Carbon recombination lines towards the Riegel–Crutcher cloud and other cold H I regions in the inner Galaxy

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ABSTRACT

In the first paper of the series, Roshi, Kantharia & Anantharamaiah published the Galactic plane survey of carbon recombination lines (CRRLs) at 327 MHz. CRRLs were extensively detected from the inner Galaxy (longitudes < 20°). We report here, for the first time, the association of low-frequency CRRLs with H I self-absorbing clouds in the inner Galaxy and that the CRRLs from the innermost \(\sim 10°\) of the Galaxy arise in the Riegel–Crutcher (R–C) cloud. The R–C cloud is amongst the most well known of H I self-absorbing (HISA) regions located at a distance of about 125 pc in the Galactic Centre direction. Taking the R–C cloud as an example, we demonstrate that the physical properties of the HISA can be constrained by combining multifrequency CRRLs and H I observations. The derived physical properties of the HISA cloud are used to determine the cooling and heating rates. The dominant cooling process is emission of the C II 158 \(\mu\)m line whereas the dominant heating process in the cloud interior is photoelectric emission. Constraints on the far-ultraviolet flux (G0 \(\sim 4–7\)) falling on the R–C cloud are obtained by assuming thermal balance between the dominant heating and cooling processes. The H2 formation rate per unit volume in the cloud interior is \(\sim 10^{-10}–10^{-12} \text{s}^{-1} \text{cm}^{-3}\), which far exceeds the H2 dissociation rate per unit volume. We conclude that the self-absorbing cold H I gas in the R–C cloud may be in the process of converting to the molecular form. The cold H I gas observed as HISA features is ubiquitous in the inner Galaxy and forms an important part of the interstellar medium. Our analysis shows that combining CRRLs and H I data can give important insights into the nature of this cold gas. We also estimate the integration times required to image the CRRL-forming region with the upcoming Square Kilometre Array Pathfinders. Imaging with the Murchison Widefield Array telescope is feasible with reasonable observing times.

Key words: ISM: atoms – ISM: general – ISM: molecules – photodissociation region (PDR) – Galaxy: general – radio lines: ISM.

1 INTRODUCTION

In earlier papers (Roshi & Anantharamaiah 2000, 2001a,b), we presented the details of a 327-MHz recombination line survey of the inner Galaxy made with the Ooty Radio Telescope (ORT). Results of the preliminary analysis of carbon recombination lines (CRRLs) detected in this survey were presented in Roshi, Kantharia & Anantharamaiah (2002, Paper I). The CRRLs at low frequencies (\(\lesssim 1.4\) GHz) arise in diffuse C II regions in the Galaxy. The ionization potential of carbon (11.3 eV) is less than that of hydrogen (13.6 eV) and hence carbon can remain in the singly ionized state outside regions where hydrogen is fully ionized. Low-frequency CRRLs are thus useful as diagnostics of partially ionized clouds. However, the reduced abundance of carbon (solar abundance relative to hydrogen, 2.9 \(\times\) 10\(^{-4}\); Lodders 2003) and the consequent weak strength of the CRRLs make the detection of these lines difficult. Generally, stimulated emission or absorption against a strong background radiation field facilitates their detection.

The first CRRL from a diffuse C II region was detected towards the direction of the supernova remnant Cas A and this direction has since been extensively observed in CRRLs at frequencies ranging from 15 MHz in absorption to 1400 MHz in emission (Blake, Crutcher & Watson 1980; Konovalenko & Sodin 1981; Ershov et al. 1984, 1987; Konовалenko & Sodin 1984, 1990; Payne, Anantharamaiah & Erickson 1989; Sorochenko & Walmsley 1991;
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I − × I

survey data. In Fig. 1, we show an example CRRL spectrum, and latitude T = σ I 2 were covered in the 2 (Jenkins & absorption and < spectra with angular resolutions 0 × 12 l I spectra towards G13.9 K; warm neutral medium) and 'cold' (° 35–75 K (Payne, Anantharamaiah & 'narrow lines') and (b) 'broad lines' with b is observationally studied using 21-cm gas observed

2 89 ° II 2 I ≲ l 519–528 SELF-ABSORPTION × 20 regions.

− (the most abundant gas phase ion in the CNM) fine- and C absorption observed towards 'self-absorption' (HISA; e.g. Knapp 6 arcmin; Roshi & Anantharamaiah 2000, 2001a). A Galactic longitude range −28° < l < 89° and latitude b = 0° were covered in the low-resolution (2 × 2°) survey. CRRLs have been detected almost contiguously from −2° < l < 20° and also in a few positions at other longitudes (Paper I). A few of these positions were then ‘mapped’ with the high-resolution beam (2 × 6 arcmin; Roshi & Anantharamaiah 2001a). In Paper I, we discussed some of the results from this survey. Summarizing, we find that the radial distribution of the CRRLs near 327 MHz is similar to that of star-forming regions traced by the 3-cm hydrogen RRLs (Lockman 1989) and 12CO (Dame et al. 1987). Our multiresolution ORT data also indicate that some of the diffuse C II regions have an angular extent of a few degrees.

3 CRRLs AND H I SELF-ABSORPTION REGIONS

We use the median linewidth (~17 km s⁻¹) to classify the CRRLs detected in the ORT survey into two groups: (a) lines with width (FWHM) ≤ 17 km s⁻¹ (‘narrow lines’) and (b) ‘broad lines’ with width ≥ 17 km s⁻¹. The median linewidth is obtained from the 2° × 2° survey data. In Fig. 1, we show an example CRRL spectrum.

Figure 1. CRRL and H I spectra towards G13.9+0.0. CRRL (top panel) spectra at 327 MHz are obtained with an angular resolution of 2° × 2°. The 0.1 value of the spectral noise is also shown in the top panel. The middle and bottom panels show H I spectra with angular resolutions 0.6 × 0.6 and 2° × 2°, respectively (Kalberla et al. 2005). The low-resolution H I spectrum is centred at the Galactic coordinates l = 14°0 and b = 0°. The arrows are placed at the LSR velocity of the ‘narrow’ carbon lines. The good LSR velocity coincidence of ‘narrow’ CRRL and HISA features suggests an association between the two line-forming regions.

2 SUMMARY OF OUR CRRL DATA

The ORT recombination line survey data were obtained with two angular resolutions (2° × 2°, Roshi & Anantharamaiah 2000; 2° × 6 arcmin, Roshi & Anantharamaiah 2001a). A Galactic longitude range −28° < l < 89° and latitude b = 0° were covered in the low-resolution (2 × 2°) survey. CRRLs have been detected almost contiguously from −2° < l < 20° and also in a few positions at other longitudes (Paper I). A few of these positions were then ‘mapped’ with the high-resolution beam (2 × 6 arcmin; Roshi & Anantharamaiah 2001a). In Paper I, we discussed some of the results from this survey. Summarizing, we find that the radial distribution of the CRRLs near 327 MHz is similar to that of star-forming regions traced by the 3-cm hydrogen RRLs (Lockman 1989) and 12CO (Dame et al. 1987). Our multiresolution ORT data also indicate that some of the diffuse C II regions have an angular extent of a few degrees.

