

LOFAR observations of decameter carbon radio recombination lines towards Cassiopeia A

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ABSTRACT

We present a study of carbon radio recombination lines towards Cassiopeia A using low frequency array (LOFAR) observations in the frequency range 10–33 MHz. Individual carbon α lines are detected in absorption against the continuum at frequencies as low as 16 MHz. Stacking several $C\alpha$ lines we obtain detections in the 11–16 MHz range. These are the highest signal-to-noise measurements at these frequencies. The peak optical depth of the $C\alpha$ lines changes considerably over the 11–33 MHz range with the peak optical depth decreasing from 4×10^{-3} at 33 MHz to 2×10^{-3} at 11 MHz, while the linewidth increases from 20 km s^{-1} to $\sim 150 \text{ km s}^{-1}$. The combined change in peak optical depth and linewidth results in a roughly constant integrated optical depth. We interpret this as carbon atoms close to local thermodynamic equilibrium. In this work, we focus on how the 11–33 MHz carbon radio recombination lines can be used to determine the gas physical conditions. We find that the ratio of the carbon radio recombination lines to that of the $158 \mu\text{m}$ [C II] fine-structure line is a good thermometer, while the ratio between low-frequency carbon radio recombination lines provides a good barometer. By combining the temperature and pressure constraints with those derived from the linewidth, we are able to constrain the gas properties (electron temperature and density) and radiation field intensity. Given the 1σ uncertainties in our measurements these are: $T_e \approx 68\text{--}98 \text{ K}$, $n_e \approx 0.02\text{--}0.035 \text{ cm}^{-3}$ and $T_{r,100} \approx 1500\text{--}1650 \text{ K}$. Despite challenging radio frequency interference and ionospheric conditions, our work demonstrates that observations of carbon radio recombination lines in the 10–33 MHz range can provide insight into the gas conditions.

Key words: ISM: clouds – ISM: individual objects: Cassiopeia A – radio lines: ISM.

1 INTRODUCTION

Radio recombination lines (RRLs) are an important diagnostic tool to study the properties of the interstellar medium (ISM) in galaxies (e.g. Gordon & Sorochenko 2009). The population of carbon ions in a given n level is determined by the gas density, temperature and radiation field, as well as the atomic physics involved (e.g. Shaver 1975; Watson, Western & Christensen 1980; Salgado et al. 2016a). By comparing the optical depth of carbon radio recombination lines (CRRLs) for a set of levels, the gas properties can be determined.

Low-frequency CRRLs have been observed towards a number of galactic sources (Konovalenko 1984; Erickson, McConnell &

Anantharamaiah 1995; Roshi & Anantharamaiah 2000; Kantharia & Anantharamaiah 2001) and in particular against the bright radio source Cassiopeia A (Cas A, e.g. Konovalenko & Sodin 1981; Ershov et al. 1982; Konovalenko 1984; Anantharamaiah, Erickson & Radhakrishnan 1985; Lekht, Smirnov & Sorochenko 1989; Payne, Anantharamaiah & Erickson 1989; Anantharamaiah et al. 1994; Payne, Anantharamaiah & Erickson 1994; Stepkin et al. 2007; Asgekar et al. 2013; Oonk et al. 2017). Towards Cas A, three velocity components have been identified in CRRL emission and absorption (e.g. Payne et al. 1989), which correspond to gas located in the Perseus arm of the Galaxy and the Orion spur. Recent analysis by Oonk et al. (2017) has shown that the Perseus arm gas traced by low-frequency CRRLs has a temperature of $\sim 85 \text{ K}$, an electron density of $\sim 0.04 \text{ cm}^{-3}$ and large column densities ($N_H \sim 10^{22} \text{ cm}^{-2}$). These properties suggest that the gas traced by CRRLs is in the interface between atomic (e.g. Shuter

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& Verschuur 1964; Davies & Cummings 1975; Bieging, Goss & Wilcots 1991; Schwarz, Goss & Kalberla 1997) and molecular gas (e.g. Liszt & Lucas 1999; Mookerjee et al. 2006; Kilpatrick, Bieging & Rieke 2014). The data used by Oonk et al. (2017) consisted of observations between 300–390 MHz and 33–78 MHz obtained with the Westerbork radio telescope (WSRT) and the low frequency array (LOFAR), respectively.

Previous low-frequency CRRL observations and models have suggested that at lower frequencies ($\nu < 33$ MHz) the integrated optical depth of the CRRLs increases with increasing principal quantum number (e.g. Payne et al. 1994). This would make observations below 33 MHz particularly interesting, since (i) given the large integrated optical depths involved the lines should be easily detected, and (ii) at these low frequencies, collisional and radiation broadening of RRLs provide insight into the physical conditions of the emitting gas (Shaver 1975; Salgado et al. 2016a,b).

Low-frequency observations are hindered by ionospheric phase distortions, scintillation and strong radio frequency interference (RFI). Below 20 MHz, these observations are very difficult due to the plasma frequency cutoff that is typically located around 10 MHz, but varies depending on the ionospheric conditions (e.g. Budden 1985; Fields et al. 2013). Nevertheless, CRRLs have been detected at frequencies as low as 12 MHz (Konovalenko, Stepkin & Shalunov 2002).

Previous $\nu < 33$ MHz studies have been carried out with the Ukrainian T-shaped radio telescope, Mark 2 (UTR-2) telescope in Ukraine (Braude et al. 1978). Using this telescope, Konovalenko & Sodin (1980) reported the detection of a spectral line at 26 MHz towards Cas A, which was later identified as a CRRL with principal quantum number $n = 631$ (Blake, Crutcher & Watson 1980; Konovalenko & Sodin 1981). They also reported the detection of six $C\alpha$ lines between 16.7 and 29.9 MHz (Konovalenko 1984), and more recently showed a spectrum of five $C\alpha$ lines around 20 MHz and a number of $C\beta$ lines (Konovalenko 2002). These studies showed that the line peak optical depth decreases while the linewidth increases when the frequency decreases. Stepkin et al. (2007) reported the detection of $C\alpha$, $C\beta$, $C\gamma$ and $C\delta$ lines towards Cas A at 26 MHz. Their detection of a $C\delta$ line sets the record for the largest bound atom ever detected with a principal quantum number $n \sim 1000$.

LOFAR, operating at 10–240 MHz (van Haarlem et al. 2013), provides a new opportunity to study RRLs at frequencies down to 10 MHz. Due to its large bandwidth, hundreds of lines can be detected in a single observation. This opens up the possibility to study a broad range in principal quantum number with the same telescope. The LOFAR low band antenna (LBA) operates in the frequency range 10–90 MHz. Previous LOFAR studies have focused on the higher frequency range (33–70 MHz) of the LBA (Asgekar et al. 2013; Morabito et al. 2014; Oonk et al. 2014, 2017) as the sensitivity of the LBA peaks in this frequency range (van Haarlem et al. 2013).

In this paper, we report on LOFAR LBA observations of Cas A between 10 and 33 MHz, the lowest frequency range LOFAR can reach. Our aim is to (i) determine if observations with LOFAR in this frequency range can yield CRRL detections, (ii) test if the integrated optical depth of the lines at high principal quantum number increases as suggested by previous observations, (iii) determine how low-frequency CRRL observations can be used to constrain the physical conditions of the cold ISM.

The observations and data reduction are described in Section 2. The results are presented in Section 3 and then compared with models and previous results in Section 4. This is followed by our conclusions in Section 5.

Table 1. LBA low observations.

Observations ID	L69891, L69893
Integration time per visibility	1 s
Observation dates	2012 October 20, 21 (15:00–01:00 UT)
Total on-source time	10 h, 10 h
Correlations	XX, XY, YX, YY
Frequency setup	10–33 MHz full coverage
Bandwidth per sub-band	195.3125 kHz
Channels per sub-band	512
Channel width	4–12 km s ⁻¹

2 OBSERVATIONS AND DATA REDUCTION

2.1 LOFAR observations

Cas A was observed with the LOFAR LBA for two separate runs on 2012 October 20 and 21 for a total integration time of 20 h. This data were taken as part of the Lofar Cassiopeia A Spectral Survey (LCASS; PI, Oonk). An overview of the observations is given in Table 1. During the time of the observations, 34 Dutch LOFAR stations were available. For the L69891 observation, 26 stations recorded good data, while for L69893, this number was reduced to 21 due to ongoing upgrades. The entire 10–33 MHz range was covered with 195.3125 kHz wide sub-bands. Each sub-band had a total of 512 channels, providing a channel width of ~ 380 Hz or ~ 4 –12 km s⁻¹.

The first and last 25 channels of each sub-band were flagged due to the bandpass roll-off. To mitigate the effect of RFI, we flagged the data using AOFLAGGER (Offringa et al. 2010; Offringa, van de Gronde & Roerdink 2012). The percentage of data flagged due to RFI varied drastically across the band from about 20 per cent at 30 MHz to 40 per cent at 20 MHz and 70 per cent at 15 MHz, see Fig. 1. We also removed the last three hours of both data sets due to severe scintillation, although this part of the data was less affected by RFI by a factor of 2–3. We note that especially the first part of the observations was heavily affected by RFI, while the situation improved considerably after 23:00 UT for both data sets. Although the data were affected by scintillation after 22:00 UT, it suggests that night time observations are required to avoid severe RFI below 30 MHz.

The data were then calibrated against a 11.2 arcsec \times 9.8 arcsec resolution 69 MHz model of Cas A (Oonk et al. 2017). The calibration was performed with the New Default Processing Pipeline (NDPPP) package, which is part of the standard LOFAR software. Below 16 MHz, we could not obtain good gain solutions for several time ranges during the observations. These time ranges were also flagged and thus increase the percentage of flagged data (Fig. 1). Most likely, these periods correspond to severe ionospheric distortions. These are expected at low frequencies since the observations are carried out not far from the plasma cutoff frequency. However, signal from Cas A was observed all the way down to 10 MHz for certain time ranges. The LOFAR bandpass is very smooth and, except for the bandpass roll-off regions (about 5–10 per cent on either side of a sub-band), is well fit by a low-order polynomial. To estimate how well a polynomial corrects the sub-band bandpass, we also derived a bandpass calibration using Cygnus A. We find that the results obtained from a polynomial are equivalent to those obtained with Cygnus A. However, given that brightness of Cygnus A is comparable to that Cas A at these frequencies, using Cygnus A leads to a slightly higher spectral noise (by about a factor of $\sqrt{2}$). We therefore use a low-order polynomial to correct our sub-band spectra for the bandpass shape.

