Chapter 7

On the Origin of the Low-density Ionized Gas in the Galaxy

7.1 Introduction

In this Chapter we investigate the possible origin of the low-density ionized gas based on the observations and results discussed in Chapters 3 to 6. The origin of low-density ionized gas responsible for low frequency RRL emission in the Galaxy is not well understood although several observations exist. Some of the suggestions based on earlier work are that the lines originate (1) in evolved H II regions (Mathews et al. 1973, Shaver 1976, Mezger 1978), (2) in low-density envelopes of compact, high-density H II regions (Hart & Pedlar 1976a, Lockman 1980, Anantharamaiah 1986) and (3) in extended low density warm ionized medium (ELDWIM) proposed by Petuchowski & Bennett (1993) (Heiles 1994, Heiles et al. 1996b). A brief discussion of these different suggestions were given in Section 1.4.

7.2 Results from the Present 327 MHz RRL Survey

A distinguishing feature of our low resolution (2° × 2°) observations near 327 MHz is that they form an unbiased sampling of the inner and outer Galaxy. As discussed in Chapter 3, 51 adjacent positions were observed in the longitude range $l = 330°$ to 0° to 89° (inner Galaxy) and $b = 0°$ and 14 positions separated by $\sim 5 - 7°$ were observed in longitude range $l = 172°$ to 252° of the outer Galaxy. Observations were also made along the galactic latitude, up to $b = \pm 4°$, at two specific longitudes ($l = 0°$ & 13°.9). A selected set of 2° and 6° wide fields in the inner Galaxy were further observed with a 2° × 6′ beam obtained with the full ORT. The results of the survey and the analysis of the data can be summarized as follows:

1. In the low resolution (2° × 2°) survey hydrogen RRLs were detected in almost all positions in the longitude range $l = 330°$ to 0° to 89°.

2. In the outer Galaxy ($l = 172°$ to 252°) hydrogen lines were marginally detected in only three positions out of the 14 observed. These observations were also made with an angular resolution of 2° × 2°.

3. Along the galactic latitude, lines were detected up to $b = \pm 3°$ in the low resolution survey. A lower limit to the scale height of line emission of ~ 100 pc was deduced

from these observations.

4. In the inner Galaxy, the velocity integrated line intensity shows large fluctuations as a function of galactic longitude. These fluctuations imply that the line emitting region is not an uniform homogeneous medium.

5. The *lv* diagram and the derived radial distribution of RRL emission at 327 MHz show good agreement with those of "intense" ^{12}CO emission and to some extent with those of high frequency RRL emission from H II regions. On the other hand, the distribution of the Hα emission and H I emission in the galactic disk is different from that of the RRL emission near 327 MHz.

6. The density of the ionized gas as derived by combining the 327 MHz data with the RRL observations near 1.4 GHz is in the range $1 - 10$ cm^{-3} . Upper limits obtained for the temperature and size of the line emitting regions are $\sim$ 10,000 K and $\sim$ 600 pc respectively. The sizes of the line emitting regions estimated by assuming a temperature of 7000 K for the ionized gas are in the range $20 - 200$ pc.

7. In the higher resolution (2° $\times$ 6′) observations, lines were detected in almost all the observed positions with longitude $l < 35°$. The line emission, however, does not appear to originate from a homogeneous medium and in many cases shows structures over an angular scale of $\sim$ 6′.

8. Analysis of line emission towards the field G45.5+0.0 indicates that an individual line emitting region may have an angular size $\geq$ 1°. This angular size corresponds to a linear size $>$ 110 pc for a kinematic distance of $\sim$ 6.3 kpc. The central velocities of the line emission at different positions within the 2° wide field are comparable with those of the H II regions in the field.

9. The median width of the hydrogen lines observed in both high and low resolution surveys is $\sim$ 30 km s^{-1} which is somewhat larger than the median line width observed from normal H II regions ($\sim$ 26 km s^{-1})

7.3 Origin of the Low-Density Ionized Gas

We consider two of the existing models for the origin of the low-density ionized gas: the ELDWIM (Petuchowski & Bennett 1993, Heiles 1994, Heiles et al. 1996b) and the H II –envelope model (Hart & Pedlar 1976a, Lockman 1980, Anantharamaiah 1986; see also Section 1.4). We examine these models in the light of the new RRL observations presented in this thesis.