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Table 1. ‘Narrow’ 327-MHz CRRL and H\textsc{i} line parameters.

<table>
<thead>
<tr>
<th>Source name</th>
<th>T\textsubscript{L}/T\textsubscript{sys} \times 10^{-3}</th>
<th>ΔV (km s\textsuperscript{-1})</th>
<th>V\textsubscript{LSR} (km s\textsuperscript{-1})</th>
<th>T\textsubscript{L} (K)</th>
<th>ΔV (km s\textsuperscript{-1})</th>
<th>V\textsubscript{LSR} (km s\textsuperscript{-1})</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>G2.3+0.0</td>
<td>0.55 (0.04)</td>
<td>16.1 (1.3)</td>
<td>6.4 (0.6)</td>
<td>48.5 (1.5)</td>
<td>4.2 (0.2)</td>
<td>6.5 (0.1)</td>
<td>R–C cloud</td>
</tr>
<tr>
<td>G4.7+0.0</td>
<td>0.76 (0.06)</td>
<td>8.5 (0.07)</td>
<td>7.0 (0.3)</td>
<td>64.7 (2.3)</td>
<td>4.7 (0.2)</td>
<td>7.0 (0.1)</td>
<td>R–C cloud</td>
</tr>
<tr>
<td>G7.0+0.0</td>
<td>0.64 (0.08)</td>
<td>12.1 (1.9)</td>
<td>8.0 (0.8)</td>
<td>51.0 (1.5)</td>
<td>3.9 (0.1)</td>
<td>7.1 (0.1)</td>
<td>R–C cloud</td>
</tr>
<tr>
<td>G13.9+0.0</td>
<td>0.35 (0.04)</td>
<td>6.8 (1.0)</td>
<td>18.4 (0.4)</td>
<td>10.4 (0.8)</td>
<td>5.5 (0.1)</td>
<td>19.3 (0.2)</td>
<td></td>
</tr>
<tr>
<td>G18.4+0.0</td>
<td>0.36 (0.05)</td>
<td>17.3 (2.5)</td>
<td>24.1 (1.1)</td>
<td>21.1 (0.5)</td>
<td>6.0 (0.2)</td>
<td>22.8 (0.1)</td>
<td></td>
</tr>
</tbody>
</table>

\footnote{CRRL parameters for all positions except G13.9+0.0 are taken from Roshi & Anantharamaiah (2001b). The parameters for the position G13.9+0.0 are taken from Paper I. The CRRL data are obtained with an angular resolution of \(\sim 2^\circ \times 2^\circ\). H\textsc{i} line parameters are obtained from Kalberla et al. (2005) after smoothing the data to an angular resolution of \(\sim 2^\circ \times 2^\circ\).}

\footnote{T\textsubscript{L}/T\textsubscript{sys} is approximately the carbon line optical depth near 327 MHz. T\textsubscript{sys} is the background continuum temperature at the observed frequency.}

\footnote{The given value is in T\textsubscript{L}/T\textsubscript{sys}, where T\textsubscript{sys} is the system temperature.}

\footnote{The HISA parameters are obtained from the 0:6 \times 0:6 H\textsc{i} spectrum centred at l = 18.5 and b = 0.0.}

The majority (63 per cent) of the narrow CRRLs observed in the \(2^\circ \times 2^\circ\) ORT survey have a corresponding HISA feature at the same LSR velocity. The absence of a corresponding HISA in some of the directions where narrow CRRLs are observed may be due to the following reason. Detection of HISA depends on favourable observing conditions. In order to detect a cool H\textsc{i} cloud in self-absorption, background H\textsc{i} emission with brightness temperature greater than the spin temperature of the cool cloud is required. Variation in the background emission temperature over the observing region can make the self-absorption difficult to detect, especially when observed with a coarse angular resolution. The need for higher angular resolution H\textsc{i} observations to detect HISA has been demonstrated, for example, by Bania & Lockman (1984). CRRLs do not need such favourable conditions for their detection. In Fig. 2, we show examples where narrow carbon lines are detected but no HISA is seen in the \(2^\circ \times 2^\circ\) averaged H\textsc{i} spectrum (lowermost panels). While the higher angular resolution (0.6 \times 0.6) H\textsc{i} spectrum (middle panel) shows an HISA feature towards G18.4+0.0, no such feature is seen towards G16.1+0.0 even in the higher angular resolution spectrum.

The H\textsc{i} spectra obtained close to the Galactic plane show a wealth of structures and many of these structures are self-absorption features as shown, for example, by Bania & Lockman (1984) in their high angular resolution observations. The ORT survey has not detected carbon lines corresponding to all these features. The typical upper limit on the CRRL optical depths from these features is
~2.0 \times 10^{-4}\) (Roshi et al. 2002). The possible reasons for these are as follows.

1. The CRRL survey is biased towards detecting carbon-line-emitting regions with large angular extent such that the beam dilution factor is insignificant.
2. The optical depths of CRRLs in all the regions are not high enough to be detected. Variation in carbon optical depth is seen, for example, towards the R–C cloud (see Section 4).
3. The Galactic non-thermal background radiation field is not strong enough to make the CRRL detection possible. The low Galactic radiation field may be the reason for non-detection of CRRLs towards HISA at \(l \gtrsim 20^\circ\).

Difficulties in quantifying the observed properties of HISA features have been elaborated by several authors (e.g. Levinson & Brown 1980). The observed line parameters listed in Table 1 are obtained by fitting a Gaussian to the absorption feature after removing either the second- or the third-order polynomial ‘baseline’ to the H\(_{1}\) emission near this feature. Levinson & Brown (1980) have also shown, through simulation, that the observed central velocity of the H\(_{1}\) absorption can be ‘shifted’ compared to the actual central velocity and this shift depends on the slope of the background H\(_{1}\) emission. A rough estimate of this shift in the cases listed in Table 1 shows that it is insignificant compared to the errors in the line parameters.

A well-known HISA feature towards the Galactic Centre direction is the Riegel–Crutcher (R–C) cloud. In the next section, we concentrate on CRRL detection towards the R–C cloud. In particular, we demonstrate the usefulness of combining CRRL and H\(_{1}\) observations to infer the physical properties and processes in the cloud. The physical processes that are discussed here are now part of well-known numerical codes, which implement models for photodissociation regions (PDRs; see for example Hollenbach, Tachihashi & Tielens 1991; Hollenbach & Tielens 1997). Here we present a semi-analytic estimation of the physical properties and energetics in the R–C cloud. A detailed PDR modelling will be presented elsewhere.

