Physical conditions in Centaurus A’s northern filaments I: APEX mid-J CO observations of CO-bright regions

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ABSTRACT

NGC 5128 (Centaurus A) is one of the best targets to study AGN-feedback in the local Universe. Optical filaments located at 16 kpc across the galaxy along the radio jet direction show recent star formation, likely triggered by the interaction of the jet with an HI shell. A large reservoir of molecular gas has been discovered outside the HI. In this reservoir, lies the Horseshoe complex: a filamentary structure seen in CO with ALMA and in Hα with MUSE. The ionised gas is mostly excited by shocks, with only a minor contribution of star formation. We used the Atacama Pathfinder EXperiment (APEX) to observe the $^{12}$CO(3-2) and $^{12}$CO(4-3) transitions, as well as dense gas tracers in the Horseshoe complex. $^{12}$CO(3-2) and $^{12}$CO(4-3) are detected for the first time in the northern filaments of Centaurus A, with integrated intensity line ratios $R_{32}$ $\sim$ 0.2 and $R_{43}$ $\sim$ 0.1, compared to the $^{12}$CO(1-0) emission. We also derived a line ratio $R_{32}$ $\sim$ 0.6, based on the previous $^{12}$CO(2-1) observations of Salomé et al. (2016b). We used the non-LTE radiative transfer code RADEX and determined that the molecular gas in this region has a temperature of 55 $-$ 70 K and densities between 2 $-$ 6 $\times$ 10$^3$ cm$^{-3}$. Such densities are also in agreement with results from the Paris-Durham shock code that predicts a post-shock density of a few 100 cm$^{-3}$. However, we need more observations of emission lines at a better angular resolution in order to place tighter constraints on our radiative models, whether they are used as a stand-alone tool (LVG codes) or combined with a shock model.

Key words. methods: data analysis - galaxies: individual: Centaurus A - galaxies: evolution - galaxies: ISM - galaxies: star formation - radio lines: galaxies

1. Introduction

NGC 5128 (also known as Centaurus A) is the most nearby and well studied radio galaxy, at a distance of 3.8 Mpc (Harris et al. 2010; scaling conversion of 18.3 pc/″). The galaxy is surrounded by gaseous shells that have been detected in HI (Schiminovich et al. 1994), CO emission (Charmandaris et al. 2000), and dust continuum (Auld et al. 2012). Such gaseous shells are likely the result of a past minor merger event (Malin et al. 1983). Along the northern radio jet, optically bright filaments are observed at distances of several kiloparsec, the so-called northern outer filaments (Blanco et al. 1975; Graham & Price 1981; Morganti et al. 1991). These filaments are thought to be the place of star formation as confirmed by GALEX data (Auld et al. 2012) and young stellar clusters (Rejkuba et al. 2001). The outer filaments are observed at the interaction of the radio jet with an HI shell, and were not widely studied until recently.

Recent $^{12}$CO(2-1) observations with APEX have revealed the existence of a large reservoir of molecular gas outside the HI gas (Salomé et al. 2016a). ALMA observations showed that this large reservoir lies in a filamentary structure that we called the Horseshoe complex (Salomé et al. 2017). The Horseshoe complex is associated with Hα emission that follows the same morphology as CO (see figure 1) and shares similar velocities. Based on a pixel-by-pixel BPT diagram (Baldwin et al. 1981; Kewley et al. 2006), MUSE data of the Horseshoe complex revealed that the Hα emission is mostly excited by shocks, with only few HII regions (Santoro et al. 2016; Salomé et al. 2017). Moreover, the Horseshoe complex does not seem to be associated with recent star formation. We hypothesised that the northern filaments of Centaurus A are an example of inefficient jet-induced star formation. The jet likely enhances star formation by triggering the HI to H$^+$ transition (Salomé et al. 2016a,b), with a H$^+$-to-HI mass ratio larger than 3. However, this star formation is very inefficient, likely due to a strong injection of kinetic energy, as suggested by the relatively high virial parameter of the molecular clouds.

