A derivation of the free–free emission on the Galactic plane between \( \ell = 20^\circ \) and \( 44^\circ \)

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ABSTRACT
We present the derivation of the free–free emission on the Galactic plane between \( \ell = 20^\circ \) and \( 44^\circ \) and \(|b| \leq 4^\circ\), using radio recombination line (RRL) data from the H\(_I\) Parkes All Sky Survey (HIPASS). Following an upgrade of the RRL data reduction technique, which improves significantly the quality of the final RRL spectra, we have extended the analysis to three times the area covered in Alves et al. The final RRL map has an angular resolution of 14.8 arcmin and a velocity resolution of 20 km s\(^{-1}\).

The electron temperature (\( T_e \)) distribution of the ionized gas in the area under study at 1.4 GHz is derived using the line and continuum data from the present survey. The mean \( T_e \) on the Galactic plane is 6000 K. The first direct measure of the free–free emission is obtained based on the derived \( T_e \) distribution. Subtraction of this thermal component from the total continuum leads to the first direct measurement of the synchrotron emission at 1.4 GHz. A narrow component of width 2\(^\circ\) is identified in the latitude distribution of the synchrotron emission. We present a list of H\(_II\) regions and supernova remnants (SNRs) extracted from the present free–free and synchrotron maps, where we confirm the synchrotron nature of the SNRs G42.0\(^{-}\)0.1 and G41.5\(^{+}\)0.4 proposed by Kaplan et al. and the SNR G35.6\(^{-}\)0.4 recently re-identified by Green.

The latitude distribution for the RRL-derived free–free emission shows that the Wilkinson Microwave Anisotropy Probe (WMAP) maximum entropy method is too high by \( \sim 50 \) per cent, in agreement with other recent results. The extension of this study to the inner Galaxy region \( \ell = -50^\circ \) to 50\(^\circ\) will allow a better overall comparison of the RRL result with WMAP.

Key words: radiation mechanisms: general – methods: data analysis – H\(_II\) regions – ISM: lines and bands – Galaxy: structure – radio lines: ISM.

1 INTRODUCTION
Radio recombination lines (RRLs) are a powerful diagnostic of the interstellar medium (ISM), tracing the ionized component, its electron temperature, velocity and radial distributions. They can be used to determine the free–free emission measure on the Galactic plane where heavy obscuration makes optical measurements impossible. In Alves et al. (2010, hereafter Paper I), we have presented a unique method of determining the free–free emission on the Galactic plane using RRLs. In the present work we include a determination of the electron temperature of the ionized gas, based on the separation of the continuum, free–free and synchrotron emission.

Once the free–free emission is determined, the synchrotron component is available by comparing with the total continuum emission at the same frequency, from the same survey. This approach is more rigorous than the normal method of using the different spectral indices of the two components to make the separation. It allows a first clear image of the Galactic latitude and longitude distributions of the two components.

Paper I showed the feasibility of the RRL approach. The aim of the present paper is to extend the work to a larger longitude range in order to sample a greater volume of the Galaxy. The original paper covered the Sagittarius arm in the first quadrant; here we...
include more of the Sagittarius arm and a section of the Scutum arm. Separating the emission from the two spiral arms allows the investigation of the $z$-thickness of the ionized layer in these arms. Early determinations of the latitude distribution of the diffuse RRL emission on the Galactic plane gave a thin layer of scale height 40–100 pc (Gordon & Cato 1972; Hart & Pedlar 1976; Mezger 1978). These values are in agreement with the $z$-distribution of the $\text{H}^\text{\upshape II}$ regions within the solar circle, with a full width at half-maximum (FWHM) of $\sim$90–120 pc (Paladini, Davies & DeZotti 2004), and somewhat greater than that of the OB stars with a FWHM of 73 pc (Bronfman et al. 2000).

The analysis of Paper I was based on the deep Zone of Avoidance (ZOA) Galactic plane survey and it made a first attempt at removing the spectral ripples encountered in RRL work. We improve the signal-to-noise ratio of the spectra and the effects of the spatial ripple by including the $\text{H}\alpha$ Parkes All Sky Survey (HIPASS) data which were acquired by scanning in declination and complement the Galactic longitude scanning in the ZOA survey. We describe the update of the RRL reduction pipeline used in Paper I, which includes a new bandpass algorithm exclusively designed for the analysis of RRL spectral line data in HIPASS. It extends the analysis from the previous $8^\circ (\ell) \times 8^\circ (b)$ region centred at $(\ell, b) = (40^\circ, 0^\circ)$ to a $24^\circ (\ell) \times 8^\circ (b)$ area centred at $(\ell, b) = (32^\circ, 0^\circ)$.

The paper is organized as follows. Section 2 gives the HIPASS/ZOA survey parameters. In Section 3 we describe the RRL data reduction and the properties of the final data cube. The derivation of the free–free median of the data as a whole. Fig. 2 shows a channel map over these integrations as the bandpass correction. The number of median flux density in each section and then uses the minimum of the five values as the bandpass correction for the entire scan. However, $\text{minmed}_{5}$ was found to produce spectral negatives and loss of emission on the Galactic plane. The spectral negatives were found to arise from large-scale distortions of the bandpass response by very strong continuum sources, for which the system temperature $T_{\text{sys}}$ increases by nearly a factor of 2. For these reasons, a new algorithm was developed for the exclusive treatment of extended emission from RRLs in HIPASS, called $\text{tsysmin}_{n}$.

$\text{tsysmin}_{n}$, the $n$ integrations in a scan for which $T_{\text{sys}}$ is a minimum and, for each spectral channel, takes the median value over these integrations as the bandpass correction. The number of integrations $n$ should be as large as possible to provide good statistics for the baseline, but not so large that it includes regions of emission. We chose $n = 10$ which corresponds to 10 integrations or 10 per cent of the data although we did not explicitly optimize for this value. This is found to be the best compromise for deriving a reliable median of the data as a whole. Fig. 2 shows a channel map of the ZOA-032 data cube at $V = -13.4 \text{ km s}^{-1}$, reduced with both $\text{minmed}_{10}$ and $\text{tsysmin}_{10}$. The former is a refinement of $\text{minmed}_{5}$.
The free–free emission on the Galactic plane

Figure 2. Top: maps of the ZOA-032 data cube at \( V = -13.4 \text{ km s}^{-1} \) reduced with \( \text{minmed}_{10} \) (left) and \( \text{tsysmin}_{10} \) (right). Bottom: the corresponding H167\( \alpha \) spectra at \((\ell, b) = (35.6, 0.0)\).

which was also tested and demonstrates the same problems. Fig. 2 also shows H167\( \alpha \) spectra towards G35.6+0.0. The \( \text{tsysmin} \) estimator is clearly less susceptible to baseline negatives; it provides cleaner spectra with higher peak values and recovers more extended emission on the Galactic plane.

