LOFAR detections of low-frequency radio recombination lines towards Cassiopeia A

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1. Introduction

Radio recombination lines (RRLs) arise from ions recombinating with electrons in diffuse, partially ionised gas. At high principal quantum numbers (i.e. \( n \geq 200 \)) at frequencies \( \leq 1 \) GHz, RRLs are an important probe of the temperature and density of the cool (\( T \leq 100 \) K) interstellar medium (e.g., Payne et al. 1983, Konovalenko 1984). RRL measurements have distinct advantages over other tracers of the ionised gas; the extinction caused by dust and the contamination from other sources are negligible. However, there have been only a limited number of surveys that have studied RRLs from carbon at low radio frequencies (\( \lesssim 330 \) MHz; e.g. Erickson et al. 1995, Kantharia & Anantharamaih 2001, Roshi et al. 2002). Also, the low angular resolution of these early surveys, from several degrees to around 6 arcmin, did not allow the location of the line-emitting gas to be determined, and also limited their capability to detect faint RRL sources due to beam dilution effects.
and has a sightline that is already known to display strong carbon RRLs in low frequency spectra (see Stepkin et al. [2007] and references therein). In Sect. 2, we present our LOFAR commissioning observations and data analysis steps. Our carbon RRL detections are presented in Sect. 3 and we discuss these detections and present our conclusions in Sect. 4.

2. Observations & Data Reduction

The data sets for our RRL study are taken from two LOFAR commissioning observations of Cas A in the 30 to 90 MHz (LBA) band. The first data set (Data-1) was taken on 2011 May 4 using the 16 core stations and 7 remote stations that were constructed at the time, giving baselines up to about 24 km. These data were taken with 1-s visibility integrations and 244 separate frequency subbands, each with a bandwidth of 195 kHz and 256 spectral channels. The second data set (Data-2) was observed on 2011 October 15 using 24 core stations and 8 remote stations, and had a maximum baseline length of about 83 km. Data-2 was taken in a multi-beam mode that is used for standard continuum observations, with one beam on Cas A and a second beam on Cygnus A. This resulted in only half of the available bandwidth being used for the observation of Cas A. Also, a coarser spectral resolution of 64 spectral channels within each of the 122 subbands of 195 kHz bandwidth was used. The visibility integration time was again 1 s. After the first step of interference removal using the AOflagger routine (Offringa et al. [2010]), the data were averaged in time and/or frequency as required.

In total, we produced 3 data sets for our work. First, to make a continuum image of Cas A, we produced an intermediate data set from Data-1 that had a coarse spectral resolution of $\sim 50$ kHz channel$^{-1}$ in order to speed up the calibration process later. Next, we created two RRL data sets. For Data-1, we included only those baselines between the separate core-stations ($< 2.6$ km) and retained the full spectral resolution of 762 Hz channel$^{-1}$. Data-2 was processed to retain a spectral resolution of 3.1 kHz channel$^{-1}$ and to also include longer baselines ($< 24$ km) so that spectra could be extracted from individual regions across the supernova remnant. For these two RRL data sets, we decided to concentrate our search to those frequencies between 40 to 50 MHz. This was because the RRL absorption was expected to be stronger at the lower end of the LBA spectrum due to the steep broadband spectral energy distribution of Cas A. The lower frequency end of the search window was chosen because the level of terrestrial interference increases below 40 MHz (Offringa et al. [2013]). The resulting time and frequency resolution for each data set after these preprocessing steps are summarized in Table 1.

