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ULTRACOMPACT H II REGIONS IN THE OUTER GALAXY

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RESUMEN

Se reportan los resultados preliminares de una búsqueda de regiones H II ultracompactas en las partes exteriores de la Galaxia, usando el VLA. Se describen brevemente el contexto histórico y la motivación de esta búsqueda, además de los resultados más importantes. Se encontró emisión compacta en el radio cerca de 41 de las 101 fuentes de *IRAS* que observamos, lo que da un límite superior de 40% de "éxito" a los criterios de colores de *IRAS* usados para indentificar candidatos a regiones H II ultracompactas. No fueron encontrados nuevos tipos de morfologías, y sobre todo, no se detectó el alto grado de aglomeración que fue encontrado en otras búsquedas. Terminamos con algunos comentarios generales y preventivos, sobre el uso de las densidades electrónicas y los tamaños de regiones H II en la comparación de los tipos morfológico con modelos de estas regiones.

ABSTRACT

We report the preliminary results of a VLA survey of ultracompact H II regions in the outer Galaxy. A brief historical context and motivation for the survey is given, along with the more important results. Compact radio emission was found near 41 of the 101 *IRAS* sources observed, providing an upper limit of 40% to the success rate" of the *IRAS* color selection criteria used to identify candidate ultracompact H II regions. No new morphological types were seen, and very notably absent was the high degree of clustering of sources seen in other surveys. We conclude with a few general, cautionary remarks concerning the use of electron densities and H II region sizes in the comparison of morphological types with models of these regions.

Key words: **H II REGIONS — STARS: EARLY-TYPE — STARS: FORMATION**

1. INTRODUCTION

Surveys of ultracompact H II regions (UC H II regions) have seemed almost common in recent years. The largest undertakings were made by Wood & Churchwell (1989a, hereafter WC) and by Kurtz, Churchwell, & Wood (1994, hereafter KCW), but significant numbers of new regions have also been observed by Garay et al. (1993), Miralles, Rodríguez, & Scalise (1994), Becker et al. (1994), and Gaume et al. (1995), among others.

To put the larger of these surveys into a brief historical context, we note that the first survey, the multi-wavelength (2 and 6 cm) sub-arcsecond ($0\farcs5$) survey of WC, was based on existing, low-resolution radio surveys of the Galaxy. Wood & Churchwell essentially used bright, un-resolved sources from the survey of Wink, Altenhoff, & Mezger (1982) as candidates for locating UC H II regions. Their method was reasonably fruitful: they detected some 75 compact sources in about 50 fields and had some 31 non-detections. It was their work that first demonstrated the existence of five distinct morphological types (cometary, core-halo, shell, spherical, and irregular or multiply-peaked). Just as important, if not more so, was their next step: they looked for *IRAS* point sources nearby the compact radio sources. By examining the far infrared colors of these *IRAS* sources with radio counterparts, they were able to devise a set of two-color selection criteria to locate candidate UC H II regions using the *IRAS* Point Source Catalog. In particular, they found that most of the *IRAS* sources that had nearby ($\lesssim 1'$) compact radio sources fell into a region of the color–color plane described by *IRAS* flux densities that satisfied the relations $F_{60}/F_{12} > 19.9$ and $F_{25}/F_{12} > 3.7$. Because of the sensitivity of *IRAS* and its nearly all-sky coverage, the color criteria can potentially locate almost all embedded early-type stars in the Galaxy. Searching the Point Source Catalog, Wood & Churchwell found $\sim$ 1700 sources that satisfied these criteria and hence were UC H II candidates. From this result they drew a number of significant conclusions regarding the probable number of UC H II regions in the Galaxy and the lifetimes of these small, dense nebulae (Wood & Churchwell 1989b).

