THE PROTOPLANETARY DISC OF HD 163296 AS OBSERVED BY ALMA

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Abstract:
HD 163296 is one of the few proto-planetary discs displaying rings in the dust component. The present work uses ALMA observations of the 0.9 mm continuum emission having significantly better spatial resolution (~8 au) than previously available, providing new insight on the morphology of the dust disc and its double ring structure. The disc is shown to be thin and its position angle and inclination with respect to the sky plane are accurately measured as are the locations and shapes that characterize the observed ring/gap structure. Significant modulation of the intensity of the outer ring emission have been revealed and discussed. In addition, earlier ALMA observations of the emission of three molecular lines, CO(2-1), C\(^{18}\)O(2-1), and DCO\(^{+}\)(3-2), having a resolution of ~70 au, are used to demonstrate the Keplerian motion of the gas, found consistent with a central mass of 2.3 solar masses. An upper limit of ~9% of the rotation velocity is placed on the in-fall velocity. The beam size is shown to give the dominant contribution to the line widths, accounting for both their absolute values and their dependence on the distance to the central star.

Keywords: planetary systems, protoplanetary disks, submillimeter.

1. Introduction

The study of ring-like structures observed in the dust emission of proto-planetary discs is expected to shed light on the mechanisms governing the formation of planets. Only two such discs were known before the discovery of the ring/gap structure of the HD 163296 disc [1]: TW Hya [2] and HL Tau [3]. Though still being debated, such ring/gap structure is thought to be associated with the presence of newly formed giant planets [4]. It is therefore important to identify effects that differentiate between planet formation and other gap opening mechanisms. There exist indeed other processes able to open gaps as, for example, aggregation of solids in low turbulence regions [5] and changes of dust opacity at the frost line of volatile elements [6, 7]. Keplerian shear resulting from the radial velocity gradient can cause turbulence and, therefore, at a certain distance from the star, formation of a gap similar to those carved by planets. A difference is that a planet will suck up all the material around it, gas and dust. But turbulence removes only the dust, not the gas.

HD 163296, the third system known to host multiple rings in dust emission at millimetre wavelength, is a Herbig Ae star of intermediate mass (2.3 solar masses). It is about 4 million years old and located at a distance of 122 pc from Earth [8]. The gas disc is in Keplerian motion with a radius of about 550 au and the millimetre continuum emission from solid particles is confined within 250 au from the star [9, 10].

Both gas and dust emissions from HD 163296 have been observed by ALMA. According to the analysis of Isella et al. [1], the 1.3 mm continuum emission observed with a spatial resolution of 25 au reveals three concentric gap/ring pairs, the dust depleted gaps being located at ~54, ~100, and 160 au from the central star. The gas morphology displayed by CO(2-1), \(^{13}\)CO(2-1) and C\(^{18}\)O(2-1) emissions shows no clear evidence for ring/gap modulation although small deviations from a smooth radial dependence have been observed with the same resolution of ~25 au and interpreted by Isella et al. [1] as a gas deficit.
restricted to the outer dust gaps but absent from the inner gap. They suggest that the outer gaps, at radial distances of 100 au and 160 au, are created by planets, probably about the mass of Saturn, but that the inner gap is due to gas turbulence or other physical phenomena within the disc. However, they do not exclude other possible interpretations. They evaluate the orbital radius and mass of the hypothetical planets from the location and shape of the dust gaps. The present study aims at providing additional information about this very interesting proto-planetary system.

2. Continuum emission

2.1 Observations
The continuum data used in the present study were collected on August 15th, 2017 and were reduced by the ALMA staff. The beam size is 0.069x0.061 arcsec$^2$ (FWHM) with position angle of $-88.8^\circ$, three times smaller than for earlier observations [1]. The data have been corrected for the proper motion of the source, (−7.61, −39.42) mas yr$^{-1}$, implying that the source has moved (−0.14, −0.70) arcsec to the south-west direction from its position in J2000. The continuum, observed at 330.588 GHz (~0.9 mm wavelength), displays a well behaved Gaussian noise having a standard deviation of 0.26 mJy beam$^{-1}$. In what follows, we apply a 3-$\sigma$ cut to the data unless explicitly mentioned otherwise.