We initially calibrated our continuum data using the BlackBoard Self-calibration package (ubss: Pandey et al. [2009]), with a relatively simple initial model, containing about a dozen point sources and one shapelet model. We then used the scacal package (Kazemi et al. [2011]) to solve for the direction-dependent amplitude and phase variations in the data and to update the shapelet model for Cas A. To mitigate artefacts due to Cygnus A, present about 30 degrees away, we simultaneously solved for direction-dependent gains towards Cas A and Cygnus A, and subtracted the latter in the visibility data using a shapelet model. We then imaged the source using the casa imager (http://casa.nrao.edu/) and constructed a composite sky model from the image by fitting for point and shapelet sources (see e.g., Yatawatta et al. [2011]). We iterated over this scheme (ubss calibration $\rightarrow$ imaging $\rightarrow$ sky-model $\rightarrow$ calibration) to obtain high-resolution continuum images and improved source models. In Fig. 1 we present a 40 arcsec resolution continuum image of the supernova remnant at 52 MHz (single subband). Given the excellent spatial resolution of LOFAR, a number of complex features are clearly resolved (c.f., Kantharia et al. [1998]; Lane et al. [2005]). Further details of the calibration strategy and a full discussion of the continuum imaging of Cas A, and the wider surrounding field, will be presented in a companion paper (Yatawatta et al., in prep).

To detect RRLs along the line-of-sight to Cas A, we calibrated the RRL visibility data sets (see Table 1) with the use of our final sky model that was obtained from our analysis of the continuum data. Multi-channel maps were constructed using the clean algorithm within casa, and image cubes from the individual subbands were analysed separately. Spectra were then extracted over the whole remnant and over the brightest hotspot (see Fig. 1). The resultant spectra displayed a few artefacts, such as breaks at the subband boundaries and bad channels on the edge of each subband; typically around 5 per cent of the channels per subband. These bad channels were removed during further analysis. Doppler correction terms are currently not incorporated in the LOFAR imaging pipeline, hence the spectra were Doppler corrected after extraction. This leads to an uncertainty of $\leq 1$ km s$^{-1}$ in the determination of the central velocities and line widths. This error is negligible compared to the velocity resolution of our data.

3. Results

The subset of Data-1 that was used for the RRL analysis only contained the short baselines between the core-stations ($\leq 2.6$ km), for which Cas A is practically unresolved. Therefore, spectra were obtained over the whole remnant with a spectral resolution of 762 Hz channel$^{-1}$, which is equivalent to a velocity resolution of $\sim 5$ km s$^{-1}$ at 45 MHz. We report the detection (at $> 16\sigma$ level) of four carbon $\alpha$ RRLs (C518$\alpha$, C538$\alpha$, C541$\alpha$, and C546$\alpha$).
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Table 1. Summary of the LOFAR data sets used for our analysis: raw visibilities from Data-1 were processed twice to create two separate intermediate data sets for i) continuum imaging and ii) the RRL detections (see Section 2). The velocity resolutions were computed at 45 MHz.

<table>
<thead>
<tr>
<th>Data set</th>
<th>LOFAR id</th>
<th>Start date</th>
<th>Time (UT)</th>
<th>Duration (h)</th>
<th>Int. time (s)</th>
<th>Processed resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data-1 (continuum)</td>
<td>L25937</td>
<td>2011 May 4</td>
<td>23:00:01.5</td>
<td>18</td>
<td>5</td>
<td>48.768</td>
</tr>
<tr>
<td>Data-1 (RRL)</td>
<td>L25937</td>
<td>2011 May 4</td>
<td>23:00:01.5</td>
<td>18</td>
<td>5</td>
<td>0.762</td>
</tr>
<tr>
<td>Data-2 (RRL)</td>
<td>L31848</td>
<td>2011 Oct 15</td>
<td>12:00:02.5</td>
<td>15</td>
<td>5</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Fig. 2. A representative detection of a carbon $\alpha$ RRL towards Cas A with LOFAR. We show spectra of the RRL C538$\alpha$ that was measured using Data-1 (black solid) and Data-2 (blue dashed). For comparison, we have also smoothed the Data-1 spectrum to the same spectral resolution as Data-2 (red dashed). These spectra demonstrate the spectral stability of the LOFAR system for making spectral line measurements.