To test the efficacy of the Wood & Churchwell criteria, KCW conducted a follow-up VLA survey at 2 and 3.6 cm, also with sub-arcsecond resolution. Their selection criteria were blind, in that no attempt was made to reject known objects prior to the observations. Their only formal requirement was that the sources have the Wood & Churchwell colors. However, they also chose sources which were quite luminous at 100 μm; all were over 1000 Jy, and most were over 2000 Jy. This may have important implications for the "success" of the color criteria, as we shall see below. KCW also found about 75 compact sources, and reported an upper limit to the "success rate" of the color criteria of 80%. They found roughly equal rates of occurrence of the various morphological types reported by WC. As with WC, however, the sources observed by KCW were primarily in the first two galactic quadrants. The survey which we report here extends these studies to the outer Galaxy region. This survey will tell us how well the color selection criteria work in the outer Galaxy. It will also serve as a tracer of massive star formation in the outer Galaxy and give us some idea of possible physical differences between the UC H II regions in the inner and outer galactic regions.

2. THE SURVEY

From the list of *IRAS* point sources with the Wood & Churchwell colors, we selected $\sim$ 15 sources in each 25° interval of galactic longitude, between $90° \leq l \leq 270°$. There generally were more than 15 potential sources in each interval, and to select the 15 we would observe we picked objects with lower galactic latitudes and larger 100 μm flux densities. Presumably these biases will tend to favor the detection of UC H II regions. Although massive stars may form in the galactic warp and thus be further from the plane, or be nearby, and thus have higher galactic latitudes, generally one expects massive star formation to occur relatively close to the plane. Hence, rejecting high latitude sources might improve the detection rate. Similarly, some UC H II regions might have relatively low far infrared flux densities because they are more distant. But because other types of objects (e.g., galaxies or giant F stars) might have similar colors but be much less luminous, rejecting the lower flux density sources might also tend to weed out non-UC H II regions from the sample, thus raising the detection rate.

It is worth noting some differences between this sample and that of the KCW survey. The two largest differences, in fact, relate to galactic latitudes and 100 μm flux densities. Despite the source selection biases noted above, the present survey has more sources at higher latitudes and is much fainter at 100 μm, compared to the KCW survey. In Figure 1 we show a histogram of all *IRAS* sources meeting the Wood & Churchwell color criteria, with $|b| \leq 5°$, $F_{100} \geq 100$ Jy and lying within the latitude range mentioned above. Even omitting the sources with $F_{100} < 100$ Jy from the histogram, it is obvious that the $F_{100} > 2000$ Jy sources of KCW constitute an extreme with respect to the present sample. Recent work by Codella, Felli, & Natale (1994) suggests that for H II regions in general (not just ultracompact regions) the probable association with the infrared counterpart drops significantly when the 60 μm flux density falls below about 300 Jy (the color criteria do not ensure that $F_{100} > F_{60}$, but this is almost always the case). As Figure 1 indicates, this is precisely the flux density which occurs most frequently in our sample. Moreover, KCW found that UC H II regions *never* have far-infrared (100 μm) to optically thin radio (2 cm) flux density ratios which are are smaller than about 1000. They explained this in terms of the properties of early type stars, in particular, the relative fraction of ionizing radiation produced. When the factor of 1000 reduction in flux density is applied to the relatively lower F_{100} values of this survey, one is left with flux densities $\lesssim$ 1 mJy, which would be only marginally detectable by the 3.6 cm data, and well beyond the reach of the 2 cm observations. Indeed, at this level, one would wonder if in fact an UC H II region was being observed, or perhaps an ionized stellar wind.

The distribution of our sample with respect to the galactic plane is evident in Figure 2, where we show the latitude of all sources detected in both the WC and KCW surveys, along with the candidate regions of the present survey. A handful of sources from the earlier surveys were located well out of the plane; most of these are in the Orion region. For the most part, the sources from the WC and KCW sources are very highly confined to the disk, while very few of the sources from the present survey are within a degree or so of the disk. This may, in fact, have some relation to the low 100 μm flux densities. KCW, in their figure 155, plot F_{100} vs. galactic latitude, and note that the distribution in latitude is narrowest for the higher flux densities, spreading somewhat as the flux densities drop, and flaring out dramatically for F_{100} values less than several hundred Janskys.

