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On the Origin of the Galactic Ridge Recombination Lines

K. R. Anantharamaiah* *Raman Research Institute, Bangalore 560080*

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Abstract. Radio recombination lines are known to be observable at positions along the galactic ridge which are free of discrete continuum sources. Based on the results of a recent survey of H272α lines it is shown that most of the observed galactic ridge recombination lines can be explained as emission from outer low-density envelopes of normal HII regions. The distribution of low-density ionized gas and discrete HII regions as a function of the distance from the galactic centre is also derived.

Key words: Galaxy, recombination lines—galactic ridge— HII regions,low-density envelopes, distribution

1. Introduction

More than 15 years ago Gottesman & Gordon (1970) detected radio recombination lines of hydrogen from positions in the galactic plane which are free of discrete continuum sources. Since then a number of observations of similar lines have been made mainly at centimetre wavelengths (Jackson & Kerr 1971; Gordon & Cato 1972; Matthews, Pedlar & Davies 1973; Jackson & Kerr 1975; Mebold *et al.* 1976; Lockman 1976; Hart & Pedlar 1976b). There has been considerable debate in the literature about the origin of these galactic ridge recombination lines (GRRL). Initially it was argued that these lines arise in the partially ionized hot and/or cold component of the general interstellar medium itself (Gordon & Gottesman 1971; Cesarsky & Cesarsky 1971; Lockman & Gordon 1973). This interpretation, although attractive, could not explain many of the observed properties of GRRLs, for example their absence at longitudes l > 40° and the correlation between line and continuum intensities. In addition such models required high interstellar ionization which conflicts with the average interstellar electron densities derived from pulsar dispersion measures.

Subsequent interpretations have all been in terms of hot ionized gas (Matthews, Pedlar & Davies 1973; Jackson & Kerr 1975; Hart & Pedlar 1976a; Shaver 1976; Lockman 1980) presumed to be in weak or evolved HII regions or the outer envelopes of normal HII regions. As most of the observations were made at high frequencies (> 1 GHz) the main difficulty so far has been in separating the contribution to the GRRLs from the normal HII regions themselves. In this context, normal HII regions are those which can be identified as discrete sources in continuum surveys of the galactic plane (for example the 5 GHz survey of Altenhoff *et al.* 1978).

* Present address: National Radio Astronomy Observatory, VLA, P O Box 0, Socorro, NM 87801, USA

2. Results from the 325 MHz Survey

We have earlier presented (Anantharamaiah 1985a–hereafter Paper I) the observational data obtained using the Ooty Radio Telescope, and a preliminary discussion of the 47 directions in the galactic plane towards which the H272α line was detected. These directions included 29 well known H II regions, 11 SNRs, the galactic centre and 6 blank regions which are devoid of any strong discrete sources within the beam used for the observations. In Anantharamaiah (1985b—hereafter Paper II) the properties of the ionized gas responsible for these lines were deduced by combining the data of Paper I with higher frequency measurements available in the literature. The main results of Papers I and II which are relevant for the present discussion are as follows. Some of the arguments are repeated here for continuity.

1. In the first quadrant of the Galaxy, for the longitude range $l < 40°$, the H272α line was detected towards every direction irrespective of whether it corresponded to an HII region, an SNR or a blank region (Paper I).

2. The line intensities are typically 0.1 per cent of the total continuum intensity and there is no marked difference in this between the directions of HII regions, SNRs and blank regions (Paper I).

3. The electron density of the ionized gas towards SNRs and blank regions is uniquely determined by combining the H272α line intensity with the measurements at higher frequencies (typically H 166α). The derived densities are in the range 0.5–6 cm^{-3} (Paper II).

4. The electron temperature and emission measure are deduced by considering high frequency continuum emission, the average interstellar electron density and the geometry of the line-emitting regions. The electron temperatures are in the range 3000–8000 K and emission measures 500–3000 pc cm^{-6}. The corresponding pathlengths are 50–200 pc (Paper II).

