# DETECTION OF ONE HUNDRED AND THIRTY "DIFFUSE" GALACTIC HII REGIONS

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## ABSTRACT

The paper reports the results of a search for diffuse Galactic HII regions using radio recombination lines. Unlike most previous surveys, which have been directed toward fairly bright, compact radio continuum sources, we observed unprepossessing objects that might be optically obscurred analogs to the Rosette nebula. The sources observed here are typically a factor of two fainter in the continuum than those that have been detected before. One hundred thirty nebulae have been measured in radio recombination lines for the first time; most require at least one main sequence O star to provide their ionization. The diffuse HII regions appear to have essentially the same distribution in the Galaxy as compact HII regions. There is some indication that the diffuse nebulae have a low abundance of ionized helium, possibly due to their low excitation. Several newly discovered nebulae are associated with peculiar kinematic features in the Galactic nucleus. The surface density of radio HII regions in the inner Galaxy follows the surface density of CO fairly closely from $4 \leq R \leq 8$ kpc. In this area there is $\sim 1$ radio HII region for each $10^6 M_{\odot}$ of molecular hydrogen. However, HII regions are a factor $\sim 2$ more confined to the Galactic Plane than the molecular gas from which they form.

*Subject headings:* nebulae: HII regions – radio lines: ISM – Galaxy: structure

## 1. INTRODUCTION

Galactic HII regions come in a variety of forms. First, and most prominent, are the bright, high emission measure objects like Orion A and W49 which have resonably well-defined boundries and are easily distinguished on radio continuum maps or in the infrared. Nebulae like Orion A can be detected in radio recombination lines out to $\sim 20$ kpc from the Sun if they are not confused with other continuum sources (Lockman 1990), and surveys of radio recombination lines have measured velocities for many hundreds of these "dense" or "compact" HII regions (Downes et al 1979; Caswell and Haynes 1987; Lockman 1989). Second, there are low surface brightness objects typified by the Rosette Nebula, whose emission measure is orders of magnitude below that of Orion A. Third, there are large regions of low density ionized gas that are evidently common in the inner Galaxy but which usually cannot be identified with specific structures on radio continuum maps. They constitute a kind of smooth background of ionized gas in the inner Galactic plane. Recombination line surveys of this component suggest that it may arise in the outskirts of large complexes of dense HII regions (Lockman 1976; Hart and Pedlar 1976; Anantharamaiah 1985) or in the inner walls of HI shells and supershells (Heiles 1994; Heiles et al 1996b). Finally, there is the very low density, low emission measure ionized gas that is detectable throughout the Galaxy as the dispersive agent of pulsar pulses (Taylor and Cordes 1993), and near the Sun can also be detected through sensitive H$\alpha$ specroscopy. This component constitutes perhaps one-quarter of the mass of the entire interstellar medium (see Reynolds 1989, 1991). Its morphology, origin, density, and ionization state are poorly known and controversial; it appears to have a scale height an order of magnitude larger than the other forms of ionized gas (Taylor and Cordes 1993; Reynolds 1989).

This paper concentrates on objects in the second category, which we will call "diffuse" HII regions to distinguish them from the more well-known "compact" HII regions. They have been underrepresented in every observational census of Galactic ionized gas that has been made to date. Consider the Rosette nebula, for example. It has about the same radio continuum luminosity as Orion A, it is ionized by a stellar association as rich as Orion OB1, and it is associated with a giant molecular cloud. But it has a peak emission measure of only a few $10^3$ cm$^{-6}$ pc, it has very weak radio and IR emission, and its 3 cm radio recombination line is $\sim$ 200 times weaker than the identical line from Orion A. If the Rosette were located in the inner Galaxy and obscurred by dust, it would not be conspicuous against the Galactic radio continuum and would not have been observed in any discrete-source HII region survey to date (see Lockman 1990 for a discussion of selection effects in HII region surveys, and Blitz 1992 for further comments on the Rosette).