VLA observations of 101 *IRAS* sources were made in scaled B and C arrays, giving approximately 1″ resolution at both 3.6 and 1.3 cm. The observations were sensitive to structures $\lesssim$ 20″ in size. Five and ten minute snapshot observations were made (at 3.6 and 1.3 cm respectively) giving 3σ detection levels of $\sim$ 0.2 mJy at 3.6 cm and $\sim$ 2.5 mJy at 1.3 cm.

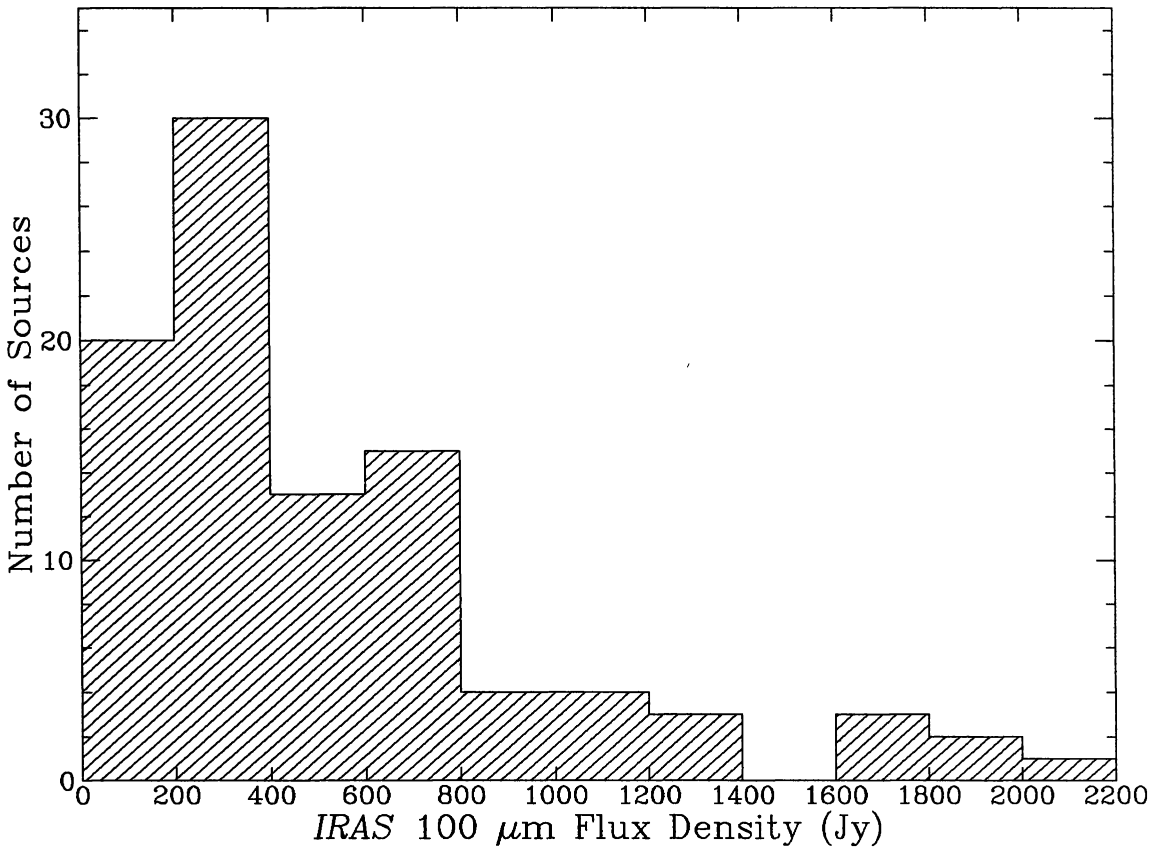

Fig. 1. A histogram of the *IRAS* 100 μm flux densities for the sources observed in this survey. Note in particular that the bulk of the sources have flux densities of several hundred Jy, while only a few have fluxes greater than 2000 Jy, the nominal ***lower limit*** for the KCW survey.