5. The lines observed towards SNRs and blank regions fall under the category of GRRLs. Therefore the above parameters represent the properties of the gas responsible for them.

6. The sizes of these regions are very small compared to the total pathlength through the Galaxy (filling factor < 0.005). Therefore the GRRLs cannot be considered as coming from a widely distributed component of the interstellar medium.

7. The normal HII regions studied in Papers I and II are too dense and/or too small to produce the H272α lines detected towards them because of pressure broadening, continuum optical depth and beam dilution. The lines must therefore arise in some other lower density gas present in the same direction. In other words, for the H272α lines the directions of normal HII regions are similar to those of SNRs and blank regions, in the sense that there are no known discrete continuum sources in any of these directions which can produce the observed H272α lines. Most of the observed H272α lines can therefore be identified with the GRRLs.

8. The observed velocity of the H272α line is generally in good agreement with that of the HII regions in the same direction (as determined from high frequency recombination lines like H110α). This agreement suggests a physical association between the lower-density gas seen in the H272α line and the dense HII region. The most reasonable picture is that the low density gas is in the form of an outer envelope of the normal HII regions. In other words HII regions have a core-halo structure.

9. The electron density and emission measure of the envelopes are deduced by using

the intensity of the H272α lines and the core-halo model. It is assumed that the haloes have similar temperatures as the cores. The derived densities of the envelopes are in the range 1–10 cm^{-3} and the linear sizes of 30–300 pc (Paper II).

We note from the above that the density, temperature and sizes of low-density envelopes of normal HII regions (as derived from H272α observations) are quite similar to the parameters we have deduced for the ionized gas which produces the GRRLs. It was necessary to postulate large low-density envelopes to explain the observed H272α lines at the same velocity as the normal HII regions in these directions. We wish to take this result one step further and suggest that a large part of the observed GRRLs arise in the outer envelopes of normal HII regions. In order to assess the plausibility of this hypothesis we should demonstrate;

(a) that the distribution of HII regions in the galactic disc is similar to that of the gas responsible for the GRRLs or in other words that of the gas seen in H272α

(b) that there is other observational evidence indicating large low-density envelopes to be associated with most of the normal HII regions.

(c) that there is a sufficiently large number of HII regions in the galactic plane (with $l < 40°$) to ensure that most of the lines of sight in this longitude range intersect at least one low density envelope.

3. The distribution of low-density ionized gas and HII regions

A longitude velocity (*l*-*v*) diagram is an indicator of the distribution of the gas in the galactic disc. As a sufficiently large number of H272α observations have been made (Paper I) over the longitude range $0° < l < 60°$, the *l*-*v* diagram can give a reasonable indication of the distribution of the gas. In Fig. 1 we have shown the velocity extent of the H272α line emission at different longitudes superposed on a *l*-*v* diagram for the H166α recombination lines observed by Lockman (1976). Some of the smoothness in the H166α distribution is (as noted by Lockman 1976) a result of the coarse sampling of the galactic plane in his observations. In Fig. 1 we have also marked with thick dots the location of normal HII regions observed in the H110α survey of Downes *et al.* (1980).

Most of the H110α sources are high-emission-measure (10^4–10^6 pc cm^{-6}), small-angular-diameter (few arcmin) objects and would be nearly optically thick at 325 MHz. They produce practically no detectable H272α line. On the other hand, they are easily detected in the H166α line observations such as those of Lockman (1976) and Hart & Pedlar (1976b). It is therefore remarkable that the *l*-*v* diagram for the observed H272α lines agrees so well with those for the H166α and H110α lines. This would indeed be the case if the H272α emission comes from low density gas associated with the normal HII regions, seen in the H110α surveys.

The *l*-*v* diagram of Fig. 1 is only a qualitative indicator of the gas distribution. This diagram, when combined with a model of the galactic rotation will give a quantitative picture of the distribution.