We now aim to study the jet-driven energy injection in the northern filaments and its relation with the star formation efficiency. In the present paper (Paper I), we investigate the physical conditions of gas (temperature, density), as well as the characteristics of shocks within the Horseshoe complex. To do so, we observed mid-J CO transitions ($J_{up}$ $=$ 3, 4), as well as high density tracers, in the brightest CO-spot from Salomé et al. (2016a). We compare these observations with radiative transfer predictions from the RADEX non-LTE radiative transfer code, in order to constrain the temperature and local density of the gas.

We then compare the observed ratios of the CO line integrated intensities with a small grid of the Paris-Durham shock model. We aim to show how the Paris-Durham model can be compared to extragalactic observations, in order to infer physi-
Sub-millimetre observations were made with the APEX telescope between July and December 2016. We focused on the Horseshoe complex, and more precisely on the region with the strongest $^{12}$CO(2-1) emission discovered by Salomé et al. (2016a) (so-called position 16; J2000 $\alpha$ =13:26:27.47, $\delta$ =-42:48:50.9). We looked for the $^{12}$CO(3-2), $^{13}$CO(4-3) and HCN/HCO$^+$ (3-2) lines in one pointing, centred on the centre of position 16. We finally used the remaining observation time to look for the [CI] $^{3}P_{1}-^{3}P_{0}$ line. The observations were made with the SHeFi/APEX-1, APEX-2, APEX-3 receivers and backends XFFTS (bandwidths of 2.5 GHz; resolution of 88.5 kHz). Observing conditions are summarised in Table 1.

The data were reduced using the IRAM package CLASS. After dropping bad spectra, a linear baseline was subtracted from the average spectrum, except for the $^{12}$CO(4-3) average spectrum for which we substracted a degree 4 polynomial in order to correct for baseline oscillations. For detections, the baseline was subtracted at velocities outside the range of the emission line. Each spectrum was smoothed to a spectral resolution of $\sim 3 - 12$ km.s$^{-1}$ (Table 1).

2.2. ALMA $^{12}$CO(1-0) short-spacings with ACA

In Salomé et al. (2017), we presented $^{12}$CO(1-0) observations with the Atacama Large Millimeter/submillimeter Array 12m array (ALMA). The data were taken during Cycle 3 using Band 3 receivers. We mapped a region of 6.1$^\prime\times 4.3^\prime$ with a mosaic of 34 pointings (integration time between 140 and 430s), at a resolution of 1.30$^\prime\prime$ $\times$ 0.99$^\prime\prime$ $\sim$ 23.8 $\times$ 18.1 pc (PA = 81.5$^\circ$).

The maximum recovered angular scale (MRS) by the 12m array was 14$^\prime$ $\sim$ 260 pc. To recover the short-spacings, we also observed the northern filaments with the Atacama Compact Array 7m array (ACA) using Band 3 receivers during Cycle 3 (project ADS/JAO.ALMA#2015.1.01019.S; PI: Salomé Q.). The map consists in a mosaic of 15 pointings, each with an integration time between 11.7 and 41 min, covering the same region as the ALMA observations. The baselines of the 7m array range from 8.85m to 48.95m that produces a synthesised beam of 13.68$^\prime\prime$ $\times$ 8.28$^\prime\prime$ $\sim$ 250.3 $\times$ 151.5 pc (PA = 90.5$^\circ$).

Both sets of data were calibrated using the Common Astronomy Software Applications (CASA) pipeline. We then combined the data in the uv plane within CASA$^2$. The imaging and cleaning was made using the tclean routine in CASA. The resolution is slightly smaller than that of the ALMA 12m data alone, with a synthesised beam of 1.40$^\prime\prime\times 1.10^\prime\prime$ $\sim$ 25.6$^\prime\times 20.1$ pc (PA = 82.9$^\circ$). Figure 2 shows the moment 0 map of the combined data. The histogram of the noise level peaks at 6.2 mJy/beam at a spectral resolution of 1.47 km.s$^{-1}$.