Fig. 3. The spectrum of the RRL C541$\alpha$ measured over the whole remnant (red) and only over the hotspot region (blue) using Data-2. These data demonstrate that the integrated optical depth over the hotspot region is higher than across the remnant, showing that there is likely structure in the absorbing gas on scales of $\sim 1$ pc.

and C543$\alpha$) towards Cas A in Data-1 between 40 to 50 MHz. In Fig. 2 we present a representative spectrum of a RRL detection, with respect to the local standard of rest (LSR). For each detected RRL, we measured the line widths and integrated optical depths ($\int \tau d\nu$) by fitting Gaussian components to the spectra, the results of which are presented in Table 2. Only single Gaussian-line profiles were used because our spectra do not currently have a sufficient signal-to-noise ratio to reliably measure multiple components in the line structure. All of the detected RRLs have measured velocities at $v_{\text{LSR}} \sim -48 \pm 1$ km s$^{-1}$, consistent with the velocity of the gas in the Perseus arm, the likely absorber along the line-of-sight to Cas A (Konovalenko 1984 Ershov et al. 1984 1987 Payne et al. 1989 1994). These RRL detections from Data-1 represent the first spectral-line measurements made with LOFAR.

The main goal of our study is to investigate whether there is any structure in the absorbing gas by detecting a variation in the integrated optical depths of the RRLs over the extent of the remnant. For this, LOFAR’s unparalleled spatial resolution at frequencies below 100 MHz is required. We extracted spectra using Data-2 in two ways; one towards the compact hotspot component and the other over the entire area of the remnant. We detected five carbon $\alpha$ RRLs (at $> 5\sigma$ level) in both our integrated spectra and the spectra extracted over the brightest hotspot component in the remnant. As these lines were only marginally resolved, we estimated their integrated optical depths by summing the measured optical depth over two channels. The results of these measurements are also given in Table 2. In Fig. 3 we show a representative detection of a carbon $\alpha$ RRL (C541$\alpha$) against the whole remnant and the hotspot. Earlier studies (see e.g., Payne et al. 1989) reported two components at $v_{\text{LSR}} \sim 50$ and $\sim 40$ km s$^{-1}$, where the former dominates by a factor 2–3. Due to insufficient signal-to-noise ratio we cannot currently separate these components, but the observed line-profile asymmetry in our spectra (see Fig. 2 and 3) is consistent with two components.

We also carried out a search for hydrogen and helium RRLs in the individual subbands of our data sets (without any folding in frequency), but found no significant detection. The spectral noise per channel in our most sensitive data set (Data-1) is $\sim 10^{-4}$, so we derive an upper limit (3$\sigma$) on the peak optical depth of hydrogen and helium RRLs of $3 \times 10^{-4}$, or an equivalent integrated optical depth of 0.9 s$^{-1}$. Following Shaver (1976), we derive an upper limit of $4 \times 10^{-18}$ s$^{-1}$ for the interstellar ionisation rate of hydrogen. Our limit is significantly lower than the previously reported values despite the uncertainties in determining various parameters (see e.g., Payne et al. 1994 Gordon & Sorochenko 2009 §3.3.6), indicating that cosmic rays can not ionise the intercloud gas to the observed degree.

4. Discussion & Conclusions

In total, we have detected five carbon $\alpha$ RRLs towards Cas A from our two LOFAR commissioning data sets. In Fig. 3 we plot the integrated optical depths of these RRLs as measured from each LOFAR data set, and also the integrated optical depths for
Table 2. The derived line parameters for the RRLs measured from Data-1 and Data-2. For the case of Data-1, the spectral resolution was sufficient to resolve the lines and the fitted Gaussian full width at half maximum (FWHM) is reported. For Data-2, the RRLs were not fully resolved and so the integrated optical depths were obtained over two spectral channel widths. The integrated optical depths have been calculated over the full remnant (SNR) for datasets Data-1 and Data-2, and around the region of the bright hotspot for Data-2 (see Fig. 1).