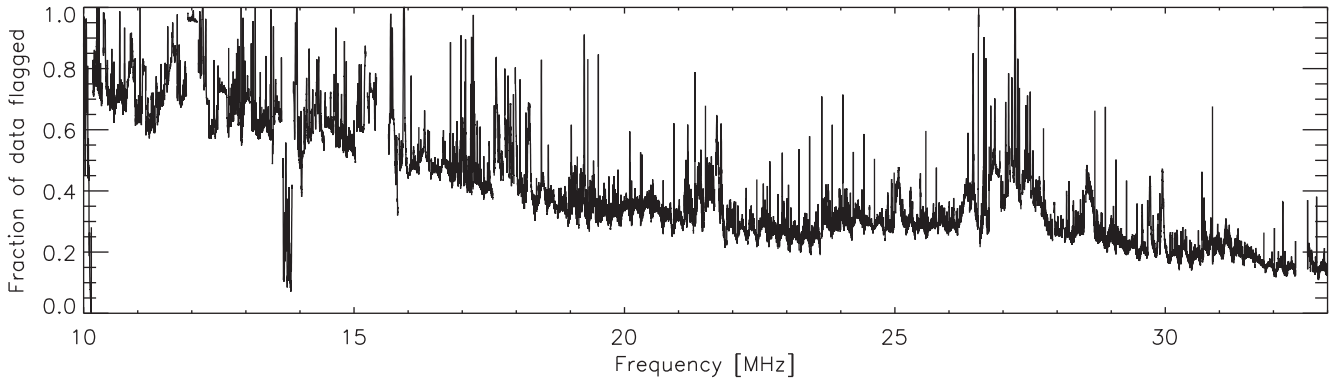


Figure 1. Fraction of data flagged due to RFI or bad calibration solutions as function of frequency for the L69891 data set (results for L69893 are very similar). The frequency width is the same as the one used in the observations, i.e. 380 Hz.

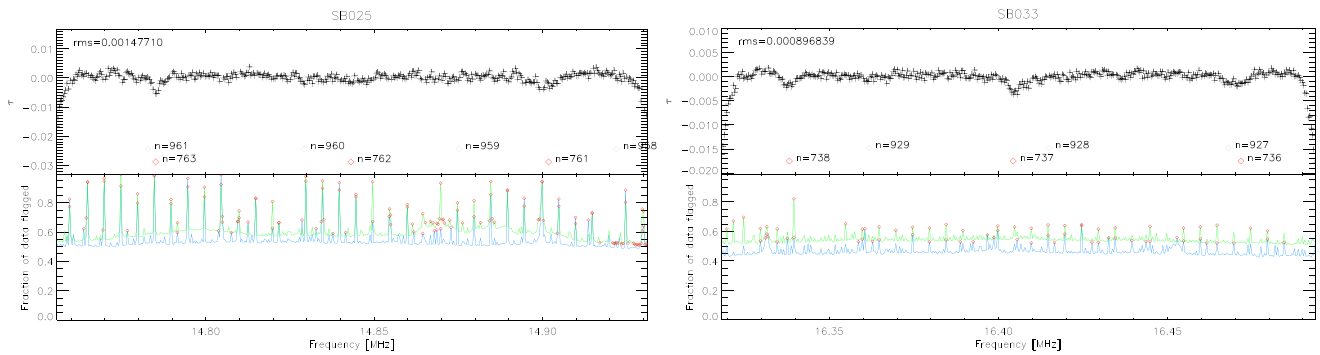


Figure 2. Spectra of two individual sub-bands, 25 and 33. The top panels show the optical depth τ as function of frequency. The red diamonds show the location of $C\alpha$ lines, while the empty labels those of $C\beta$. The bottom panels show the percentage of data flagged for the L69891 and L69893 data sets in blue and green, respectively. Red diamonds mark channels which were removed because their flagging percentage is larger than 5 per cent of the sub-band mean.

Image cubes were made with AWIMAGER (Tasse et al. 2013) by splitting and imaging one channel at a time. The images were convolved with a Gaussian beam with a size ranging between 23 arcmin at 10 MHz and 5 arcmin at 30 MHz. Given the size of the convolving beam the background source is unresolved (Cassiopeia A has a radius of ~ 2.5 arcmin at 74 MHz, e.g. DeLaney et al. 2014; Oonk et al. 2017). Spectra were then extracted from a tight box around the source at each channel. We combined the spectra from the two different runs by weighting with the fraction of usable data at the corresponding frequency. Channels whose amplitude deviated more than 1σ from the median were removed. To determine the median, we used a running median window filter with a box size of five channels. σ was determined using Tukey’s biweight [e.g. equation (9) in Beers, Flynn & Gebhardt 1990]. This typically resulted in less than 10 per cent of the data being flagged. We also discard any channels where the percentage of flagged data deviated more than 5 per cent from the median amount of flagged data in the sub-band (see the bottom panel of Fig. 2).

In each sub-band, we estimate the continuum level by fitting a linear function to line-free channels. Then the spectra are converted to optical depth units using (e.g. Oonk et al. 2014)

$$\tau_v = I_v / I_v^{\text{cont}} - 1. \quad (1)$$

Here I_v is the spectrum extracted from the data cubes and I_v^{cont} is the continuum determined from line-free channels. Of the 286 $C\alpha$ lines observable in the 10–33 MHz range, 219 were observed. Missing lines lie in the sub-band gaps or close to flagged edge channels.

2.2 Herschel PACS archival data

Cas A was observed with the Photoconductor Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) instrument onboard the Herschel space observatory (Pilbratt et al. 2010) during 2011 January (observation IDs: 1342212243–1342212260). These observations consist of nine footprints, each with 5×5 spaxels of $9.4 \text{ arcsec} \times 9.4 \text{ arcsec}$. These nine PACS footprints cover ~ 20 per cent of Cas A. The observations were made using range spectrography scans between 140 and 210 μm with a 30 km s^{-1} sampling near the 158 μm line. To remove the instrument response, the chopping/nodding mode was used. However, the off source scans show significant line emission at the same velocity as the on-source spectra. Because of this we used the on-source spectra without removing the off-source spectra. To separate on- and off-source scans HIPE version 14.0.0 was used (Ott 2010).

2.3 CRRL stacking

Since the 10–33 MHz range is heavily populated by CRRLs, we used a procedure similar to that of Stepkin et al. (2007) to stack individual lines and obtain robust line profiles. This stacking procedure also helps in removing residual bandpass structure. First, we searched the spectra for $C\alpha$ and $C\beta$ lines that were not blended with other lines, were not heavily affected by RFI and were far from the sub-band bandpass roll-off. We stacked these lines in the frequency ranges indicated in Figs 3 and 4. The stacking was performed by interpolating to a regular grid in velocity, with a bin size equal to

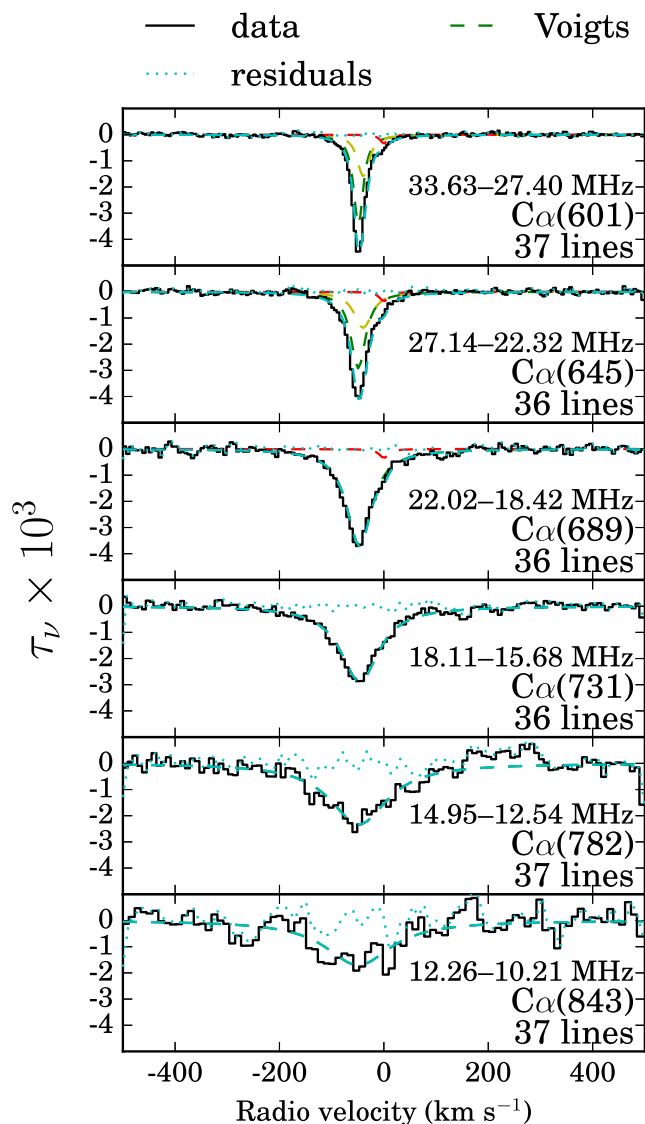


Figure 3. Stacked $C\alpha$ spectra. The black steps show the stacked spectra after processing, the green, yellow and red dashed lines show the best-fitting Voigt profiles for the different components, the cyan dashed line shows the combined best-fitting Voigt profile and the cyan dotted line shows the residuals. The spectra are shown in optical depth units.

the coarsest velocity resolution of the spectra included in the stack. Each individual spectrum was weighted by the inverse of its channel to channel variance.