In the Lockman (1989) recombination line survey of compact HII regions (hereafter L89) there are about forty objects that are actually "diffuse" by our classification, and were observed as a pilot project to see if they might be detectable in significant numbers in the Galaxy. The observations described here follow on L89 with a systematic search for these diffuse HII regions – analogs to the Rosette nebula – in the inner Galaxy. The goals were to derive the surface density of diffuse nebulae, to compare their distribution to that of the higher emission measure nebulae, and to see if diffuse nebulae are an intermediate type or link between the compact HII regions and the other classes of ionized gas in the Galaxy.

## 2. OBSERVING STRATEGY AND SELECTION CRITERIA

The antenna temperature of a radio recombination line from a homogeneous, isothermal, low emission measure HII region at a frequency where it is very optically thin is $T_L \approx T_e \tau_L^* \Omega_s/\Omega_b$ where $\tau_L^*$ is the LTE optical depth and $T_e$ is the electron temperature (see, e.g., Brown et al 1978). The quantity $\Omega_s/\Omega_b$ is the beam dilution factor, which is the ratio of the source solid angle to that of the antenna beam. It must always be $\leq 1$. If a nebula is large compared to the antenna beam, has a line width of 25 km $s^{-1}$, and 10% He by number, the peak antenna temperature of the recombination line is approximately

$$T_L \approx 3\; n_2^3\; T_4^{-1.5}\; E_3 \quad mK, \tag{1}$$

where $n_2$ is the principal quantum number of the transition divided by $10^2$, $T_4$ is the electron temperature in units of $10^4$ K, and $E_3$ is the emission measure in units of $10^3$ $cm^{-6}$ pc. The brightest part of the Rosette nebula has $T_4 \approx 0.6$ and $E_3 \approx 3$ (Celnik, 1985), and eq (1) predicts a $T_L = 14$ mK at H85$\alpha$, in good agreement with observation (L89).

Provided that the above assumptions hold, low emission measure nebulae that fill the antenna beam are detected most easily at large n, i.e., at low frequency, because $T_L \propto n^3 \propto \nu^{-1}$. In contrast, at frequencies where the nebula does not fill the antenna beam equation 1 has the proportionality $T_L \propto n^{-3} \propto \nu^{+1}$ because for any given telescope $\Omega_b^{-1} \propto \nu^{+2}$. The optimum frequency to search for low emission measure nebulae is thus the lowest frequency at which the brighter parts of the source are still large compared to the angular resolution of the telescope being used. Note that this strategy not only optimizes the probability of detecting diffuse HII regions, but it discriminates against compact objects, because they have high emission measure cores of small angular size which are suffering beam dilution as well as becoming optically thick at low frequency. The antenna beam of the 140 Foot telescope of the NRAO at Green Bank WV would be smaller than the brighter parts of the Rosette nebula at observing frequencies $\nu \geq 3$ GHz (wavelengths $\leq 10$ cm), even if the Rosette were at a distance of 10 kpc.

There are numerous candidate diffuse nebulae in the Galactic plane radio continuum maps of Altenhoff et al. (1978; hereafter ADPS). Figure 1 shows a portion of the plane near longitude 5° where four continuum sources are marked. The two brighter ones were observed and identified as HII regions in the 3 cm survey (L89). The other two are prototypical candidate diffuse HII regions because they have a relatively low surface brightness and are extended. Their peak continuum brightness is at least a factor of two below the level at which the L89 survey is complete, and they represent objects that have not been systematically observed in radio recombination lines before this experiment.

Most sources that were observed were selected from the ADPS survey maps. Additional candidate objects came from the continuum surveys of Wendker (1984) and Altenhoff et al. (1970), as well as compilations of optical nebulae or other lists of radio sources that had not yet been detected in a radio recombination line (e.g., Reynolds 1987; Shinohara & Ishida 1976). The inner Galaxy sample ($358° < \ell < 55°$) is the most complete. In other parts of the sky, especially the outer Galaxy, most nebulae have optical counterparts and were observed in the L89 survey.

This project was not intended to be a complete survey of extended Galactic HII regions. Most of the continuum sources in the ADPS survey between longitudes 2° and 60° that have a peak flux density of at least 0.5 Jy above the background were observed, but the limit varies with longitude and the survey is not complete at this level. Some detected nebulae had a peak flux of only 0.3 Jy. In directions like Cygnus and the Galactic anticenter, only a few selected objects were observed. This lack of uniformity is taken into account when comparisons with other surveys are made.