Consider an annular ring around the galactic centre extending from R to $R + \Delta R$, where R is the distance from the galactic centre. Let this ring be inside the solar circle. In any spectrum taken at a longitude $l < \sin^{1} (R/R_0)$, the gas present in this ring will contribute over the velocity range V_1 to V_2. V_1 and V_2 are the radial velocities corresponding to the inner and outer edges of the ring along the line of sight and R_0 is the distance of the Sun from the galactic centre. The contribution will come, at the

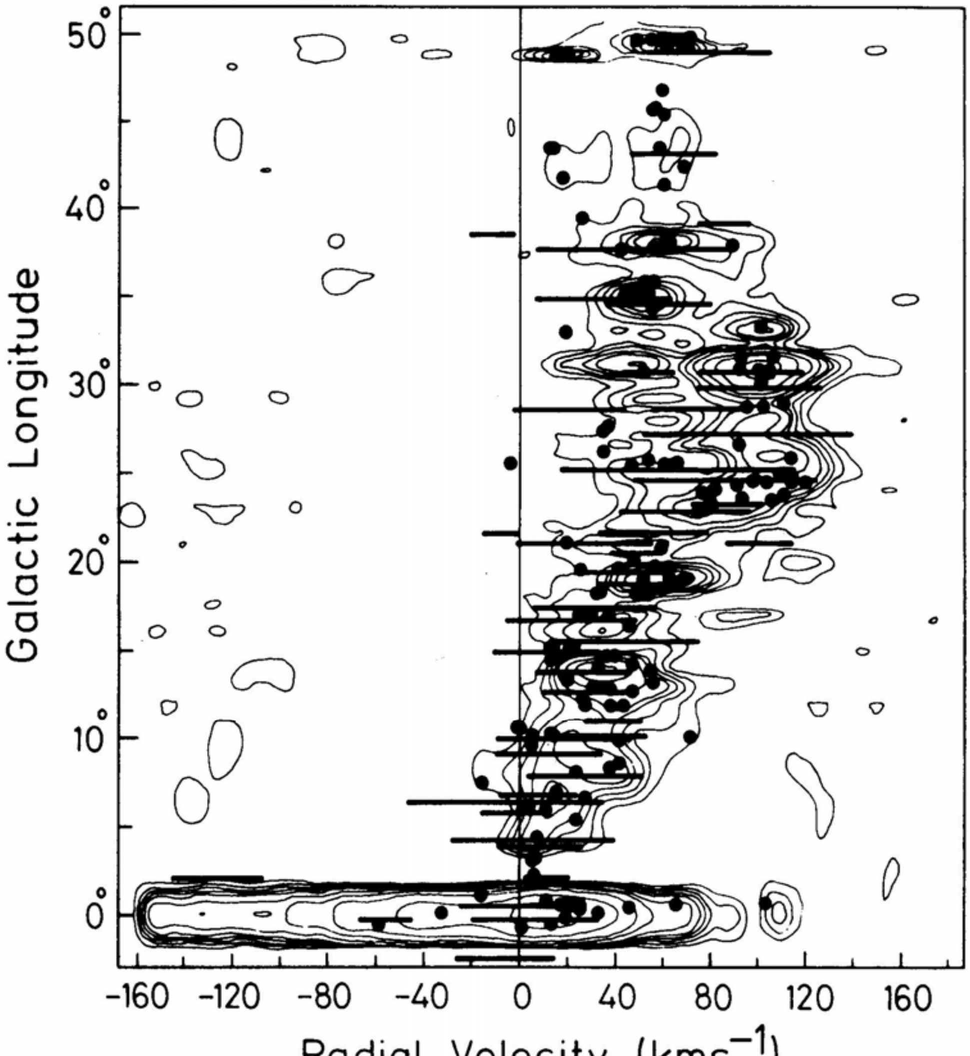

Figure 1. Longitude-velocity diagram of the recombination lines H272α (horizontal lines), H166α (contours) and H110α (dots). The horizontal lines indicate the observed half-power width of the H272α lines. The data for the three lines are taken from Paper I, Lockman (1976) and Downes *et al.* (1980) respectively.