After bandpass correction and calibration, the spectra are smoothed using the Tukey filter (Tukey 1967) to suppress the Gibbs ringing caused by the strong Galactic H\( \text{I} \) line at 1420.406 MHz, which affects the H166\( \alpha \) RRL. The three RRLs are extracted from each spectrum, shifted by the correct fractional number of channels by Fourier interpolation and then stacked. The errors introduced by stacking the lines in frequency space rather than in velocity space are less than 2 per cent of the channel width. The three lines are stacked using a weighted mean, where the weights are proportional to the square root of the bandpass response measured at each line’s rest frequency. The weights are 0.35, 0.39 and 0.26 for H168\( \alpha \), H167\( \alpha \) and H166\( \alpha \); the lower H166\( \alpha \) weight is due to the Gibbs ringing.

The 3D \( \ell–b \) velocity cube for each \( 8^\circ \times 8^\circ \) zone is generated from the weighted median of the stacked spectra within a cut-off radius of 6 arcmin of each pixel, using the package \textsc{gridzilla} (Barnes et al. 2001). The weight for each input spectrum is based on its angular distance from the pixel and its system temperature. The resulting data cube has 4 arcmin\(^2\) pixels and a local standard of rest velocity range of \( \pm 335 \text{ km s}^{-1} \).

Further improvement of the spectra was achieved by combining HIPASS data with ZOA data. The HIPASS declination scans cross the plane at an angle of \( \sim 30^\circ \) in the longitude range under study here and therefore yield a real minimum for the bandpass estimation, as opposed to the longitude ZOA scans. We first calculate the DC level between the two surveys by subtracting the ZOA cube from the HIPASS cube, after going through the same reduction pipeline. The DC offset added back to the ZOA spectra is computed as the median of the difference cube at each Galactic latitude and spectral plane. After correction, both data sets are averaged giving five times more weight to the ZOA survey since it is five times deeper than the HIPASS survey. Finally, spectra in the combined cube are further Tukey smoothed and baseline removed by fitting a polynomial. Fig. 3 shows two examples of spectra improved with the DC level correction and combination of ZOA and HIPASS data. The negative at \( V \sim 40 \text{ km s}^{-1} \) in the ZOA spectrum of G33.1–0.1 is removed after it is combined with HIPASS. The improvement of the baselines is clear for spectra on and away from the plane, as Fig. 3(d) shows.

The improved data reduction pipeline does not significantly change the results in Paper I regarding the \( 8^\circ \times 8^\circ \) zone centred at \( \ell = 40^\circ \). The difference map between the new and the previous...
Figure 3. ZOA (left) and ZOA+HIPASS spectra after DC level correction (right) at two positions: (top) G33.1−0.1 and (bottom) G28.6−2.1. The improvement after combining both data sets is visible even for spectra away from the Galactic plane.

RRL-integrated emission has an rms noise of 1.6 per cent of the maximum line integral, which is 5.6 K km s$^{-1}$ for both maps. There is $\sim$6 per cent increase in the extended emission at higher latitudes in the present map, which is the result of more stable spectral baselines particularly away from the Galactic plane.

3.2 Final data cube

The three $8^\circ \times 8^\circ \times 51$ channel data cubes are combined into a final $24^\circ \times 8^\circ \times 51$ channel data cube that covers the $\ell$-range 20°−44°, $|b| \leq 4^\circ$ and $V_{\text{LSR}} = \pm 335$ km s$^{-1}$. The final spectral resolution after the second Tukey smoothing is degraded from 16 to 20 km s$^{-1}$. The typical noise level in each channel is 3.5 mJy beam$^{-1}$ or 3.0 mK. The final spatial resolution was measured on the total integrated RRL map using two compact H II regions, W49A and W40. The average beam size is 14.8 arcmin with an uncertainty of 0.6 arcmin, which is consistent with the intrinsic resolution of 14.4 arcmin. It is also consistent with simulations which inject false Gaussian sources into the data prior to imaging where, with weighted median gridding, the broadening of the intrinsic 14.4-arcmin beam is negligible. The brightness temperature conversion of 0.84 K Jy$^{-1}$ is obtained from the Rayleigh–Jeans relation for a Gaussian FWHM of 14.4 arcmin at the frequency of the H167α line. This was checked using well-known bright sources and has an uncertainty of 0.03 K Jy$^{-1}$. The conversion factor is consistent with previous measurements by Staveley-Smith et al. (2003) and Kalberla et al. (2010) that indicate a value of 0.80 K Jy$^{-1}$.

The total-power map from the HIPASS survey is available for the region under study (Calabretta et al., in preparation) and is shown in Fig. 7. It is reduced using ZOA and HIPASS data similarly to the RRL, in order to recover the zero levels on the Galactic plane and gridded with the same parameters.

3.3 Helium and carbon RRLs

Helium and carbon RRLs are observed in the HIPASS/ZOA spectra. The recombination lines of H, He and C are at different frequencies due to their different Rydberg factors. When converted to the H RRL velocity scale, the He and C lines lie at $-122.1$ and $-149.5$ km s$^{-1}$, respectively. Due to the spectral resolution of 20 km s$^{-1}$, these two
RRLs are sometimes blended. However, C RRLs may be shifted to lower velocities as a result of maser amplification by colder gas lying in front of the continuum source (Dupree & Goldberg 1969). In the case of the H II region W47 shown in Fig. 4, the C line has been shifted to the lower velocities of the Local spiral arm and is separated by $\sim 25$ km s$^{-1}$ relative to the H RRL.

Further investigation will provide information on the He and C RRLs from the diffuse ionized gas in the inner Galaxy. This will be presented in a future work.

4 CONVERSION TO A FREE–FREE TEMPLATE

The RRL emission from diffuse ionized hydrogen gas can be expressed in terms of the integral over spectral line temperature as

$$\int T_\nu dV = 1.92 \times 10^3 T_e^{1.5} EM,$$

where $\nu$ is the frequency (GHz), $T_e$ is the electron temperature (K) and the emission measure (EM) is in cm$^{-6}$ pc. The corresponding continuum emission brightness temperature is

$$T_b = 8.235 \times 10^{-2} a(T_e) T_e^{-0.35} v^{-2.1}_{\text{GHz}} (1 + 0.08) EM,$$

where $a(T_e)$ is a slowly varying function of temperature and $v$ is the frequency in GHz (Mezger & Henderson 1967). The $(1+0.08)$ term represents the additional contribution to $T_b$ from helium. These equations lead to an expression for the ratio of the line integral to the continuum

$$\frac{\int T\nu dV}{T_b} = \frac{1}{a(T_e) (1 + 0.08)} T_e^{-1.15} v^{1.1}_{\text{GHz}},$$

where $V$ is in km s$^{-1}$ (Rohlfs & Wilson 2000).