3. THE RESULTS

Of the 101 *IRAS* sources observed, 41 showed signs of compact radio structures at 3.6 cm, with a total of 46 individual sources. When these 41 were re-observed at 1.3 cm, 23 were found to have radio emission. A substantial fraction of the sources detected at 3.6 cm would ***not*** be detected at 1.3 cm unless the source had an optically thick thermal spectrum (i.e., $S_\nu \propto \nu^2$). The 3σ noise level at 1.3 cm is more than ten times higher than the corresponding 3.6 cm values (i.e., 2.5 mJy vs. 0.2 mJy). Hence, any source with an optically thin thermal spectrum ($S_\nu \propto \nu^{-0.1}$) and a 3.6 cm flux density of a few mJy would not be detected by our 3.6 cm observations.

Using the 41 detections, we report an upper limit to the "success rate" of the color criteria of 40%. We stress that this is an upper limit because we have ***not*** confirmed that all 46 sources are in fact UC H II regions. We can calculate spectral indices only for the 23 sources which have detections at both wavelengths (none

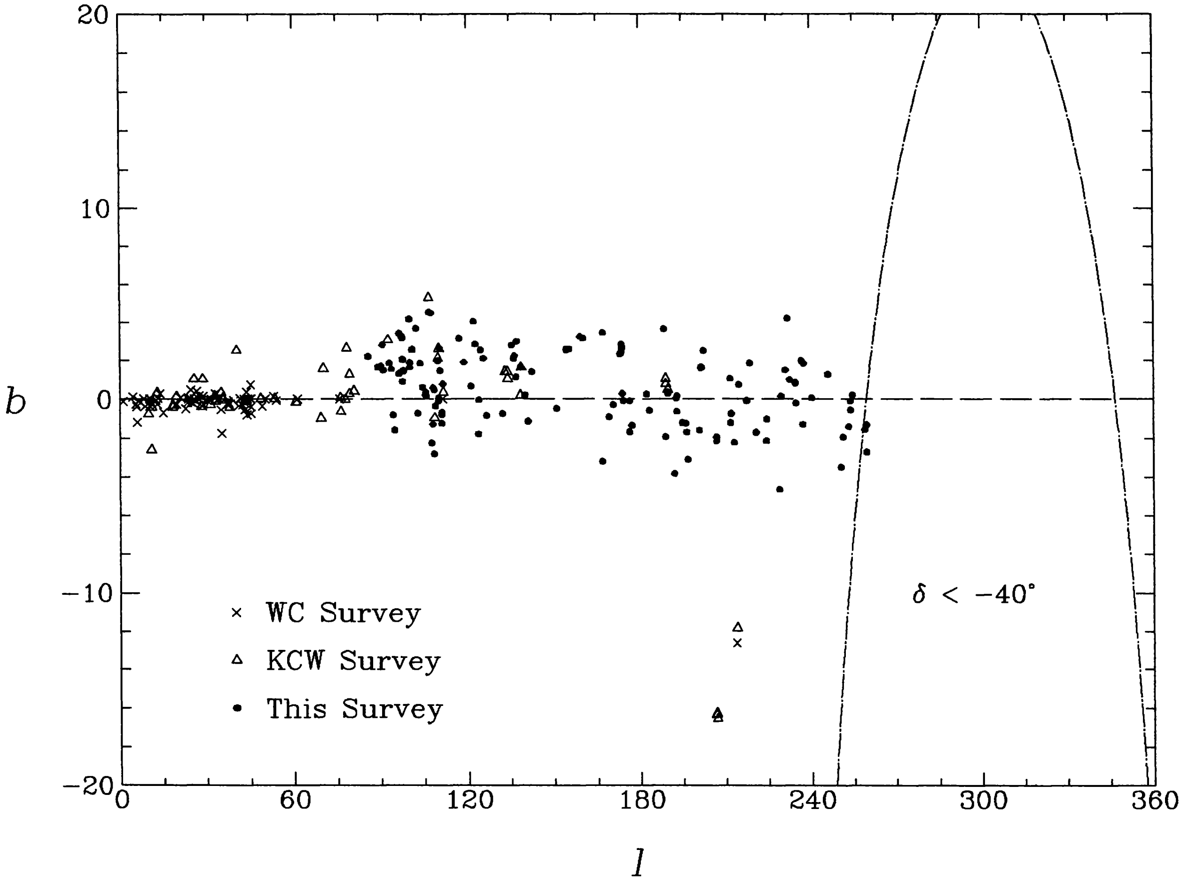

Fig. 2. The distribution in galactic coordinates of the sources from the WC, KCW, and the present, outer Galaxy surveys. The dashed line (indicating sources with declinations south of −40°) shows the region not accessible from the VLA. The WC and KCW sources are clearly concentrated toward the inner Galaxy and are tightly confined to the galactic plane, while the present survey extends to the limits of the VLA coverage and has sources lying much further from the galactic plane, on average.