## 3. OBSERVATIONS

All observations were made on the 140 Foot telescope of the NRAO at Green Bank, WV in recombination line transitions at wavelengths near 6 cm and 9 cm where the telescope has a half-power beam-width of $6'$ and $9'$, respectively. The survey was begun at 6 cm and concluded with an observing session at 9 cm. Four spectra were taken simultaneously in each band: the $109\alpha$ and $111\alpha$ in both linear polarizations at 6 cm, and the $126\alpha$ and $127\alpha$

in both linear polarizations at 9 cm. Both receiving systems were dual-channel with HFET amplifiers. At 6 cm the total system temperature at zenith was about 35 K, and at 9 cm it was about 30 K. There were no systematic differences between the continuum properties of the sources observed in the 6 cm and 9 cm lines.

Observations were made by switching the telescope between the direction of interest and a blank region of the nearby sky. A typical source was observed for a total of 30 minutes, including the time spent on reference observations. Spectra covered $> 500$ km s$^{-1}$ and included ample emission-free regions on either side of the lines. The different spectra had somewhat differing velocity resolution, so all spectra for a given object were convolved to a uniform 4 km s$^{-1}$ resolution and then combined. A baseline, typically parabolic, was removed from the final spectrum and a Gaussian function was fit to any detected line. No attempt was made to measure the continuum temperature of these HII regions, for given their low surface brightness and the relatively low frequency of this survey, contamination by nonthermal emission and confusion with unrelated sources can be severe. In a later section we use continuum information from published 5 GHz maps to estimate the luminosity of the nebulae.

## 4. THE DATA

Table 1 gives the properties of the 130 new nebulae detected in the survey. Columns 1 - 4 give the Galactic longitude, latitude and the equatorial coordinates (B1950) of each object. The peak antenna temperature, $T_L$, the line full-width at half-maximum, $\Delta V$, and the line velocity, V, were derived from the Gaussian analysis, and are given in columns 5 - 10. The error estimates are $1\sigma$ from the Gaussian fit. Columns 11 and 12 give noise estimates for the data: *Grms* is the noise derived from the Gaussian fit to the line; *Brms* is the noise derived from the spectral baseline region. In most cases $Grms \approx Brms$.

Significant differences between these two quantities can arise from asymmetries or wings on the line which increase *Grms*. Spectral confusion from multiple line-emitting sources in the beam can also make $Grms > Brms$. The typical value of the signal-to-noise ratio given by $T_L/Brms$ is 5.

The Notes in Table 1 identify the wavelength of observation and give the common name for a few optical nebulae. The Note "6+9" means that the final numbers derive from a combination of observations at both wavelengths weighted by the individual values of $(T_L/Brms)^2$.

In all, 107 continuum sources out of about 150 that were observed showed detectable recombination line emission. About 20% of these had two independent lines in the spectrum, yielding 130 separate spectral features that are listed as individual HII regions in Table 1. Continuum sources which showed multiple lines are noted with a 'D' in column 13. One source had a line component that probably originates in a nearby HII region overlapping on the sky with the object under study. It was not included in Table 1. We believe that the objects presented here and discussed in the rest of this paper can all be associated with the specific continuum sources that were observed, although in some cases what appears to be a single continuum source at the angular resolution of the ADPS survey must actually be a superposition of unrelated objects at different distances.

### 4.1. Objects Without Detectable Recombination Lines

Table 2 lists objects whose continuum brightness is in the range of the detected nebulae but which do not have a detectable recombination line. Column 6 gives the approximate 5 GHz antenna temperature in the continuum observed on the Efflesberg 100 meter telescope by ADPS or Wendker (1984) except for 75.167–0.575 where the number comes from the 10

GHz observations of Reich et al (1986).

These sources must be HII regions with a much lower than average line-to-continuum ratio, or they must be nonthermal. The continuum source 9.707–0.045, for example, has no observable line, but has a peak continuum brightness equal to and an angular size larger than the nearby nebula 9.176+0.032 whose line was detected easily. A similar comparison can be made between the lineless object 5.558+0.298 and the diffuse HII region 6.744-0.818. High resolution continuum observations of lineless sources in the L89 survey resulted in the discovery of several new SNRs and extragalactic radio sources near the Galactic plane (Helfand et al 1989), so it is likely that most of the objects in Table 2 are nonthermal.