### 4 THE RIEGEL–CRUTCHER CLOUD

A prominent cool neutral cloud (the R–C cloud; Heeschen 1955; Riegel & Crutcher 1972) has been observed in H\(_{1}\) self-absorption in early surveys of the Galactic Centre region. The self-absorption cloud has an extent of at least 40\(^\circ\) along Galactic longitude and \(\sim 10^\circ\) along Galactic latitude (Riegel & Jennings 1969; Riegel & Crutcher 1972). Line emissions from molecules such as \(^{13}\)CO and OH have been detected in many directions towards the R–C cloud (Crutcher 1973). The distance to the R–C cloud was determined to be 125 \(\pm\) 25 pc from Na\(_{1}\) observations against background stars (Crutcher & Lien 1984). Optical observations have also constrained the LOS thickness of the cloud to be between 1 and 5 pc (Crutcher & Riegel 1974). Recent high-resolution (\(\sim 100\) arcsec) H\(_{1}\) line observations have revealed filamentary structures in the cloud with a typical transverse width of 0.1 pc (McClure-Griffiths et al. 2006). McClure-Griffiths et al. (2006) also discussed the possibility that the LOS extent of the R–C cloud may be much smaller than 5 pc as inferred by Crutcher & Riegel (1974) from their optical observations. They suggested that the LOS thickness may be \(\sim 0.1\) pc, similar to the transverse width of the filaments. The H\(_{1}\) absorption measurements have been used to infer a mean spin temperature of \(\sim 40\) K and H\(_{1}\) column density \(N_{\text{HI}}\) of \(\sim 10^{20}\) cm\(^{-2}\) for the R–C cloud (Montgomery, Bates & Davies 1995; McClure-Griffiths et al. 2006).

H\(_{1}\) spectra towards the R–C cloud in the longitude range of \(\sim 2^\circ–7^\circ\) are shown along with the CRRL spectra in Fig. 3. The angular resolution of the H\(_{1}\) spectra is \(0.6 \times 0.6\) and that of the CRRL spectra is \(2^\circ\) (along \(b\)) \(\times 0.5\) (along \(l\)). The prominent self-absorption feature seen in the H\(_{1}\) spectra is due to the R–C cloud. The H\(_{1}\) line and CRRL parameters obtained from the spectra with \(2^\circ\) (along \(b\)) \(\times 2^\circ\) (along \(l\)) resolution in the same longitude range are given in Table 1.

It is evident from Fig. 3 and the line parameters given in Table 1 that the LSR velocities of CRRLs and HISA coincide. Based on this

![Figure 3](https://academic.oup.com/mnras/article-abstract/414/1/519/1094386/figure3)

**Figure 3.** CRRL (top panels) and H\(_{1}\) (bottom panels) spectra towards the Riegel–Crutcher cloud. CRRL spectra at 327 MHz and H\(_{1}\) spectra (Kalberla et al. 2005) are obtained with angular resolutions of \(2^\circ\) (along \(b\)) \(\times 0.5\) (along \(l\)) and \(0.6 \times 0.6\), respectively. The 1\(\sigma\) values of the noise in CRRL spectra are also shown in the top panels. The spectra are centred near the Galactic coordinates marked in the top panel. The arrows are placed at the LSR velocity of the carbon lines detected at the different positions.
coincidence we conclude that the carbon line-forming regions are associated with the R–C cloud.

The extent of the R–C cloud is \( \sim -15^\circ < l < \sim 25^\circ \) (Riegel & Crutcher 1972). However, CRRL emission from the R–C cloud could be identified only in the longitude range of \( \sim 2^\circ - 7^\circ \). Close to the Galactic Centre (i.e. \( |l| \lesssim 2^\circ \)) it is difficult to identify the CRRL emission associated with the R–C cloud due to the degeneracy in LSR velocity of recombination line emission from several regions along the LOS. In the other longitude range spanned by the R–C cloud the non-detection of CRRL emission may be either due to sensitivity limitation or due to variation in the fraction of ionized carbon in the R–C cloud.

4.1 CRRL and HISA linewidths

The average width of the carbon line from the R–C cloud is \( \sim 12 \, \text{km s}^{-1} \) (FWHM) which is about three times the width of the \( \text{H}_\alpha \) absorption line (FWHM \( \sim 4.0 \, \text{km s}^{-1} \)). CRRLs detected in several other directions also have a larger width compared to the \( \text{H}_\alpha \) line (see Table 1). If the two line-forming regions coexist then the spectral lines from such regions are expected to have the same widths (this is true if the linewidths are dominated by non-thermal motions, which is the case for the R–C cloud). A possible explanation for the difference in the linewidths of CRRL and \( \text{H}_\alpha \) is the following. As mentioned above, detection of cool \( \text{H}_\alpha \) clouds in self-absorption needs favourable observing conditions and angular resolution (Bania & Lockman 1984). On the other hand, detection of CRRLs does not need such favourable conditions as long as the line-forming regions fill a substantial portion of the observing beam and the Galactic background radiation field is strong. If there are several cool \( \text{H}_\alpha \) clouds with different velocities within the \( 2^\circ \times 2^\circ \) field of the CRRL observations, the coarser beam will detect a broad carbon line while the \( \text{H}_\alpha \) spectrum will be dominated by absorption due to the coldest gas. In addition, any velocity gradient within the observing beam can also contribute to the linewidth. Such a velocity gradient has been detected for \( \text{H}_\alpha \) absorption in the R–C cloud (Montgomery et al. 1995). The R–C cloud also exhibits multiple \( \text{H}_\alpha \) absorption features (e.g. Montgomery et al. 1995). Comparing CRRL and \( \text{H}_\alpha \) spectra obtained with similar (high) angular resolution may help in evaluating these possibilities.

4.2 Modelling the line-forming region in the R–C cloud

The CRRL data towards the R–C cloud at 327 MHz combined with existing data at 76 MHz (angular resolution \( \sim 4^\prime \); Erickson et al. 1995) and 34.5 MHz (angular resolution \( \sim 21 \, \text{arcmin} \times 25^\circ \); Kantharia & Anantharamaiah 2001) are used to model the physical properties of the line-forming region. At 76 MHz both \( \alpha \) and \( \beta \) transitions were detected towards the R–C cloud. To study the average properties of the \( \text{C}^7 \) region in the R–C cloud, all the available CRRL data in the range \( l \sim 2^\circ \to 7^\circ \) and \( b \pm 2^\circ \) at 327 and 76 MHz were averaged. These averaged values are listed in Table 2. Since the 34.5-MHz observations used a fan beam, no averaging was done and we have included the parameter fit to the spectrum towards \( l = 5^\circ \) and \( b = 0^\circ \). The linewidth and central velocities for all these transitions roughly match; any differences, particularly the difference between the 327- and 34.5-MHz line parameters, are attributed to the differences in the observing beam. To determine the physical properties, we followed the method described by Kantharia & Anantharamaiah (2001) where a uniform slab of line-emitting region with electron temperature, \( T_e \), electron density, \( n_e \), and LOS extent, \( S \), is considered.

