identify additional criteria to reduce this contamination. First, we use the differences in the radio emission between the cores with embedded high- and low-mass stars to segregate them. Then, through a latitude analysis we further improve the reliability. Effectively, the total number of potential UC H II regions is brought down by a factor of ~ 4. This reduction eases the birth rate problem for massive stars, and offers a more reliable list of young massive stars for galactic structure studies. In the process, we have also identified a group of objects which may contain high-mass equivalents of the class 0 objects and clusters of intermediate-mass stars.

Key words: stars: early-type – H II regions.

1 INTRODUCTION

Stars of spectral type (SpT) earlier than B0.5, being short-lived objects, are likely to trace the galactic spiral structure accurately. They also inject substantial amounts of energy and momentum into the ISM and thus affect its evolution significantly. Furthermore, issues like birth rates of neutron stars and supernova remnants depend crucially on the birth rate of these massive stars. Therefore, it is of fundamental importance to know their number, birth rate and distribution in the Galaxy. Such massive stars, when newly born and still embedded in their natal cloud, manifest as ultracompact (UC) H II regions. They produce copious IR radiation, which makes it possible to detect them in the entire Galaxy. Clearly, methods of identifying them from Galaxy-wide data bases like the *IRAS* Point Source Catalog (PSC) are very desirable. The first effort in this direction was made by Wood & Churchwell (1989b, hereafter WC). Based on the similarity of the FIR spectra of the known UC H II regions, WC evolved a two-colour criterion (hereafter, WC-FIR criterion) that characterizes them. Applying this WC-FIR criterion to the entire *IRAS* PSC they found the total number of potential UC H II regions in the Galaxy to be between 1500 and 3000. This number implied too high a birth rate of massive stars compared with that derived by other methods. This problem was somewhat eased by extending the duration of the compact phase of H II regions using the relative motion between the clouds and the embedded massive stars. Observed cometary morphology of many UC H II regions supports this explanation. However, only ~ 20 per cent of the observed sources have this morphology, indicating that other explanations are also needed. WC recognized that their sample is likely to be contaminated by cores with low-mass stars (hereafter, cores) but considered this to be insignificant (see reviews by Churchwell 1990a,b). In this paper we show that the WC-FIR sample may actually be dominated by objects other than UC H II regions and we present methods to improve the situation. It is important to improve the reliability of these identifications for accurate birth rate estimation, studies of galactic structure and higher angular resolution studies of UC H II regions.

In Section 2, we demonstrate that substantial contamination due to the cores is expected. Section 3 deals with an additional constraint that can be used to segregate the

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potential UC H II regions from the cores based on the differences in their spectral behaviour in the radio regime. In Section 4, we apply this constraint to the WC-FIR sample using the 1987 Green Bank (87GB) and Parkes-MIT-NRAO (PMN) Galaxy-wide 5-GHz radio survey data, which became available recently, to separate the cores and the UC H II regions. An analysis of the latitude distribution of the sources presented in Section 5 shows that the WC-FIR/radio criterion is still insufficient and an additional flux constraint is needed to reliably identify UC H II regions. In Section 6, we discuss the various kinds of objects present in the WC-FIR sample and isolate a list of sources that are highly likely to be UC H II regions.

2 LEVEL OF CONTAMINATION DUE TO THE CORES

The *IRAS* colour–colour plot in Fig. 1 (adapted from WC) shows the known UC H II regions and *IRAS* point-sources from arbitrarily chosen comparison regions. The WC criterion region and the embedded colours region bounded by the criterion of Emerson (1987) are also shown. The latter sources include H II regions, reflection nebulae and embedded young stars. Not surprisingly, there is appreciable overlap between the regions bounded by these criteria.