are non-thermal). We have kinematic distances for about 30 of these objects; assuming that only one star is responsible for the ionization of each nebula, and that the nebulae are ionization bounded and dust-free, we are able to calculate the spectral type of the exciting star. The resulting spectral types range from O6 to B3. Five sources clearly had emission within the field, but at size scales too large for us to image in the given VLA configuration (i.e., structures $\gtrsim 20''$ in size). The detection rate of 40% is exactly half that found by KCW. This probably reflects the generally accepted fact that there is relatively little massive star formation taking place in the outer Galaxy. This result probably does not call into question the conclusions of Wood & Churchwell (1989b), because the number of *IRAS* sources with Wood & Churchwell colors drops significantly in the outer Galaxy. That is, the much lower "success rate" combined with the relatively few sources in the outer Galaxy does not produce a large effect in the overall result.

No new morphological types were seen in this survey. The frequency of occurrence of the various morphologies, however, did change somewhat from the previous surveys. Moreover, we were forced to adopt a new category of "unknown". This latter category occurred because a number of sources were detected at too low a S/N to be confident of a morphological classification. It seems likely that they fit into one of the various categories established by WC, but our detection was too weak to be certain of which category is appropriate; Figure 3 shows an example of this, where a region has currently been classified as a core-halo morpholgy, with a core of relatively bright emission, surrounded be a halo of lower brightness emission. With very little imagination, however, the source might be classified as cometary, based on the steeper gradient of the emission contours toward the northwest, compared to more gradual fall-off to the southeast.