In the ELDWIM model, the low-density ionized gas responsible for RRL emission are produced by bare O stars that are formed in the late stage of evolution of H II regions (Mezger 1978). It is believed that all O stars are formed in dense clouds of gas which, when ionized, produce an associated radio H II region. The O stars outlive the radio H II region phase because of their longer life time (6×10^6 yr) compared to that of the H II regions (life time $\sim 5 \times 10^5$ yr; Smith, Biermann & Mezger 1978) thus forming bare O stars. The RRL observations, however, shows that the line emission is associated with the currently active star forming regions. This association is evident from the fact that the distribution of RRL emission near 327 MHz in the galactic disk is similar to that of "intense" ^{12}CO emission and compact, higher density H II regions. The "intense" ^{12}CO emission originate from the "warm" molecular clouds, which are sites of active star formation (Solomon, Sanders & Rivolo 1985). These arguments suggest that the ELDWIM is not a favored site for the origin of low frequency RRLs. However the caveats to these arguments are (1) the bare O stars can have a distribution similar to that of star forming regions since the OB associations produce several generation of stars and some of the stars formed in the early stages of the OB association can become bare O stars and (2) since the angular resolution of the observations is 2°, the linear scale sampled by the beam at a typical distance of 5 kpc is 200 pc which is much greater than the typical size of giant molecular clouds ($\sim$ 40 pc; Combes 1991) and hence the argument of the association with star forming region is not strong.

A distinguishing characteristic of the ELDWIM model is that the low-density ionized gas is pervasive and widely distributed in the inner Galaxy (Heiles et al. 1996a). This implies that the filling factor of this medium should be large at least in the inner Galaxy. Our estimates of the physical properties, however, indicate that the low-density gas producing RRLs has a path length of only 20 – 200 pc for a typical temperature of 7000 K for the ionized region. If we consider the diameter of the galactic disk to be $\sim$ 20 kpc, then the filling factor of this ionized gas is < 1 %. This value is comparable with that derived by Heiles et al. (1996b) towards the direction $l \sim 20°$ in the galactic plane. The filling factors cannot be, in any case, higher than 3 % since the upper limit on the path lengths obtained from our analysis is $\sim$ 600 pc. Furthermore, the low frequency RRLs have a median line width $\sim$ 30 km s^{-1} which is much smaller compared to the spread of radial velocity due to galactic differential rotation. The relatively narrow width of the lines indicate that the line emitting region is not spread out along the line of sight. A region with a low filling factor and confined to small regions along the line of sight cannot be considered as a distributed medium. We therefore conclude that the low-density ionized gas responsible for the RRL emission does not form a pervasive medium as suggested by the term ELDWIM.

In the morphological model proposed by Petuchowski & Bennett (1993) for the ELDWIM, the two observationally distinct distributions of the ionized gas (i.e. the WIM and the low-density ionized gas) are conflated. According to this model, the RMS electron density $< n_e^2 >^{\frac{1}{2}}$ of the WIM becomes large enough in the inner Galaxy to produce observable RRL emission. If this is true, then we expect the distribution of the RRL emitting gas to have similarity with that of the WIM. Such a similarity is not seen when we compare the *lv* diagram and the radial distributions obtained from the Hα and RRL emissions. (Hα is the main spectral tracer of the WIM.) However, this comparison should be treated with caution since Hα photons suffer large interstellar extinction.

There are three other difficulties with the ELDWIM model. As described above, the O stars producing the low-density ionized gas are thought to evolve beyond the H II region phase and hence not to have any associated dense ionized gas. However McKee & Williams (1997) argue that it is difficult to disperse the dense gas, from which the massive stars are formed, during the lifetime ($\sim 4 \times 10^6$ yr; Williams & McKee 1997) of the stars responsible for most of the ionization.

The second difficulty concerns the spectrum of the ionizing radiation. Using RRL observations near 1.4 GHz, Heiles et al. (1996a) have put constraints on the required spectrum of the ionizing radiation for the ELDWIM. They showed that it is difficult to generate the ionizing photons spectrum from the current models of star formation, which they refer to as the ionizing-spectrum problem. They have inferred this spectrum from the measured ratio of ionized helium to hydrogen (n_{He^+}/n_{H^+}) from their RRL observations. The upper limit to this ratio measured from the RRL observations near 1.4 GHz is $\sim$ 0.013 (Heiles et al. 1996a). This ratio corresponds to an upper limit on the helium ionization fraction of $\sim$ 0.13 if we assume that the hydrogen is fully ionized in the ELDWIM. Such a small ionization fraction can be achieved in H II regions if the ionizing radiation field is produced by massive stars with temperatures $<$ 35,000 K (equivalent to an O7 star; Osterbrock 1989). From our current knowledge of the initial mass function and the total galactic star formation rate, it is difficult to simultaneously obtain the required ionizing radiation field and the total ionization requirement for the WIM and the H II regions (Heiles et al. 1996a).