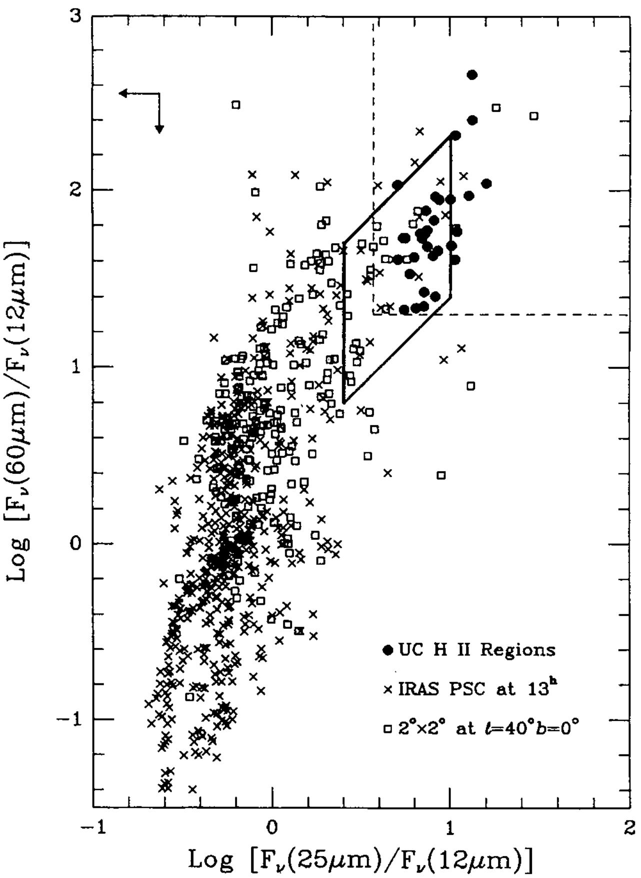

Figure 1. The *IRAS* colour–colour plot (adapted from WC) showing the UC H II regions. The WC criterion region is indicated by broken lines and the embedded colours region of Emerson (1987) by continuous lines.

When a star is embedded in a dense core, most of its short wavelength radiation is reprocessed by the surrounding dust cocoon into FIR radiation before it escapes. While the FIR luminosity is nearly equal to the total luminosity of the embedded source, the resultant FIR spectrum reflects the characteristics of the optically thick cocoon (such as dust composition, grain sizes, etc.) rather than of the inner source. Since the properties of the dust cocoons for all embedded stars are likely to be similar, it is natural that their emergent spectra, and hence their colours, will be similar as well. Thus, the WC-FIR criterion will select both low- and high-mass stars embedded in molecular clouds. WC have argued that the cores with low-mass stars, being faint, are detectable only in a small local volume, and hence would be small in number. Even though this is true, their number density is large and hence they can contribute substantially to and contaminate the sample selected on the basis of WC-FIR criterion. The following calculation, considering each core to have only one star, demonstrates this.

To compute the level of contamination, one needs to determine how many cores and UC H II regions would have been detected by *IRAS*. Given a certain sensitivity, the number of stars in a mass interval $[M_1, M_2]$ detectable through their reprocessed radiation can be expressed as

$$N(M_1 < M \leq M_2) \propto \int_{M_1}^{M_2} \tau_M A_M M^{-2.7}\, \mathrm{d}M. \tag{1}$$

Here, τ_M is the time a star of mass M spends in the embedded phase and A_M is the area of that portion of the Galactic disc over which it would be detected by the *IRAS* survey. We have used a power-law mass function with an index of -2.7 to represent the mass dependence of the area density of stars. Owing to the lack of any systematic studies, we will assume τ_M to be a constant. To determine A_M, one needs to know the form of the average spectrum for the objects with embedded colours. A power-law relationship of the form $S_\nu = S_0(\nu/\nu_0)^{-\alpha}$ is found to fit the spectra of the known objects of this kind, over the FIR region, with α lying between 1 and 2.5. Taking α to be 1.65 and assuming that 50 per cent of the stellar radiation is converted into FIR, one obtains the following relation between the stellar luminosity and the flux density at a frequency ν (by setting $4\pi d^2 \int_{\mathrm{FIR}} S_\nu\, \mathrm{d}\nu = L_*/2$):

$$S_\nu = \frac{L_*}{(2.4\,\nu_0 \times 4\pi d^2)} \times \left(\frac{\nu_0}{\nu}\right)^{1.65}. \tag{2}$$

Here, ν_0 is 3×10^{12} Hz, the frequency corresponding to 100 μm. The flux determined in this way is within a factor of 2 of the fluxes determined using the extreme values for α. Setting this flux equal to the *IRAS* detection limit at 12 μm which is 0.4 Jy, one obtains the limiting radius. Then, for any given mass, using the corresponding luminosity, A_M can be found as the area of intersection between the circle of this radius and the Galactic disc. For this purpose, we take the Galactocentric distance of the Sun to be 8.5 kpc and the radius of the Galactic disc to be 15 kpc. Table 1 lists the various quantities of interest in these calculations. The stellar masses, luminosities, spectral types, limiting radii and A_M are given in columns 2, 3, 4, 5 and 6, respectively. Stars with

Table 1. Contamination in WC-FIR sample owing to the cores.