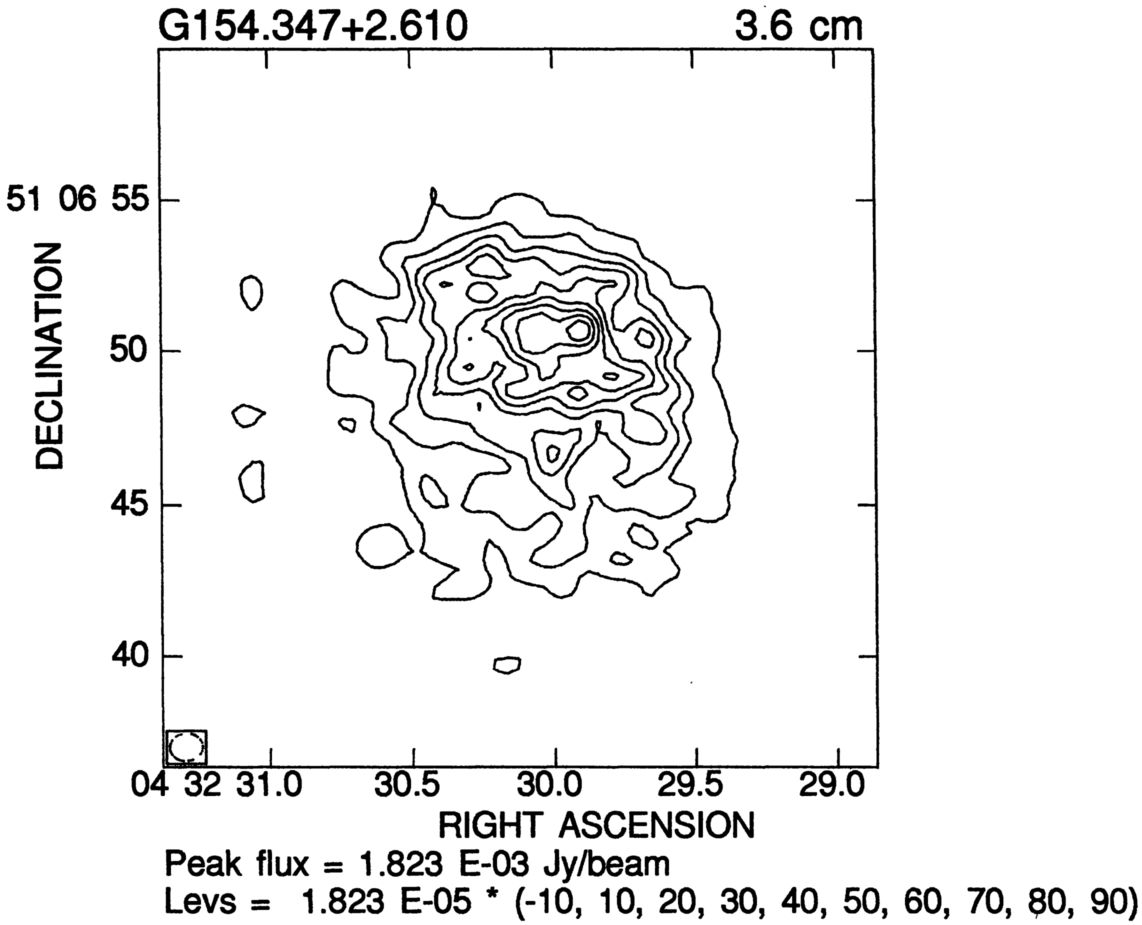

Fig. 3. Plot of a source with an indistinct morphology. This source is presently classified as having a core-halo morphology. There are several tell-tale signs (e.g., the hint of a leading arc to the northwest) that suggest the this source might be classified as cometary if the signal-to-noise in the image were higher.

The statistics of this survey are not large, and we caution against undue attention to the different incidence of morphologies compared to the WC and KCW surveys. We found nine irregular or multiply-peaked sources or 20% of our total (vs. 18% for the combined WC and KCW surveys); 19 spherical or unresolved, or 41% of the total (vs. 46%); three cometary (7% vs. 19%); ten core-halo (22% vs. 14%); no shell-type regions (vs. 4%); and we report five regions (11%) as having an unknown morphology —a category not used by WC or KCW. Given the subjectivity of the classification process, and the possibility of re-assigning five sources to different categories when higher quality images become available, we are not inclined to view the differences with earlier surveys as particularly significant.

The average integrated flux density is also of some interest, since it gives a quick estimate —albeit rather crude— of the strength of the ionizing stars. In the KCW survey, with most sources having over 2000 Jy at 100 μm, the mean integrated flux density was 271 mJy. In the present survey, with its much less luminous *IRAS* sources, the mean is 72 mJy.

Perhaps the greatest difference between the results of the three surveys is the amount of clustering of sources. WC noted that many fields contained multiple and distinct regions. KCW found similar results, and reported an average of 2.7 distinct regions per *IRAS* field with radio detections. In the present work, however, 46 sources in 41 fields with emission yields an average of only 1.1 sources per field. All questions of source identification (as UC H II regions) aside, there is simply no way that the outer Galaxy can have the degree of clustering that has been seen in the inner Galaxy: the clusters simply are not there.