3. Results

3.1. APEX observations

$^{13}$CO(3-2) emission is well detected at $> 5\sigma$ with APEX and the spectrum reveals two velocity components around $\sim 230$ and $\sim 270$ km.s$^{-1}$, relative to Centaurus A, with widths of about 40 km.s$^{-1}$. Similarly, the $^{12}$CO(2-1) emission was re-reduced and decomposed in two velocity components (figure A.1). The redder component is stronger than the bluer one. We also detected $^{12}$CO(4-3) emission at $> 3\sigma$, but the presence of two velocity components is less clear. We integrated the intensities over two ranges of velocity: $-360 < v < -260$ km.s$^{-1}$ for the blue component and $-260 < v < -160$ km.s$^{-1}$ for the red component. We summarise the characteristics of the $^{12}$CO emission in Table 2.

| Line     | $v_{obs}$ (GHz) | FWHM | t$_{obs}$ (min) | $\sigma_v$ (km.s$^{-1}$) | rms (mK) |
|----------|----------------|------|-----------------|-------------------------|----------|
| CO(2-1)  | 230.1178       | 27.4'' $\times$ 500 pc | 17.8 | 3.2 | 5.6 |
| CO(3-2)  | 345.1657       | 18.2'' $\times$ 330 pc | 23.6 | 6.4 | 6.8 |
| CO(4-3)  | 460.2005       | 13.7'' $\times$ 250 pc | 62.0 | 6.4 | 9.2 |
| HCN(3-2) | 265.4018       | 23.7'' $\times$ 430 pc | 168.0 | $\sim$ 11.0 | 1.5 |
| HCO$^+$ (3-2) | 267.0699 | 23.7'' $\times$ 430 pc | 168.0 | $\sim$ 11.0 | 1.8 |
| [CI]     | 491.2637       | 12.8'' $\times$ 230 pc | 43.3 | 12.0 | 19.5 |

Table 1: Journal of observations with APEX, the $^{12}$CO(2-1) line comes from Salomé et al. (2016a). The rms were determined with both polarisations and are given in main beam temperature for the indicated spectral resolution.

1 http://www.apex-telescope.org/heterodyne/shif/

2 https://casaguides.nrao.edu/index.php/M100_Band3
In the following, the intensities used to derive the line ratios will always be expressed in \(K \cdot \text{km} \cdot \text{s}^{-1}\).

| Line         | \(\int T_{mb}dv\) (line) (K \cdot \text{km} \cdot \text{s}^{-1}) | \(\int T_{mb}dv\) (CO10) (K \cdot \text{km} \cdot \text{s}^{-1}) | \(R_{line}\) |
|--------------|-------------------------------------------------|-------------------------------------------------|------------|
| CO(2-1) blue | 3.18 ± 0.49                                      | 4.57 ± 0.69                                      | 0.70 ± 0.21|
| CO(2-1) red  | 4.43 ± 0.67                                      | 7.91 ± 1.19                                      | 0.56 ± 0.17|
| Total        | 7.61 ± 1.16                                      | 12.48 ± 1.88                                    | 0.61 ± 0.18|
| CO(3-2) blue | 1.36 ± 0.26                                      | 5.57 ± 0.84                                      | 0.24 ± 0.08|
| CO(3-2) red  | 2.29 ± 0.38                                      | 12.22 ± 1.83                                    | 0.19 ± 0.06|
| Total        | 3.65 ± 0.64                                      | 17.79 ± 2.67                                    | 0.21 ± 0.07|
| CO(4-3) blue | 0.51 ± 0.24                                      | 6.77 ± 1.02                                      | 0.08 ± 0.05|
| CO(4-3) red  | 1.68 ± 0.34                                      | 15.69 ± 2.35                                    | 0.11 ± 0.04|
| Total        | 2.19 ± 0.58                                      | 22.46 ± 3.37                                    | 0.10 ± 0.04|
| HCN(3-2) blue| < 0.24                                           | 4.84 ± 0.73                                      | < 0.05     |
| HCN(3-2) red | < 0.24                                           | 9.28 ± 1.39                                      | < 0.03     |
| Total        | < 0.48                                           | 14.12 ± 2.12                                    | < 0.03     |
| HCO\(^+\)(3-2) blue | < 0.29                                      | 4.84 ± 0.73                                      | < 0.06     |
| HCO\(^+\)(3-2) red  | < 0.29                                      | 9.28 ± 1.39                                      | < 0.03     |
| Total        | < 0.58                                           | 14.12 ± 2.12                                    | < 0.04     |
| [CI] blue    | < 3.10                                           | 7.07 ± 1.06                                      | < 0.44     |
| [CI] red     | < 3.10                                           | 16.50 ± 2.48                                    | < 0.19     |
| Total        | < 6.20                                           | 23.57 ± 3.54                                    | < 0.26     |