No.	M	L	SpT	R_l	A_M	NΔM	cum(NΔM)
	$M_\odot$	$L_\odot$		kpc	$(kpc)^2$		%
1	120	2437810.8	O3	331.6	707.0	0.09	00.38
2	85	1606941.3		269.2	707.0	0.17	01.06
3	60	970510.0	O5	209.2	707.0	0.37	02.56
4	40	494310.7		149.3	707.0	0.88	06.15
5	25	194984.5	O8	93.8	707.0	0.79	09.39
6	20	115080.0	O9	72.0	707.0	1.56	15.76
7	15	54575.8	B0.5	49.6	707.0	1.88	23.46
8	12	28973.4	B1	36.2	707.0	3.69	38.57
9	9	11561.1	B2	22.8	700.3	4.18	55.66
10	7	4830.6	B3	14.8	446.1	5.03	76.23
11	5	1419.1		8.0	188.1	2.35	85.84
12	4	597.0	B8	5.2	84.6	1.88	93.52
13	3	183.2	A0	2.9	25.9	0.62	96.04
14	2.5	83.9		2.0	11.9	0.46	97.93
15	2	32.2	A5	1.2	4.6	0.19	98.73
16	1.7	15.7	A8	0.8	2.2	0.10	99.14
17	1.5	9.8	F2	0.7	1.4	0.11	99.57
18	1.25	4.5	F5	0.5	0.6	0.08	99.90
19	1	1.7	G0	0.3	0.2	0.02	100.00
20	0.9	1.2	G5	0.2	0.2		

masses $\gtrsim 5\,M_\odot$ can be seen up to the edge of the Galaxy and hence the area applicable is that of the Galactic disc. For stars with masses $\lesssim 3\,M_\odot$, the circles with the limiting radii are completely enclosed by the Galactic disc and thus the relevant areas are simply those of the circles. Column 7 lists the integral in equation (1) with the limits being the successive entries in column 2. Column 8 is the cumulative sum of the entries in column 7, expressed as percentages. Fig. 2, which presents this data graphically, shows that ~ 50 per cent of the sources seen by *IRAS* come from masses of less than $10\,M_\odot$ and that the degree of contamination is ~ 75 per cent, if stars more massive than $\sim 15\,M_\odot$ (SpT $\sim$ B0.5) result in UC H II regions and those less massive manifest as cores. This calculation is admittedly simplistic. For example, it assumes that τ_M is independent of mass, while it is actually likely to decrease with increasing mass. Also, the pre-main-sequence luminosities are likely to be higher for lower mass stars (Fletcher & Stahler 1994). These effects would make the contamination more severe. On the other hand, the above analysis assumes that all cores with embedded low-mass stars satisfy the WC criterion. This is not true, as can be seen from Fig. 1. This would reduce the contamination. Thus, while the calculation is not rigorous, it does show that there will be significant contamination and further filtering is needed to obtain a reliable list of UC H II regions in the Galaxy.

3 RADIO EMISSION CRITERION

It is clear from the above discussion that the contamination due to the cores can be significant. We propose a simple method of using cm-wavelength continuum fluxes to filter out the cores from the WC-FIR sample, based on the differences in the observed flux density distributions of the UC H II regions and the cores. Although both kinds of objects are likely to have similar FIR spectra owing to the

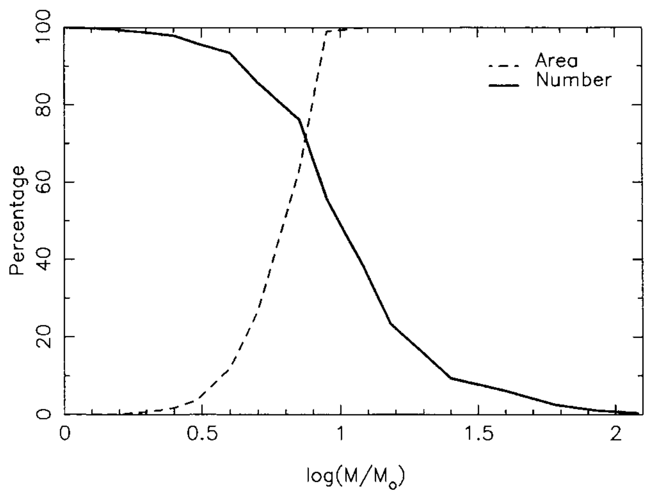

Figure 2. Plot showing relative contributions to *IRAS* detections by stars with various masses (x-axis). The broken line shows area seen by *IRAS* as a percentage of the total Galactic disc area. The solid line shows the percentage cumulative contribution from stars up to a given mass.