4.1 The $T_e$ of the thermal emission from $\ell = 20^\circ$ to $44^\circ$

In order to convert the RRL integral into a free–free brightness temperature, a value for the electron temperature of the ionized gas is needed. The variation of $T_e$ in discrete H II regions with longitude, or Galactic radius $R_G$, is well known (Shaver et al. 1983; Paladini et al. 2004). It is caused by the greater cooling of the H II regions closer to the Galactic Centre due to a higher metal content in the inner Galaxy. Paladini et al. (2004) use all the published data for 404 H II regions with reliable Galactocentric distances to derive

$$T_e(K) = (4166 \pm 124) + (314 \pm 20) R_G \text{ (kpc)}.$$

It follows that the mean $T_e$ at the Galactic radius of the Local arm, 8.5 kpc, is 6835 K and decreases to 5740 K at 5.0 kpc, the radius of the Scutum arm.

The line-to-continuum ratio given by equation (3) is one of the most reliable methods to determine the electron temperature of an H II region and this survey has the advantage of providing both the line and continuum data at the same resolution, after going through the same reduction pipeline. However, $T_b$ in equation (3) must correspond to the thermal component only; thus, an estimate of the synchrotron emission within the beam must be removed from the total continuum.

Fig. 5 shows the longitude distribution at $b = 0^\circ$ of the total continuum, the free–free emission estimated from the RRLs with the local $T_e$ of 7000 K and the difference which corresponds to the synchrotron emission. The arrows indicate three regions of decrease in the derived synchrotron emission coincident in shape and position with H II regions. This is due to an overestimation of the free–free emission caused by an overestimation of $T_e$. The opposite occurs for example for the H II region W40, where an increase in the synchrotron distribution is correlated with the free–free emission. This indicates that the electron temperature of this local H II region is higher than 7000 K. Fig. 5 also shows that the synchrotron longitude distribution is relatively smooth. We use this fact to estimate the synchrotron emission underlying H II regions situated away from any strong synchrotron-emitting source.

We selected 15 H II regions in the area under study that have well-defined longitude profiles and spectra with only one velocity component, for which $T_e$ is obtained from equation (3). Using the longitude profiles taken at the central latitude of each H II region, we estimate the object’s longitude extent from its free–free distribution. The synchrotron background, $T_{\text{sync}}$, is the average of the synchrotron distribution either side of the H II region. The thermal continuum, $T_b$, is calculated from the difference of the total $T_c$ and the synchrotron temperatures. These are measured at the centre of the object, along with the line integral $\int T\nu dV$ as in equation (3). The uncertainties on these quantities are the rms of the corresponding maps measured away from the Galactic plane, typically at $|b| = 3^\circ–4^\circ$. Table 1 lists the H II regions with the corresponding RRL velocities and Galactocentric radii, along with the derived $T_e$. The Galactocentric distance is calculated using the Fich et al. (1989) rotation curve, with $R_G = 8.5$ kpc, assuming that the object moves around the Galactic Centre in a circular orbit with radial velocity $V$.

The electron temperatures obtained for the 15 H II regions are shown in Fig. 6 as a function of the Galactocentric distance. The best linear fit to the data gives

$$T_e = (3609 \pm 479) + (496 \pm 100) R_G,$$

where the uncertainties on $T_e$ are taken into account by the least-squares fitting procedure. As shown in Fig. 6, this result is in general agreement with the Paladini et al. (2004) and Shaver et al. (1983) results with larger samples. The difference between the three line fits in Fig. 6 is mainly caused by the lack of data points beyond the solar radius in the present sample and the two higher $T_e$ values from the local H II regions W40 and W45. There is an intrinsic scatter at any given $R_G$ in all the studies due to the different properties of each H II region.

4.2 The total free–free brightness temperature

We are now in a position to convert the RRL integral into free–free brightness temperature at each pixel using the derived $T_e-R_G$ relationship in equation (5). The Galactocentric distance is calculated

**Figure 4.** Spectrum for the H II region W47 ($\ell, b) = (37.8, -0.3)$ showing the H, He and C RRLs. The vertical dotted lines indicate the rest velocity of each line. The C RRL is amplified by maser emission in the foreground gas and shifted to lower velocities ($\sim 25$ km s$^{-1}$ relative to the H RRL).
using the velocity at the peak of each spectrum. The minimum and
maximum of the derived \( T_e \) distribution for this region are 5030
and 8690 K, respectively. The fact that we are ignoring a possible sec-
ond weaker velocity component at some positions does not affect
the resulting \( T_e \) by more than its uncertainty. If we use the Paladini
et al. (2004) and Shaver et al. (1983) data which are 5–10 per cent
lower in this region, our estimate of the free–free emission would
be 6–12 per cent lower.

The final free–free map for our region is shown in Fig. 7, along
with the total and synchrotron emission maps. The synchrotron map
will be discussed in Section 5. The free–free map shows the thermal
emission arising from particular objects, mostly lying close to the
Galactic plane, plus a narrow diffuse component. The broader dif-
fuse component of the total continuum is mainly associated with the
non-thermal emission. While there is evidence of incomplete sep-
aration of the synchrotron and free–free emission, for example, in

Table 1. List of H\( \text{II} \) regions selected for the study of the electron temperature variation with Galactocentric
distance. \( R_G \), in column 3, is calculated using the RRL central velocity and the Fich, Blitz & Stark (1989)
rotation curve with \( R_G = 8.5 \) kpc. The velocities and corresponding uncertainties, in column 2, are
the result of a Gaussian fit. \( T_C \), \( T_{\text{sync}} \), \( T_{\text{ff}} \) and \( \int T_L \Delta V \) are obtained from the longitude profiles using the method
described in the text; the uncertainties, taken as the rms measured on the maps away from the Galactic
plane, are 0.6, 0.6, 0.2 and 0.05 K km \( \text{s}^{-1} \), respectively. \( T_e \) is calculated using equation (3). The last column
identifies each H\( \text{II} \) region by its commonly used name (Paladini et al. 2003).