Table 2: Integrated intensity of the lines observed with APEX, and the \(^{12}\text{CO}(1-0)\) emission observed with ALMA+ACA, at the corresponding APEX resolution. The intensities were derived by adding all the channels in the velocity ranges \(-360 < v < -260 \text{ km} \cdot \text{s}^{-1}\) (blue) and \(-260 < v < -160 \text{ km} \cdot \text{s}^{-1}\) (red), relative to Centaurus A. For non detections, an upper limit at 3\(\sigma\) has been derived assuming a linewidth of 50 \text{ km} \cdot \text{s}^{-1}, that is the typical linewidth of the \(^{12}\text{CO}(1-0)\) line. The last column gives the ratio of the line with the \(^{12}\text{CO}(1-0)\).

Contrary to the CO lines, we did not detect the HCN and HCO\(^+\)(3-2) lines at the present noise level. The [CI] line was not detected either. However, this is due to the poor noise level we reached in the small amount of time we observed this line. For those three lines, we estimated upper limits at 3\(\sigma\), assuming a line width of 50 \text{ km} \cdot \text{s}^{-1}.

3.2. Line ratios

To study the excitation of molecular gas and its properties (temperature, density), we used the ratio between the different transitions. However, we cannot compare our APEX observations between themselves because of the different beam sizes (and since we only observed one position). It is therefore impossible to accurately estimate the line ratios with our APEX observations alone. To overcome this difficulty, we used our high-resolution \(^{12}\text{CO}(1-0)\) observations obtained with ALMA+ACA to determine the \(^{12}\text{CO}(1-0)\) emission contained in the different APEX beams (see figure 3).

We first recovered the signal using a coherent Gaussian decomposition method, based on the method of Miville-Deschênes et al. (2017). We then adapted the clustering method of Miville-Deschênes et al., which is based on a threshold descent applied to a cube of integrated flux. Due to the low signal-to-noise ratio, the signal is difficult to recover completely. Therefore, we first decreased the spatial resolution to 2.2\(\prime\). Once we extracted the signal from the data, we reconstructed a cube of the modelled \(^{12}\text{CO}(1-0)\) emission. We then applied the ALMA KJy conversion factor of 19.17 to obtain a cube of the main beam temperature. To get the \(^{12}\text{CO}(1-0)\) emission contained in the APEX beam, we smoothed the reconstructed \(^{12}\text{CO}(1-0)\) cube to the different APEX resolutions, and extracted the spectrum at the central position of the APEX observations. At every resolution, the \(^{12}\text{CO}(1-0)\) spectrum shows two distinct velocity components. As for the APEX observations, we integrated the spectra in the same velocity ranges to estimate the integrated intensity of both components (see Table 2). Figure A.1 enables a quick comparison of the profiles obtained with APEX and the \(^{12}\text{CO}(1-0)\) at the same resolution.
We were thus able to estimate the integrated intensity $I_{[K\cdot \text{km}\cdot \text{s}^{-1}]}$ line ratio of the different transitions observed with APEX compared to the $^{12}$CO(1-0) emission. The line ratios are reported in Table 2.