## 5. LINE WIDTH

The HII regions detected in this survey have line widths similar to those of the compact nebulae in L89 and Caswell and Haynes (1987). The typical line width is 25 km $s^{-1}$, and most of the nebulae have $18 \leq \Delta V \leq 35$ km $s^{-1}$. The median $\Delta V$ for the diffuse sample is 26 km $s^{-1}$.

It is interesting that four diffuse nebulae have line widths $\leq 12.5$ km $s^{-1}$, for this implies that these nebulae have $T_e < 3500$ K. All four lines, however, have fairly low signal-to-noise ratios $< 4$ and all occur in sources that have multiple line components (only 20% of *all* spectra have multiple components). There is a significant potential for systematic error in fitting multiple Gaussian functions to noisy data, so derived line parameters for these sources must be viewed with some suspicion. Taking all factors into account, there is no convincing evidence that any nebula in this sample has a line so narrow that the value of $\Delta V$ alone implies $T_e < 5000$ K. Cool HII regions such as those found by Shaver, McGee and Pottasch (1979) and Lockman (1989) must be rare.

The two lines in the survey with the greatest width, $\geq 50.5$ km s$^{-1}$, are both associated with sources in the galactic center and will be discussed below. There are 10 lines with $\Delta V \geq 45$ km s$^{-1}$, and only two come from spectra with multiple components, consistent with a 20% incidence of multiple components in the survey. Wide lines are always suspect, though, for they may be blends of emission from unrelated nebulae within the relatively large antenna beam of this survey.

## 6. LOCATION IN VELOCITY AND LONGITUDE

The scale of the velocity-longitude diagram of detected nebulae in Figure 2 is set by several very high-velocity objects at low longitudes. Two nebulae near 359° have $V \sim -200$ km s$^{-1}$ and continuum morphologies more akin to compact HII regions than to the diffuse nebulae which are the focus of this paper. Also, they have the largest linewidths in the current survey, both exceeding 50 km s$^{-1}$. They are certainly related to 358.62–0.07 detected by Caswell and Haynes (1982) at a velocity of –212 km s$^{-1}$. Caswell and Haynes have assigned 358.62–0.07 to a hypothesized elliptical disk or bar structure in the Galactic nucleus, but Liszt (1992), who subsequently detected H70$\alpha$ emission at V $\sim -210$ km s$^{-1}$ from 358.797+0.058 and 358.600–0.060 , believes that all these objects are part of an active star-forming molecular cloud complex some 200 pc from the Galactic center called Sgr E.

Another newly-detected nebula with a conspicuous location in Figure 1 is 7.700–0.079 at a velocity of +152 km s$^{-1}$. This object lies near the locus of the "+135 km s$^{-1}$ expanding arm" (Oort 1977; Bania 1980), and has associated emission in HI and CO. It is in a region of $\ell$-V space that contains no other known HII region. There seems to be nothing at all peculiar about this object except for its velocity: if it is in pure circular rotation it must lie about 1.4 kpc from the Galactic center.

Apart from the Galactic nucleus, the highest velocity HII region in the survey is a component of 30.693–0.630 with a velocity of 129 km $s^{-1}$. This component was detected at 6 and 9 cm separately, although in both spectra it is blended with lower-velocity emission and is thus uncertain. There is a hint of very low-level CO emission in the data of Dame and Thaddeus (1994) at a position and velocity consistant with the recombination line. If real, this would be a most interesting star-forming region, for it appears to have a velocity $> 20$ km $s^{-1}$ higher than permitted by galactic rotation.

## 7. GALACTIC DISTRIBUTION OF DIFFUSE AND COMPACT NEBULAE

The comparison of the distributions of diffuse and compact nebulae will be restricted to objects with $2.5° \leq \ell \leq 52°$ where both surveys are resonably uniform. The "diffuse" sample includes the nebulae from Table 1 except for sources 2.510–0.028 and 31.607+0.334, which have the morphology of compact objects, and all the HII regions in the L89 survey that were detected at 9 cm. The "compact" sample consists of the remaining objects from L89 plus 2.510–0.028 and 31.607+0.334. There are 129 HII regions in the diffuse group and 288 in the compact group.