4. A CAUTIONARY NOTE

It is perhaps worth spending a few moments considering some of the data which we have *not* looked at here. In particular, we have not discussed the sizes or electron densities of the regions observed, and these are important parameters in the characterization of UC H II regions. The examination of these data is important, but a potential pitfall awaits the unwary, and a brief cautionary note concerning the use of these data may be in order. In particular, plots of electron density vs. source size are sometimes used (e.g., KCW, Garay et al. 1993) to suggest agreement or disagreement of all UC H II regions (or those of certain morphologies) with various models of expansion or confinement/replenishment. For example, if spherical H II regions are undergoing the expansion expected in the classical Strömgren model, one would expect the electron density to vary with radius as $n_e \propto r^{-3/2}$. But if some mechanism is acting to confine or replenish the ionized gas (and thereby causing the UC H II region to remain in its compact state for a longer time than would be expected from the Strömgren model) then one would not necessarily expect a correlation between size and electron density.

WC noted that UC H II regions appear to exist longer than would be expected from the classical expansion model, because we see so many of them —many more than would be present at any one time given the accepted value of the massive star formation rate in the Galaxy. Various ideas have been suggested to explain this long life, including the bow-shock model (Van Buren et al. 1990; Van Buren & Mac Low 1992), evaporating disk winds (Hollenbach et al. 1995), mass-loading clumps (Lizano et al. 1995), more confining initial conditions (De Pree, Rodríguez, & Goss 1995), and the extension of these confinging conditions to dynamically stable structures (García-Segura & Franco 1995).

The use of diameter–density plots per se is a perfectly legitimate thing to do. The cautionary note relates to *how* the plot is generated. In particular, electron densities are often derived by the following scheme:

1) from radio continuum maps one measures the flux density S_ν and the source angular size θ_{src}, then uses some estimate of the distance D to obtain a linear source size Δs;

2) a brightness temperature is obtained from $T_B \propto S_\nu/\Omega$, which in turn

3) gives the optical depth from $T_B = T_e(1 - e^{-\tau})$ and an assumed electron temperature. The emission measure (EM) is then calculated via

4) $\tau \propto T_e^{-1.35} \nu^{-2.1}$ EM.

5) Finally one combines the linear size from step 1) with the emission measure of step 4) to obtain the electron density from $\mathrm{EM} = n_e^2 \Delta s$.

Hidden in this process are the *assumptions* that the H II region is spherical and ionization-bounded. As such, any correlation between diameter and electron density may tell us more about our assumptions than it tells us about expansion/confinement/replenishment of the ionized gas.

This is not to say that such plots cannot be used; indeed, for modeling purposes or the grouping of sources by excitation parameter, such plots can be quite helpful. To search for correlations of size with electron density, however, one really needs a model-independent measure of the electron density, obtained by some other means.

5. CONCLUSIONS

The present work has extended VLA survey coverage to all regions of the galactic plane that are accessible from the northern hemisphere. We find that the detection rate of compact radio sources drops significantly for the outer Galaxy, falling to $\lesssim 40\%$, or half the value of $\lesssim 80\%$ reported by KCW for the "inner Galaxy". This probably reflects the fact that there is less massive star formation occurring in the outer Galaxy than in the inner Galaxy. We note, however, that the *IRAS* sources observed in the present survey have higher galactic latitudes and significantly lower 100 μm flux densities than the sources from earlier surveys. These are two additional variables (along with the galactic longitude) that must be considered when evaluating the effectiveness of the two-color selection criteria. Differences in source morphology between the inner and outer galactic sources are slight or of doubtful statistical significance. The outer Galaxy sources are weaker in the radio continuum (as well as at 100 μm) compared to the inner Galaxy sources and they do *not* appear in clusters, as was commonly found in the inner galaxy. Finally, source diameter–electron density plots can be a useful analytical tool, but they must be used with some caution, and it is important to bear in mind what assumptions are made in the derivation of the electron density.

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