Fig. 1. Left: Sky map of the continuum intensity. The white ellipse shows the region used to characterize the geometry of the disc (Section 2.2). The beam is shown in the lower left corner of the map. Middle and right: Projections on the $x$ and $y$ axes integrated over $y$ and $x$ respectively (in units of Jy beam$^{-1}$arcsec).

2.2 Sky plane morphology
Figure 1 (left) shows the map of the continuum intensity. The abscissa $x$ and ordinate $y$ measure offsets in arcsec from the central star, with $x$ pointing east and $y$ pointing north. The middle and right panels show the projections of the intensity on the $x$ and $y$ axes. The dust continuum emission is observed to display central symmetry and to extend up to $\sim$±1 arcsec on the sky plane.
Figure 2 displays the dependence on $\phi$ of the mean value of the projected distance to the central star, $<R>$, where $\phi=90^\circ-tan^{-1}(y/x)$ is the position angle measured counterclockwise from north and $R=\sqrt{x^2+y^2}$. $<R>$ is calculated using intensity as weight over the region contained inside the white ellipse shown in Figure 1 (left), defined as having semi-major axis of 0.44 arcsec, semi-minor axis of 0.31 arcsec and position angle of the major axis of 138$^\circ$. It is small enough to avoid contribution of the bright ring at larger distance from the star and large enough not to introduce any bias in the evaluation of the geometry parameters of the disc. A fit to an ellipse of the dependence of $<R>$ on $\phi$ gives position angle of the major axis $\phi_0$, semi-major axis $a$, and semi-minor axis $b$ of respectively 130$^\circ$, 0.23 arcsec and 0.16 arcsec. When interpreted as a thin and flat circular disc inclined by an angle $\theta$ with respect to the plane of the sky, $\theta=cos^{-1}(b/a)=44^\circ$. Isella et al. [1] quote values of 132$^\circ$ for $\phi_0$ and 42$^\circ$ for $\theta$, respectively 2$^\circ$ larger and 2$^\circ$ smaller than the present evaluations, meaning good agreement since systematic uncertainties are expected to be at that level.

### 2.3 De-projected morphology

Figure 3 (up-left) shows the de-projected intensity map in the disc plane. What is meant here by de-projection is a simple transformation from $(x,y)$ coordinates to $(x',y')$ coordinates defined as follows:

\[ x' = x \cos 40^\circ - y \sin 40^\circ \]
\[ y' = (x \sin 40^\circ + y \cos 40^\circ) / \cos 44^\circ \]

Such a transformation would be accurate if the disc were perfectly flat and thin. In the disc plane, we define position angle $\phi'$ and radial distance $r'$ from $x'$ and $y'$ in the same way as $\phi$ and $R$ were defined from $x$ and $y$: $\phi'=90^\circ-tan^{-1}(y'/x')$ and $r'=\sqrt{x'^2+y'^2}$.

Figure 3 (up-right) shows the dependence on $\phi'$ of the intensity averaged over $r'<1.31$ arcsec. It displays small fluctuations having a standard deviation of only 7% of the mean value (1.1 mJy beam$^{-1}$). Figure 3 (down-left) displays the dependence on $r'$ of the intensity averaged over $\phi'$. When compared with the results of Isella et al. [1], the improved resolution produces much deeper gaps between the rings but gives no evidence for a third gap at $r'\sim1.31$ arcsec. This is confirmed in Figure 4 where the 3-$\sigma$ cut has been lifted. Gaussian fits to the gaps and rings give values of the mean radius and standard deviation listed in Table 1, in excellent agreement with the mean radii quoted by Isella et al. [1] for the gaps, 0.44 arcsec and 0.81 arcsec respectively.
Table 1. Parameters defining the gap and ring structure of the dust disc.