A distance was assigned to each HII region using spectrophotometric measurements of the exciting stars if the HII region has an optical counterpart (Blitz, Fich and Stark 1982), but this could be done for only 10% of the HII regions. For the rest, a kinematic distance was derived from the Burton and Gordon (1978) rotation curve scaled for a distance to the Galactic center of 8.5 kpc. This gives a unique galactocentric radius R, but usually two distances from the Sun, r1 and r2. We attempted to resolve the distance ambiguity by examining HI, $H_2CO$ and OH absorption spectra toward each nebula (from Downes et al 1980, Turner 1979; Garwood & Dickey 1989; Caswell & Haynes 1987; see Lockman 1979 for a discussion of the technique and its limitations). Seven compact nebulae between $10.^{\circ}07$

and 10°.66 were assumed to be in the "3-kpc" arm at a Galactocentric radius R=3.7 kpc based on their velocities and absorption lines (see Kalberla, Goss & Wilson 1982). The distance ambiguity could be resolved for almost half of the compact nebulae, but for only about one-quarter of the diffuse ones. Most of the newly-detected diffuse nebulae have never been observed in any absorption line, but in some cases a diffuse HII region could be associated with a compact one whose distance is known.

We were conservative in resolving the distance ambiguity. If there was any significant uncertainty in the evidence then the location of the HII region was left undetermined. Many nebulae thus have two possible distances, and a Monte Carlo technique was required to derive estimates of distant-dependent properties. Each object was assigned to either its near or far kinematic distance randomly, with twice the likelihood of the near distance. The analyses were run a number of times and the results averaged to derive probable distributions.

### 7.1. Radial Surface Density

The surface density of nebulae as a function of distance from the Galactic center, R, is not affected by any kinematic distance ambiguity, though it depends on the adopted rotation curve. Figure 3 shows the derived N(R) of compact and diffuse nebulae scaled to account for the difference in the number in each sample. The two distributions are quite similar, with a peak at R=4 kpc and a decline to larger and smaller radii. This figure shows that the diffuse sample is not dominated by objects close to the Sun, but is comprised of nebulae spread throughout the inner Galaxy. The radial distribution will be discussed further in a later section.

### 7.2. Vertical Distribution

Both diffuse and compact nebulae have a similar distribution in latitude: half lie at $|b| \leq 0\overset{\circ}{.}2$. The nebulae also have a similar distribution in distance from the Galactic plane, z. Figure 4 shows N(z) for the diffuse and compact samples; a summary of the vertical distribution is given in Table 3. Nebulae most distant from the Galactic plane in this sample are a mix of low-latitude objects with $|b| < 1^{\circ}$ that lie (or are likely to lie) at a large distance from the Sun, and nebulae with optical counterparts that have $|b| > 1^{\circ}$ and are located within a few kpc of the Sun.

HII regions, whether compact or diffuse, have the narrowest vertical extent of any known Galactic species. The full-width to half-maximum of N(z) is $\sim 50$ pc for both groups, compared to a FWHM $\sim 120$ pc for molecular clouds and a FWHM $\sim 220$ pc for HI over a similar longitude range (Bronfman et al 1988; Dickey & Lockman 1990).

Two recent continuum surveys of "ultracompact HII regions" (ucHIIs) give some information on the latitude distribution of the earliest phase of HII region formation but it is difficult to compare with the current results. Becker et al (1994) measured continuum sources in the inner Galaxy, but only at $|b| < 0\overset{\circ}{.}4$. They found that the FWHM of sources likely to be ucHIIs is only $0\overset{\circ}{.}25$ in latitude, but their survey sampled only the core of the N(b) distribution. The Kurtz et al (1994) survey was complete in latitude but restricted to $\sim 30$ objects over the Northern galactic plane. Those ucHIIs have a FWHM in the range $0\overset{\circ}{.}5$ to $0\overset{\circ}{.}8$. We believe that existing data do not contain enough information to determine if the ucHIIs have a different vertical distribution than the compact and diffuse HII regions.