Finally, the hot stars that are required to ionize the ELDWIM are usually considered to produce locally confined ionized regions (H II regions). In contrast, the ELDWIM is pervasive and widely distributed. Heiles et al. (1996a) argue that this pervasiveness lead to the difficulty that the photons from the hot stars have to travel long distances to ionize the ELDWIM, which they refer to as the morphological problem.

An alternate model for the origin of low-density ionized gas is that they are large, low-density envelopes of normal H II regions. This hypothesis was proposed by Anantharamaiah (1986) based on his RRL observations with longitudes $l < 45°$. In this longitude range, the number of normal, higher density H II regions is large ($\sim$ 700) compared to other regions of the Galaxy. Anantharamaiah (1986) argued that if these H II regions have low-density envelopes of size $\sim$ 100 pc, then practically every line of sight in this longitude range will intercept at least one of them, thus explaining the ubiquity of low frequency RRL emission within $l = 45°$. Our data indicates that the H II –envelope model can be further extended to explain the line emission in the longitude range $l = 330°$ to 0° to 89° since a good degree of similarity is seen between the distribution of RRL emission near 327 MHz in this longitude range and that of the star forming region as indicated by "intense" ^{12}CO and high frequency RRLs from normal H II regions. Furthermore, there is no observational bias in our data since the 327 MHz survey forms a complete sampling of the inner Galaxy.

The H II –envelope model for the origin of the low-density ionized gas naturally explains some of the other observed features. The large fluctuations seen in line emission as a function of longitude can be expected in this model since the line of sight intercepts H II envelopes of different physical properties. The filling factor estimated for the low-density gas from our data is reasonable for the H II –envelope model as the ionized gas responsible for line emission are individual objects of size 20 – 200 pc and thus will not form a pervasive medium as proposed by the ELDWIM model. The large scale height ($\sim$ 100 pc) derived for the observed RRL emission near 327 MHz compared to that of the H II regions is also expected in the H II –envelope model since the sizes of the low-density envelopes (20 – 200 pc) are larger than the typical sizes of H II regions (1 – 10 pc). The detection of RRLs in almost all positions in the higher resolution observations near 327 MHz, towards fields with $l < 35°$, and comparatively fewer number of lines observed towards fields with $l > 35°$ can be understood in this model as follows. About 75 % of H II regions identified in high frequency RRL surveys towards continuum sources are in the longitude range $l = 0°$ to 35° ($|b| < 1°.5$). The average separation between H II regions in this longitude is $\sim 0°.08$ compared to $\sim 0.3°$ in the longitude range $l =$ 35° to 85°. Considering that 50 % of the estimated sizes of the low-density ionized gas are between 20 – 100 pc and assuming a distance to the ionized gas as 5 kpc, the average angular size of the H II –envelope is ~ 0°.5. If we assume that most of the H II regions have an associated low-density envelope, then it is clear that the probability of almost every lines of sight in the longitude range $l = 0°$ to 35° intersecting at least one H II –envelope is high. This probability is reduced in the longitude range $l = 35°$ to 85° due to larger angular separation between the H II regions. A similar argument can explain the lack of widespread emission of lines in the outer Galaxy since the number density of H II regions in the outer Galaxy is much less compared to the inner Galaxy.

There are other evidences as well for the association of a large, low-density component with normal H II regions. A recent study of the luminosity function of OB associations in the Galaxy by McKee & Williams (1997) indicates that the H II –envelope picture is a better representation of such associations. With the aim of determining the distribution of intrinsic ionizing luminosity of OB associations McKee & Williams (1997) used the observed parameters of giant and supergiant (luminosity > 4 times that of Orion nebula) radio H II regions compiled by Smith, Biermann & Mezger (1978). The radio H II region data gives an estimate of the ionizing photon luminosity but does not include the ionizing photons that escape from the radio H II region into the lower density surrounding medium or the photons that are absorbed by dust. Thus to get the intrinsic luminosity distribution of OB association from the radio data a knowledge of the structure of H II regions is necessary. The available data do not directly provide this. Therefore McKee & Williams (1997) start by constructing the luminosity distribution of radio H II regions using the data. The resultant distribution is extrapolated to lower luminosity H II regions using a Monte Carlo method. They then estimate the total ionizing photons needed by the radio H II regions to be 0.57×10^{53} photons s^{-1} by integrating the distribution function. They find that this value is about 3.3 times less than that estimated from the diffuse radio free-free emission from the extended low-density ionized gas and independently from far-infrared line emission observed by *COBE* (1.9×10^{53} photons s^{-1}). Since OB stars are the dominant source of ionization, as shown in other galaxies (Kennicutt, Edgar & Hodge 1989), the low estimate of ionizing photons produced by all the H II regions should be understood in terms of their structure.