<table>
<thead>
<tr>
<th>Line</th>
<th>Rest frequency (MHz)</th>
<th>Center velocity (km s$^{-1}$)</th>
<th>FWHM (km s$^{-1}$)</th>
<th>Integrated optical depth (s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Data-1</td>
<td>Data-1</td>
<td>SNR Data-1</td>
</tr>
<tr>
<td>C548α</td>
<td>39.87</td>
<td>–</td>
<td>–</td>
<td>12 ± 2</td>
</tr>
<tr>
<td>C543α</td>
<td>40.98</td>
<td>–</td>
<td>19 ± 2</td>
<td>12.8 ± 0.5</td>
</tr>
<tr>
<td>C541α</td>
<td>41.44</td>
<td>–</td>
<td>19 ± 2</td>
<td>15 ± 2</td>
</tr>
<tr>
<td>C538α</td>
<td>42.13</td>
<td>–</td>
<td>20 ± 3</td>
<td>14.6 ± 0.9</td>
</tr>
<tr>
<td>C518α</td>
<td>47.20</td>
<td>–</td>
<td>18 ± 2</td>
<td>12.8 ± 0.9</td>
</tr>
</tbody>
</table>

those RRLs that were previously measured towards Cas A, with other telescopes [Ershov et al. 1984, 1987; Payne et al. 1989, 1994], as a function of the principal quantum number. We see that the integrated optical depths, as measured over the whole remnant, are consistent between Data-1 and Data-2 for the four RRLs that are common to both data sets. This demonstrates the spectral stability of our LOFAR commissioning data sets. We also find consistency for the RRL C538α, where we have both LOFAR and previously reported measurements in the literature. Although we currently do not have measurements for the other two previously detected RRLs (C502α and C552α), the reported integrated optical depths of these lines are generally consistent with the RRLs that we have detected in the LOFAR data sets.

Multiple carbon RRLs are usually modelled together in order to derive the physical conditions of the line-absorbing gas, since the electron levels are in non-local thermal equilibrium (non-LTE) conditions. Crucial inputs to these models include accurate line width measurements from high-spectral resolution data. Kantharia et al. (1998) show that previous low-frequency measurements of carbon α RRLs can be modelled as originating in cold ($T_e \sim 75$ K), low density ($n_e \sim 0.02$ cm$^{-3}$) clouds that are located approximately 115 pc away from Cas A. Higher density models ($T_e \sim 75$ K, $n_e \sim 0.1$ cm$^{-3}$) are also able to fit the data, but these are less appealing due to their thermal pressures being very high. Although our current RRL detections are consistent with these models, given the agreement with the previous measurements, future observations of RRLs over the whole LOFAR observing window, and hence over a large and densely sampled range of principal quantum number, will differentiate between these competing models. The results from such a detailed analysis using new observations will be reported in a forthcoming paper (Oonk et al., in prep).

We also find from Fig. 4 that the integrated optical depths towards the hotspot are larger by up to a factor of 2, when compared to the integrated optical depths measured over the whole remnant. This shows that there is small-scale angular structures and/or the geometry of the RRL-absorbing gas is such that there is varying levels of absorption over the face of the remnant (see, e.g. Kantharia et al. 1998). This corresponds to structure in the RRL-absorbing gas on the order of ~ 1 pc. To model this structure, we plan to make new LOFAR observations with a higher spectral and spatial resolution in the future.

Our results from the commissioning data sets demonstrate that LOFAR can be used to carry out spectral line observations

![Fig. 4. The integrated optical depths as a function of the principal quantum number for both data sets (Data-1 and Data-2) and for those previously reported in the literature (Ershov et al. 1984, 1987; Payne et al. 1989, 1994). We find good agreement between the measurements made over the whole remnant from the two LOFAR data sets and with those in the literature. We also find that the integrated optical depths of the RRLs are higher over the bright hotspot component with respect to the measurements over the whole remnant, implying that there is likely small-scale structure in the absorbing gas distribution.](image-url)
Kosovalenko, A. A. 1984, SvA, 10, L384

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