| H\( \text{II} \) Region | \( V \) (kms\(^{-1}\)) | \( R_G \) (kpc) | \( T_C \) (K) | \( T_{\text{sync}} \) (K) | \( T_{\text{ff}} \) (K) | \( \int T_L \Delta V \) (K km \( \text{s}^{-1} \)) | \( T_e \) (K) | Name |
|----------------------|---------------------|---------------|-------------|----------------|-------------|-------------------------------|--------|------|
| G20.7−0.1            | 53.6 ± 0.3          | 5.0           | 23.2        | 10.3           | 12.9        | 6.3                           | 5340 ± 290 | Ke 68 |
| G22.9−0.3            | 74.8 ± 0.4          | 4.5           | 33.7        | 12.5           | 21.2        | 9.2                           | 5870 ± 220 | W41   |
| G23.5+0.0            | 92.2 ± 0.4          | 4.1           | 27.4        | 12.0           | 15.4        | 7.4                           | 5400 ± 280 |       |
| G24.8+0.1            | 108.0 ± 0.4         | 3.9           | 28.9        | 8.4            | 20.5        | 9.1                           | 5790 ± 240 | W24   |
| G25.8+0.2            | 107.6 ± 0.4         | 4.0           | 27.7        | 10.0           | 17.6        | 7.4                           | 6060 ± 290 |       |
| G27.1+0.0            | 92.9 ± 0.5          | 4.4           | 20.9        | 8.6            | 12.3        | 4.8                           | 6500 ± 440 | 3C 387|
| G28.8+3.5            | 1.5 ± 0.4           | 8.3           | 24.7        | 6.0            | 18.7        | 5.1                           | 8770 ± 560 | W40   |
| G30.0−0.1            | 97.3 ± 0.4          | 4.5           | 61.0        | 8.9            | 52.1        | 23.7                          | 5780 ± 280 |       |
| G30.8−0.0            | 97.5 ± 0.6          | 4.6           | 61.0        | 8.9            | 52.1        | 23.7                          | 5660 ± 190 | W43   |
| G33.1−0.1            | 98.2 ± 0.4          | 4.7           | 15.7        | 8.6            | 7.1         | 3.3                           | 5560 ± 530 | Ke 78 |
| G35.6+0.0            | 53.4 ± 0.3          | 6.0           | 19.4        | 8.8            | 10.6        | 4.0                           | 6650 ± 410 |       |
| G36.3−1.7            | 62.2 ± 0.5          | 5.7           | 7.0         | 3.8            | 3.2         | 1.3                           | 6210 ± 1480 | RWC 179|
| G37.7−0.2            | 60 ± 1              | 5.9           | 22.3        | 7.3            | 15.0        | 5.8                           | 6520 ± 350 |       |
| G37.8−1.1            | 59 ± 1              | 5.9           | 21.1        | 6.4            | 14.7        | 6.0                           | 6180 ± 340 | W47   |
| G40.5+2.5            | 25.9 ± 0.7          | 7.1           | 9.5         | 5.0            | 4.5         | 1.3                           | 8360 ± 1590 | W45   |

Figure 5. Comparison between the total continuum, free–free emission estimated from the RRLs with \( T_e = 7000 \) K and the synchrotron, versus longitude at \( b = 0^\circ \). The arrows show three regions of decrease in the derived synchrotron emission coincident in shape and position with H\( \text{II} \) regions.
the W40 H II region, most of the compact sources are well separated as either H II regions or SNRs.

4.3 Catalogue of H II regions

A catalogue of H II regions from the present free–free map was created using the source extractor program SExtractor (Bertin & Arnouts 1996). The main parameters to adjust in SExtractor are the background mesh size, detection threshold and minimum area. The background map and the corresponding rms noise map are estimated in each grid cell which is set to 16 pixels, ≃1'. The detection threshold is 2σ, where σ is an average value of the rms map. The estimated σ by SExtractor is 0.26 Jy beam$^{-1}$, so the threshold limit for detection is 0.53 Jy beam$^{-1}$. The minimum area over which the source has to extend to trigger a detection is 2 pixels. The filter function used is a Mexican hat filter of width equal to 3 pixels which is equivalent to the 14.8-arcmin beam. The contrast parameter, which controls the deblending of multiple sources, is set to 0.005. These parameters, namely those associated with the background and also the filter function, were tuned to recover the bright sources easily visible in the maps.

Table 2 lists the 48 H II regions extracted from the free–free map. After the source is detected in the filtered map, it is fitted for an elliptical shape. The fit uses the second-order moments which measure the rms dispersion of the object profile along a given direction. The resulting parameters a and b correspond to the ellipse major and minor axes, respectively. The position angle (PA) listed is the angle between the semimajor axis of the source and the longitude axis measured counterclockwise in the Galactic frame. The peak flux of the source is measured directly from the input map background subtracted. The uncertainty in the peak flux is estimated using the uncertainties in the free–free map and the background rms map generated by SExtractor, evaluated at the position of each source. Since SExtractor does not provide flux densities from Gaussian fitting, we use the peak flux and the observed size ($a \times b$) to calculate it assuming a Gaussian profile for the source:

$$S = S_p \frac{a \times b}{\text{fwhm}^2},$$

where $S_p$ is the peak flux in Jy beam$^{-1}$ and fwhm is the beam FWHM of 14.8 arcmin. The uncertainty in $S$ is estimated using the uncertainties in $S_p$ and in $a$ and $b$, which are given by SExtractor. The maximum uncertainty in the observed size is 4 arcmin. A source of 5 arcmin in size is observed by the 14.8-arcmin beam to have a diameter of 15.6 arcmin. This small broadening of the beamwidth is difficult to measure, especially for a weaker object. For the objects whose derived area is smaller than the beam area, the flux density is taken as the peak, $S = S_p$. In such cases, the PA has a large uncertainty. PA is also uncertain for circular and non-resolved sources. The flag parameter in Table 2 is 1 if the object has bright neighbours, 2 if the source was originally blended with another one and 3 in cases where 1 and 2 apply. It shows that blending occurs mainly in the large H II complexes W47, W42 and W41. In the case of W43 where we find an extended source of 29 × 12 arcmin$^2$ with $S = 236$ Jy, Altenhoff et al. (1970) have a compact object of 5 arcmin and $S = 104$ Jy which is within W43.

4.3.1 Properties of the catalogue

From Section 3.2 it follows that the RRL-integrated fluxes for a given source are accurate at the 10 per cent level. However, the ~1000 K uncertainty on the $T_e$ relationship in equation (5) means that the integrated flux densities in Table 2 are accurate at the 20 per cent level.

In order to assess the quality of the flux densities and sizes listed in Table 2 we compare our results with those at 1.4 GHz by Reich, Reich & Fürst (1990a). The comparison is presented in Table 3 for three H II regions in unconfused backgrounds. The results show that both the flux density and the sizes agree within the errors between the two data sets.