McKee & Williams (1997) considered two main possibilities for the structure of H II regions. (1) There are more OB associations than are observed as radio H II regions with the remainder being "extended low density" H II regions (Mezger 1978). This increase in the number of OB associations results in scaling their distribution function by the factor 3.3. (2)Only 30 % of the ionizing photons emitted by an association are absorbed by the corresponding radio H II regions, so that the actual ionizing luminosity is higher by the factor 3.3. In this case, the H II regions are partially density bounded and hence have an associated low-density envelope which are not bright in radio continuum and this low-density envelope on the average absorbs ~ 2/3 of the ionizing photons from the H II regions. Comparing the luminosity distribution of H II regions in the Galaxy with that of other galaxies McKee & Williams (1997) concluded that the H II –envelope picture is a better representation of the OB association in the Galaxy.

There are direct observations which provide evidence for the association of large, low-density gas with normal H II regions. Analysis of the H166α observations from W3, W4 and W5 H II region complexes by Hart and Pedlar (1976a) shows the presence of low-density ionized gas that are associated with the H II regions. Recent observations of RRLs near 1.4 GHz by Heiles et al. (1996b) have detected lines which are attributed to walls of cavities in the galactic gaseous disk formed by clustered supernovae. These walls, which are termed "worms" by Heiles et al. (1996b), are ionized by photons from the hot stars in the cluster whose supernovae created the cavity. Heiles et al. (1996b) estimated that about 17 % of the observed low frequency RRL emission originate in these "worms". Most of the OB associations, to which a worm can be associated with, do indeed have radio H II regions. Thus, as pointed out by McKee & Williams (1997), worms can also be classified in the H II –envelope picture, in that they are also generated by ionizing photons that escape from the density bounded H II regions.

The H II –envelope model offers a natural resolution to two of the three problems encountered by the ELDWIM model that were mentioned before. As described above, in the H II –envelope model, the low-density ionized gas is physically associated with normal, higher density H II regions. Thus in this model it is not required to disperse the dense ionized gas during the lifetime of the stars itself as needed by the ELDWIM model. For the same reason, the ionizing photons need not travel long distances from the hot stars to produce the low-density ionized gas thus resolving the morphological problem of the ELDWIM model.

In summary, H II –envelope model explains the association of the low-density ionized gas with normal, higher density H II regions as indicated by the 327 MHz RRL data and also other facts implied from the 327 MHz observations such as the low filling factor of the low-density gas, large fluctuations observed in line emission as a function of longitude in the inner Galaxy and lack of widespread emission of lines in the outer Galaxy. Independent evidence for H II –envelope model representing the OB associations in the Galaxy is available from the study of the luminosity function of such associations by McKee & Williams (1997). Observations of RRL near 1.4 GHz from W3, W4 and W5 H II region complexes also indicate the association of large, low-density gas with the bright H II regions. Thus we conclude that the low-density ionized gas associated with the H II regions in the H II –envelope model is responsible for the RRL emission observed near 327 MHz.

7.4 Summary

In this chapter we discuss the origin of low-density ionized gas in the context of two of the existing models – the ELDWIM model and the H II –envelope model. The results obtained in the previous chapters from the analysis of our RRL survey data near 327 MHz are summarized. On the basis of the similarity of the distribution of the RRL emission in the galactic disk with that of the star forming regions and the range of derived physical properties, we suggest that the RRL emission originates from low-density ionized gas which forms envelopes of normal H II regions. Our estimated filling factor for the low-density ionized gas is $< 1\%$. This low filling factor indicates that the ionized gas does not form a pervasive medium as suggested by the term 'extended low-density warm ionized medium (ELDWIM)' that has been used in the literature to describe this component.

Chapter 8

Summary and Conclusions

In this thesis we have presented an observational study of the low-density ionized gas in the galactic disk. The main tool used for the investigation is radio recombination lines near 327 MHz. We have simultaneously observed 270α, 271α, 272α and 273α transitions of hydrogen and carbon. All the observations presented in this thesis were made with the Ooty Radio Telescope. A new multi-line spectrometer, capable of simultaneously observing eight RRL transitions with a spectral resolution of ~ 1 km s^{-1} , was specially built for these observations. The thesis describes details of this spectrometer and other equipments used for the observations, the data reduction procedures, the observations themselves and the results obtained. Detailed interpretation of the data in terms of the distribution of the low-density ionized gas in the galactic plane and its physical properties forms a major part of the thesis. Possible origin of the low-density gas is discussed towards the end of the thesis.