## 8. LUMINOSITY

From the ADPS survey maps, which cover $357^\circ\!.5 \leq \ell \leq 60^\circ$ at $|b| \leq 1^\circ$, it is possible to estimate an integrated flux density, and thus a luminosity, for many of the diffuse nebulae. Sources with multiple recombination lines were not analyzed because it is not possible to know which fraction of the continuum to assign to each spectral component. Source confusion and uncertainty in the background level are the largest sources of error in the flux measurements.

The diffuse nebulae have 5 GHz continuum fluxes in the range $0.07 \leq S \leq 6.3$ Jy with a mean of 0.8 Jy (Figure 5). The radio continuum flux is related to the number of ionizing Lyman continuum photons needed to maintain the HII region through $N_{Lc} \geq 1.0 \times 10^{47}\ S\ r^2$ photons s$^{-1}$ where S is the 5 GHz flux density in Jy, r is the distance in kpc, $T_e = 8000$ K, and the inequality recognizes that a nebula may be density bound (see, e.g., Kurtz et al 1994). In analyzing $N_{Lc}$ we restrict the sample to diffuse HII regions at $\ell > 2^\circ\!.5$ to avoid objects whose kinematic distances might have a large error. For nebulae with an unresolved distance ambiguity, a Monte Carlo method was used to choose between the near and far kinematic distance, with the near favored two to one. A number of runs were averaged to derive the "most probable" distribution of $N_{Lc}$ shown in Figure 6. Since a single zero-age main-sequence B0 star has $log(N_{Lc}) = 47.36$ (Panagia 1973), it is clear that the vast majority of the diffuse nebulae detected here require at least one main sequence O star to maintain their ionization. Some must be ionized by a cluster of early-type stars.

The ionizing flux summed over the 79 of 130 nebulae that we are able to measure is $\geq 3 \times 10^{50}\ s^{-1}$ , which suggests that the total for all sources in Table 1 is $> 5 \times 10^{50}\ s^{-1}$. This is about twice the luminosity of the extremely luminous HII region W49A.

Some diffuse nebulae listed individually in Table 1 are probably resolved components of larger HII regions. One example can be found around $12^\circ\!.4 - 0^\circ\!.5$, where all the continuum peaks have a similar recombination line velocity. The individual components each have $S < 1$ Jy, but the overall region contains about 23 Jy. At the near kinematic distance of 2.7 kpc this implies $log(N_{Lc}) > 49.2$ photons s$^{-1}$ for the complex. This is about 25% of the luminosity derived from the Rosette's 5 GHz continuum flux (350 Jy at a distance of 1.42 kpc, see Celnik 1985), so the cluster of HII regions around 12.5-0.5 is a resonable analog to the Rosette nebula. Most of the diffuse nebulae, however, are much less luminous than the Rosette. They are also less luminous than the compact HII regions observed in the L89 survey, which virtually all have $S > 1$ Jy at 5 GHz. Examples of isolated diffuse nebulae are 16.823+0.126, 21.143–0.298, and 44.981–0.646.

## 9. HELIUM

Because the purpose of this survey was to find as many diffuse nebulae as possible, no one object was observed long enough to detect the helium recombination line, which is typically < 10% the antenna temperature of the hydrogen recombination line. The *average* He/H line ratio in the sample of diffuse nebulae, however, can be determined from an average of all detected sources. Spectra were shifted so that the H lines were aligned, then were averaged with a weight proportional to $(T_L/Brms)^2$. The 6 cm and 9 cm data were treated separately. The samples were further divided by longitude and latitude, to see if the data might be dominated by specific sources. No evidence of this was found; the subsets are used to estimate the uncertainty in derived values.