same velocity, from the gas present at both the near and far distance of the ring from the Sun. The contribution to the power *P* in the observed line from the gas present in unit area of the ring is given by

$$P = \frac{\int_{V_1}^{V_2} T_L \, \mathrm{d}V}{(r_1 + r_2).\theta.\Delta r}. \tag{1}$$

r_1 and r_2 are the near and far distances of the ring from the sun. The factor in the denominator is the area of the ring intercepted by the telescope beam of size θ parallel to the galactic plane (the size perpendicular to the galactic plane is large enough to include all the gas of interest). Δr is the extent of the ring along the line of sight and T_L is the observed line temperature. For lines of sight intersecting only the outer edges of the ring (*viz.* directions with $\sin^{-1}((R + \Delta R)/R_0) < l < \sin^{-1}(R/R_0)$), V_2 corresponds to the velocity of the tangent point. If the ring is outside the solar circle the area intercepted by the beam is $r.\theta\Delta r$, where r is the distance to the ring.

The average amount of gas present per unit area of the ring will be proportional to the quantity P. (Equation 1) averaged over all the spectra taken up to a maximum longitude of $\sin^{-1}((R + \Delta R)/R)$. This was computed as a function of the distance of the ring from the galactic centre using the data presented in Paper I. In Equation 1 we used $|\tau_L|(= T_L T_C)$ instead of T_L since the H272α lines are dominated by stimulated emission (Paper I). The velocities and distances were calculated using the Schmidt model of galactic rotation. We used the analytical approximation to the Schmidt rotation curve given by Burton (1971). For $R <$ 4kpc we used the rotation curve given by Simonson & Mader (1973). The result of the calculation is shown in Fig. 2 (continuous line).

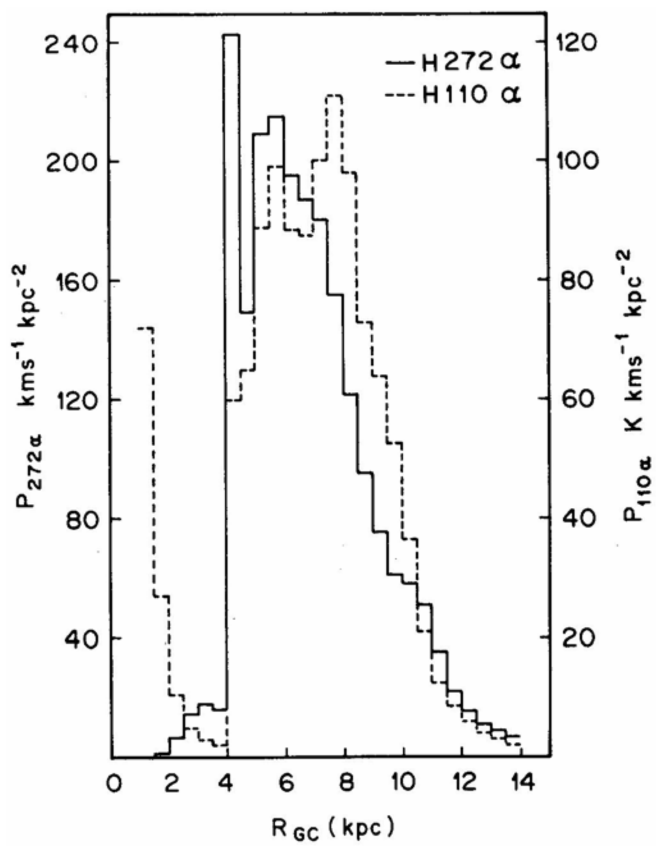

Figure 2. The distribution of low-density gas (seen in H272α) and discrete HII regions (seen in H110α) as a function of distance from the galactic centre. The data used are taken from Paper I (H272α) and Downes *et al.* (1980).

As seen in this figure, the distribution of the ionized regions responsible for the observed H272α lines is confined to galactocentric radii R < l0 kpc. The peak of the distribution occurs at $R \sim 6$ kpc and most of the gas is found between 4 kpc and 10 kpc. Inside of 4 kpc (where we have used the rotation curve of Simonson & Mader 1973), large noncircular velocities are known to be prevalent and therefore the implied distribution for this range is not reliable.