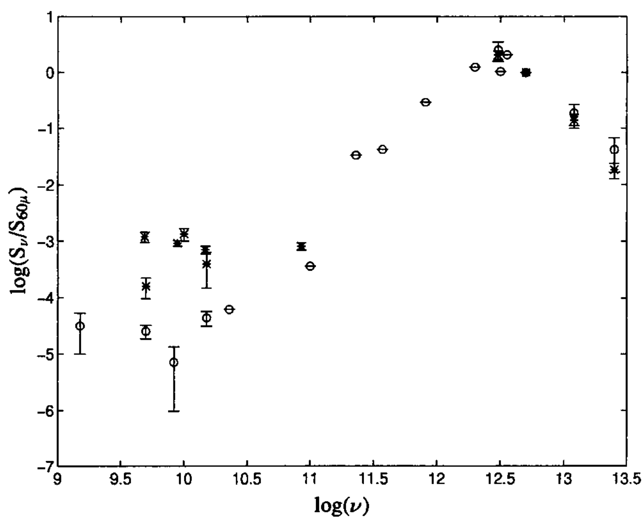

Figure 3. Normalized and ensemble-averaged spectral energy distributions of known UC H II regions ($*$) and embedded low-mass stars (O).

similarity in the conditions of their dust cocoons, the low-mass stars inside the cores are not hot enough to create an ionized nebula. Therefore, their radio spectrum is expected to fall off at lower radio frequencies where the sources with H II regions will have substantially higher flux densities due to the thermal free–free emission from the ionized gas. The observed spectral energy distributions, normalized with respect to S_{60}, of some known UC H II regions ($*$) and the cores (O) are shown in Fig. 3 (data from Wood & Churchwell 1989a,b, Kenyon, Calvet & Hartmann 1993, Reipurth 1994 and Andre & Montmerle 1994). Each point in the figure is an average over many sources for which relevant data were available. The error bars are 1σ of the source-to-source variations. The figure clearly shows that while the flux densities overlap in the *IRAS* bands causing the contamination, at centimetre wavelengths the flux density from the cores is smaller than that from the UC H II regions by up to a factor of 100. Even with the scatter taken into account, the two populations appear clearly separated. We propose to use a limit on the ratio $S_{100\,\mu m}/S_{5\,GHz}$ as an additional constraint to eliminate the cores.

4 CORRELATION OF *IRAS* PSC WITH 5-GHz RADIO SURVEYS

Having found out from the existing radio data that the cm-wavelength radio fluxes can be used as a means of filtering out the cores from the WC-FIR sample, we undertook such an exercise using Galaxy-wide 5-GHz continuum surveys. We used the 87GB (Gregory & Condon 1991), PMN Southern (PMNS) and PMN Tropical (PMNT) source catalogues which together cover almost the entire sky (Griffith et al. 1994; Wright et al. 1994). As the PMN Zenith survey data are not yet available, a small portion of the Galactic plane is left out. The sensitivity of these surveys, which is in the range of 20–50 mJy, is sufficient to pick out most of the UC H II regions except the most distant ones (assuming a value of 10^3 for the ratio $S_{100\,\mu m}/S_{5\,GHz}$, a B0.5V star can be seen up to 15 kpc). Hence, we correlated the radio point-sources obtained from these surveys with the WC-FIR sample, which resulted in 594 radio-loud (detections) and 1140 radio-quiet (non-detections) sources, after excluding sources from the Large and Small Magellanic Clouds. Clearly, this constraint has been quite useful in that it has reduced the number of potential UC H II region candidates by a factor ~ 3. Some of the faint FIR sources may still be UC H II regions but radio-quiet due to the sensitivity limit. We show in Section 6 that the number of such objects is small.