The stacked spectra were then fitted with a Voigt profile centred at -47 km s^{-1} . Using the results of the fit to the stacked $C\alpha$ and $C\beta$ lines, we then subtracted the best-fitting Voigt profile from each spectrum. In the $C\alpha$ and $C\beta$ subtracted spectrum, we searched for $C\gamma$ lines that were far from the roll-off of the sub-band bandpass, not blended with $C\delta$ lines and not heavily affected by RFI. These $C\gamma$ lines were stacked in four frequency ranges. Of these ranges, only one yields a detection, see Fig. 5. In the remaining frequency ranges, the signal-to-noise is below 3σ . The $C\gamma$ stacks were fitted with a Voigt profile. The best-fitting $C\gamma$ Voigt profile was also removed from the $C\alpha$ and $C\beta$ free spectra. In the residual spectra, we then searched for $C\delta$ lines by stacking all the available transitions in two frequency ranges. These yielded non detections with 3σ upper limits on the peak optical depth of 10^{-4} for $n = 1020$ and 2×10^{-4}

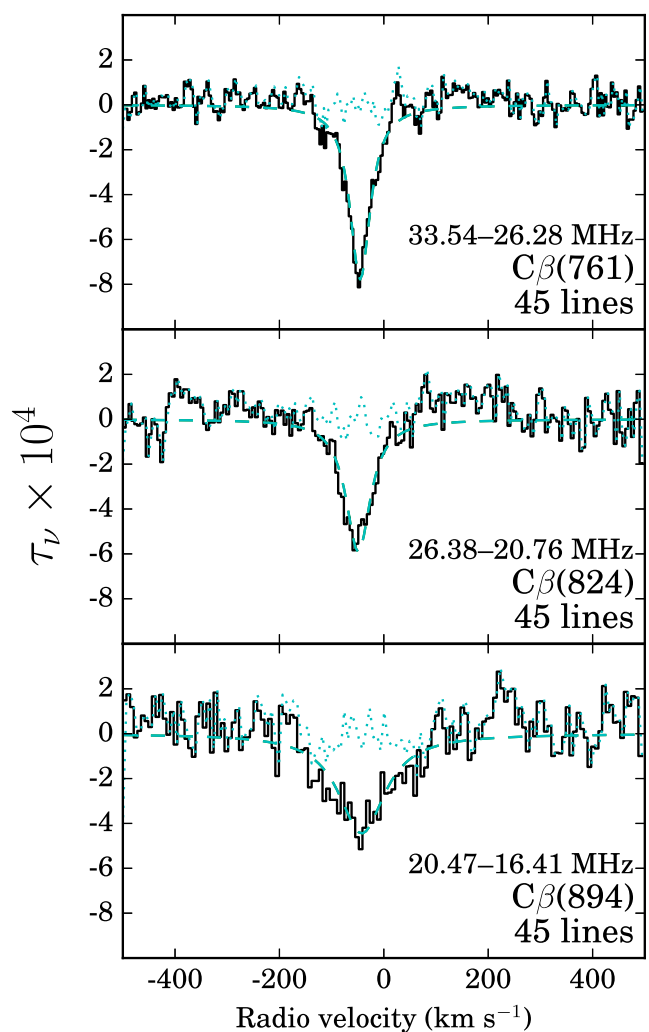


Figure 4. Stacked $C\beta$ spectra. The black steps show the stacked spectra after processing, the cyan dashed line shows the best-fitting Voigt profile and the cyan dotted line shows the residuals. This is the same as in Fig. 3.

for $n = 1248$. The $C\delta$ stack was also removed from the spectra. After this we performed a baseline correction on the line removed spectra using a polynomial of order 0. Using the baseline-corrected spectra, we repeated the stacking of the lines. This was repeated five times increasing the polynomial order by 1 in each step. Finally, spectra with only one kind of transition were obtained by removing the corresponding best-fitting Voigt profiles from the spectra. The final $C\alpha$, $C\beta$ and $C\gamma$ spectra are shown in Figs 3, 4 and 5, respectively. In the final spectra, lines which were partially flagged due to RFI were also included.

Payne et al. (1994) showed that a finite bandwidth combined with a baseline-removal process can cause systematic biases in the observed line profiles. To test whether the stacking and baseline-removal procedure combined with the correlator setup used introduces any biases in the measured line properties, we performed a test using synthesized spectra. The synthetic spectra are generated with known line properties. These synthetic spectra are stacked in the same way as the observed data, including the baseline and line-removal (e.g. removing the $C\beta$, $C\gamma$ and $C\delta$ lines from the $C\alpha$ stack) steps. Then, by comparing the known input model properties with the measured line properties after stacking we can determine if the measured line properties are distorted by the stacking

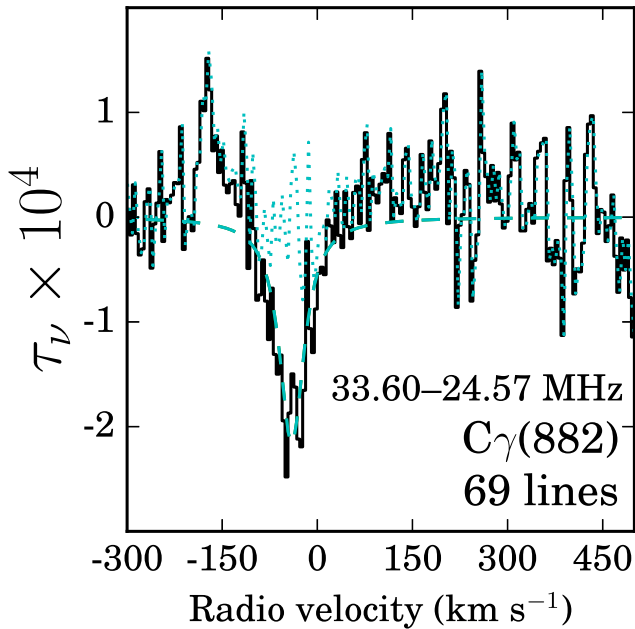


Figure 5. Stacked $C\gamma$ spectrum. The black steps show the stacked spectra after processing, the cyan dashed line shows the best-fitting Voigt profile and the cyan dotted line shows the residuals. This is the same as in Fig. 3.

procedure. The tests show that without baseline and line removal the line properties are up to 40 per cent different from those of the input model. If we apply the baseline and line removal during stacking the difference is less than 15 per cent, where the highest n data is the hardest to recover. From this we conclude that baseline corrections on scales larger than the linewidth and line removal help recover the line profiles. These tests also show that we can recover the line properties of the dominant velocity component at -47 km s^{-1} . To do so, we need to fit three velocity components up to $n \approx 650$ and two components from $n = 650$ to 700. The details of these simulations can be found in the Appendix.

3 RESULTS

We display examples of individual sub-band spectra in Fig. 2. Individual $C\alpha$ lines are visible above 16 MHz. The peak optical depth ranges from 4.6×10^{-3} at 30 MHz to 2×10^{-3} at 11 MHz. Individual $C\beta$ lines are visible above $\nu \gtrsim 28$ MHz.

The line profiles obtained after stacking are shown in Figs 3, 4 and 5. These figures show how the linewidth increases while the peak optical depth decreases towards lower frequencies. The $C\alpha$ stacks show detections down to the lowest frequency of 10.96 MHz, with a signal-to-noise ratio of 3.7σ . To our knowledge this is the lowest frequency detection of a $C\alpha$ line to date.

The line centroid is found to be offset by -47 km s^{-1} with respect to the local standard of rest, v_{LSR} , as expected from all previous CRRL observations in the direction of Cas A. This velocity is coincident with the strongest H I absorption component observed against Cas A and it is associated with gas in the Perseus arm of our Galaxy (e.g. Davies & Cummings 1975). Spectra of CRRLs at higher frequencies, where the line broadening is not as severe and the velocity resolution is better, show that along this line of sight two additional velocity components can be identified. One is at -38 km s^{-1} , also associated with the Perseus arm of the Galaxy, and the other is at 0 km s^{-1} , associated with the Orion spur (e.g. Payne et al. 1989).

3.1 Line fitting

3.1.1 CRRLs

Based on the results of the fits to the simulated line profiles we use a different number of Voigt profiles to fit the stacked lines. The number of profiles is determined by requiring that the residuals are reduced by more than a factor of 2 while still recovering reasonable line parameters. For $n < 650$, using three profiles, two for the Perseus arm and one for the Orion spur components, results in the lowest residuals. The Doppler widths of the -47 , -38 and 0 km s^{-1} components are fixed at 3.4, 6.8 and 2.5 km s^{-1} , respectively (Oonk et al. 2017). For $650 < n < 700$, we fit two Voigt profiles, one for the Perseus component and one for the Orion component. For $n > 700$, a single component is used to fit the line profile. The best-fitting parameters are given in Table 2. Here we see that even when we fit a single component the observed $C\alpha$ line centre is close to -47 km s^{-1} . This indicates that this velocity component still dominates at the lower frequencies. While the observations clearly reveal the presence of CRRLs up to $n = 843$ (see Fig. 3), corresponding to $\nu = 10\text{--}12$ MHz, quantitative analysis of this data is limited by recovery of the line wings (see Appendix A). We have ignored the $C\alpha(843)$ data in further analysis.

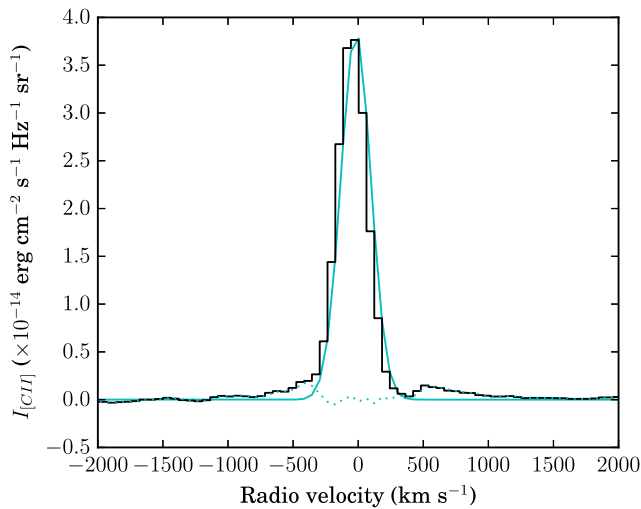
To test the fit results, we varied the noise properties of the stacked spectra and repeated the fit. To do this, we subtract the best-fitting Voigt profiles from the stacked spectra. The best-fitting Voigt profiles are then added to a spectra with a different noise level. The noise level was randomly drawn from a Gaussian distribution with a standard deviation equal to the rms in the stack. The stacks with the different noise levels were then fit again. We repeated this 1000 times for every stacked spectrum. The measured line properties varied little between different realizations of the noise. For each stack, we made histograms of the measured line properties. The distribution of the line parameters showed Gaussian distributions for the linewidth and integrated optical depth. The standard deviation of these distributions is comparable to the errors given for the line parameters in Table 2.