In a complex of H II regions the 14.8-arcmin beam cannot resolve the individual components; thus, comparing the total integrated flux with the individual flux densities from higher resolution catalogues, such as the Paladini et al. (2003) catalogue, is not straightforward. The 2.7-GHz survey by Reich et al. (1990b) at a resolution of 4.3 arcmin, and included in the Paladini et al. compilation, was used to identify the individual H II regions within the source G26.66−0.14 listed in Table 2 with a size of 22 arcmin × p. These are G26.6−0.1 and G26.6−0.3, listed in the Paladini et al. catalogue with angular sizes of 5.5 ± 1.9 and 11.0 ± 3.6 arcmin, and velocities 104.2 ± 1.8 and 69.2 ± 1.6 km s$^{-1}$, respectively. The present RRL spectrum at ($\ell, b$) = (26.66, −0.14) has two velocity components, 101.7 and 73.0 km s$^{-1}$, which means that the emission is indeed arising from a combination of these two H II regions.

Several other sources in Table 2 have two velocity components. In such objects a complex structure is observed at 2.7 GHz and several objects are identified within the source area given in Table 2. These are often in the two spiral arms. All the bright H II regions (S $\geq$ 10 Jy) in Paladini et al. (2003) are detected in this study; about 90 per cent of the sources in Table 2 have at least one counterpart in Paladini et al. (2003).

4.4 The latitude distribution of individual H II regions

In this section we compare the latitude distribution of the H II regions from the higher resolution Paladini et al. (2003) catalogue with that from the present, lower resolution catalogue. The Paladini et al. list contains the flux density at 2.7 GHz for 264 H II regions in this longitude range. We use this catalogue since it is a compilation of results from various authors and surveys and it also contains velocity information. There are 159 objects in Paladini et al. with RRL velocity measurements in the longitude range. The 2.7-GHz flux densities listed are extrapolated to 1.4 GHz assuming the free–free emission is optically thin and therefore is well approximated...
by a power law with $\alpha = -0.1$. The flux densities and sizes from both catalogues are used to simulate Gaussian profiles and to create the spatial distribution of the H$\text{\textsc{ii}}$ regions in the form of brightness temperature maps at 1.4 GHz and 14.8-arcmin resolution. We also estimate the contribution of the 220 ultracompact (UC) H$\text{\textsc{ii}}$ regions catalogued at 1.4 GHz and 5-arcsec resolution by Giveon et al. (2005) to the total free–free emission in the area under study. For that, we calculate the apparent brightness temperature of each UCH$\text{\textsc{ii}}$ region and consider that if it is above 2000 K, which corresponds to an optical depth of $\sim 0.3$ for the average $T_e = 6000$ K, it becomes optically thick. We find that this is the case for about 20 per cent of the 220 objects. However, their contribution to the total free–free emission is found to be relatively low, 1–2 per cent. Thus, the optically thin assumption for the free–free emission is not significantly affected by the presence of these compact objects. The comparison between our catalogue and that by Paladini et al. (2003) is shown in Fig. 8(a) as a function of latitude, averaged over the whole longitude range. The two distributions are very similar, with FWHM of $0.48 \pm 0.01$ and $0.53 \pm 0.01$ for the Paladini et al. and the present lists, respectively. The catalogue from this work includes the more extended emission around and between features that is not included in the higher resolution Paladini et al. (2003) catalogue which consequently contains $\sim 20$ per cent less flux.

Fig. 8(b) compares the latitude distribution of the H$\text{\textsc{ii}}$ regions recovered with SE\textsc{Extractor} with that of the total free–free emission, in the longitude range $20^\circ - 44^\circ$. It can be seen that the H$\text{\textsc{ii}}$ regions are a narrower distribution than the total diffuse emission, with about half the FWHM. The individual H$\text{\textsc{ii}}$ regions account for $\sim 30$ per cent of the total free–free emission in this region of the Galaxy, with 70 per cent being diffuse emission. This result is similar to that found in Paper I for the smaller longitude range $\ell = 36^\circ - 44^\circ$. 

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Figure 7. Maps of the total continuum, free–free and synchrotron emission at 1.4 GHz and 14.8-arcmin resolution. The free–free emission is estimated from the RRL integral using the $T_e - R_G$ relationship from equation (5). The synchrotron is the difference between the total continuum and the free–free emission and shows a narrow diffuse emission confined to the plane. The colour scale is linear and in units of brightness temperature (K).
5 DERIVATION OF A 1.4-GHZ SYNCHROTRON TEMPLATE

The synchrotron emission at 1.4 GHz for the region \( \ell = 20^\circ -44^\circ \), and \( |b| \leq 4^\circ \) can now be obtained by subtracting the free–free emission from the total continuum. The result is show in Fig. 7. Well-known SNRs are identified in the map along with a broad background emission falling to \( \sim 4 \) K at \( |b| \leq 4^\circ \). There are some positive and negative residuals at the position of a few \( \text{H} \beta \) regions in the synchrotron map, which are most likely related to the electron temperature estimated by equation (5). Since the free–free emission is proportional to \( T_e^{1.5} \), the adoption of a temperature for the \( \text{H} \beta \) region which is lower than that of the diffuse gas will cause an underestimation of the free–free emission. This is the case for W40.

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Table 3. Comparison of the flux densities and angular sizes measured from the present free–free map with those from the Reich et al. (1990a) survey at 9-arcmin resolution and at 1.4 GHz.

| Source  | Flux (Jy)       | Size (arcmin$^2$) | Reich et al. (1990a) | Flux (Jy)       | Size (arcmin$^2$) |
|---------|-----------------|-------------------|----------------------|-----------------|-------------------|
| W40     | 30.5 ± 5.5      | (11 × 6) ± 2      |                      | 37.9 ± 3.4      | (8.2 ± 0.5) × (7.4 ± 0.5) |
| G35.6−0.0 | 14.4 ± 3.6      | (10 × 8) ± 2      |                      | 16.3 ± 1.6      | (12.4 ± 0.9) × (8.4 ± 1.1) |
| W49A    | 41.0 ± 6.8      | (10 × 6) ± 2      |                      | 51.5 ± 10.3     | (9.0 ± 1.5) × (3.4 ± 3.0) |

Figure 8. (a) Comparison between the contribution from the 159 Paladini et al. (2003) sources (dotted line) and the 48 sources extracted from this work (solid line), versus latitude. (b) Separation between the diffuse emission and the emission from individual H II regions at 1.4 GHz. The solid line represents the total free–free emission and the dotted line is the contribution from the SExtractor H II regions. Both plots are for the longitude range 20°–44° with 0.2 latitude bins.

and W48. However, for W40, the broad emission underlying the compact source is thought to be of non-thermal origin since it is seen in the total continuum with no significant RRL emission to account for it. The opposite applies to W47 and W43 which are groups of several H II features, some of which have higher $T_e$ than the diffuse emission.

Fig. 9 gives the synchrotron emission versus latitude, averaged over the 24° range in longitude, using 4-arcmin latitude bands.