<table>
<thead>
<tr>
<th>Table 2. CRRL parameters observed towards the R–C cloud.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq. (MHz)</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>327</td>
</tr>
<tr>
<td>76</td>
</tr>
<tr>
<td>76</td>
</tr>
<tr>
<td>34.5</td>
</tr>
</tbody>
</table>

$^a$Multiplied transitions were observed at all three frequency bands. We list here the central transitions observed at each band.

$^b$The \( \sigma \) errors on the line parameters are given in bracketed values.

References: 1, Roshi & Anantharamaiah (2001b); 2, Erickson et al. (1995); 3, Kantharia & Anantharamaiah (2001).

The integrated line optical depth is related to these parameters through the equation (Shafer 1975)

\[
\int \tau_l \, d\nu \approx 1.07 \times 10^7 b_\alpha \beta_{n,\Delta n} K(\Delta n)\Delta n T_e^{-2.5} n_e^2 S \text{ s}^{-1},
\]

where \( b_\alpha \) and \( \beta_{n,\Delta n} \) are the non-LTE departure coefficients for principal quantum number \( n \) and transition \( \Delta n \). \( K(\Delta n) = 0.1908 \) and \( 0.0263 \) for \( \Delta n = 1 \) and \( \Delta n = 2 \) transitions, respectively. \( \beta_{n,\Delta n} \) is defined as

\[
\beta_{n,\Delta n} = 1 - 3.2 \times 10^{-6} n_e^3 T_e^{-1} \left( b_\alpha - b_{\alpha+\Delta n} \right). \]

In the above equations the unit of \( T_e \) is \( \text{K} \), the unit of \( n_e \) is cm\(^{-3} \) and the unit of \( S \) is pc. The departure coefficients, which are computed using the programs of Payne et al. (1994), a modified version of the original program of Walmsley & Watson (1982), depend on the background continuum radiation field. We used 5000 K at 100 MHz as the background temperature. This background temperature is obtained from the continuum map at 34.5 MHz (Dwarakanath 1989; see also Kantharia & Anantharamaiah 2001) and scaled to 100 MHz using a spectral index of \(-2.6 \). The derived parameters of the line-emitting region change by a few per cent for a factor of 2 change in the background temperature. An abundance for carbon \( A_c \) of \( 1.4 \times 10^{-4} \) obtained from the solar abundance of \( 2.9 \times 10^{-4} \) (Lodders 2003) and assuming a depletion factor of 0.48 (Wolfire et al. 2003; Jenkins 2009) is used for the modelling. Since the R–C cloud has a large angular extent, no beam dilution factor is used for the 327- and 76-MHz observations to convert the observed line antenna temperature to brightness temperature. We could not find a single model which fitted all the three observed points. The 34.5-MHz observations were made with a beam \( \sim 25^\circ \) in size along Galactic latitude and hence the observed line optical depth may have to be corrected by an unknown beam dilution factor. Therefore we constrained the model parameters using the 76- and 327-MHz data. Modelling of the data at 76 and 327 MHz resulted in the following physical properties: \( T_e \sim 40 \to 60 \, \text{K} \), \( n_e \sim 0.8 \to 0.05 \, \text{cm}^{-3} \) and \( S \sim 0.03 \to 3.5 \, \text{pc} \). For \( T_e \) larger than 60 K we find that models with lower \( n_e \) (\( \lesssim 0.05 \, \text{cm}^{-3} \)) also fit the CRRL data; however, the path lengths are longer than the LOS extent of 5 pc which is the thickness of the R–C cloud as obtained by Crutcher & Riegel (1974). We hence rule out these higher temperature models.

The above modelling for the carbon lines used the departure coefficients estimated after including the dielectric-like recombination process (Watson, Western & Christensen 1980; Walmsley & Watson 1982; see also Payne et al. 1994) which involves the excitation of the fine structure transition in the core electrons in carbon giving rise to a spectral line at 158 \( \mu \text{m} \). This process
Transitions of CRRL observations. The expected integrated optical depth, \( \tau \), is the visual extinction, and \( 2P_{414} \), is in the R–C cloud. PDR modelling of this region will be \( 0.05 \) pc. For these models, \( T \) is the number of \( n_I \) data to get more insight into the \( n_p \) is the hydrogen nuclear density, \( n_I \) is in atomic form (the remaining fraction is \( H_2 \)) is the hydrogen molecular density, \( N \) is the hydrogen atomic density, \( n_{HI} \) is the hydrogen molecular density, \( f = 2n_{HI}/n_I \) is the molecular fraction, \( N_{HI} \) and \( N_{H_2} \) are the atomic and molecular column densities, respectively.

Partial pressure of \( H_2 \) is tabulated in units of K cm\(^{-3}\).

Table 3. Physical properties of the Riegel–Crutcher cloud.\(^a\)

<table>
<thead>
<tr>
<th>Model No.</th>
<th>( T_e ) (K)</th>
<th>( n_e ) ( (\text{cm}^{-3}) )</th>
<th>( S ) (pc)</th>
<th>( n_{HI} ) ( (\text{cm}^{-3}) )</th>
<th>( A_v )</th>
<th>( n_{HI} ) ( (\text{cm}^{-3}) )</th>
<th>( n_{H_2} ) ( (\text{cm}^{-3}) )</th>
<th>( f )</th>
<th>( P_{HI} ) ( (\times 10^{20}) )</th>
<th>( N_{HI} ) ( (\text{cm}^{-2}) )</th>
<th>( N_{H_2} ) ( (\text{cm}^{-2}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>0.1</td>
<td>1.1</td>
<td>700</td>
<td>1.4</td>
<td>90</td>
<td>300</td>
<td>0.9</td>
<td>5</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>0.3</td>
<td>0.15</td>
<td>2100</td>
<td>0.6</td>
<td>500</td>
<td>800</td>
<td>0.8</td>
<td>27</td>
<td>2.5</td>
<td>3.7</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>0.6</td>
<td>0.04</td>
<td>4300</td>
<td>0.3</td>
<td>1430</td>
<td>1430</td>
<td>0.7</td>
<td>57</td>
<td>1.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>

\(^a\) \( T_e, n_e, S \) are the model parameters, \( n_{HI} \) is the hydrogen nuclear density, \( A_v \) is the visual extinction, \( n_{HI} \) is the hydrogen atomic density, \( n_{H_2} \) is the hydrogen molecular density. \( f = 2n_{HI}/n_I \) is the molecular fraction, \( N_{HI} \) and \( N_{H_2} \) are the atomic and molecular column densities, respectively.

Figure 4. Integrated CRRL optical depth from models for the Riegel–Crutcher cloud plotted against principal quantum number. The optical depths of \( C_n \) and \( CnB \) for the best-fitting model parameters are shown by solid and dashed lines, respectively. The values of model parameters (electron temperature, \( T_e \), electron density, \( n_e \), and line-of-sight path-length, \( S \)) are indicated on the plots. The observed integrated optical depths of \( Cn \) lines are indicated by circles and that of the \( CnB \) line is shown by a cross. The error bars represent \( \pm 1 \)\( \sigma \) values.