The results are quite interesting. For the 6 cm observations the ratio of line areas gives $He^+/H^+ = 1.8\%$ with a very large uncertainty, as some subsets of the spectra show virtually no He emission at all. At 9 cm, however, $He^+/H^+ = 6.6\%$ with a range covered by $\pm 1.3\%$. We have no explanation for the apparent difference in He abundance at the two different transitions. Most likely this is another example of experimental difficulties in deriving accurate $He^+/H^+$ ratios from radio recombination lines (see Lockman and Brown 1982). The overall low value of $He^+/H^+$, however, may be significant, because there are other indications that the ionized helium abundance in diffuse ionized gas is low, and that that this gas has a low ionization state (Reynolds and Tufte 1995; Heiles et al 1996a). Some of the diffuse nebulae may be ionized by later-type O stars and thus have significant amounts of neutral helium (see, e.g., Osterbrock 1989). There is no strong trend in the $He^+/H^+$ ratio between groups of diffuse nebulae sorted by their ionizing flux, $Lc$, but this result does not have high statistical significance. This entire subject deserves more study.

## 10. STAR FORMATION AND MOLECULAR CLOUDS

The set of diffuse nebula presented here, together with the compact nebulae detected in previous surveys of the northern and southern galactic plane (L89; Caswell and Haynes 1987) can be combined to give the most complete picture to date of the distribution of HII regions in the inner Galaxy. It is especially interesting to compare the surface density for the combined sample of HII regions with the surface density of molecular clouds derived from northern and southern CO surveys (Bronfman et al 1988). The surface density of HI is approximately constant over $3 \lessapprox R \lessapprox 8$ kpc, (Burton, 1988), so any relationship between star formation and gas content must show up in the HII/CO ratio. For this comparison the Bronfman *et al* results have been scaled to a sun-center distance of 8.5 kpc and the HII region sample restricted to those that lie in the longitude range $12° \leq \ell \leq 60°$, $300° \leq \ell \leq 348°$, where the CO surveys are complete. This gives 517 nebulae at R< 8.5 kpc, with 339 in the North (first longitude quadrant) and 178 in the South (fourth longitude quadrant).

Figure 7 shows the observed HII region surface density as a solid line, and the CO emissivity expressed as an equivalent surface density of molecular hydrogen (Bronfman *et* *al* 1988) as crosses. A preliminary version of this figure that did not include the new diffuse nebulae has appeared earlier (Lockman 1990). The most significant feature of Figure 7 is that the surface density of HII regions has an approximately exponential decrease outward from its peak near 4 kpc just as the CO does. Earlier studies, using a much smaller sample of only the brightest nebulae, derived a flatter distribution of HII regions with prominent peaks near 4.5 and 6 kpc (e.g., DWBW; Lockman 1979). While this could indicate that the most lumimous HII regions, the so-called giant HII regions, have a unique distribution, we suspect instead that the earlier results reflect only the relatively small number of nebulae that were then available to be counted.

The data can be used to estimate an HII region production efficiency over the Galaxy. For this we attempt to correct for the sensitivity difference between the northern and southern HII surveys by scaling the southern values of N(HII) by 339/178, the ratio of the numbers of nebulae currently known in each quadrant at R $<$ 8.5 kpc. The ratio $N(HII)/\sigma(H_2)$ is then calculated separately for the northern and southern data, and the results averaged and displayed in Figure 8. This correction assumes that there is intrinsically the same number of HII regions in each quadrant, and that the observed difference is due entirely to the differing sensitivity of the recombination line surveys.

Kennicutt (1990; 1996) has reviewed the relationship between young stars and gas in external galaxies. In many galactic disks tracers of star formation like the H$\alpha$ surface brightness are proportional to the gas surface density to a power that is $\gtrsim 1$, though with large variations from galaxy to galaxy. Figure 8 is our best estimate for the ratio of the surface density of HII regions to $H_2$ in the inner Galaxy at the sensitivity limits of current radio recombination line surveys. Over a rather large region of the Galaxy at $R > 4$ kpc, the ratio is approximately constant at one HII region per $10^6$ $M_\odot$ of $H_2$. At R$<$ 4 kpc the ratio drops by a factor of more than two, perhaps indicating that the gas abundance has dropped below the threshold necessary for star formation. It would be preferable to compare the luminosity of the radio HII regions instead of their numbers, but this is not yet possible.

## 11. FINAL COMMENTS

There are a large number of diffuse, low surface brightness nebulae in the Galaxy that have not before been studied systematically. More than 150 are now known from radio recombination line observations, and this must be only a fraction of the total population.