The thesis begins with a brief introduction to the various components of ionized gas in the interstellar medium and their properties as inferred from various observations over a large range of the electro-magnetic spectrum. The galactic plane contains several forms of ionized gas such as the warm ionized medium (WIM) and the hot ionized medium (HIM), which are a part of the general ISM (McKee & Ostriker 1977), H II regions which are formed around "hot" young stars and partially ionized regions either adjacent to H II regions or mixed with the largely neutral component (e.g. the cold neutral medium (CNM)). Somewhere in between the very low-density distributed ionized components of the ISM (WIM & HIM) and the relatively high density H II regions (which occupy only a small volume of the Galaxy), there appears to be a low-density extended ionized component in the inner Galaxy. This component has been referred to as "extended low-density" (ELD) ionized gas by Mezger (1978) and as "extended low-density warm ionized medium" (ELDWIM) by Petuchowski & Bennett (1993), Heiles (1994) and Heiles et al. (1996b). Observationally the low-density extended ionized medium in the inner Galaxy was identified more than two decades ago through the detection of low frequency (< few GHz) radio recombination lines at several positions along the galactic plane which are free of discrete continuum sources (Gottesman & Gordon 1970, Gordon & Cato 1972). Subsequently, this low-density component has been systematically observed in radio recombination lines near 1.4 GHz by Hart & Pedlar (1976b), Lockman (1976, 1980), Cersosimo (1990) and Heiles et al. (1996b). Recombination lines from this gas were also observed by Anantharamaiah (1985a, b) near 325 MHz. In this thesis, we have presented new extensive observations of the low-density ionized component in radio recombination lines at frequencies near 327 MHz using the ORT.

There are other observational evidences for the presence of an extended low-density ionized component in the galactic disk. These include (i) the *COBE* (Cosmic Microwave Background Explorer) observations of widespread emission in the galactic plane of far-infrared fine structure transitions of C II ($\lambda = 158$ μm) and N II ($\lambda = 205$ μm), (ii) "turnovers" seen in the continuum spectra of galactic supernova remnants and low-latitude extragalactic continuum sources at frequencies $<$ 100 MHz, (iii) absorption of galactic non-thermal background emission at frequencies $<$ 100 MHz and (iv) occurrence of enhanced scattering of radio waves in the inner Galaxy. The relevant results from these observations are summarized in this thesis.

All the observations presented in this thesis were made using the Ooty Radio Telescope. A brief discussion of the characteristics of the telescope has been presented. A large scale survey of RRLs at a low frequency is extremely time consuming, since the lines are very weak (line to continuum temperature ratio is $\sim 10^{-3}$) requiring long integrations ($>$ 15 hours per position) to detect them. To reduce the actual observing time a new multi-line spectrometer was built. This spectrometer is capable of observing eight RRL transitions simultaneously with a spectral resolution of $\sim$ 1.0 km s^{-1} . We observed two sets of four adjacent recombination line transitions with this spectrometer. At the observing frequency, the nearby RRL transitions carry essentially the same physical information. Hence the eight spectra were eventually averaged to improve the signal to noise ratio and thus reduce the observing time by a factor of eight. A detailed description of the multi-line spectrometer has been presented. An efficient software package for careful editing of man-made interferences for reduction of the large volume of data from the survey was developed. The strategies used for the data analysis are described in this thesis.

A key to understand the extended low-density ionized gas in the inner Galaxy is to determine its physical properties such as density, temperature and sizes of the regions and to determine the distribution of the gas in the galactic plane. With these objectives in mind, we made a survey of RRLs near 327 MHz in the galactic plane using the ORT. The RRL transitions observed were H270α, H271α, H272α and H273α. The observing strategy was the following. Observations were made in the two longitude ranges that can be observed with the ORT. These ranges are l = 332° to 0° to 89°, referred to as the inner Galaxy, and l = 172° to 252°, the outer Galaxy. The inner Galaxy was observed with two different angular resolutions – (a) 2° × 2° (low resolution mode) and (b) 2° × 6′ (high resolution mode). Higher resolution (2° × 6′) was obtained by using all the 22 'modules' of the ORT, which together form a telescope of size 530 m × 30 m, and the lower resolution (2° × 2°) is obtained by using only a single 'module', which effectively is a telescope of size 24 m × 30 m. In the low resolution mode, we made an unbiased contiguous sampling of the galactic plane in the inner Galaxy and also observed 14 positions ($b = 0°$) in the outer Galaxy. To study the latitude extent of the line emission, we observed over ± 4° along galactic latitude at two specific longitudes (l = 0° & 13°.9). In the high resolution mode, we sampled a selected set of 2° and 6° wide fields in the inner Galaxy. These observations, results and their interpretation are presented in this thesis.