4.3 Atomic and molecular hydrogen densities

We combine the CRRL and \( H_1 \) data to get more insight into the physical state of the R–C cloud. The inferred \( N_{HI} \) for the R–C cloud from \( H_1 \) observations is between a few times \( 10^{19} \) and \( 4 \times 10^{20} \) cm\(^{-2}\) (Montgomery et al. 1995; McClure-Griffiths et al. 2006) which is typical of CNM clouds in our Galaxy. This high \( N_{HI} \) implies that photoionization due to EUV/soft X-rays does not dominate in the interior of the R–C cloud (see for example Glassgold & Langer 1974) and most of the ionization is due to far-ultraviolet (FUV) photons which ionize carbon atoms. So, unlike in CNM clouds with canonical ISM pressure (\( \sim 3000 \text{ K cm}^{-2} \)), where electrons are due to ionization of hydrogen atoms (Wolfire et al. 2003), most of the electrons in the R–C cloud are due to carbon ionization. This fact can thus be used to estimate the number density of hydrogen, \( n_{HI} \), in the cloud: \( n_{HI} = n_e/A_v \) (see Table 3) where \( A_v \) is the number abundance of gas-phase carbon atoms taken to be \( 1.4 \times 10^{-4} \) (see Section 4.2). The fraction of hydrogen which is tied up in the atomic form, i.e. \( H_1 \), is inferred as follows. The \( H_1 \) optical depth from the CRRL models is obtained by assuming that (a) some fraction of \( n_{HI} \) is in atomic form (the remaining fraction is \( H_2 \) molecules) and (b) the spin temperature is equal to the electron temperature, which is generally the case for cold \( H_1 \) regions (e.g. Kulkarni & Heiles 1988). In addition, we assume that the carbon and \( H_1 \) line-forming regions coexist along the LOS. This assumption means that, for models with \( T_e \sim 60 \) and \( 50 \text{ K} \) the LOS thickness of the \( H_1 \) region is respectively \( \sim 1 \) pc, close to the value suggested by Crutcher & Riegel (1974; i.e. 1–5 pc), and \( \sim 0.15 \) pc, close to 0.1 pc suggested by McClure-Griffiths et al. (2006). For models with \( T_e \sim 40 \text{ K} \), the LOS thickness of the \( H_1 \) region will be 0.05 pc. For these models, it is possible that the CRRL emission originates from an interface region between the \( H_1 \) and \( H_2 \) in the R–C cloud. PDR modelling of the R–C cloud is needed to investigate this possibility. Following literature, we define the molecular fraction in terms of the \( n_{H_2} \).
content; \( f = \frac{2n_{\text{H}_2}}{n_{\text{H}_2} + n_{\text{H}_1}} = \frac{2n_{\text{H}_1}}{n_{\text{H}_1} + n_{\text{H}_2}} \), where \( n_{\text{H}_2} \) and \( n_{\text{H}_1} \) are the \( \text{H}_2 \) and \( \text{H}_1 \) densities, respectively. The \( \text{H}_1 \) optical depths due to CRRL models are then equated to the observed value (mean peak optical depth in the R–C cloud \( \sim 0.7 \); McClure-Griffiths et al. 2006) to determine \( f \). The estimated \( f \), \( n_{\text{H}_1}, n_{\text{H}_2} \) and \( \text{H}_1 \) partial pressure, \( P_{\text{H}_1} = n_{\text{H}_1}T_{\text{e}} \), for the three representative models are listed in Table 3.

The higher temperature models (i.e. \( T_\ell \sim 40 \) K) model which predicts an extinction of 0.3 and \( I \) are erg s\(^{-1}\) are due to the R–C cloud. The molecular density compared to the \( \text{H}_1 \) density is higher in these models. The LOS extent of lower temperature models (i.e. \( T_\ell \sim 40 \) K) model which predicts an extinction of 0.3 and \( I \) are due to transitions in \( \text{C}^\text{ii} \). The \( \text{H}_1 \) partial pressure in these models is an order of magnitude higher than the mean interstellar pressure. Note that for all the models the total gas pressure is at least an order of magnitude higher than the mean interstellar pressure and hence the cloud has to be supported by either gravity or magnetic pressure. In the next subsection, we compare the model predictions with other existing UV and optical observations with the intention of narrowing down the range of parameter values.

### 4.4 Comparison with UV and optical observations

Several stars beyond the R–C cloud have been observed in the optical and UV, thus sampling the gas in the intervening cloud. From these observations we take data towards two stars, HD165246 (\( l = 6:4, b = -1:56 \), distance = 1.85 kpc; Jenkins 2009) and HD164402 (\( l = 7:1, b = 0:0 \), distance = 1.74 kpc; Savage et al. 1977), which overlap with the directions in which CRRLs from the R–C cloud are observed. The measured visual extinctions \( A_I \) towards these two stars are 1.1 and 0.95 and the measured \( N_{\text{H}_2} \) are \( 1.4 \times 10^{20} \) and \( 3 \times 10^{19} \) cm\(^{-2} \) (Savage et al. 1977; Jenkins 2009), respectively. About 10 per cent of the extinction and almost all the \( \text{H}_2 \) are due to the R–C cloud (Montgomery et al. 1995). \( A_s \) from our model parameters using the equation \( A_s = N_{\text{H}_2}/(1.7 \times 10^{21}) \) (Bohlin, Savage & Drake 1978) are listed in Table 3. The observed extinction due to the R–C cloud, i.e. 0.1 to 0.095, is closest to our lower temperature model (\( T_\ell \sim 40 \) K) model which predicts an extinction of 0.3 and \( N_{\text{H}_2} \) of 1.8 \( \times 10^{20} \) cm\(^{-2} \). Spectroscopic observations of the spectral lines of Na\(^{i}\) (Crutcher & Riege 1974), Mg\(^{i}\) and Mg\(^{ii}\) (Bates, Montgomery & Kemp 1995) towards stars behind the R–C cloud can be used to determine the electron density in the cloud. The derived electron densities are typically \(<0.1 \text{ cm}^{-3} \). Although we did find models with such low electron densities which fitted the observed data points, we do not favour these due to the long path-lengths, and hence correspondingly high \( A_s \), required to explain the observed line strengths. However, relaxing some of the assumptions made in deriving \( n_{\text{e}} \) from optical line observations can increase the estimated electron density. For example, Bates et al. (1995) obtained \( n_{\text{e}} \sim 0.3 \) cm\(^{-3} \) by considering that the Mg\(^{ii}\) line is mainly from the cloud core and the Mg\(^{ii}\) is distributed along the line of sight. This value is within the range of models that we derive for the carbon line-forming region in the R–C cloud (see Table 3). However, it is not sufficient to favour the lowest temperature model over the others. Thus, it appears that it is difficult to narrow down the range of physical parameters listed in Table 3 for the R–C cloud with existing data.