3.1.2 $158 \mu\text{m}$ [C II] line

From each of the nine PACS footprints, we extracted an average spectrum. We fitted the [C II] $158 \mu\text{m}$ line in this average spectrum with a Gaussian. To account for the continuum emission, we fit a linear function to line-free channels. The source-averaged spectra with the continuum subtracted is shown in Fig. 6. The line centroid is $-16 \pm 19 \text{ km s}^{-1}$, its full width at half-maximum (FWHM) $218 \pm 3 \text{ km s}^{-1}$ and its amplitude $0.096 \pm 0.003 \text{ Jy arcsec}^{-2}$. The average line intensity integrated over frequency over the face of Cas A is $(7.0 \pm 0.2) \times 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. Because the PACS footprints cover only ~ 20 per cent of the supernova remnant, the uncertainty on the line intensity can be larger. Given the velocity resolution of the PACS observations, the line is not resolved. This implies that the Perseus, Orion and any other velocity components present in [C II] appear as a single component. Even background [C II] emission could contaminate our spectra. Observations of other tracers, with higher spectral resolution, such as the 21 cm spin-flip transition of H I (Bieging et al. 1991) and CO (Kilpatrick et al. 2014), show that the most prominent component is at -47 km s^{-1} . Since we do expect a correlation between [C II], CO and H I (e.g. Pineda et al. 2013), the $158 \mu\text{m}$ line intensity should be dominated by the contribution from the -47 km s^{-1} component.

Table 2. Line parameters.

n	n range	Frequency (MHz)	I_l/I_c $\times 10^{-3}$	Line centre (km s $^{-1}$)	Lorentz linewidth (km s $^{-1}$)	Integrated optical depth (Hz)	Spectral rms $\times 10^{-4}$
$C\alpha$							
601	580–621	30.23	3.44 ± 0.05	-48 ± 3	17 ± 2	11.9 ± 0.1	0.4
			1.59 ± 0.04	-39 ± 3	22 ± 2	6.8 ± 0.1	0.4
			0.33 ± 0.06	0 ± 3	13 ± 3	0.9 ± 0.1	0.4
645	623–665	24.46	2.92 ± 0.07	-49 ± 4	29 ± 2	12.7 ± 0.3	0.5
			1.38 ± 0.06	-39 ± 4	35 ± 2	7.3 ± 0.3	0.5
			0.3 ± 0.1	0 ± 4	23 ± 4	1.1 ± 0.2	0.5
689	668–709	20.07	3.6 ± 0.1	-46 ± 5	58 ± 1	22.8 ± 0.4	0.8
			0.3 ± 0.1	0 ± 5	20 ± 8	0.7 ± 0.4	0.8
			2.88 ± 0.07	-46 ± 6	89 ± 3	22.7 ± 0.5	1.4
731	713–748	16.80	2.3 ± 0.1	-47 ± 8	132 ± 12	22 ± 1	3.0
782	760–806	13.73	1.7 ± 0.1	-48 ± 10	153 ± 26	15 ± 1	4.0
$C\beta$							
761	731–793	29.74	-0.78 ± 0.02	-45 ± 4	45 ± 2	5.6 ± 0.1	0.5
824	792–858	23.43	-0.58 ± 0.04	-48 ± 5	54 ± 5	3.9 ± 0.2	0.8
894	862–928	18.35	-0.44 ± 0.04	-41 ± 6	103 ± 14	4.4 ± 0.4	1.0
$C\gamma$							
882	836–928	28.62	0.21 ± 0.01	-39 ± 4	44 ± 7	1.5 ± 0.1	0.5

**Figure 6.** [C II] 158 μm line spectra obtained with PACS. The line was averaged over the face of Cas A after removing the continuum. The black steps show the data, the cyan solid line shows the best-fitting Gaussian profile and the dotted cyan line shows the fit residuals. This is similar to Fig. 3.

3.2 CRRL observed properties

In the frequency range 10–33 MHz, two properties of the observed CRRL profiles can be used to determine the gas physical conditions, the linewidth and its integrated optical depth. Here we present the change in line properties, which will be later used to determine the gas physical conditions.

The linewidths determined from fitting Voigt profiles to the CRRL stacks are shown in Fig. 7. Here we see how the lines get broader as the principal quantum number increases. The increase in linewidth causes the lines to become blended as frequency decreases. In the top panels of Fig. 3 it is possible to see the asymmetry in the line profile towards positive velocities due to the presence of additional gas. This is washed away as the dominant component gets broader.

Our data in combination with the LCASS data (Oonk et al. 2017) at higher frequencies clearly reveal the transition from Doppler-dominated to Lorentz-dominated linewidths in the range $n = 500$ –600.

The integrated optical depths are shown in Fig. 8. Since for part of the low-frequency spectra presented here ($n > 700$), it is not possible to find a unique solution to separate the different velocity components, we show the sum of the optical depths from the Perseus arm gas at -47 and -38 km s $^{-1}$. This is done by adding the two components together when more than two Voigt profiles are fit, or by subtracting a 5 per cent contribution, corresponding to the Orion component, when one Voigt profile is fit. The LCASS points at $n > 600$ show a fairly constant integrated optical depth as n increases up to 800. In Fig. 8, we also show the LCASS data (Oonk et al. 2017) at higher frequencies, the latest compilation of integrated optical depths (Kantharia, Anantharamaiah & Payne 1998) as well as the more recent $C\alpha$ data from Stepkin et al. (2007) and Sorochenko & Smirnov (2010). The linewidth and integrated optical depth are used in the following section to constrain the gas properties.

4 ANALYSIS

In this section, we analyse CRRLs below 33 MHz in combination with the 158 μm [C II] line. For the analysis, we exclude the $C\alpha$ (843) line for the reasons given in Section 3.1.1.

4.1 Linewidth

Two effects dominate the broadening of low-frequency CRRLs. These are pressure broadening, which depends on the electron temperature and density, and radiation broadening, which depends on the radiation field in which the atoms are immersed (Shaver 1975; Salgado et al. 2016a). Both effects affect the Lorentzian wings of the line profile. As mentioned in Section 2.3, the linewidth at the low frequencies, where the lines are heavily blended, will be dominated by the most prominent component. In this case, this is the -47 km s $^{-1}$ component. For principal quantum numbers below

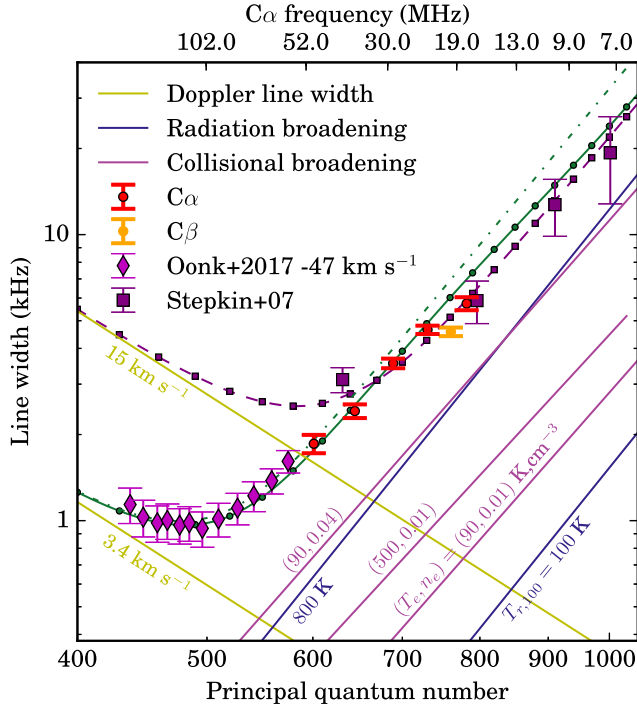


Figure 7. Linewidth for the -47 km s^{-1} velocity component as a function of principal quantum number. The red and orange points show the measured linewidths from this work (Table 2). The purple diamonds show the linewidths from Oonk et al. (2017) and the purple squares the $C\alpha$, $C\beta$, $C\gamma$ and $C\delta$ data from Stepkin et al. (2007). The coloured solid lines show the contribution from Doppler broadening (yellow lines), pressure broadening (purple lines) and radiation broadening (blue lines). The purple line with squares shows the linewidth produced by the Stepkin et al. (2007) model. The green dot-dashed line shows the linewidth for a model with a Doppler linewidth of 3.4 km s^{-1} , $T_e = 85 \text{ K}$, $n_e = 0.04 \text{ cm}^{-3}$, and a power-law radiation field with $\alpha = -2.6$ and $T_{r,100} = 1400 \text{ K}$ (Oonk et al. 2017). The green line with circles shows the linewidth for a model with the same physical conditions as the green dot-dashed line, but in this case the radiation field is a combination of a power law with $T_{r,100} = 800 \text{ K}$ and $\alpha = -2.6$ plus a contribution to the radiation field from Cas A. To model the contribution from Cas A, we use its observed flux density (Vinyaikin 2014). We can see that the linewidth due to the radiation field from the observed flux density of Cas A (Vinyaikin 2014) decreases faster than that of a power law with $\alpha = -1$ (Stepkin et al. 2007, line with squares versus line with circles).