These plots are the synchrotron results using $T_e = T_e(R)$, 7000 and 5000 K in the free–free estimation. The similarity between the three plots for $|b| > 1°$ reflects the fact that the RRL line integral is low away from the plane, and therefore the synchrotron emission is the major contributor at 1.4 GHz for $|b| > 1°$. The contribution of the strongest SNR in this region, W44 (G34.7−0.4), is visible at $b \approx -0.4$ in all of the plots. The smoother distribution given by the solid and dashed plots in Fig. 9 as compared to the dotted line indicates that $T_e$ of the diffuse ionized gas on the Galactic plane is similar to that of the individual H II regions. The synchrotron distribution appears to have two components – one with a FWHM of ~10° and a narrow Galactic plane component with a FWHM of ~2°. This narrow component is identified here for the first time after direct subtraction of the free–free emission and arises from SNRs of different ages on the Galactic plane.

5.1 Catalogue of synchrotron features

The synchrotron map derived in this work is a clean measure of synchrotron emission at 1.4 GHz. It enables the detection of synchrotron features, most of which are known SNRs. SExtractor was used to create a list of SNRs in the region $\ell = 20°−44°$. The background mesh size and the detection minimum area are the same as for the free–free map. The detection threshold is decreased from 2σ to 1.5σ, since the average rms estimated by SExtractor, 0.69 Jy beam$^{-1}$, is higher than in the free–free map. The threshold limit for a detection is therefore 1.03 Jy beam$^{-1}$. A Gaussian filter was also used along with the Mexican hat filter in order to detect diffuse and extended objects such as the W50 SNR. This well-known SNR is visible in the map but is not easily detected by the Mexican
Table 4. SNRs in the region $\ell = 20^\circ$–$44^\circ$, extracted from the present synchrotron map using SExtractor. The column descriptions are the same as in Table 2. The last column identifies a source by its commonly used name as in the Green (2009a) catalogue. The flag parameter 16 for the first and last SNRs listed means that the objects are close to the image boundary. The seven objects with the star symbol before the number are those extracted using a Gaussian filter instead of the Mexican hat filter. The last three sources in the table are <2$\sigma$ detections (see text).

| Number | $\ell$ (°) | $b$ (°) | $\theta_a$ (arcmin) | $\theta_b$ (arcmin) | PA (°) | Peak Flux (Jy beam$^{-1}$) | Flux (Jy) | Flag | Name |
|--------|-----------|---------|---------------------|---------------------|--------|---------------------------|----------|------|------|
| 1      | 19.94     | −0.21   | 17.1                | p                   | −47    | 12.0 ± 1.7                | 18.3 ± 4.6 | 16   |       |
| 2      | 21.50     | −0.87   | p                   | p                   | 0      | 8.2 ± 2.1                 | 8.2 ± 2.1  | 0    |       |
| 3      | 21.81     | −0.57   | 14.5                | 7.3                 | 34     | 32.5 ± 2.0                | 51.0 ± 6.2 | 0    | Kes 69 |
| 4      | 22.67     | −0.24   | 17.3                | p                   | 73     | 15.5 ± 2.0                | 23.9 ± 5.1 | 0    | W41   |
| 5      | 23.17     | −0.24   | 8.8                 | p                   | 81     | 13.0 ± 2.3                | 15.1 ± 4.2 | 2    |       |
| 6      | 24.58     | 0.62    | 10.1                | p                   | 23     | 11.4 ± 1.7                | 13.8 ± 3.4 | 0    |       |
| 7      | 24.73     | −0.70   | p                   | p                   | 90     | 5.4 ± 1.5                 | 5.4 ± 1.5  | 0    |       |
| 8      | 27.37     | 0.00    | p                   | p                   | −51    | 8.9 ± 1.3                 | 8.9 ± 1.3  | 3    | 4C 04.71 |
| 9      | 27.75     | 0.60    | p                   | p                   | 0      | 10.9 ± 1.4                | 10.9 ± 1.4 | 0    |       |
| 10     | 28.61     | −0.05   | p                   | p                   | −72    | 8.6 ± 1.8                 | 8.6 ± 1.8  | 0    |       |
| 11     | 29.69     | −0.27   | p                   | p                   | 80     | 7.9 ± 2.0                 | 7.9 ± 2.0  | 0    | Kes 75 |
| 12     | 31.89     | 0.04    | p                   | p                   | 25     | 14.7 ± 1.7                | 14.7 ± 1.7 | 0    | 3C 391 |
| 13     | 32.86     | −0.05   | p                   | p                   | −1     | 6.5 ± 1.5                 | 6.5 ± 1.5  | 0    | Kes 78 |
| 14     | 33.67     | 0.06    | p                   | p                   | 43     | 10.3 ± 1.6                | 10.3 ± 1.6 | 0    | Kes 79 |
| 15     | 34.68     | −0.44   | 26.0                | 15.4                | −56    | 71.2 ± 1.6                | 208.1 ± 18.6 | 0    | W44   |
| 16     | 35.59     | −0.44   | p                   | p                   | 55     | 6.7 ± 1.5                 | 6.7 ± 1.5  | 0    |       |
| 17     | 39.22     | −0.32   | p                   | p                   | −14    | 12.7 ± 1.8                | 12.7 ± 1.8 | 0    | 3C 396 |
| 18     | 39.78     | −2.34   | 113.4               | 53.2                | 73     | 4.9 ± 1.3                 | 141.3 ± 40.3 | 0    | W50   |
| 19     | 40.58     | −0.45   | 34.0                | 28.0                | −13    | 5.0 ± 1.6                 | 26.9 ± 9.2 | 3    |       |
| 20     | 41.10     | −0.30   | p                   | p                   | −3     | 13.3 ± 1.5                | 13.3 ± 1.5 | 0    | 3C 397 |
| 21     | 41.45     | 0.39    | 26.8                | 20.3                | 1      | 4.3 ± 1.4                 | 15.0 ± 5.1 | 1    |       |
| 22     | 42.12     | −0.21   | 51.3                | 41.1                | 78     | 3.8 ± 1.3                 | 40.3 ± 14.4 | 1    |       |
| 23     | 43.23     | −0.13   | 16.0                | p                   | 58     | 29.8 ± 1.3                | 44.0 ± 4.8  | 0    | W49B  |
| 24     | 33.21     | −0.51   | 8.0                 | p                   | 14     | 2.3 ± 1.4                 | 2.6 ± 1.7  | 0    |       |
| 25     | 36.61     | −0.83   | 21.0                | p                   | −51    | 2.3 ± 1.4                 | 4.0 ± 2.4  | 0    |       |
| 26     | 43.98     | 1.60    | 35.4                | 25.4                | −77    | 2.0 ± 1.1                 | 10.1 ± 5.8 | 16   |       |

The free–free emission on the Galactic plane

Hat filter which filters out large angular scale structures. Table 4 gives the angular size, PA, peak and total flux density for the 26 SNRs recovered by SExtractor. The latest published compilation of Galactic SNRs is given by Green (2009a). It contains 36 SNRs in the $\ell$-range under study, 23 of which are detected in this survey and listed in Table 4. Objects 16, 21 and 22 are not in the Green catalogue and are described in more detail in the next section. Most of the 13 SNRs in the Green catalogue not detected at 1.4 GHz in this work have flux densities below ~3 Jy, which is comparable with the lowest flux density in Table 4. Sources 24, 25 and 26 are low significance detections, less than $2\sigma$. However, they are included in Table 4 since they correspond to sources in the Green catalogue that are poorly defined, both in flux density and angular size. These results can be taken as upper limits.