## 5 THE PHYSICAL STATE OF THE R–C CLOUD

In this section, we use the model parameters to investigate the cooling and heating processes in the R–C cloud. We also estimate the neutral carbon fraction and molecular formation and dissociation rates in the cloud.

### 5.1 Cooling in the R–C cloud

The derived properties of the R–C cloud are used to determine the cooling rate in the gas. The major cooling processes in these clouds are due to transitions in \( \text{C}^\text{ii}, \text{C}^\text{i} \) and \( \text{O}^\text{i} \) and molecular transitions in \( \text{H}_2 \) and CO. The \( \text{C}^\text{ii} 158 \mu\text{m} \) is believed to be the major coolant in diffuse clouds with temperature \( \sim 100 \) K (Dalgarno & McCray 1972). The cooling rate due to \( \text{C}^\text{ii} 158 \mu\text{m} \) line emission is calculated following Watson (1984) and using the values for collision rate coefficients and the Einstein A-coefficient given by Schöier et al. (2005). The combined cooling rate due to \( \text{C}^\text{i}, \text{O}^\text{i} \) and molecular transitions in \( \text{H}_2 \) and CO is calculated from fig. 1. of Gilden (1984). These cooling rates along with the estimated intensity of the \( \text{C}^\text{ii} 158 \mu\text{m} \) line, are given in Table 4 for the three representative models. The combined cooling rate due to atoms and molecules is at least a factor of 4 smaller than that due to the \( \text{C}^\text{ii} 158 \mu\text{m} \) emission.

### 5.2 Heating in the R–C cloud

The heating processes which are important in diffuse clouds and considered here are photoelectric emission, \( \text{H}_2 \) dissociation, carbon ionization and cosmic rays. The heating efficiency of photoelectric emission depends on the grain charge which in turn is a function of the electron density and \( G_0 \), the interstellar FUV (6–13.6 eV) radiation field in Habing units (1.6 \( \times 10^{-3} \) erg s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\); Habing 1968). The heating rate per unit volume due to photoelectric emission is

<table>
<thead>
<tr>
<th>Model No.</th>
<th>( \Lambda^b_{\text{C}^\text{ii}} ) ((\text{x}10^{-23}))</th>
<th>( \Lambda^b_{\text{other}} ) ((\text{x}10^{-23}))</th>
<th>( \int I_{\text{C}^\text{ii} \text{dio}} ) ((\text{x}10^{-5}))</th>
<th>( G_0 )</th>
<th>( \Gamma^b_d ) (\text{phdiss} ) ((\text{x}10^{-25}))</th>
<th>( R_{\text{form}} ) ((\text{cm}^{-3} \text{erg}^{-1})) ((\text{x}10^{-11}))</th>
<th>( R^d_{\text{dis}} ) ((\text{cm}^{-3} \text{erg}^{-1})) ((\text{x}10^{-11}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>3</td>
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<td>4</td>
<td>0.1</td>
<td>0.2</td>
<td>0.003</td>
</tr>
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<td>8</td>
<td>2.7</td>
<td>7</td>
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<tr>
<td>3</td>
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<td>14</td>
<td>1.5</td>
<td>6</td>
<td>28</td>
<td>11.6</td>
<td>0.7</td>
</tr>
</tbody>
</table>

*\( \Lambda^b_{\text{C}^\text{ii}} \) is the cooling rate due to \( \text{C}^\text{ii} 158 \mu\text{m} \) radiation, \( \Lambda^b_{\text{other}} \) is the total cooling rate due to atomic and molecular line emission, \( I_{\text{C}^\text{ii} \text{dio}} \) is the intensity of \( \text{C}^\text{ii} 158 \mu\text{m} \) line emission, \( G_0 \) is the flux density of the FUV radiation field in Habing units, \( \Gamma^b_d \) is the heating rate due to the dissociation of \( \text{H}_2 \) molecules, \( R_{\text{form}} \) and \( R_{\text{dis}} \) are the \( \text{H}_2 \) formation and dissociation rates, respectively.

The units of \( \Lambda^b_{\text{C}^\text{ii}}, \Lambda^b_{\text{other}}, \Gamma^b_d \) are erg s\(^{-1}\) cm\(^{-3}\) sr\(^{-1}\). The intensity of \( \text{C}^\text{ii} \) line is tabulated in units of erg s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\).

\( \text{d} \) \( \Gamma^b_d \) and \( R_{\text{dis}} \) are estimated at \( A_s/2 \). The \( A_s \) obtained for the models is given in Table 3.

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given by (Wolfire et al. 2003)

$$\Gamma_{pe} = 1.3 \times 10^{-24} n_H \epsilon G_0 \text{ erg s}^{-1} \text{ cm}^{-3},$$  \hspace{1cm} (3)

where the photoelectric emission efficiency, $\epsilon$, is

$$\epsilon = \frac{4.9 \times 10^{-2}}{1 + 4 \times 10^{-3} (G_0 T_e^{-0.5}/(n_e \phi_{\text{PAH}})^{0.73})}$$

$$+ \frac{3.7 \times 10^{-2} (T_e^{-0.5}/n_e \phi_{\text{PAH}})^{0.7}}{1 + 2 \times 10^{-6} (G_0 T_e^{-0.5}/n_e \phi_{\text{PAH}})^{0.7}},$$  \hspace{1cm} (4)

In the above equation, $\phi_{\text{PAH}}$ is a parameter introduced by Wolfire et al. (2003) to modify the electron–dust collision rates; following them we take its value to be 0.5. The values for $n_e$, $n_H$, and $T_e$ are taken from Table 3 for estimating the heating rate.

The second process we examine is fluorescent photodissociation of $H_2$. This process results in the production of energetic H atoms which in turn leads to the heating of the cloud. The heating rate is essentially the product of the photodissociation rate per unit volume (see equation 7 in Section 5.4) and the mean kinetic energy ($\sim 0.25$ eV) of the dissociated atoms (Stephens & Dalgarno 1973; Tielens 2005). We examine the relative importance of the four processes in heating the HISA cloud for $G_0$ ranging between 1 and 10. We find that heating due to carbon ionization (Tielens 2005) for a carbon neutral fraction $\lesssim 0.08$ (see Section 5.3) as well as cosmic ray heating are insignificant compared to the other two heating processes.