Relative to compact HII regions, the diffuse nebulae appear to have a virtually identical distribution in distance from the Galactic center and in distance from the Galactic plane. For this reason it is likely that the diffuse nebulae have evolved in the same location as the compact HII regions, or are a later stage of development of compact HII regions. The typical diffuse nebula detected here needs at least one main sequence O star for its ionization and possibly more if it is density bound. The apparent low abundance of ionized Helium should be confirmed with more sensitive observations.

When the total sample of known radio HII regions is considered, the following picture of the inner Galaxy emerges: First, the HII regions are very confined to the Galactic Plane, with a most likely FWHM in z of only $\sim 50$ pc. In contrast, CO emission, and thus molecular gas, has a FWHM $\sim 120$ pc over the same area. Neither the compact nor the diffuse HII regions seem to be related in any straightforward way to the most widely distributed forms of ionized gas which have a scale height $\sim 1$ kpc (Taylor & Cordes, 1993; Reynolds 1989).

Second, the surface density of HII regions increases smoothly from R=2 to R $\sim 4$ kpc, then decreases to larger radii, unlike that of HI, but qualitatively similar to CO emission from molecular clouds. This pattern was not apparent in earlier studies of the distribution of the brighter HII regions (e.g. Lockman 1979; DWBW 1982). In the range $4 \lesssim R \lesssim 8$ kpc there is $\sim 1$ radio HII region per $10^6$ $M_\odot$ of $H_2$. At smaller radii the ratio drops by more than a factor of two. This behavior is consistant with observations of some other galaxies, where the star formation rate is proportional to the gas surface density (above some threshold) to a power $\gtrsim 1$ (Kennicutt 1990; 1996). Our observations, however, show that in detail the situation must certainly be more complex than this, for regardless of the relationship between *surface densities*, the large difference in *scale height* between HII regions and both HI and $H_2$ imply that with respect to the Galactic plane the star formation rate must go as a much higher power of the gas density than unity.

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FIGURE CAPTIONS:

Fig.1 – A 5 GHz radio continuum map of the galactic plane near longitude 5° from the Altenhoff et al (1978; ADPS) survey. Objects marked "1" and "2" are "compact" HII regions and have been detected in previous recombination line surveys. Those marked "3" and "4" are "diffuse" and are typical of the nebulae which are detected here for the first time. The highest contours drawn for sources 1 through 4, are, respectively, 1.6, 0.8, 0.5 and 0.5 Jy per beam over the $2\rlap{.}'6$ (FWHM) beam.

Fig. 2 – Velocity-longitude diagram showing the diffuse nebulae detected between longitudes 355° and 90°. Note the high negative velocity HII regions near 359° and the high positive velocity HII region at $7\rlap{.}^\circ7$.

Fig. 3 – The surface density of the diffuse and compact HII region samples plotted against distance from the Galactic center, scaled so that there is equal area under the two curves. The two types of nebulae have a similar distribution.

Fig. 4 – The vertical distribution of the diffuse and compact HII region samples, scaled so that there is equal area under the two curves. The full-width to half-maximum is $\sim 50$ pc for both groups.

Fig. 5 – Estimated 5 GHz continuum flux density of diffuse nebulae. The sample contains the 79 nebulae whose flux could be measured with reasonable accuracy from the ADPS maps.

Fig. 6 – The most probable Lyman continuum luminosity of the diffuse nebulae whose

fluxes could be estimated. The Lyman continuum luminosity of a zero-age main sequence B0 star is marked. Most diffuse nebulae require at least one O-type star to maintain their ionization.

Fig. 7 – The solid line shows the surface density of all known radio HII regions in the specified longitude interval, while the crosses show the surface density of molecular hydrogen inferred from CO observations over the same region (from Bronfman et al 1988). The two species have a similar distribution at R $>$ 4 kpc.

Fig. 8 – The implied surface density of all radio HII regions divided by the surface density of molecular gas at R$<$ 8.5 kpc in the longitude range $12^\circ \leq \ell \leq 60^\circ$ and $300^\circ \leq \ell \leq 348^\circ$. Values of $N_{HII}$ have been corrected for the differing sensitivity of the northern and southern surveys. Over $4 \leq R \leq 8$ kpc there is approximately one radio HII region per million solar masses of $H_2$.