Most of the sources in Table 4 are smaller than the beam, with flux densities in overall agreement with the values in the Green catalogue. The strongest SNR in this region of the Galaxy, W44, is fitted in the present synchrotron map with a size of $26.0 \times 15.4$ arcmin$^2$ and a flux density of $208 \pm 19$ Jy. The flux density given by Green for this object is $203$ Jy at 1.4 GHz, extrapolated from 1 GHz with the listed spectral index $\alpha = 0.37$, and the angular size is $35 \times 27$ arcmin$^2$. We note that the angular sizes derived in this work are based on moments, whereas those listed in Green (2009a) refer to the total extent of the object. This explains the smaller size also found for W50. We note that the flux of W49B is overestimated presumably because of the extension of W49A in the direction of W49B and the uncertainty in the electron temperature used to correct for the free–free emission.

5.2 Comments on individual synchrotron sources

5.2.1 G42.12−0.21 and G41.45+0.39

These objects correspond to two of the three SNR candidates by Kaplan et al. (2002). The angular sizes and flux densities found here are larger than the values obtained by Kaplan et al. using the 1.4-GHz NRAO VLA Sky Survey (NVSS; Condon et al. 1998) data, which may resolve out some of the extended emission. This can also be due to the fact that these two faint objects are recovered with the Gaussian filter and thus are likely to be confused with the strong background on the plane. Moreover, they are both flagged as having bright sources nearby. The third possible SNR in Kaplan et al. (2002), G43.5+0.6, is too faint in the NVSS to derive a flux density, and it is indeed only marginally visible, at a ~1.2$\sigma$ level, in the present synchrotron map.

5.2.2 G35.6−0.4

This SNR has been recently re-identified by Green (2009b) using VLA Galactic Plane Survey (VGPS; Stil et al. 2006) data and data from other single-dish surveys at higher frequency to confirm the non-thermal spectral index of this object. G35.6−0.4 is seen in the VGPS map with a size of $15 \times 11$ arcmin$^2$ and has an flux density...
of 7.8 Jy. These results are consistent with what is found in this work, 6.7 ± 1.5 Jy for a relatively compact source of size less than or equal to that of the 14.8-arcmin beam.

We have thus confirmed the synchrotron nature of the objects G42.12−0.21, G41.45+0.39 and G35.6−0.4 using the present survey.

The similar resolution of the 2.7-GHz survey by Reich et al. (1990b) and the 100-μm data by Miville-Deschênes & Lagache (2005) allows the investigation of the spatial coincidence between dust and radio continuum emission used to distinguish between H II regions and SNRs (Haslam & Osborne 1987; Broadbent, Osborne & Haslam 1989). This correspondence helps us understand that the artefacts seen in the synchrotron map around the H II region complexes W47, W42 and W41 are correlated with individual H II regions having associated dust and are thus caused by electron temperature variations. On the other hand, the sources at (ℓ, b) = (30.1, +1.3) (Slee, Siegman & Mulhall 1982) and (ℓ, b) = (21.0, +2.0) (Clark & Crawford 1974) are visible in the synchrotron map but do not have associated dust emission. These are both extragalactic sources.

6 COMPARISON WITH THE WMAP MAXIMUM ENTROPY MODEL

In this section we extend the analysis performed in Paper I using the three times larger longitude coverage of the present RRL map to compare with the WMAP prediction of the free–free emission at 23 GHz.2 The maximum entropy model (MEM; Gold et al. 2011) is a spatial and spectral fit that uses external templates in regions of low signal-to-noise ratio. The spectral indices for the free–free and thermal dust emission are fixed, with β = −2.14 and +2.0, respectively (T0 ∝ νβ). Any additional component of emission such as the anomalous microwave emission (AME) is included in the synchrotron component. A reliable prediction of the free–free emission on the Galactic plane is important not only for foreground and component separation studies but also for Galactic studies such as the ISM of the Galactic plane (Planck Collaboration 2011) and magnetic fields (Jaffe et al. 2011).

In Paper I, the comparison between the free–free emission estimated from the RRLs and from the WMAP 7-year MEM suggested that the electron temperature of the ionized medium in the ℓ-range 36°−39° is about 8000 K. This was based on the 30 per cent higher MEM estimate of the free–free emission on the Galactic plane as compared to the prediction from the RRLs. Fig. 10 shows the comparison between the two data sets using the extended longitude range ℓ = 20°−44° from the present survey, at 23 GHz and at 1° resolution. The RRL data are smoothed using a Gaussian kernel and reflecting the pixels adjacent to the edges outwards. This procedure does not affect the edges of the free–free smoothed map since its coverage is slightly wider than 24° × 8° by 0.2. The spectral index used to extrapolate the free–free brightness temperature from the RRLs is β = −2.13 (Dickinson, Davies & Davis 2003). The free–free spectral index β is a slow function of frequency and electron temperature, decreasing as the frequency increases. The steeper spectral index β = −2.14 used in the MEM analysis reflects this behaviour. The FWHM of the MEM latitude distribution is 1.48, slightly broader than that of the RRLs, 1.36, with a ~50 per cent higher peak. The free–free brightness temperature depends on T_e.15

(Section 1). Therefore, this difference, if real, would imply an electron temperature of ~10000 K for the ionized gas on the Galactic plane compared with the mean 6000 K used in the RRL conversion to free–free emission. Based on the results presented in the previous sections, we expect the electron temperature of the diffuse free–free emission to be around 6000 K in this region of the Galactic plane where the emission comes from R0 = 4–6 kpc.

Similar results are reported by Jaffe et al. (2011) who recover 80 per cent or less of the MEM free–free emission in their model of the Galactic magnetic field. Results from the Planck satellite also indicate that the MEM overpredicts the ionized component on the Galactic plane (Planck Collaboration 2011). In this case, the MEM estimation is ~20 per cent higher than that recovered from the Galactic inversion model.

The fact that the MEM model does not include a fit for a separate AME template may contribute to the excess deduced for the free–free template relative to the RRL observations. Furthermore, we note that the use of a flatter spectral index for the dust emission than their value of β = +2.0 would lead to a lower free–free contribution at lower frequencies.