In the low resolution survey, hydrogen RRLs were detected at almost all the observed positions in the inner Galaxy. In the outer Galaxy, lines were detected towards only three positions. The observations as a function of the galactic latitude detected lines up to $b \sim \pm 3°$. The line emission is well correlated (correlation coefficient = 0.88) with the largely non-thermal continuum emission in the same direction indicating that stimulated emission is dominant. The median width of the observed line is 31 km s^{-1} which is larger than the median line widths observed from normal H II regions. The data from inner Galaxy were used to derive the distribution of the low-density ionized gas in the galactic disk and to obtain constraints on the physical properties of the ionized gas. Comparison of the results with other observations in the galactic plane was also made.

The longitude-velocity (*lv*) diagram obtained from the low resolution survey data shows some concentration of hydrogen line emission in spiral arms at longitudes $l < 50°$. The derived distribution of RRL emission near 327 MHz as a function of Galactocentric distance shows a sharp peak near 4 kpc with more than 70 % of the emission originating between 2.5 kpc and 6 kpc. The *lv* diagram and the radial distribution obtained from the present data shows good similarity with that of the RRL emission near 1.4 GHz, the "intense" ^{12}CO emission and to some extent with the RRLs observed near 3 cm from normal H II regions. These distributions are distinctly different from that of the Hα emission and the H I emission from the galactic disk. The difference between the distributions of the RRL and Hα is mainly due to obscuration by dust of the Hα emission and the difference in sensitivity of recombination lines in optical and radio bands. Based on the similarity in the distribution of RRL emission at 327 MHz, ^{12}CO emission at 3 mm and the RRL emission at 3 cm from normal H II regions, we conclude that the diffuse RRL emission in the galactic disk is associated with star forming regions. We also conclude that most of the line emission near 1.4 GHz originates from the same ionized gas which is responsible for the RRL emission near 327 MHz.

Combining the RRL observations near 1.4 GHz with our data, constraints were derived for the physical properties of the gas producing the line emission. A brief discussion of the theory of RRLs and the details of the modeling used for deriving the physical properties are presented. The measured line strengths at 1.4 GHz and 327 MHz place a strong constraint on the density of the ionized gas. The derived densities are in the range 1 – 10 cm^{-3}. We used the upper limit to the RRL intensity near 75 MHz to check the consistency of the cloud model obtained from the 1.4 GHz and 327 MHz RRLs. Using the measured continuum near 10 GHz and 2.7 GHz, and dispersion measure ($\int n_e dl$) obtained from the electron density model by Taylor & Cordes (1993), we obtain upper limits on the temperature and the physical size of the ionized regions in different directions. The upper limits obtained for the temperature are typically 10,000 K and that obtained for the pathlengths are $\sim$ 600 pc. In a few positions, the upper limits to the electron temperature, as obtained from the width of the line, are less than 4800 K. By assuming a temperature of 7000 K for the ionized cloud, we estimated the sizes of the line emitting region. The estimated sizes are in the the range 20 – 200 pc.

Using the derived physical properties of the clouds that produce the RRL emission near 327 MHz, we estimated the expected C II 158 μm and N II 205 μm line emission from these low-density ionized clouds. We found that most of the N II emission and a considerable fraction of the C II emission observed by the *COBE* satellite could originate in the ionized gas responsible for the RRL emission. We also computed the expected free-free absorption of the galactic non-thermal emission near 34.5 MHz due to the presence of these ionized clouds. We again found that a considerable fraction, if not all, of the absorption of the background radiation at frequencies < 100 MHz could be due to the low density ionized gas which is responsible for the observed RRL emission near 327 MHz

The higher resolution (2° × 6′) observations using the full ORT were used to study the clumpiness of the low-density ionized gas in the galactic plane. The fields that were observed using the full ORT are positions where lines were detected in the low resolution survey made using a single module of the ORT. In the higher resolution observations, hydrogen lines were detected at almost all positions within all the five selected fields at $l < 35°$. However, the parameters of the detected line vary considerably on angular scales of $6'$ at many positions. Beyond $l = 35°$, although lines were not detected at many individual positions, the integrated spectrum obtained by averaging the spectra at different positions within a $2° \times 2°$ area shows the presence of the line emission. A detailed study of line emission towards the field G45.5+0.0 has been presented. Comparison of the signal to noise ratio of the line in the integrated spectrum with that detected at positions inside the $2° \times 2°$ area, indicates that the angular extent of line emission in this field should be larger than the high resolution beam. Averaging subsets of spectra spanning different angular regions within the field G45.5+0.0 resulted in lines with different parameters indicating that the line emitting region is quite clumpy. We estimate that the sizes of the clumps can be as large as one degree or more. There is some evidence for the association of these clumps with known H II regions in this field.