$$R_{\text{line}} = I_{\text{line}} / I_{^{12}\text{CO}(1-0)}$$ (1)

For the different CO lines, we estimated two intensity line ratios, one for each velocity component. For the blueshifted component, we found line ratios of about 0.7, 0.25 and 0.1 for the $^{12}$CO(2-1), $^{12}$CO(3-2) and $^{12}$CO(4-3), respectively. The red component presents lower line ratios of about 0.55, 0.2 and 0.1. Such difference in the line ratios is likely related to different excitation between the two velocity components. The typical CO(2-1)/CO(1-0) line ratio in the Milky Way and nearby galaxies spans between 0.6 to 1.0 with a typical value of 0.8 (Hasegawa 1997; Sakamoto et al. 1997; Oka et al. 1998; Leroy et al. 2009; Vlahakis et al. 2013). The observed CO(2-1)/CO(1-0) line ratio is consistent with those values. We also found CO(3-2)/CO(1-0) and CO(4-3)/CO(1-0) line ratios consistent with the ratios found in the Milky Way and M51 (Nieten et al. 1999; Kim et al. 2002; Carilli & Walter 2013; Vlahakis et al. 2013).

For the other lines, we used the $3\sigma$ upper limits to derive upper limits of the corresponding line ratios. For each line, we derived two upper limits, one for each velocity component. The line ratios of the dense gas tracers have upper limits of about $3 - 6\%$ when compared with the $^{12}$CO(1-0) emission. Such non-detection may be explained by the fact that the dense molecular gas is more compact and the emission is diluted by the beam. Another possible explanation is that very little HCN/HCO$^+$ (3-2) emission is produced in this region because of an insufficient gas density to excite these transitions ($n_{\text{crit}} \sim 10^6 - 10^7 \text{ cm}^{-3}$; see below).

Finally, the non-detection of the [CI] line is not a surprise. Indeed, we derived upper limits of the [CI]/CO(1-0) line ratio of $20 - 35\%$. This is higher than the typical [CI]/CO(1-0) line ratio of 20% found in galaxies at low- and high-redshift (Gerin & Phillips 2000; Weiss et al. 2005; Jiao et al. 2017). Therefore, deeper observations are clearly necessary for the atomic carbon detection.

4. Discussion

4.1. LVG modeling of the CO emission

We used the non-LTE radiative transfer code RADEX (van der Tak et al. 2007), based on the low-velocity gradient (LVG) approximation. We run a first grid of models with $T_{\text{kin}}$ between 10 and 100 K, $N_{^{12}\text{CO}}$ between $10^{15} - 10^{19} \text{ cm}^{-2}$ and $n_H$ in the range $10^3 - 10^7 \text{ cm}^{-3}$. We fixed a linewidth $\Delta V = 50 \text{ km} \cdot \text{s}^{-1}$, which gives $N_{^{12}\text{CO}}/\Delta V = 2 \times 10^{13} - 2 \times 10^{17} \text{ cm}^{-2}(\text{km} \cdot \text{s}^{-1})^{-1}$. Plotting the parameter space (figure B.1), we obtained a first constraint on the column and volume densities of gas. The CO column density is in between $10^{17} - 10^{18} \text{ cm}^{-2}$. Considering a CO abundance $N_{^{12}\text{CO}}/N_{\text{H}_2} \sim 10^{-4}$ and a standard $X_{^{12}\text{CO}} = N_{^{12}\text{CO}}/I_{^{12}\text{CO}} = 2 \times 10^{-20}$, this leads to a filling factor $f_f = N_{^{12}\text{CO}}/N_{\text{H}_2} / 0.1 = 0.15$.