Another point to note is that distant diffuse H II regions with associated or line-of-sight embedded colour objects would also be included in the list of potential UC H II regions, as the angular resolution of the surveys was only ~ 3 arcmin (comparable to that of *IRAS*). In this regard, it may be noted that Codella, Felli & Natale (1994) have found that a subset of diffuse H II regions also satisfies the WC-FIR criterion. However, more than 62 per cent of them have associated UC H II regions and hence do not represent contamination. Based on their data we estimate the contamination due to diffuse H II regions that are not associated with UC H II regions to be only $\lesssim 15$ per cent. This we consider not to be significant.

5 MEAN LATITUDE OF SOURCES IN VARIOUS FLUX DENSITY RANGES

After segregating the WC-FIR sample into radio-quiet and radio-loud groups using 5-GHz surveys, we set out to test the hypothesis that the radio-loud WC-FIR sources are most likely to be UC H II regions. If this hypothesis is true, then, among the radio-loud sources the FIR-bright ones are likely to be nearby while the FIR-faint ones are likely to be farther away. Accordingly, for a given scaleheight, the FIR-bright sources would span a larger width in galactic latitude while the rest would span a narrower width. In other words, with respect to S_{60} flux density, the mean of the absolute latitude of sources should be expected to increase. With this in mind, we binned the two groups of sources separately into various S_{60} flux density ranges with constant logarithmic separation. This yielded a similar number of sources in most of the bins except at the ends. We calculated the mean absolute latitude for each of the bins by weighting the source latitudes with $1/\cos(b)$. This weighting accounts for the dependence of the source distribution on latitude due to the coordinate system. With this weighting an isotropic distribution will give a mean latitude of 45°. Fig. 4(a) shows the variation of these mean absolute latitudes with S_{60}. Surprisingly, the faint IR sources have a wider latitude distribution while the brighter ones tend to be more confined to the Galactic plane, contrary to our expectation. The break between the faint and bright IR sources occurs at around a value of 90 Jy for S_{60} which, henceforth, will be referred to as the knee point. The fact that the radio-loud sources have a nearly isotropic distribution (mean latitude = 45°) below the knee point suggests that they may be of extragalactic origin. We correlated these sources (a total of 165) with sources from the Catalogued Galaxies and Quasars Detected in the IRAS Survey (Persson et al. 1985) and found 42 of them to be associated. Of the 165 sources, only 51 had absolute latitudes $>5°$ of which 40 were among these associations, suggesting that most of the sources outside 5° latitude are extragalactic. The fall in the mean lati-

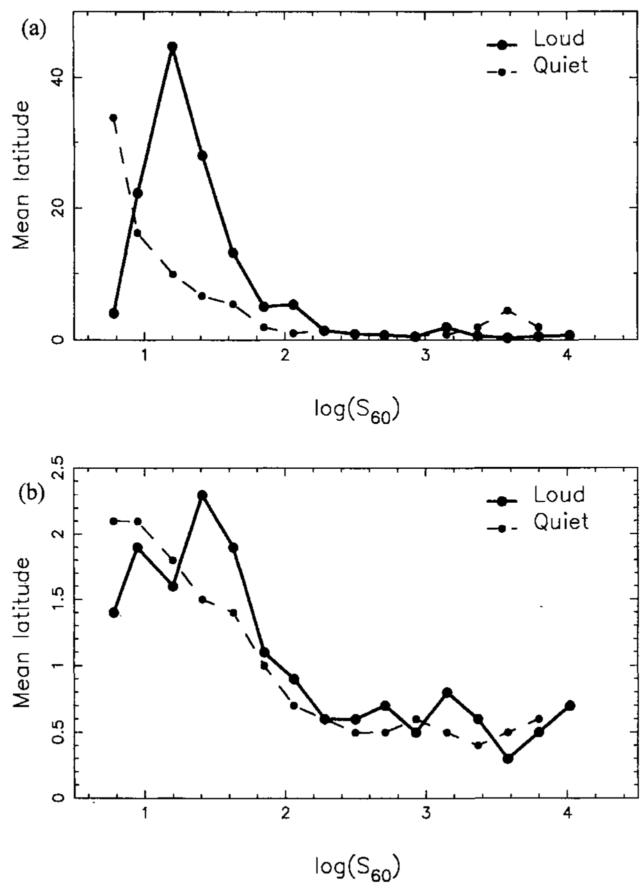

Figure 4. (a) Dependence of mean latitudes on the 60-μm flux of all the WC-FIR-selected sources. The solid line is for the radio detections and the broken line for the non-detections. A mean latitude of 45° indicates isotropic distribution. (b) Same as (a), but for sources within 5° latitude alone.