~ 700 , the line profiles of the -47 and -38 km s^{-1} components can be decomposed. For $n > 700$, the line profile shows no deviations from a single Voigt, but at this point the -47 km s^{-1} is so broad that it dominates the linewidth. In Fig. 7, we present the linewidth for the -47 km s^{-1} velocity component as a function of principal quantum number over the full LBA frequency range. The higher frequency data for the -47 km s^{-1} component is taken from Oonk et al. (2017). In Fig. 7, we see that the linewidth increases with principal quantum number.

The coloured curves in Fig. 7 show the contribution from pressure and radiation broadening on the lines. The linewidth due to pressure broadening is (e.g. Salgado et al. 2016b)

$$\Delta\nu_p = \frac{1}{\pi} 10^a n_e n^{\gamma_c} \text{ Hz.} \quad (2)$$

Here, n_e is the electron density, n the principal quantum number, a and γ_c are constants that depend on the electron temperature of the gas, T_e . The values of a and γ_c are tabulated in Salgado et al. (2016b). Using this model, the maximum electron density of the

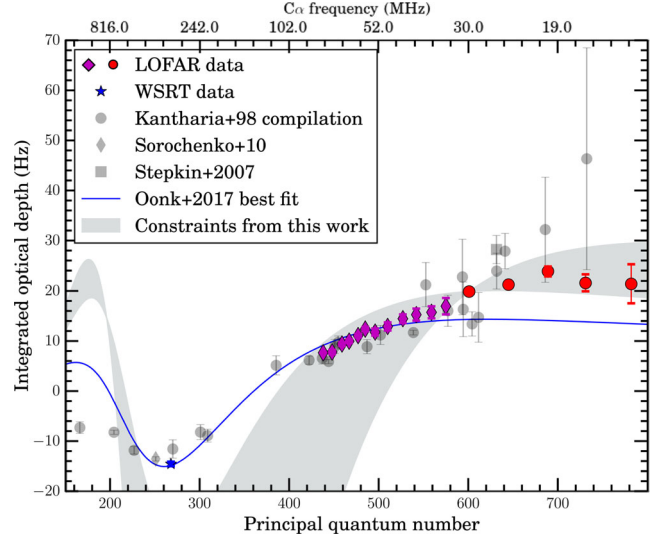


Figure 8. Integrated optical depth as a function of principal quantum number for the sum of the Perseus arm components at -47 and -38 km s^{-1} . The LCASS data are shown with red circles for the data presented in this work and purple diamonds for the higher frequency data (Oonk et al. 2017). The LCASS WSRT data are shown with a blue star. Data from the literature are shown in grey. The best-fitting model from Oonk et al. (2017) for the sum of the -47 and -38 km s^{-1} components is shown with a blue line. The models which correspond to the physical constraints from this work are shown in a grey shaded region. In some cases, the error bars are smaller than the symbols.

gas is 0.3 cm^{-3} for the lowest temperature in our grid of models, i.e. $T_e = 10 \text{ K}$. The maximum allowed electron density decreases for higher temperatures.

Radiation broadening produces a linewidth given by (Salgado et al. 2016b)

$$\Delta\nu_r = \frac{1}{\pi} \sum_{n \neq n'} B_{n'n} I_\nu \text{ Hz.} \quad (3)$$

Here, $B_{n'n}$ is the Einstein coefficient for stimulated emission and I_ν the intensity of the radiation field. At low frequencies, the background radiation field is generally due to synchrotron emission and can be described by a power law $T_r \propto \nu^\alpha$. Using the available low-frequency surveys Zheng et al. (2016) find that the spectral index of synchrotron emission below 408 MHz is $\alpha_{\text{MW}} = -2.52 \pm 0.02$. Studies of low-frequency CRRLs in the Milky Way usually assume that $\alpha = -2.6$ (e.g. Payne et al. 1989; Kantharia et al. 1998; Oonk et al. 2017). The difference in $\Delta\nu_r$ between using a power-law index of -2.52 and -2.6 is less than 20 per cent for $n = 400$ – 1000 . Here we will adopt the value of $\alpha_{\text{MW}} = -2.6$ to be consistent with previous work. In this case, the linewidth due to radiation broadening becomes

$$\Delta\nu_r \approx 0.8 \left(\frac{T_{r,100}}{1000 \text{ K}} \right) \left(\frac{n}{600} \right)^{5.8} \text{ kHz.} \quad (4)$$

Where, $T_{r,100}$ is the brightness temperature of the radiation field at 100 MHz in units of K.

Using equation (4) and the linewidths for $n < 750$ (see Section 3.1.1), we constrain $T_{r,100}$ to $< 2000 \text{ K}$. This is a strict upper limit, since pressure broadening is not considered. An approximate lower limit can be obtained from the lowest brightness temperature of the Milky Way in a region of similar galactic latitude to Cas A. Using the global sky model of de Oliveira-Costa et al. (2008) we have a value of $T_{r,100} \gtrsim 800 \text{ K}$. However, the exact value

is highly uncertain. Fitting a power law to the change in linewidth with principal quantum number in the range $n = 601\text{--}731$, we find that we cannot discriminate between collisional or radiation broadening. This is because both effects have a similar dependence on n . Oonk et al. (2017) find a gas electron density of 0.04 cm^{-3} , a temperature of 85 K and a radiation field intensity at 100 MHz of 1350 K, for the -47 km s^{-1} velocity component. If we use these results for the gas conditions, then the relative contributions from pressure and radiation broadening are similar. This suggests that both pressure and radiation broadening are of importance in setting the behaviour of the linewidth along this line of sight.

If we combine the Doppler-, pressure- and radiation-induced broadening terms and fit it to the data with frequencies greater than 30 MHz, then we arrive at the following relation for T_e , n_e and $T_{r,100}$:

$$\left(\frac{n_e}{\text{cm}^{-3}}\right) = \left(0.8 - 0.38 \left(\frac{T_{r,100}}{1000\text{ K}}\right)\right) \left(\frac{T_e}{\text{K}}\right)^{-0.46}. \quad (5)$$

This expression is valid for this line of sight when $T_{r,100} \lesssim 1600\text{ K}$ and accurate to within 10 percent. In Section 4.5, we adopt this relation to constrain the gas properties. In Section 4.5, we also assume that this relation is valid for both the -47 and -38 km s^{-1} velocity components. This assumption is based on the similitude between the derived gas physical properties from both velocity components (Oonk et al. 2017). The physical conditions in this case are derived using higher frequency data, where the line profile can be more reliably decomposed.

Stepkin et al. (2007) showed that using a power-law radiation field with $T_{r,100} = 3200\text{ K}$ overestimated the linewidths for $n > 600$. To solve this issue they argued that the contribution from Cas A to the radiation field has to be taken into account when modelling the linewidths. The spectrum of Cas A has a turnover point close to 30 MHz (e.g. Braude et al. 1978; Vinyaikin 2014), which causes its flux density to decrease for frequencies lower than the turnover frequency. This solved the apparent discrepancy between the observed linewidths and the model predictions. Here we make use of the broadening expressions derived by Salgado et al. (2016b). These result in an ~ 30 per cent lower Lorentz linewidth with respect to the Shaver (1975) expressions used by Stepkin et al. (2007). For $n \lesssim 650$, the use of expressions that predict a smaller linewidth combined with our attempt to fit three velocity components results in linewidths which are consistent at the 3σ level with a power-law line broadening. However, as our simulations show, recovering the correct linewidth for $n \lesssim 700$ depends on the number of components fit to the blended line profiles, which has no unique solution. Additionally, for $n \geq 800$, the line profiles are likely to be underestimated due to the severe line broadening. At some point the width of the lines within a single sub-band is such that it is no longer possible to find line-free channels. We believe that the combination of these effects could mimic a deviation from a power-law line broadening (e.g. a broken power law).

In Fig. 7, we also show the linewidth when the contribution from Cas A is taken into account. To include the contribution from Cas A to the radiation field (I_ν in equation 3), we add it to the radiation field from the Milky Way. To model the intensity of the radiation field due to Cas A at frequencies lower than 100 MHz, we use two different models. One is the model by Stepkin et al. (2007), in which a broken power law is used. This broken power law has a turnover at $\nu = 26\text{ MHz}$; for frequencies below this point, the spectral index is $\alpha = -1$. Above the turnover, the spectral index is the same as that from the Milky Way radiation field, i.e. $\alpha = -2.6$. In this model, the

contribution from Cas A to the radiation field at the cloud is $T_{r,100} \approx 360\text{ K}$. The second model we use is based on the observed flux density from Cas A (Vinyaikin 2014). In this case, the contribution from Cas A is $T_{r,100} \approx 360\text{ K}$, which is determined from a fit to the observed linewidths.

4.2 Integrated optical depth

The observed change in integrated optical depth with principal quantum number, n , can be used to constrain the properties of the CRRL emitting gas (e.g. Dupree 1971; Shaver 1975; Walmsley & Watson 1982; Ershov et al. 1984; Payne et al. 1989; Ponomarev & Sorochenko 1992; Kantharia et al. 1998; Salgado et al. 2016a,b; Oonk et al. 2017). Here we compare the observed integrated optical depth to those predicted by the updated models of Salgado et al. (2016a,b). In these models, the level populations are fully determined by the atomic physics involved, including the effect of dielectronic capture (Watson et al. 1980). The level populations are obtained by self-consistently solving the statistical equilibrium equations. Deviations from local thermodynamic equilibrium (LTE) in the level population are characterized by the departure coefficient b_n , while the contribution from stimulated emission to the line intensity is characterized by $\beta_{n'n}$ (Shaver 1975; Salgado et al. 2016a).

To model the line optical depth, we assume that the absorbing gas is a plane parallel slab that completely covers the face of Cas A. We assume a constant electron temperature and density. The assumption of constant temperature and density is justified since we are studying a small frequency range (10–33 MHz) and density filter effects should be small. The assumption of a unity beam filling factor seems reasonable given the spatially resolved observations of Anantharamaiah et al. (1994), which show emission all over the face of Cas A (Oonk et al. 2017). When we compare the integrated optical depth to the models, we use the combined optical depth of the -47 and -38 km s^{-1} velocity components. We do this based on the detailed analysis at higher frequencies (Payne et al. 1994; Oonk et al. 2017), which suggests that both velocity components trace gas with similar temperature and density. In this case, the combined integrated optical depth of both velocity components will show the same behaviour with n scaled by the total emission measure. These assumptions will be used in the rest of the analysis.