We thus run another grid with kinetic temperatures between 25 and 70 K. CO column densities $N_{^{12}\text{CO}} = 10^{17}, 5 \times 10^{17}, 10^{18} \text{ cm}^{-2}$ and total volume densities $n_H = 2, 4, 6, 8, 10 \times 10^2 \text{ cm}^{-3}$. We then fitted the spectral line energy distribution (SLED), for both velocity component separately. We assume that the excitation of the different clouds is the same in this region. We consider a model as reliable if the predicted line ratios are within the error bars.

For the blueshifted component, the RADEX grid predicts that the volume densities and kinetic temperature are more likely in the ranges $2 - 6 \times 10^2 \text{ cm}^{-3}$ and $55 - 70 \text{ K}$. For the redshifted component, none of the models fits the data points. This seems to be due to an overestimated CO(4-3)/CO(1-0) intensity line ratio (see figure B.1). We enabled the predicted $^{12}$CO(4-3) line ratio to be smaller than the observed one, and we obtained the same predictions as for the blueshifted component. For a given $N_{^{12}\text{CO}}$, the higher the volume density, the lower the temperature. Moreover, it appears that, for a given temperature, the blueshifted component is denser than the redshifted one. Similarly, the blueshifted component tends to be warmer for a given density.
The present study is the best we can do with the current data. Nevertheless, we are aware of number of caveats that we discuss in the following. We know that the emission contained in the beam of APEX comes from a collection of molecular clouds. Therefore, RADEX only constrains the average density of these clouds. But it is very likely that the density range of the molecular clouds spans over a larger range when considered individually, and the density predicted by RADEX is affected by the filling factor. Moreover, the fraction of diffuse-to-dense gas within the APEX beam needs to be taken into account. Finally, as we have only one pointing for each transition and the beam size is not the same, we do not cover the same regions. It is thus possible that we introduce a bias in the line ratios. All these factors can explain why we found a degeneracy between (n, n, T). More observations are needed to lift this degeneracy, in particular high resolution observations with ALMA+ACA for several CO transitions. Indeed, only this will allow us to take only the regions emitting in the different lines into account (see Paper II for a preliminary study).

4.2. Paris-Durham shock code

We then attempted to interpret our observations by combining a radiative transfer treatment based on the LVG approximation with a shock model. The shock model is the Paris-Durham code (Flower & Pineau des Forêts 2015). It simulates the propagation of a one-dimensional shock wave through the interstellar medium and self-consistently calculates the physical, dynamical and chemical structure of a shocked layer. The radiative transfer code dealing with CO lines has been presented in Gusdorf et al. (2008), where it was used to perform comparisons with observations of shocked CO in protostellar outflows. The application of such a combination of models to observations was later systematized in the study of shocks in the W28F supernova remnant (Gusdorf et al. 2012). In such a Galactic environment, this method yields accurate constraints on physical parameters, and enables the subsequent characterization of shock energetics (momentum and energy injected by the shocks in interacting clouds).

Here, we attempted to compare the observed ratios of CO line integrated intensities with the results of a small grid of models. This kind of grid was first used in an extragalactic environment in Lee et al. (2016) in the N159W region of the Large Magellanic Cloud. It consists of an ensemble of stationary C-type and J-type shock models with pre-shock densities $n_H = 10^2, 5 \times 10^2, 5 \times 10^3, 10^3, 5 \times 10^3, 5 \times 10^4, 10^4$ cm$^{-3}$. The shock velocities ($v_s$) were varied between 4 and 20 km s$^{-1}$ for C-type models, and between 4 and 30 km s$^{-1}$ for J-type ones (by definition, the velocity of a C-type shock is limited by the magnetosonic velocity of the medium where it propagates). The external radiation field characterized by a scaling factor 'G0' was set equal to 0 or 1 with respect to the mean interstellar radiation field as described by Draine (1978). As a first step, our aim is to start placing constraints on these input parameters of the model thanks to the comparison with observations. After such an exploration and with more observations, we will fine-tune other input parameters. This will be the case of e.g. the magnetic field strength perpendicular to the shock propagation. In the current grid, this quantity was set as $B_L (\mu G) = [n_H (cm^{-3})]^{1/2}$.