tude at the faint FIR end for the radio-loud sources is possibly due to the radio sensitivity limit which is consistent with the absence of such a fall-off for the radio-quiet sources. Among the 133 radio quiet sources below the knee point and lying outside 5° latitude, 48 were found to be extragalactic. The rest are likely to be cores. We restrict further discussion to sources within 5° latitude. There will be hardly any extragalactic contamination (five sources, as estimated from the above numbers) in this restricted sample. Their mean latitudes are plotted in Fig. 4(b). The break at 90 Jy, which persists, corresponds to the flux expected from either a star of spectral type B0.5 at ~ 15 kpc or A0 at ~ 0.6 kpc. Hereafter, sources having FIR fluxes above 90 Jy will be referred to as FIR-bright and those below as FIR-faint. Thus, in combination with the radio data, we have four categories of sources: radio-loud and FIR-bright; radio-loud and FIR-faint; radio-quiet and FIR-bright; and, finally, radio-quiet and FIR-faint. The number of sources in each of them, respectively, is 419, 115, 573 and 415.

6 DISCUSSION

Now we discuss the kinds of sources making up the four categories. Stars that cause UC H II regions (earlier than SpT $\sim$ B0.5) located closer than 15 kpc will be radio-loud and FIR-bright and the cores farther than 0.6 kpc will be radio-quiet and FIR-faint and would dominate their respective groups. Hence, we conclude that the 419 sources in the first group are highly likely to be UC H II regions. The radio-loud and FIR-faint group is likely to be made up of nearby UC H II regions caused by relatively lower mass stars, with partial dust coverage, and line-of-sight coincidences of cores with normal H II regions. The radio-quiet and FIR-bright group can contain only a small fraction of normal UC H II regions, which are undetected in radio observations due to the limited sensitivity. We have estimated the number of such objects as follows. First, we constructed the distribution function of the ratio $S_{5\,\mathrm{GHz}}/S_{100\,\mu\mathrm{m}}$ for the UC H II regions using the radio-loud and FIR-bright sources. This distribution is shown in Fig. 5 (actually $S_{100\,\mu\mathrm{m}}/S_{5\,\mathrm{GHz}}$ is shown for easier comparison with earlier work). Then, we convolved the $S_{5\mathrm{GHz}}/S_{100\mu\mathrm{m}}$ distribution with the

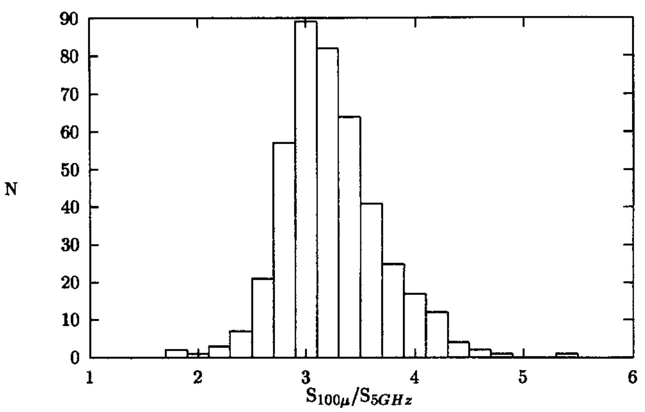

Figure 5. Histogram showing the distribution of the ratio of the 100-μm flux to the 5-GHz flux.

$S_{100\,\mu\mathrm{m}}$ distribution of the radio-quiet and FIR-bright objects. We found that of the 573 objects in this category only 27 could have had fluxes below 50 mJy and, thus, could be UC H II regions but undetected at radio wavelengths. Hence, most of the radio-quiet and FIR bright sources are unlikely to be normal UC H II regions. Considering that their mean latitude dependence with S_{60} is very similar to that of the potential UC H II regions, it appears that they must also be distributed all over the Galaxy in a way very similar to the UC H II regions. One explanation could be that they are clusters of intermediate-mass stars producing sufficient total luminosity but not enough in the UV region to create UC H II regions. A more interesting possibility is that some of these sources are the Class 0 equivalents of high-mass stars (HMC0 hereafter; Wilner, Welch & Forster 1995), representing very early stages in their evolution. Clearly they are not accompanied by older massive stars, which would have otherwise shown up in radio. This gives an ideal opportunity to identify and study isolated HMC0 objects: since massive star formation seems to proceed in clusters, HMC0 objects are often found in the vicinity of UC H II regions; this makes higher angular resolution interferometric studies difficult owing to dynamic range problems; therefore, finding isolated HMC0 objects is important, and the radio-quiet and FIR bright sample may contain many of them. It is important to determine the frequency of HMC0 objects in the sample, to understand the length of this phase and the role of dust in delaying the onset of UC H II phase that follows it. In any case, it would be interesting to investigate the nature of the objects in the radio-quiet and FIR-bright category.