The actual distribution of the gas will in fact be narrower than suggested by Fig. 2. This is because in the above calculation we have implicitly attributed all of the observed velocity extent of the line emission to galactic rotation. The intrinsic width of the line arising from thermal motions and turbulence has not been taken into account. This will result in a smearing of the distribution.

We have also computed the distribution of normal HII regions, using the above method, from the observed line parameters in the H110α survey of Downes *et al.* (1980). This distribution is also shown in Fig. 2 (broken line).

It is clear from Fig. 2 that the sources of GRRLs and normal HII regions are distributed in a similar way in the galactic disc.

4. Sizes and number of HII regions, angular separations, scale height and galactic thermal background

The sizes derived for HII regions (Paper II) with their attendant low-density envelopes are in the range 50–300 pc. These are much larger than the sizes (1–10 pc) derived from radio continuum maps (*e.g.* Shaver & Goss 1970; Altenhoff *et al.* 1978). In the continuum, the essential contribution is from high density cores of the HII regions. The low-density envelopes are missed due to sensitivity and dynamic range limitations and also confusion with the galactic non-thermal background. All attempts to explain the observed line-to-continuum ratio as a function of frequency have always required that the HII regions have lower density gas associated with them (*e. g.* Brocklehurst & Seaton 1972; Parrish, Conklin & Pankonin 1977; Shaver 1980). Optical studies, although sensitive to low-density regions, suffer from obscuration by dust for distant objects in the galactic plane. Even so the optical data on nearby galactic HII regions (Georgelin 1971) show that more than 30 per cent of them have diameters greater than 50 pc. We also note here that the sizes of HII regions in external galaxies derived from optical studies are always greater than several tens of parsecs and extend all the way to several hundred parsecs (see for example, van den Bergh 1981; Kennicutt & Hodge 1980; Kennicutt 1984; Viallefond & Goss 1986). In fact a core-halo picture for extragalactic H II regions has been invoked by Sandage & Tammann (1974).

The total number of discrete sources in the 5 GHz survey of Altenhoff et al. (1978) over 40 square degrees of the galactic plane in the range $0° < l < 40°$ and $-0\overset{\circ}{.}5 < b < +0\overset{\circ}{.}5$ is . ~ 750. About 25 of these sources have been identified as galactic SNRs (see for example Green 1984). Further, from 5 GHz source counts (*e.g.* Ledden *et al.* 1980) we expect only about 25 extragalctic sources in this area with flux density > 0.1 Jy, which may have been detected in the above survey. Therefore this area of the galactic plane contains about 700 normal HII regions, strong and weak. The distances to identified HII regions range from 1 kpc to 17 kpc (see Downes *et al.* 1980). The number of HII regions at the far and near kinematic distances are about equal. Assuming an average distance of 9 kpc to these HII regions and an average size of 100 pc for their outer envelopes we see that the latter have angular sizes of ~ 0°.6. An examination of the 5 GHz map of Altenhoff *et al.* (1978) reveals that the angular separation between prominant HII regions is on the average ~ 0°.5 up to a longitude of 40°. The separation between somewhat weaker HII regions which still appear as discrete sources at 5 GHz is much less (~ 0°.l). If, on the average, these HII regions have low-density envelopes of angular size 0°.2–0°.6 then practically every line of sight in this longitude range will intercept at least one such envelope.

Lockman (1979) has analysed the distribution of HII regions in the inner galaxy and concluded that they have a scale height ($z_{1/2}$) of 33 pc. If some of these HII regions have envelopes of 50–300 pc then the scale height of the low density gas will be a factor of 2–3 larger which is consistent with 70–80 pc scale height derived by Lockman (1976) and Hart & Pedlar (1976b) from the latitude extent of the H166α line emission.