Finally, in this thesis we have discussed the origin of the low-density ionized gas in the galactic disk. Two of the existing models for the origin of low-density ionized gas are examined: (1) the extended low-density warm ionized medium (ELDWIM) (Petuchowski & Bennett 1993, Heiles 1994, Heiles et al. 1996b) and (2) the H II – envelope model (Hart & Pedlar 1976a, Lockman 1980, Anantharamaiah 1986). In the ELDWIM model, the low-density ionized gas is produced by "bare" O stars that are formed in the late stage of the evolution of H II regions (Mezger 1978). In this model, the low-density ionized gas thus formed is pervasive and widely distributed in the inner Galaxy implying that the filling factor of the gas is large. Results from our RRL observations, however, are incommensurate with both these features of the ELDWIM model. Analysis of the RRL emission in the galactic disk shows that the distribution of the ionized gas responsible for line emission is similar to that of the currently active star forming regions. The pathlengths obtained for the ionized gas from the RRL data are in the range 20 – 200 pc indicating that the filling factor of this gas is only 1% or less. These observed facts, on the other hand, are naturally explained by the H II – envelope model. In this model, the low-density ionized gas forms envelopes of density bounded normal H II regions and thus is associated with the currently active star forming regions. The low filling factor estimated for the low-density gas is reasonable for the H II –envelope model as the ionized gas responsible for line emission are individual objects of size 20 – 200 pc. There are other supporting evidences for the H II –envelope model as well. H II regions with large low-density components are expected from models of star formation (Zuckerman 1973). A recent study of the luminosity function of OB associations in the Galaxy also indicates that radio H II regions have envelopes that absorb $\sim 2/3$ of the ionizing photons from their central OB stars (McKee & Williams 1997). Thus, in our opinion, the low frequency RRLs originate from extended low-density envelopes associated with normal H II regions. The low-density gas is unlikely to form a pervasive medium as suggested by the term 'extended low-density warm ionized medium (ELDWIM)' which has been used in the literature to describe this component (Mezger 1978, Petuchowski & Bennett 1993, Heiles 1994, Heiles et al. 1996b).

8.1 Future Work with the Survey Data

Several lines of further investigations are possible with the kind of survey data presented in this thesis.

As described here, the present low resolution survey is biased towards low-density ionized regions of relatively large angular size. This bias is because of the large beam width of the survey and the dominance of stimulated emission at low frequencies as well as the rather limited sensitivity of the observations. The effect of such observational biases on the interpretation of the data has not been studied in the present analysis. Computer simulations using a distributed low-density ionized gas in the galactic disk and determining the observed parameters from simulations may give a closer insight into the effects of such a bias on the final results.

Further, the ionization requirements of the low-density gas are not discussed in this work. Such a study may lead to a clearer understanding of the origin of the low-density gas, as well as some implications for the star formation rate in the Galaxy.

The full telescope data towards all the observed fields can be further analyzed to obtain a more statistically significant result on the angular extent of the ionized gas and its association with the H II regions in the corresponding fields. The velocity correlation of the line emission from H II regions falling within the higher resolution beam and the observed RRLs near 327 MHz may be used to check the latter.

There are several phenomena observed in the inner Galaxy that may be due to the low-density ionized gas responsible for RRL emission near 327 MHz. In this thesis, results from two of these observations, namely (1) N II 205μm and C II 158μm FIR line emission, (2) the absorption of the galactic background emission near 34.5 MHz, are compared with the estimated values obtained using the derived physical properties of the low-density ionized gas. For comparison of the FIR line intensities, we have used the observed values from *COBE* FIRAS measurements. This comparison is, however, limited due to the large difference in angular resolution of the RRL observations near 327 MHz (2°× 2°) and the *COBE* FIRAS measurements (5°× 7°) and also due to lack of central velocity measurements of the FIR lines. A better comparison can be made with results from the on-going Balloon borne observations, which have finer angular resolution (15′× 15′) and provide the central velocity measurements (e.g. Nakagawa et al. 1998). Such a comparison will help in estimating the amount of FIR emission that originate from the low-density ionized gas.

One of the assumptions made in the estimation of the absorption of non-thermal continuum near 34.5 MHz presented in the thesis is that the emissivity of the background emission is uniform in the galactic disk. The computation can be further improved by considering a model for the distribution of the non-thermal emissivity (e.g. Beuermann, Kanbach, Berkhuijsen 1985) in the galactic disk. Contribution to continuum opacity from other components of ionized gas, such as Hα emitting clouds and WIM, along different line-of-sights can also be included in the estimation. Such a computation can give an improved understanding of the absorption of galactic non-thermal background at low frequencies in the inner Galaxy.