When solving the statistical level population problem using the models of Salgado et al. (2016a,b), we use atomic hydrogen and electrons as collisional partners and we chose to ignore collisions with molecular hydrogen since we expect their importance to be relatively small given the gas physical conditions (Oonk et al. 2017). We evaluate the models in a grid in $n_e\text{--}T_e\text{--}T_{r,100}$ space. For the electron density, the grid spans the range $n_e = 0.01\text{--}1.1\text{ cm}^{-3}$ in steps of 0.005 cm^{-3} . The electron temperature is evaluated between 10 and 150 K in steps of 5 K. $T_{r,100}$ is evaluated at 800, 1200, 1400, 1600 and 2000 K.

The integrated optical depth as a function of n is shown in Fig. 8. In this figure, we also show the latest compilation of CRRL observations towards Cas A presented in Kantharia et al. (1998), the $C\alpha$ data points from Stepkin et al. (2007) and Sorochenko & Smirnov (2010), and the LCASS data (Oonk et al. 2017). The LOFAR points at $n > 600$ show a fairly constant integrated optical depth as n increases up to 800. The observed shape of the change in integrated optical depth is similar to the one predicted by the models of CRRL emission (Salgado et al. 2016a). In these models, a constant optical depth is reached faster than in previous ones (e.g. Payne et al. 1994). A constant integrated optical depth is expected if the population of carbon atoms is close to LTE ($b_n \sim 1$). When b_n gets close to unity,

$\beta_{n'n}$ has an almost constant value. This is reflected in a constant integrated optical depth as a function of n . The models of Salgado et al. (2016a) show that this happens for $n > 600$ in regions that satisfy $n_e > 0.015 \text{ cm}^{-3} (T_e/60 \text{ K})^{-2}$. Under these conditions, the highest n levels are close to collisional equilibrium, while the lower n levels decay rapidly radiatively. As density or temperature increases, a larger fraction of the levels is close to collisional equilibrium and hence the total population of the collisionally dominated levels increases. This translates into an increment in the optical depth of the high n transitions.

The LCASS data shows a similar trend when compared with previous results, but with a smaller scatter. LOFAR, with its large fractional bandwidth and high spectral resolution, is an ideal instrument for low-frequency CRRL observations. Additionally, systematic differences arising from different calibration and data-reduction strategies are minimized when using the same instrument. The trend in linewidth and integrated optical depths shows a smooth change with n . This suggests that there are no major systematic differences between the different LCASS LBA data sets. This is not the case for the literature data, for which a larger point to point scatter is observed.

Another advantage of LOFAR for CRRL observations is given by the frequency coverage of its sub-bands. The frequency coverage of the LOFAR sub-bands results in sufficient velocity coverage to measure the Lorentzian wings of the line profiles for $n \lesssim 800$. This was not the case for older receivers. As noted by Payne et al. (1994), some of the previous decametric observations could have underestimated the line profiles. This is because in previous observations the velocity coverage of the spectrometers was comparable to the linewidth. In this case, there are no line-free channels from which to determine the continuum. This led Payne et al. (1994) to estimate how much the line profiles could have been underestimated and derive a correction based on this. However, such a correction depends on the model used for its derivation and the physical conditions assumed. Models that predict larger linewidths will require larger correction factors for a fixed velocity coverage. Given that the gas conditions are not known a priori, this kind of correction can lead to erroneous determination of the gas properties.

4.3 Carbon lines ratio

A way of breaking the degeneracy between different gas properties of the observed CRRL properties is to compare the CRRLs with the 158 μm [C II] line (Natta, Walmsley & Tielens 1994; Salgado et al. 2016b). Both lines are emitted by ionized carbon, but the line strengths have different temperature dependences. This makes the CRRL/[C II] line ratio a good thermostat. Though, this also means that emission from both tracers can have different contributions from different phases of the ISM. The contribution from different phases of the ISM to the [C II] line intensity is still poorly constrained (e.g. Pineda et al. 2013). In the case of CRRLs, this is still an open question (see e.g. Anantharamaiah et al. 1994; Sorochenko 1996). Since the derived temperature for the CRRL gas is 85 K (Oonk et al. 2017), which is close to the temperature required to excite the carbon $^2P_{3/2} \rightarrow ^2P_{1/2}$ core, here we will assume that both lines have equal contributions from different ISM phases.

To model the line intensity of the [C II] line, we use the equations of Salgado et al. (2016b). Given the gas conditions (Oonk et al. 2017) and the atomic hydrogen column density (Mebold & Hills 1975), the [C II] line will be optically thick. We assume that the [C II] emission in the PACS spectra comes from the two velocity components at -47 and -38 km s^{-1} . For the linewidths we use 3.4

and 6.8 km s^{-1} , respectively (Oonk et al. 2017). Additionally, we assume that the path length of the -38 km s^{-1} velocity component is half that of the -47 km s^{-1} , as determined from higher frequency CRRL observations (Oonk et al. 2017). Under these assumptions, we evaluate the intensity of the [C II] line in a n_e - T_e grid that is the same as for the CRRLs.

Towards Cas A, the ratio between the integrated optical depth of the C(731) α line and the [C II] line is $(-3.7 \pm 0.1) \times 10^5 \text{ Hz/(erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1})$. The region of parameter space consistent with this ratio to within 3σ is shown in Fig. 9 with red lines. The gas electron temperature is constrained to the range $T_e = 70$ – 100 K for the lowest densities in our grid ($n_e < 0.02 \text{ cm}^{-3}$). For higher densities, the allowed temperature range narrows considerably, decreasing to 60 – 70 K for the highest density in our grid ($n_e = 0.11 \text{ cm}^{-3}$). As the temperature increases, the number of carbon atoms in the $^2P_{3/2}$ state is larger. This translates into an increase of the [C II] line intensity. In practice, this means that for a smaller CRRL/[C II] ratio the allowed temperature would be higher.

We do recognize that the [C II] 158 μm intensity used only refers to ~ 20 per cent of the Cas A supernova remnant and is unresolved in velocity. As shown by Gerin et al. (2015), observations of [C II] unresolved in velocity can hide absorption features. This has the effect of lowering the observed [C II] intensity when absorption and emission features are convolved with the spectrometer response. Further high spectral resolution observations with the Stratospheric Observatory for Infrared Astronomy (SOFIA) are necessary to determine this ratio well.

4.4 CRRL ratio

A way in which the emission measure dependence is eliminated is by considering the ratio between the integrated optical depths of CRRLs. The ratio between CRRLs has a weaker dependence on calibration uncertainties. The measured $\text{Ca}(731)/\text{Ca}(601)$ integrated optical depth ratio has a value of 1.12 ± 0.07 . The region of parameter space that produces a line ratio consistent with the observations to within 3σ is shown in Fig. 9 as the hatched region between yellow lines. Even if the range of pressures allowed by the 3σ values is large, it does pose a strict lower limit on the electron pressure of $P_e \geq 0.9 \text{ K cm}^{-3}$, for $T_{r,100} = 800 \text{ K}$ and $T_e \geq 20 \text{ K}$. For higher values of $T_{r,100}$, the lower limit will be larger. We can turn this in to a lower limit on the gas pressure by adopting an electron fraction. If we use an electron fraction equal to the gas-phase carbon abundance (1.5×10^{-4} , Cardelli et al. 1996; Sofia et al. 1997), i.e. all the electrons come from ionized carbon, this is $P \geq 6 \times 10^3 \text{ cm}^{-3} \text{ K}$. This gas pressure is comparable to that measured using ultraviolet absorption lines of neutral carbon (Jenkins & Tripp 2001).

4.5 Piecing it all together

Using the measured temperature from the CRRL–[C II] ratio, and the constraints from the $\text{Ca}(731)/\text{Ca}(601)$ ratio and linewidth, we can break the degeneracy between T_e , n_e and $T_{r,100}$. We can combine these constraints since the linewidth traces the most prominent velocity component at -47 km s^{-1} and we assume that the -38 km s^{-1} velocity component traces gas with similar physical properties. An example of this is shown in Fig. 9. In this figure, we can see how the linewidth relation (equation 5) and the pressure derived from the $\text{Ca}(731)/\text{Ca}(601)$ ratio intersect only at the correct value of $T_{r,100}$, when we adopt the 1σ value for the $\text{Ca}(731)/\text{Ca}(601)$ ratio. Then, from the allowed range of pressure and temperature the density can be determined. However, if we consider the 3σ range for the