In the early stages, UC H II regions may have dust mixed with the ionized gas. This diminishes the available ionizing flux and hence the emission from the ionized gas. Also, since stars seem to form in clusters, there will be low-mass stars along with high-mass stars contributing only to the FIR radiation. These effects make the ratio of the FIR to radio fluxes different from estimates based on both single-star and cluster models. Kurtz, Churchwell & Wood (1994, hereafter KCW) have studied the FIR to radio flux ratio of a limited sample of sources to assess the magnitude of these effects. They find that there is an appreciable role for volume-mixed dust as well as contribution from low-mass stars. Using Very Large Array (VLA) radio data, they find the values of $\log(S_{100\,\mu\mathrm{m}}/S_{15\,\mathrm{GHz}})$ to lie in the range 3–5.6. However, we find the values of $\log(S_{100\,\mu\mathrm{m}}/S_{5\,\mathrm{GHz}})$ to lie in the range 2–4.8, a factor ~ 10 different from the KCW values. Since the turnover frequencies are likely to lie between 5 and 15 GHz, the spectrum will be flat here and the fluxes at 5 and 15 GHz will not differ much. However, a significant contribution seems to come from the differences between single-dish and array fluxes, with the single-dish fluxes being higher. According to KCW, confusion and contamination from nearby sources and extended galactic background emission affect the single-dish radio fluxes. We would like to point out that: (a) the method of measuring the fluxes with respect to the baseline, adopted in the PMN and 87GB surveys, should reduce the contamination from extended galactic background; (b) it is appropriate to include all the sources that fall within the *IRAS* beam for the purpose of finding FIR to radio flux ratios, and this will indeed reduce the ratio. A more likely cause for the difference could be the flux in structures larger than 18 arcsec being missed by the VLA (see for example, Balser et al. 1995). It is not clear why UC H II regions should have such extended emission. The clumpy nature of the ISM close to the birth sites could be responsible. Nevertheless, such extended emission seems to be present and we believe it is appropriate to use the ratios based on single-dish fluxes as they have angular resolutions comparable to that of *IRAS* (1 to 2 arcmin). If our values were used, the measured points would shift to the left in Fig. 157 of KCW, implying a lesser role for volume-mixed dust. We cannot, at present, comment on the contribution to the FIR flux from low-mass stars because distances to most of the sources in the sample are not known. As noted above, however, the FIR-bright radio-quiet sources indicate that star formation is likely to happen in a clustered mode with sizeable contribution to the FIR coming from low-mass stars. In any case, the difference between the VLA and single-dish fluxes needs to be understood, quantitatively, as do the absorption by dust and the effect of low-mass stars, to make the numbers of UC H II regions estimated here more accurate.

We conclude that the number of UC H II regions in the Galaxy detected by *IRAS* is likely to be between 400 and 500. This is a factor of 4 less than the number arrived at by WC. This reduction in contamination will help in the investigation of the Galactic spiral structure and ease the birth rate problem. Massive pre-main-sequence stars probably have no detectable radio emission during their rapid accretion phase, and will not be found in our list of UC H II regions. Since this phase is likely to be very short-lived, the number of such objects will be very small, and in any case they are not UC H II regions although they will become so in future.

7 SUMMARY

We have examined the problem of identifying UC H II regions from Galaxy-wide data bases. It was demonstrated that there may be significant contamination of the WC-FIR sample by objects other than UC H II regions. The contamination was reduced in two steps: (1) by using radio continuum data; (2) through a latitude analysis. Effectively, the total number of potential UC H II regions has been brought down by a factor ~ 4. This reduction facilitates study of the galactic structure using massive stars and eases their birth rate problem. In the process, we have also identified a group of objects that may be clusters of intermediate-mass stars or high-mass equivalents of the class 0 objects.

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