The photodissociation heating depends on the dissociation rate $R_{\text{ph,diss}}$, which is a function of FUV radiation intensity inside the cloud. As described in Section 5.4, opacity of FUV lines in the cloud plays an important role in determining the dissociation rate inside the cloud. It can be shown that the opacity effect reduces the dissociation rate considerably at $H_2$ column densities $> 10^{14}$ cm$^{-2}$. This effect is termed ‘self-shielding’ (see for example Draine & Bertoldi 1996). Observations show that the $H_2$ column density of the R–C cloud is $> 10^{16}$ cm$^{-2}$ (Savage et al. 1977; Jenkins 2009). In clouds with such column densities, detailed modelling shows that a gradient in the density ratio of hydrogen in atomic and molecular form exists and $H_2$ self-shielding becomes important (e.g. van Dishoeck & Black 1986). Such detailed modelling, which is implemented in PDR codes (for example Hollembach & Tielens 1997), is beyond the scope of the present work and will be presented elsewhere. In the subsequent part of the paper, we provide estimates of various quantities at a depth where the visual extinction ($A_v$) is about half the total $A_v$ due to the cloud. We refer to this depth in the cloud as $A_v/2$ and note that self-shielding effects need to be included while estimating the physical processes in the R–C cloud. Estimates of the heating at a depth of $A_v/2$ for $G_0$ ranging between 1 and 10 show that photoelectric heating dominates in the cloud interior.

As mentioned above, photoelectric and photodissociation heating depends on the background FUV flux $G_0$. Constraints on $G_0$ may be obtained by assuming that the R–C cloud is in thermal equilibrium i.e. by equating the $Cn$ 158 $\mu$m cooling rate per unit volume to the heating rate per unit volume. We estimate that $G_0$ is between 4 and 7 (see Table 4). For comparison with the photoelectric heating rate, which is approximately equal to the $A_{\text{C}_1}$ listed in Table 4, the heating rates due to photodissociation processes at $A_v/2$ are included in Table 4 for the estimated $G_0$.

### 5.3 Neutral carbon in the R–C cloud

In this section, we estimate the neutral fraction of carbon in the R–C cloud using our model parameters. To a large extent, the background FUV flux and the fraction of neutral carbon determine the ionization of carbon in the cloud (see Glassgold & Langer 1975 for other factors affecting carbon ionization). We estimate the neutral fraction by assuming that carbon ionization is dominated by FUV radiation and that all electrons are due to carbon ions. The ionization equilibrium of carbon implies

$$n_e n_C \alpha_R = f_C n_C + \Gamma_{\text{ion}},$$  \hspace{1cm} (5)

where $n_C$ is the number density of carbon ions, $\alpha_R = 6.38 \times 10^{-11}$ cm$^3$ s$^{-1}$ is the recombination coefficient (Nahar 1996) and $f_C = n_e/n_C$ is the neutral fraction. The ionization rate, $\Gamma_{\text{ion}}$, is obtained by integrating the ionization cross-section over the energy range 11.26–13.6 eV. For this integration, we used the radiation spectrum given by Draine (1978) and a constant ionization cross-section of $1.74 \times 10^{-17}$ cm$^2$ (Nahar & Pradhan 1997). If we assume that the spectrum of the background radiation is independent of its integrated flux density i.e. $G_0$, then equation (5) can be used to estimate $f_C$ for the $G_0$ required for thermal balance. The neutral fraction estimated at a depth of $A_v/2$ is 0.08 for the model with $T_e = 60$ K and is 0.03 for the model with $T_e = 40$ K listed in Table 3. These are about a factor of 10 higher than the neutral fractions inferred for CNM clouds ($\lesssim 3 \times 10^{-3}$; Jenkins & Tripp 2001) but not unreasonable for clouds with $H_2$ column density $N_{H_2} \sim 10^{20}$ cm$^{-2}$ and $G_0 \sim 5$ (Hollenbach et al. 1991).

### 5.4 Formation and dissociation of molecular hydrogen in the R–C cloud

The properties of the R–C cloud discussed above can be used to examine the formation and dissociation of $H_2$ in the cloud. Conventionally, the rate of formation of $H_2$ is obtained from the frequency of collision between H atoms and grains scaled by an efficiency factor for recombination on the grain surface. The collision rates depend upon the temperature and densities of H atoms and grains and the efficiency factor is estimated by making some reasonable assumptions regarding the properties of the grains (Hollenbach & Salpeter 1971). The rate of $H_2$ formation per unit volume can be written as (van Dishoeck & Black 1986)

$$R_{\text{form}} = 3 \times 10^{-18} T_e^{-0.5} n_H n_H \gamma_{vd} \text{ s}^{-1} \text{ cm}^{-3},$$  \hspace{1cm} (6)

where $\gamma_{vd}$ is a parameter which takes into account the sticking probability and formation efficiency. $\gamma_{vd}$ is taken as unity for the calculations presented here. The formation rates obtained for the representative models vary from about $0.2 \times 10^{-11}$ s$^{-1}$ cm$^{-3}$ for the highest temperature model to about $12 \times 10^{-11}$ s$^{-1}$ cm$^{-3}$ for the lowest temperature model. These rates are given in Table 4.

The $H_2$ molecules in the cloud will be destroyed by FUV photons ($11–13.6$ eV) and cosmic rays. Photodissociation is initiated by line absorption (Lyman and Werner lines) and subsequent fluorescence to the vibrational continuum of the ground state of $H_2$ (Solomon, private communication, reported in Field, Somerville & Dressler 1966; Stecher & Williams 1967). Since the opacity to the UV lines from the $H_2$ molecule increases with depth (self-shielding) and several line transitions are involved, the dissociation rates at different depths are calculated numerically. Further, attenuation of the FUV radiation field due to dust has to be taken into account to calculate the dissociation rate. An analytical approximation to the dissociation rate taking into account these effects is given by Draine & Bertoldi (1996):

$$R_{\text{ph,diss}} = \left( N_{H_2}/10^{14} \right)^{-0.75} e^{-4.04 \alpha},$$

$$\times 4.17 \times 10^{-11} G_0 n_{H_2} \text{ s}^{-1} \text{ cm}^{-3}.$$  \hspace{1cm} (7)
Here $e^{-4.0A_b}$ takes into account the dust attenuation near $\sim 12$ eV. The self-shielding effect is absorbed in the term $(N_H/10^{14})^{-0.75}$ which is set to unity for $N_H \leq 10^{14}$ cm$^{-2}$. We used the G0 estimated for thermal balance (Table 4) to determine the dissociation rate per unit volume at a depth of $A_v/2$ in the cloud. The estimated values for dissociation rate per unit volume (tabulated in Table 4) for the different models are more than an order of magnitude smaller than the formation rate. This difference in rates may indicate that the R–C cloud is in the process of molecular formation similar to, for example, the HISA cloud G28.17+0.05 (Minter et al. 2001).

We used the survey data of Dame et al. (1987) to investigate whether $^{12}$CO line emission is associated with the R–C cloud. A $^{12}$CO line feature of similar LSR velocity and width as that of the observed H I line towards the R–C cloud is present in some directions. However, this $^{12}$CO line feature is not detected over the entire extent of the R–C cloud. This may support the fact the molecular formation in the R–C cloud is not complete. At the estimated rate of molecular formation in the R–C cloud, it should take $\gtrsim 10^5$ yr to convert all the H I to H$_2$.