7 THE 3D GALAXY

The present survey is the first fully sampled RRL survey of this region of the Galaxy and thus enables a more complete comparison of the distribution of diffuse ionized gas and H II regions in relation to the previous RRL pointed observations.

7.1 The ℓ−V diagram

Fig. 11 shows the contours of RRL temperature in longitude–velocity space for spectra averaged over 0.5 in longitude within 1° of the Galactic plane. It shows that there is no H RRL emission at negative velocities in this longitude range: the two vertical bands of emission at V < 0 km s−1 are associated with the He/C RRLs (Section 3.3). This result is very similar to that found in the H166α line survey by Lockman (1976). This survey, sampled at every 1° and at a resolution of 21 arcmin, detected emission at ~4° to 44° and also found a minimum of emission at ℓ ~ 40°, no emission at 0 km s−1 and a large change in emission with longitude.
of the Galactic plane. Contours are at $\ell = 20^\circ$ and $44^\circ$ and $|b| \leq 1^\circ$, adding to the 145 objects with RRL measurements in the same region from the Paladini et al. list. This confirms the spatial correlation between diffuse gas and individual H II regions also observed at the same frequency using pointed observations by Hart & Pedlar (1976) and Lockman (1976). Both distributions show narrow peaks, $\sim$0.75 kpc wide, at $R_G \approx 4.4$ and $5.9$ kpc that correspond to the Scutum and Sagittarius spiral arms, respectively. The $R_G$ values of the peaks correspond to tangent points in longitude of $30^\circ$ and $45^\circ$ and terminal velocities of 110 and 63 km s$^{-1}$, respectively. The fact that the present survey covers $\ell \leq 44^\circ$ indicates that it is missing part of the emission from the tangent point of the Sagittarius arm at $\ell = 50^\circ$.

### 7.3 The z-distribution of the ionized gas

Having identified the Sagittarius and Scutum arms in the $R_G$ and velocity space, we are now able to separate the emission from each of the spiral arms and investigate their latitude distributions. Figs 13(a) and (b) show the integrated RRL emission over 50 km s$^{-1}$, from 80 to 130 km s$^{-1}$, and from 30 to 80 km s$^{-1}$, respectively. Fig. 13(a) shows the narrow distribution of the high-velocity emission from the Scutum arm that covers mainly $\ell > 34^\circ$. The lower emission for $\ell > 34^\circ$ originates in the wings of RRLs in the Sagittarius arm at $V < 80$ km s$^{-1}$. The emission from the Sagittarius arm covers the whole longitude range and has a broader distribution across the plane. Fig. 13(c) shows that the RRL emission at $V \sim 0$ km s$^{-1}$ can be attributed to the local hydrogen and hydrogen beyond the solar circle, on the far side of the Galaxy.

The latitude profiles of Figs 14(a) and (b) show the narrower z-distribution of the Scutum arm, with a FWHM of $0.78 \pm 0.01$, compared with the slightly broader distribution of the Sagittarius arm, with FWHM of $0.85 \pm 0.03$. The Galactocentric distances to the tangent points give a mean distance to the Sun of 6.0 and 7.3 kpc for the Sagittarius and Scutum arms, respectively. Using the observed FWHM of the latitude profiles gives a FWHM z-thickness of about $96 \pm 4$ pc, $\sigma = 41 \pm 2$ pc, for the diffuse ionized gas about the Galactic plane. The latitude distribution of the Sagittarius arm, in Fig. 14(b), also shows a broader component of FWHM $\simeq 2^\circ$ that corresponds to the emission from the near side. In addition, the emission from the far side is responsible for the narrow component.

### 8 CONCLUSIONS

This work has confirmed that the HIPASS/ZOA survey can provide a reliable estimate of the RRL emission on the Galactic plane at 1.4 GHz and 14.8-arcmin resolution. The use of the total continuum emission from the same survey has enabled the electron temperature of individual H II regions in the area under study to be estimated, showing the well-known Galactocentric gradient consistent with previous results.

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3 Where $\sigma = \text{FWHM}/2\sqrt{2\ln(2)}$. This compares with $\sigma \sim 70$ pc, the value found by Reynolds (1991) using pulsar dispersion measures and reflects the fact that emission measures trace the densest parts of the ionized gas, $\text{EM} \propto n_e^2$, compared to dispersion measures which trace $n_e$. 
Figure 13. Maps of RRL emission integrated over 50 km s$^{-1}$, centred at 105 km s$^{-1}$ (a), 55 km s$^{-1}$ (b) and 5 km s$^{-1}$ (c), at a resolution of 14.8 arcmin. Contours are given at every 0.1 K km s$^{-1}$ from $-0.4$ to $0.4$ K km s$^{-1}$, every 0.2 K km s$^{-1}$ from $0.4$ to $2$ K km s$^{-1}$ and then at $2.5$, $3$, $4$, $5$, $6$, $7$, $8$, $9$, $10$, $15$, $20$ and $25$ K km s$^{-1}$. The negative contours are dotted.

Figure 14. The latitude profiles that correspond to maps in Figs 13(a) and (b), respectively, averaged over the velocity and longitude ranges indicated.
The unambiguous determination of the free–free emission from the present work is used to derive the synchrotron map at 1.4 GHz. The latitude distribution of the synchrotron emission shows a narrow component on the Galactic plane which is found here for the first time by the clear subtraction of the free–free emission.

The free–free and synchrotron maps are used to create a list of 48 H II regions and 26 SNRs, respectively. The fact that we detect a recently re-identified SNR, G35.6—0.4 (Green 2009b), illustrates the potential of this survey to detect and identify new objects. The contribution of the individual H II regions to the total free–free emission is found to be around 30 per cent. Their latitude distribution has a FWHM of 0.53 ± 0.01, about half the width of the total free–free distribution. This can be converted into a z-thickness for the H II emission at known distances and is consistent with previous results on the distribution of the OB stars and the width of the thin disc from dispersion measures.

The present estimate of the free–free emission based on the integrated RRLs converted to brightness temperature recovers about 50 per cent of the WMAP MEM prediction. Possible reasons for this discrepancy are associated with the thermal dust spectral index and with the fact that there is no separate AME template included in the WMAP MEM analysis.

This study will soon be extended to the full inner Galaxy region, \( \ell = -50^\circ \) to \( 50^\circ \), using the improved data analysis pipeline described in Section 3.1. We will then focus on the different applications of this result, namely on the investigation of the spectral energy distribution of the different emission components on the Galactic plane and especially on the AME, as a function of longitude. Also, the combination of H\( \alpha \) and RRL data to derive the free–free template on and near the Galactic plane, which is part of the ultimate goal of this project, will be subject of a more detailed study.

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