We present our preliminary results in Figure 5. In this figure, we compare the observations of the total line integrated intensity ratios ("Total" lines in Table 2) with the results of models. We only present results obtained with C-type models with $n_H = 100$ (left panel) and 500 cm$^{-3}$ (right panel). The three coloured rectangles (blue, red and green) show the observational results: they respectively correspond to the area between the minimum and maximum $R_{line}$ values from Table 2 for the (2-1)/(1-0), (3-2)/(1-0), and (4-3)/(1-0) ratios. The model results are shown with symbols; circles and squares for $n_H = 100$ and 500 cm$^{-3}$, filled or empty for $G_0 = 0$ or 1. Each point corresponds to a set of $[n_H, G_0, v_s]$ values, with $v_s$ values indicated in the X-axis. The figure shows the principle, successes, and current shortcomings of our modelling. A significant part of our grid does not yield satisfying fits to the observed ratios, so that we only displayed the best-fitting ones. For instance, shock models with higher pre-shock densities yield too high ratios, and J-type models produce absolute integrated intensities that are too low compared with observed values (J-type shocks are not as wide as C-type ones, and generate too low CO column densities). Among the models that are displayed, the best ones are obtained for $n_H = 100$ cm$^{-3}$ and $G_0 = 0$. This result means that, on average, the total gas encompassed by the beam behaves like the gas processed by a shock with these characteristics. In reality, the beam likely encompasses multiple shock structures with various velocities, the higher ones being diluted within its large extent. On the other
Fig. 5: Results obtained with the Paris-Durham shock model. Each panel corresponds to a different pre-shock density: \( n_H = 100 \) (left) and \( 500 \) cm\(^{-3}\) (right). The three coloured rectangles (blue, red and green) show the observational results, respectively the \((2-1)/(1-0), (3-2)/(1-0),\) and \((4-3)/(1-0)\) ratios (from Table 2). Each point corresponds to a set of \( \{n_H, G_0, \text{and } 3\sigma\} \) values, with \( \sigma \) values indicated in the X-axis. The model results are shown with symbols: filled or empty for \( G_0 = 0 \) or 1, respectively.

hand, the shock velocity value is not well constrained. A first way to place a constraint on this parameter would be examine the velocity of individual clouds caught in the beam of our observations, and compare it to our results.

Another way to constrain the shock velocity could be to examine the ratios of the \( \text{H}_2 \) line integrated intensities, which are very sensitive to the shock velocity. We show the structure of the shock layer for one satisfying model with \( n_H = 100 \) cm\(^{-3}\), \( G_0 = 0 \) and a shock velocity of 10 km.s\(^{-1}\) in Figure 6, that shows the evolution of the neutral temperature versus the width of the shock. In the context of comparisons with 1D-models considered here, the shock propagates along the line of sight, from the pre- to the post-shock gas (the shock is seen face on). We also show the local emissivity of three \( \text{H}_2 \) lines, that can be observed at high angular resolution with ground-based facilities (like the 1-0 \( S(1) \) line at 2.12 \( \mu \)m), or in the near future with the James Webb Space Telescope (like the 0-0 \( S(1) \) and \( S(5) \) lines, at respectively 17.04 and 5.51 \( \mu \)m). Overall, if confirmed, our result is encouraging.

We aim at refining it in the future, based on a more complete coverage of input parameters exploration, and principally based on more observations.

4.3. Short-spacing filtering

Using RADEX and the Paris-Durham models, we determined that the local volume density of the molecular gas traced by the CO emission is of the order of 100 cm\(^{-3}\). This is a factor of about 2-3 higher than the average volume density derived geometrically in the Horseshoe complex by Salomé et al. (2017). The critical density of the CO is of the order of a few hundreds of cm\(^{-3}\). Such difference in the volume density is therefore likely due to an underestimation using geometrical arguments.