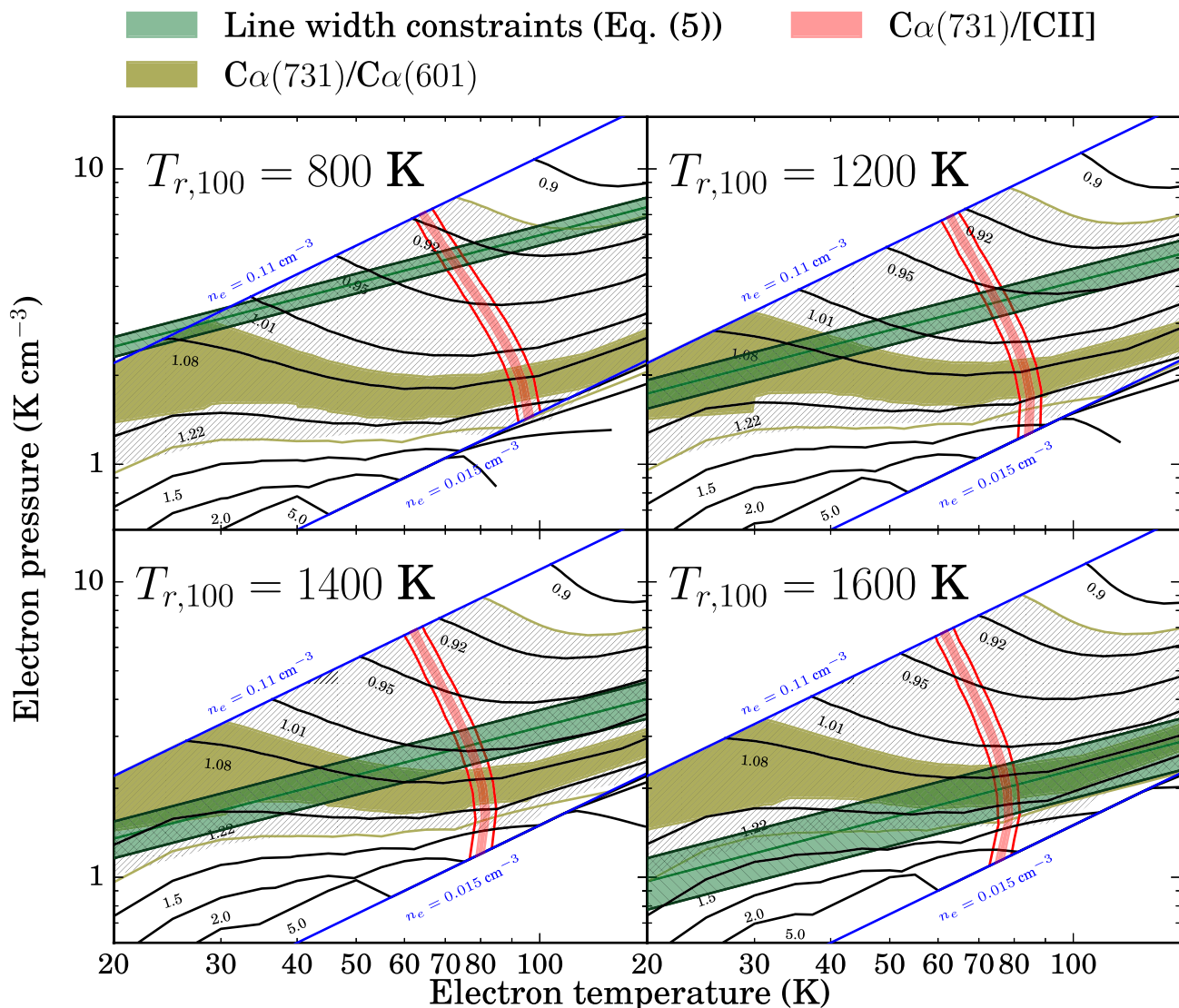


Figure 9. Pressure temperature diagrams for CRRLs below 33 MHz and the 158 μm [C II] line. These can be used to constrain the gas properties given measurements of decametric CRRLs and [C II]. The black lines show the pressure for constant values of the $\text{C}\alpha(731)/\text{C}\alpha(601)$ ratio. The red region shows the allowed temperature range derived from the $\text{C}\alpha(731)/[\text{C II}]$ ratio with a 1σ error. The red lines show the allowed temperature range when considering a 3σ error bar. The green region shows the allowed range of pressures given equation (5) for $T_{r,100} \pm 100$ K. The yellow region shows the measured value of the $\text{C}\alpha(731)/\text{C}\alpha(601)$ ratio with a 1σ error, while the densely hatched region shows the same value with a 3σ error. The difference between the 1σ and 3σ curves reflects the importance of having high signal-to-noise detections. The blue lines show constant electron density curves for $n_e = 0.015$ and 0.11 cm^{-3} . For values of $T_{r,100} > 1650$ K, the green region goes outside the allowed range of parameters.

$\text{C}\alpha(731)/\text{C}\alpha(601)$ ratio, then we are in a situation where $T_{r,100}$ and the pressure are degenerate. This shows the importance of having high signal-to-noise data to determine the gas conditions.

Using the ranges allowed by our data, we note that a value of $T_{r,100}$ lies between 1500 and 1650 K, T_e between 68 and 98 K and P_e between 1.5 and 2.9 K cm^{-3} . The density range allowed by the intersection of these constraints is $0.02\text{--}0.035 \text{ cm}^{-3}$. These results are in line with those published by Oonk et al. (2017), but here we have made use only of CRRLs below 33 MHz and the 158 μm [C II] line.

In Fig. 8, we also show how the derived range of physical conditions translate into integrated optical depth. We can see how the LOFAR data fall within the range of allowed physical conditions. However, the integrated optical depth is underestimated for the WSRT data point. When performing a spatial average, such as that

done inside the synthesized beam of the observations presented here, the observed line optical depth will be a weighted average of the line optical depth. The weight is proportional to the brightness temperature of the background source. If the background source shows spectral index variations on scales smaller than the synthesized beam, then the line profiles will sample different spatial structures with frequency. The continuum from Cas A shows variation in its optical depth on scales of arcseconds, with a flatter spectral index in its inner 50 arcsec (DeLaney et al. 2014). The spatial structure of the gas at -47 km s^{-1} shows variations on arcminute scales with the gas concentrated towards the south and west of Cas A (Anantharamaiah et al. 1994; Asgekar et al. 2013). The integrated optical depth towards the western hotspot of Cas A can be a factor of 2 larger than that extracted over the whole face of Cas A (Asgekar et al. 2013). This implies that at frequencies below 30 MHz, the line profiles

will be weighted towards the gas in the south and west of Cas A. Similarly, gas outside the supernova remnant could be sampled by the lower frequency observations. However, we estimate that the surface brightness of Cas A relative to the surrounding Milky Way at these frequencies is larger by a factor of $\gtrsim 10$. Then, the effect of gas outside the face of Cas A should be small unless its integrated optical depth is ten times larger than that of the gas that covers the face of Cas A. Another reason for underestimating the WSRT-integrated optical depth is related to the change of physical conditions traced by CRRLs at different frequencies. This can be caused because the CRRL optical depth acts as a density filter (e.g. Mohan, Goss & Anantharamaiah 2005), or because some components can be absorbed by free electrons at lower frequencies (e.g. Pankonin 1980). CRRLs act as a density filter because gas with different physical conditions will emit/absorb preferentially at different frequencies. A model with a single slab of gas does not take into account this. However, the good fit of Oonk et al. (2017) to the integrated optical depth of the -47 km s^{-1} velocity component using a single slab of gas suggests that along this line of sight low-frequency ($\nu \lesssim 1 \text{ GHz}$) CRRLs trace gas with a narrow range of physical conditions. The last possibility we consider is that the physical conditions of the -47 and -38 km s^{-1} gas are not the same. The work of Oonk et al. (2017) at higher frequencies shows that the -38 km s^{-1} velocity component is less well fit than the -47 km s^{-1} one. However, with the current data, we do not find a significant difference between the two components. Data at higher frequencies, e.g. obtained with the LOFAR High Band Antennas (HBA, 120–240 MHz), would help narrow down the physical conditions of the -38 km s^{-1} velocity component.

4.6 The Perseus arm Cas A distance

In the previous sub-sections, we have obtained a range of allowed values for $T_{r,100}$. Even if we cannot accurately determine the contribution from Cas A to the radiation field, it is interesting to use the constraints on $T_{r,100}$ to try and determine the distance between the Perseus arm gas and the background source. Fig. 9 shows that $T_{r,100}$ can take values between 1500 and 1650 K if we consider the 1σ ranges. The brightness of the source at 100 MHz extrapolated from the Vinyaikin (2014) model is $1.8 \times 10^7 \text{ K}$. If we adopt a contribution from the Milky Way to $T_{r,100}$ of 800 K and a radius of 3 pc for Cas A, then the distance between the Perseus arm gas at -47 km s^{-1} and Cas A can be between 262 and 220 pc. This distance would increase if the contribution from the Milky Way to $T_{r,100}$ is larger.

We can compare this with estimates of the distance to the Perseus arm gas based on the Galactic rotation curve. We use a flat rotation curve outside the solar circle ($R_{\odot} = 8.5 \text{ kpc}$) with a constant velocity of 220 km s^{-1} (Dickey et al. 2009). For the -47 km s^{-1} component, the distance of the Perseus arm gas to Earth is 4.5 kpc. This distance is larger than the Earth-Cas A distance (3.4 kpc Reed et al. 1995), but this cannot be the case as the lines appear in absorption. Parallax measurements of star-forming regions in the Perseus arm show that kinematic distances are in disagreement with parallax-determined distances (e.g. Xu et al. 2006; Choi et al. 2014). Based on these measurements the distance from Earth to the gas in the Perseus arm towards Cas A is $\approx 3.3 \text{ kpc}$.

5 CONCLUSIONS

We have observed Cas A in the 10–33 MHz LBA band of LOFAR. Our results show that, while observations are hampered by iono-

spheric effects and RFI noise, Ca lines can be readily detected over this frequency range up to principal quantum numbers in excess of ~ 800 and $\text{C}\beta$ and $\text{C}\gamma$ lines to even higher quantum numbers. At the lowest frequencies, analysis of this data is hindered because of severe line broadening, which leaves a dearth of line-free channels. This limits the effective analysis of Ca lines to $n \lesssim 800$. Nevertheless, this still gives access to hundreds of transitions.

As line frequencies are accurately known, stacking procedures can be used to increase the signal-to-noise and very weak lines ($\sim 10^{-3}$ in peak optical depth) can still be reliably detected ($S/N > 10$) after stacking. These lines are caused by absorption associated with the Perseus spiral arm along the line of sight towards this supernova remnant. The observed lines show a pronounced broadening with principal quantum number while the peak optical depth decreases. The integrated optical depth stays quite constant over the full n -range (600–800). This contrasts with previous observations that suggested a continuous increase in integrated optical depth with principal quantum number. The line broadening at high n reflects the importance of radiation and/or pressure broadening and provides insight into the physical conditions of the emitting gas. We find that the change in linewidth with frequency can be described by a model in which the radiation field is due to Galactic synchrotron emission, without the necessity to invoke additional contributions. However, deviations from a power law in the radiation-broadening term are difficult to measure given the biases in the line-recovery process at these low frequencies. Higher signal-to-noise observations would help to determine if the apparent flattening in the linewidth at the highest principal quantum numbers is significant.

The high- n lines presented in this work are close to collisional equilibrium and a constant integrated optical depth is expected. As they are close to LTE, the ratio of the CRRLs is not very sensitive to the physical conditions but they do put a firm constraint on the minimum gas electron pressure of $P_e \geq 0.9 \text{ K cm}^{-3}$, which corresponds to $6 \times 10^3 \text{ K cm}^{-3}$ for an electron fraction of 1.5×10^{-4} .