6 SUMMARY AND FUTURE OBSERVATIONS

In Paper I, a preliminary analysis of CRRL data obtained as part of a 327-MHz recombination line survey of the Galactic plane was presented. In this paper, we have for the first time shown that CRRLs arising near the Galactic Centre within $l \sim 10^\circ$ show an excellent kinematic correlation with the HISA features from the Riegel–Crutcher cloud, arguing for a common origin for the CRRL and HISA features. The R–C cloud is a HISA cloud located about 125 pc in the Galactic Centre direction. Additionally, we have reported the association of low-frequency CRRL emission with a few other HISA clouds in the inner Galaxy.

We have also demonstrated that low-frequency CRRL data at several frequencies along with H I observations can be used to constrain the physical properties of the cold H I regions. For the analysis presented here we made use of the CRRL observations at 327 and 76 MHz along with H I data to model the physical conditions in the R–C cloud. We find that models that fit the 76 and 327 MHz data and are constrained by the LOS size of the R–C cloud are the following: $T_e \sim 40 \rightarrow 60$ K, $n_e \sim 0.8 \sim 0.05$ cm$^{-3}$ and $5 \sim 0.03$ $\rightarrow 0.05$ pc. The derived physical properties were used to examine the heating and cooling processes in the R–C cloud. The dominant heating and cooling processes were found to be photoelectric emission and the C II 158 $\mu$m line emission, respectively. The thermal balance between these two processes was used to constrain the diffuse FUV flux density on the cloud, which in Habing units (G0) ranges between $\sim 4$ and 7. Further, we investigated the H$_2$ formation and dissociation in the cloud and found that the formation rate per unit volume exceeds the dissociation rate per unit volume by at least an order of magnitude. Based on this imbalance in the formation and dissociation rate we conclude that the R–C cloud is in the process of converting from H I to H$_2$ and will convert all its atomic hydrogen into the molecular form in a time-scale $\gtrsim 10^5$ yr.

The cold H I gas observed as HISA features is ubiquitous in the inner Galaxy and forms an important part of the ISM. Our analysis shows that combining CRRL and H I data can give important insights into the nature of this cold gas.

We investigate the possibility of imaging the CRRL emission from H I self-absorbing clouds with upcoming Square Kilometre Array Pathfinders. The Murchison Widefield Array (MWA), the Australian Square Kilometre Array Pathfinder (ASKAP), and the Karoo Array Telescope (MeerKAT) are considered for the investigation. Observing CRRL emission with the Long Wavelength Array (LWA) is discussed by Peters et al. (2011) and hence has not been discussed here. High angular resolution observation with the upcoming arrays will help, for example, to resolve the ‘linewidth problem’ (see Section 4.1). The integration times required to image CRRL emission from the inner Galaxy with the different arrays are listed in Table 5. The carbon line temperature is computed using the optical depth of the $T_e = 50$ K model given in Table 3. The peak line temperatures ($T_L$) obtained from this model for the linewidth of 12.2 km s$^{-1}$ (see Table 2) and Galactic background temperature of 500 K at 327 MHz are listed in Table 5. This background temperature is an average value over the angular resolutions of the interferometric observation. The rms brightness temperature ($\sigma_{\text{rms}}$) in K for observations with the dual polarized interferometers is calculated using the equation

$$\sigma_{\text{rms}} = \frac{T_{\text{sys}}}{\sqrt{N_{\text{base}}N_{\text{line}}}} \frac{\lambda^2}{\Delta f \theta_r^2},$$

where $T_{\text{sys}}$ is the system temperature in K, $A_{\text{eff}}$ is the effective area in m$^2$, $N_{\text{line}}$ is the number of recombination lines that can be simultaneously observed, $\Delta f$ is the frequency resolution in Hz corresponding to the linewidth of 12.2 km s$^{-1}$, $t_{\text{int}}$ is the integration time in seconds, $N_{\text{base}}$ is the number of baselines with length $\frac{\lambda}{2}$, where $\theta_r$ is the angular resolution of the image and $\lambda$ is the observing wavelength. In the above equation the unit of $\lambda$ is metres. Integration times listed in Table 5 are for detecting CRRLs at the 4$\sigma$ level. The estimated values show that imaging CRRLs with the MWA is feasible.

The MeerKAT antenna configuration details are taken from Booth et al. (2010). We have scaled $N_{\text{base}}$ approximately for the new 64 antenna configuration of MeerKAT. Since the scaling factor is not known well, we included a correction factor $f_c$ to indicate how the integration time changes with $f_c$. The 20 recombination lines will span the frequency range $\sim 600$–800 MHz.

The ASKAP parameters are taken from Gupta et al. (2008). The 10 recombination lines will span the frequency range $\sim 700$–800 MHz.

Table 5. Integration time for detecting CRRLs with SKA Pathfinders.

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Freq. (MHz)</th>
<th>$T_L$ (K)</th>
<th>$\theta_r$ (arcmin)</th>
<th>$N_{\text{base}}$</th>
<th>$T_{\text{sys}}$ (K)</th>
<th>$A_{\text{eff}}$ (m$^2$)</th>
<th>$N_{\text{line}}$</th>
<th>$t_{\text{int}}$ (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWA</td>
<td>95</td>
<td>-6.1</td>
<td>22</td>
<td>30794</td>
<td>500 + 4200</td>
<td>23</td>
<td>30</td>
<td>22</td>
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<tr>
<td></td>
<td>200</td>
<td>1.1</td>
<td>10</td>
<td>30794</td>
<td>70 + 850</td>
<td>20</td>
<td>15</td>
<td>38</td>
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<tr>
<td>MeerKAT$^a$</td>
<td>700</td>
<td>0.02</td>
<td>5</td>
<td>$400 \times f_c$</td>
<td>32 + 82</td>
<td>100</td>
<td>20</td>
<td>120/f_c</td>
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<tr>
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<td>750</td>
<td>0.02</td>
<td>5.6</td>
<td>49</td>
<td>50 + 58</td>
<td>90</td>
<td>10</td>
<td>1000</td>
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</tbody>
</table>

$^aT_{\text{sys}} = T_{\text{rec}} + T_{\text{sky}}$, where $T_{\text{rec}}$ is the receiver temperature and $T_{\text{sky}}$ is the contribution from the Galactic background emission.

$^b$The MeerKAT antenna configuration details are taken from Booth et al. (2010). We have scaled $N_{\text{base}}$ approximately for the new 64 antenna configuration of MeerKAT. Since the scaling factor is not known well, we included a correction factor $f_c$ to indicate how the integration time changes with $f_c$. The 20 recombination lines will span the frequency range $\sim 600$–800 MHz.

$^c$The ASKAP parameters are taken from Gupta et al. (2008). The 10 recombination lines will span the frequency range $\sim 700$–800 MHz.
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