The derived physical properties of the low-density ionized gas can also be used to estimate the contribution of this ionized component to other observed phenomena in the inner Galaxy. They include the observed enhancement of interstellar scattering in the inner Galaxy and "turnovers" seen in the continuum spectra of galactic supernova remnants and low-latitude extragalactic continuum sources at frequencies $\nu < 100$

MHz. Such a computation will help in identifying the various components of the ISM responsible for these observed phenomena.

The ionized gas responsible for the RRL emission near 327 MHz also give rise to spectral features in the optical and infrared regimes. The derived physical properties of the low-density ionized gas can be used for estimating the line intensities in these bands. The Brackett-gamma line of hydrogen in the infrared is fairly unaffected by interstellar extinction on the galactic scale and hence observations of these lines in the galactic plane (e.g. Kutyrev et al. 1997) can be compared directly with the predicted values.

As mentioned earlier, the carbon RRLs detected in this survey originate from ionized regions with physical properties different from those producing the hydrogen RRLs. Hence the data can be used to study the distribution of these ionized gas components in the galactic disk and their association with other components of the ISM.

8.2 Suggestion for Further RRL Studies of the Low-density Ionized Gas

Although several observational studies of RRLs from the low-density ionized gas in the galactic disk have been made, many questions remain unanswered. For example, in spite of the many supporting evidences for the H II –envelope picture it has not been possible to conclusively establish it. The physical properties of the low-density ionized gas, such as the electron temperature and size, are also not well constrained. The present analysis has only led to upper and lower bounds which are rather widely separated. Furthermore, as shown by Heiles et al. (1996a), the ratio of the intensities of the higher order RRL transitions (i.e $\Delta n > 1$ transitions) to the α transitions indicates deviations from LTE that are not easily explained by existing models. RRLs from the low-density ionized gas in the galactic disk have been mostly observed from the northern hemisphere (i.e. $180^\circ > l > 0^\circ$) and hence the distribution of ionized gas in the southern hemisphere is practically unknown. Finally, the latitude extent and scale height of the low-density ionized gas at different longitudes in the galactic disk is yet to be determined.

Multi-frequency RRL observations can help answering some of the above questions. A few of the selected $2^\circ \times 2^\circ$ fields in the RRL survey can be observed at other frequencies like 610 MHz, 1.4 GHz, 2.4 GHz and 5 GHz. To get a matched beam the $2^\circ \times 2^\circ$ area may have to be sampled with the usually smaller observing beams at the higher frequencies. The average spectrum obtained from these samples can then be combined with the Ooty observations at 327 MHz. The average spectrum would be equivalent to observing with a $2^\circ \times 2^\circ$ beam, thus removing the uncertainty in beam size, which often hampers interpretation of multi-frequency observations. These observations will form a unique data of immense value for determining the physical properties of the low-density ionized gas.

As discussed in this thesis, RRLs detected at the positions devoid of continuum sources in the galactic plane cannot originate from H II regions and therefore have to come from the extended low-density ionized gas. Deep integrations at a few selected positions inside the $2^\circ \times 2^\circ$ fields, which are apparently free of any discrete continuum sources in the 2.4 GHz survey (Reich et al. 1990), could be attempted to detect higher order ($\Delta n > 1$) RRL transitions, and possibly Helium lines, near 1.4 GHz and 2.4 GHz. The intensities of the observed Helium lines, or upper limits, can constrain the spectrum

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Observations of RRLs near 1.4 GHz in the longitude range $270° < l < 360°$ have so far not been carried out. Such a survey would be useful to study the distribution of ionized gas in the southern sky. The distribution in the southern sky can be compared with the distribution obtained from observations made in the northern sky to check if the low density gas is distributed symmetrically in the inner galactic disk. The multi-beam facility of the Parkes telescope could be a valuable instrument for such a survey of the southern Galaxy.

Finally, more systematic and extensive observation should be made to determine the latitude extent and thus the scale height of the low density gas at various longitudes. A low resolution RRL survey such as the one presented in this thesis (for $b = 0°$) could be performed at $b = \pm 2°$ and $\pm 3°$ to determine the vertical extent of the gas across the disk. As shown by McKee & Williams (1997) this low density ionized component may be absorbing about 2/3 of all the ionizing photons produced by early type stars in the galactic disk. Thus, a comprehensive study of the low-density gas in the galactic disk can play a vital role in understanding the nature of star formation in the Galaxy.

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