The filtering by the interferometer plays an important role in this underestimation. The combined ALMA and ACA \(^{12}\)CO(1-0) observations (Paper II) recover about 4.6 times the flux from ALMA only. The missing flux may result in a underestimation of the mass of the molecular clouds, and thus a lower volume density. Moreover, the majority of the molecular clouds extracted by Salomé et al. (2017) have a size of about twice the ALMA beam (1.3”x0.99”). The limited spatial resolution may partially dilute the clouds and increase the observed radius. Therefore, it is probable that part of the molecular clouds are smaller than they appear. For a given mass, the larger the cloud, the lower the density. It is now essential to conduct observations with an even higher resolution.

5. Conclusion

Following our previous studies where we mapped the \(^{12}\)CO(2-1) emission with APEX (Salomé et al. 2016a) and the
$^{12}$CO(1-0) emission with ALMA (Salomé et al. 2017) in the northern filaments of Centaurus A, we now used the Atacama Pathfinder EXperiment (APEX) to observe mid-J CO transitions in the Horseshoe complex discovered with ALMA. The $^{12}$CO(3-2) and $^{12}$CO(4-3) were detected for the first time in a region of radio jet-gas interaction, here between the radio jet and the HI shell. Each spectrum presents two velocity components centred at velocity of about $-230$ and $-270$ km s$^{-1}$, respectively. Over the rather large APEX beam at these frequencies, the higher-J transitions are not very excited on average with a SLED peaked around $\nu_{\text{up}} \sim 2 - 3$.

In this paper, we only focused on one region of the Horseshoe complex. Moreover, to get around the problem of the different spatial resolutions, we compared all the lines observed by APEX with the high resolution $^{12}$CO(1-0) map from ALMA+ACA and assumed that all the clouds contained in the beam of APEX have the same physical conditions.

We first used the non-LTE radiative transfer code RADEX to get an estimate of the physical conditions (temperature, density) of the molecular gas. A grid of models predicts a kinetic temperature of $55 - 70$ K and densities between $2 - 6 \times 10^3$ cm$^{-3}$. However, at a given kinetic temperature (resp. volume density), the blueshifted component is denser (resp. warmer) than the redshifted one.

In addition to the $^{12}$CO(3-2) and $^{12}$CO(4-3), we also looked for dense gas tracers (HCN/HCO$^+$) and one atomic carbon line [CI]. These lines were not detected, but the upper limits of the intensity line ratios with regards to $^{12}$CO(1-0) are consistent with the analysis of the CO lines, whereas they do not bring additional constrains on the physical conditions of the gas.

We also run a small grid of the Paris-Durham shock model. This grid tends to indicate the pre-shock density is of the order of $100$ cm$^{-3}$, corresponding to a post-shock density of a few 100cm$^{-3}$, in agreement with the RADEX-only comparisons. The model also predicts that the region observed with APEX would have experienced a low-velocity shock, whereas the shock velocity is not well constrained. The results we obtained are encouraging, but more observations (higher spatial resolution, additional lines and species/tracers) will be necessary in order to infer the characteristics of the region more accurately.

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Appendix A: APEX spectra

Fig. A.1: Spectra of the $^{12}\text{CO}(2-1)$, $^{12}\text{CO}(3-2)$ and $^{12}\text{CO}(4-3)$ emission observed with APEX (left), and the $^{12}\text{CO}(1-0)$ emission from ALMA convolved at APEX resolutions for lines shown in the left panel (right). For the APEX data, the spatial resolution is about 3.2 km.s$^{-1}$ for the CO(2-1) emission and 6.4 km.s$^{-1}$ for the CO(3-2) and CO(4-3) spectra. The resolution of the ALMA+ACA CO(1-0) spectra is about 4.4 km.s$^{-1}$. 
Fig. B.1: Radiative transfer predictions of the CO intensity line ratios as a function of the temperature and density. The blue, red and green lines show the predicted CO(2-1)/CO(1-0), CO(3-2)/CO(1-0) and CO(4-3)/CO(1-0), respectively. The dashed lines correspond to the error bars.

Appendix B: RADEX: parameter space