By using the CRRL-[C II] line ratio as a thermostat, the ratio between CRRLs as a barometer and the linewidths, we are able to obtain physical conditions for the gas. Based on the data in the range 10–33 MHz and its 1σ errors, we derive $T_e = 60\text{--}98 \text{ K}$, $T_{r,100} = 1500\text{--}1650 \text{ K}$ and $n_e = 0.02\text{--}0.035 \text{ cm}^{-3}$. This highlights the power of combining low-frequency CRRLs with the $158 \mu\text{m}$ [C II] line. However, we caution that these results are uncertain due to the blend of at least two velocity components along this line of sight. Adding to this uncertainty is the unknown relation between [C II] and low-frequency CRRLs. Also, due to the limited spatial coverage and spectral resolution of the Herschel PACS observations, the [C II] intensity is not very well known. High spectral and spatial resolution observations with SOFIA would greatly help to determine the [C II] intensity over the face of Cas A.

Our study demonstrates that the lowest frequency window available with LOFAR can provide important insights into the physical conditions of the gas traced by CRRLs.

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APPENDIX A: SIMULATED LINE PROFILES

We generate synthetic spectra using the same number of channels and bandwidth as the LOFAR observations. To each synthesized spectrum we add Gaussian noise that mimics the noise properties of the LOFAR data. Ripples that simulate the effect of the bandpass response of LOFAR (Romein 2008) are also added. Then we add $C\alpha$, $C\beta$, $C\gamma$ and $C\delta$ lines to the spectra using Voigt profiles and generating the line properties based on the Salgado et al. (2016a) models. For each transition and for each velocity component we add one Voigt profile. The code used can be found in Salas et al. (2016). The velocity components are centred at -47 , -38 and 0 km s^{-1} . The synthesized spectra with the line profiles are then converted to antenna temperatures by inverting equation (1) to add

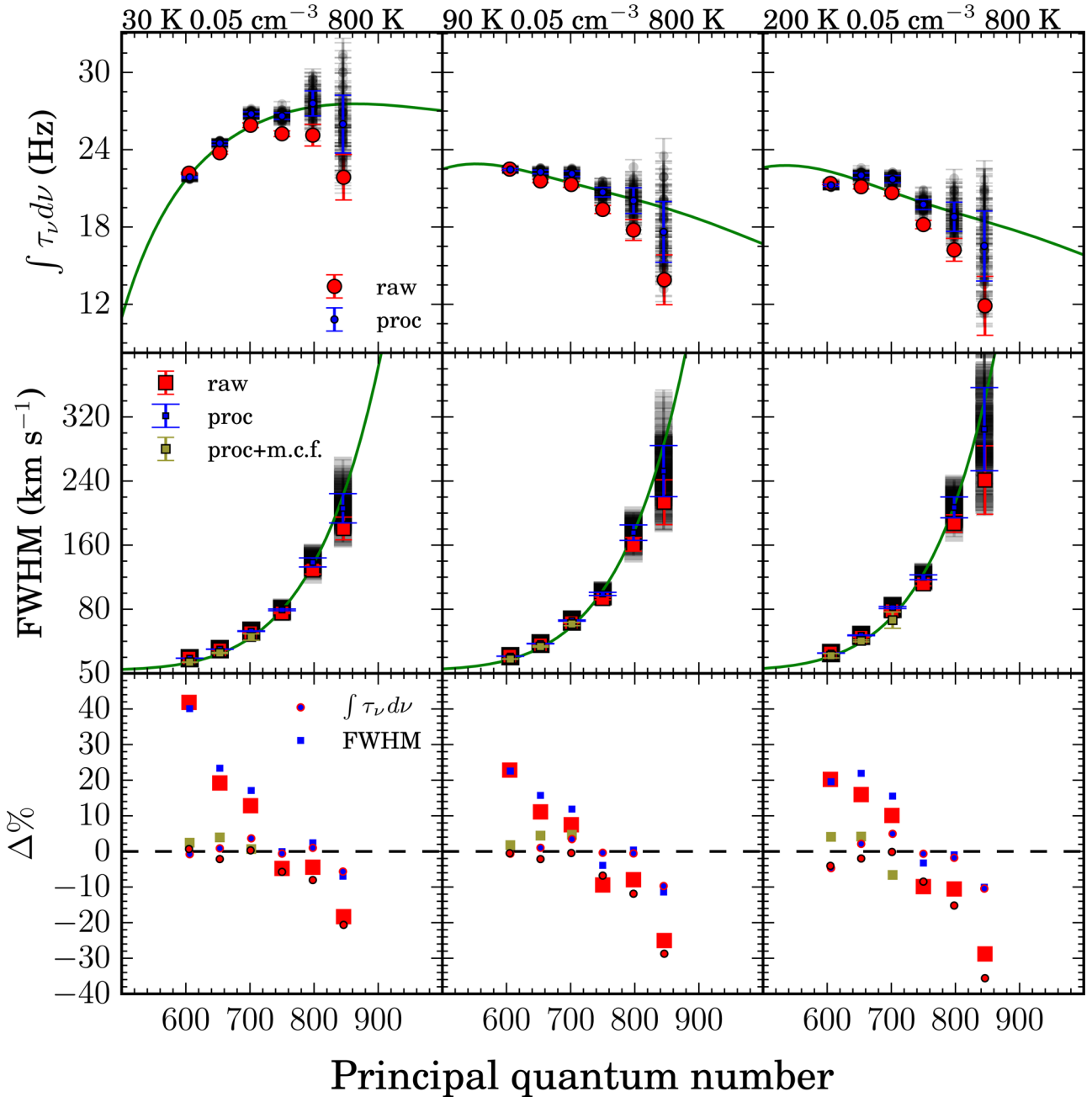


Figure A1. Comparison between the input line properties and the measured line properties of synthetic spectra. The top row shows the integrated optical depth as a function of principal quantum number. The grey points show the results of individual simulations after continuum subtraction, stacking and baseline removal, the blue points show the mean of the stacks with no baseline removal. The input line property is shown with a green line. The middle row shows the line FWHM. The symbols have the same meaning as in the top row, but the points are now squares. The yellow squares show the linewidth of the dominant component when multiple velocity components are fitted (m.c.f.) to the line profiles. The bottom panel shows the difference between the input value and the measured one. The comparison with processed data is shown by the blue symbols, while for the unprocessed data we use red symbols. The yellow squares show the difference between the input model for the dominant component and the measured linewidth for the dominant component after processing.

the continuum back. In all cases, we used a cloud covering factor of unity and a Doppler linewidth of 3.4 km s^{-1} . We use three different temperatures for the line properties, 30 K, 90 K and 200 K. The emission measure is adjusted to match the observed integrated optical depths. For the 30 K model, the emission measure of the -47 , -38 and 0 km s^{-1} components is 0.03 , 0.02 and $0.0045 \text{ pc cm}^{-6}$, respectively. For the 90 K model, these are 0.08 , 0.04 and 0.009 pc

cm^{-6} ; for the 200 K model, 0.25 , 0.1 and 0.05 pc cm^{-6} . The synthetic spectra are processed in the same way as the LOFAR spectra. First, we remove the continuum by estimating it from line-free channels and then the stacking and baseline-removal process is performed. This was repeated 60 times. Each time the noise in the synthetic spectra was recomputed. A comparison between the input models and the measured values from the stacks is shown in Fig. A1.

Here we also compare with stacks that were not processed, i.e. $C\alpha$, $C\beta$, $C\gamma$ and $C\delta$ lines are present in the spectrum while stacking and no bandpass correction was applied.

In the top panel of Fig. A1, we compare the integrated optical depth. This comparison shows that before processing the integrated optical depth is underestimated for $n > 710$. We have investigated the cause of this bias and have concluded that it arises because the number of lines per frequency unit increases with n . At $n \approx 710$, the Lorentzian wings of adjacent CRRLs begin to overlap and correctly estimating the continuum becomes difficult. To test this, we generated the same line profiles with a constant noise level of 10^{-5} , in optical depth units, and added only $C\alpha$ lines. No processing other than continuum removal and stacking was applied. The results are very similar, indicating that the underestimation is due to the presence of $C\alpha$ lines in the spectra. After processing, the measured values are closer to those of the input model. The difference between the integrated optical depth of the input model and the measured value after processing can be up to 16 per cent, in the worst case.

The middle row of Fig. A1 shows a comparison between the measured linewidth and the linewidth of the dominant component, at -47 km s^{-1} . The measured line FWHM is overestimated for $n < 710$. This is partially because for $n < 710$, the Orion component is still not completely blended with the Perseus components, so that fitting a single Voigt profile will result in a larger line FWHM. In the middle and bottom panels of Fig. A1, we also show the measured value when fitting up to three Voigt profiles. The number of profiles used is such that the fit residuals are minimized. For $n > 710$,

the profiles are blended enough that fitting a single Voigt profile is enough. Also, the results of the simulations show that after processing the linewidth is underestimated by no more than ~ 16 per cent for $n > 710$. These results also show that even if the different velocity components are blended, the measured linewidth will resemble the linewidth of the most prominent velocity component.

We also analysed the results for $C\beta$ and $C\gamma$ lines. After our processing, Section 2.3, the integrated optical depth and linewidth of $C\beta$ lines can be recovered to within 3 per cent and 10 per cent, respectively, for $n < 800$. For $C\gamma$ lines, the measured values can be recovered to within 50 per cent and 30 per cent for the integrated optical depth and linewidth, respectively. In both cases, using a single Voigt profile when fitting provides the best results. Based on these results, we choose to consider only the $C\beta(761)$ detection in the analysis.

These simulations do not include an effect that affects the data. This is contamination and loss of channels due to RFI. In some cases, strong RFI is present on top of the lines, and the affected channels have to be flagged resulting in an incomplete line profile. This is partially alleviated by the fact that the stack contains multiple lines that suffer from RFI differently. Even though we have not investigated the effect of RFI in the final stacks, we believe this will have a minor effect on the derived line properties.

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