An examination of the 5 GHz map of Altenhoff *et al.* (1978) shows that there is an extended background radiation in the galactic plane, over which the discrete sources are superposed. The outer contours of emission do not break all the way up to l = 40°. At this frequency more than 60 per cent of the background radiation is thermal in origin (Hirabayashi 1974). Most of this background emission must therefore be coming from the extended low-density envelopes of the HII regions which are numerous in this range. The background emission decreases and becomes more patchy and so does the number of HII regions for l > 40°. This again is consistent with the fact that GRRLs are seen only up to l = 40°.

In one attempt to resolve the question of the origin of GRRLs Mebold *et al.* (1976) observed a recombination line, using high angular resolution, at a position devoid of discrete continuum sources. They consider this line as a good candidate for emission from a partially ionized medium. They however note that an interpretation can also be given in terms of a low density extended HII region. An examination of their spectra clearly shows that the extent and velocity of this line is in good agreement with those from discrete HII regions which are within 0°.2–0°.6 of this position. This line can therefore very well come from the outer low-density parts of the same HII regions.

All the observational evidence is therefore consistent with the hypothesis that the galactic ridge recombination lines arise in low-density extended envelopes of conventional HII regions. It is no longer necessary to invoke any distributed component of the interstellar medium to account for these lines.

5. Discussion

An origin for the galactic ridge recombination lines in outer parts of HII regions is not a new idea. Based on their H166α observations of the extended gas associated with the HII region W3, Hart & Pedlar (1976a) have in fact made such a suggestion. Lockman (1980) noted the correlation between his observed H166α spectra and the composite Hl10α spectra formed by adding the H110α profiles from the survey of Downes *et al.* (1980). He used this correlation to conclude that most of the H166α line emission comes from extended outer parts of normal HII regions whose dense cores are prominent in the radio continuum. This is identical to the conclusion we have drawn from the analysis of the H272α lines.

However, Lockman (1980) distinguished the H166α emission near l = 36° as coming from a more broadly distributed medium that extends over a few hundred parsecs, has a density of 1 cm^{-3} and a temperature of few thousand degrees. His estimated parameters for this region are not unique and in his analysis this gas can have higher densities and smaller pathlengths. An increase in density to a mere 3 cm^{-3} will make this gas similar to that responsible for the observed H272α lines in the direction of SNRs, blank regions and HII regions. In other words, this gas would have properties similar to the regions responsible for GRRLs (namely the outer envelopes of normal HII regions).

The parameters derived by Shaver (1976) for the regions responsible for the GRRLs (density 5–10 cm^{-3}, pathlength 20–150 pc and temperature 5000 K) are similar to the ones obtained in Paper II. He however concluded that these are weak HII regions. Our conclusion differs from that of Shaver, in that we attribute most of this gas to extended outer envelopes of normal HII regions. To explain the smooth distribution of the H166α line emission Shaver's picture would require a large number of such weak HII regions. If these are all distinct from conventional HII regions which are prominent in the radio continuum, then it would be difficult to explain the good agreement in the velocities of the H110α, H116α and H272α lines in the direction of normal HII regions. However, the possibility that *some* of the GRRLs come from unknown low-density HII regions (as suggested by Shaver 1976 and argued further in Shaver *et al.* 1982) is not excluded by the present analysis.

Although, as shown earlier, the low density envelopes of conventional HII regions will intersect practically every line of sight having $l < 40°$ there can very well be variations in density and emission measure from one line of sight to another. HII regions are rarely symmetric, uniform density objects. There will be a radial gradient as well as fluctuations in the density both in the core and in the outer envelope. As a result, one can expect variations in the line intensity even in adjacent directions as observed by Jackson & Kerr (1975) using a beam of 6 arcmin.

In conclusion we have been able to show that most and perhaps all of the galactic ridge recombination lines can arise in extended outer envelopes of conventional HII regions. The H272α observations used here have the unique advantage that they are almost completely insensitive to emission from normal HII regions because of pressure broadening, optical depth and beam dilution. These observations have sampled practically only that gas which is responsible for GRRLs.

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