| Inner ring | Outer ring | Inner gap | Outer gap |
|------------|------------|-----------|-----------|
| Mean       | rms        | Mean      | rms       |
| 0.65       | 0.07       | 0.98      | 0.05      |
|            |            | 0.44      | 0.11      |
|            |            | 0.82      | 0.13      |

De-projection (see text)

| Disc          | Outer gap (inner edge) | Outer gap (outer edge) |
|---------------|------------------------|------------------------|
| PA            | θ                      | r_0’                   | θ                      |
| 40°           | 44°                    | 0.75                   | 44°                    |
|               |                        | 0.92                   | 46°                    |

Fig. 3. Up-left: intensity map de-projected in the disc plane (x’, y’). Up-right: dependence on position angle φ’ measured in the disc plane of the intensity averaged over r’<1.31 arcsec; note the off-set scale of ordinate. Down-left: dependence on r’ measured in the disc plane of the intensity averaged over φ’; the black curves are Gaussian fits to the gaps. Down-middle, same as down-left for position angles φ’ less than 30° away from the minor axis (red) and less than 30° away from the major axis (blue). Down-right: dependence on φ’ of the radius of the inner (red) and outer (blue) edges of the outer gap. The curves are fits of the form r’=r_0’+kcos2(φ’−φ_0’).
Fig. 4. Continuum intensity without application of the 3-σ cut. Left: map on the sky plane. Right: dependence on \( r' \) (averaged on \( \phi' \)).

If the disc were thick, the edges of the gaps would be smeared along the \( y' \) axis but not along the \( x' \) axis, typically by a quantity at the scale of the disc thickness. Indeed the standard deviations of the gap Gaussians \( \sim 0.12 \) arcsec are upper limits to such smearing. To check on this we compare in Figure 3 (down-middle) the radial distribution of the de-projected intensity in two 60° wide wedges bracketing the minor and major axes, defined respectively as \( |\sin \phi'|>\sqrt{3}/2 \) and \( |\cos \phi'|>\sqrt{3}/2 \). The absence of significant difference for the inner gap shows that the thickness of the dust disc cannot significantly exceed 10 au at \( r'\sim80 \) au. However, the outer gap, while showing no significant \( \phi' \) dependence of the smearing of its edges, shows a clear dependence on \( \phi' \) of both gap width and position. This is further illustrated in Figure 3 (down-right) that displays the dependence on \( \phi' \) of the position of the edges of the outer gap; the outer edge displays significant deviation from a circle. A fit to an ellipse of the form \( r'=r'_{0}+k\cos(\phi'-\phi'_{0}) \) would suggest an inclination angle \( (\theta=44°-k/r'_{0}) \) of 46°, differing slightly from that of the disc plane; however, it might also be that the thin and flat disc assumption used to evaluate the inclination does not apply to the outer ring, in which case the deviation from a circle could be associated with a dependence on \( \phi' \) of the intensity, or more generally of the morphology of the outer ring. Indeed, the dependence on \( \phi' \) of the intensity, averaged over 0.44<\( r' <0.82 \) arcsec for the inner ring and over 0.82<\( r' <1.31 \) arcsec for the outer ring, illustrated in Figure 5, shows that while the inner disc displays small fluctuations, at the level of only \( \sim 3\% \), the outer ring displays much larger fluctuations, at the level of \( \sim 31\% \). It is therefore unjustified to interpret the fluctuations of the mean radius of the outer disc as resulting from a different inclination of its plane.
Fig. 5. Dependence on $\psi'$ of the average intensity measured in the inner ring ($0.44 < r' < 0.82$ arcsec, left panel) and in the outer ring ($0.82 < r' < 1.31$ arcsec, right panel). Note the different scales of ordinate.

3. Line emissions

3.1 Observations

To study the gas present in the HD 163296 disc, we use ALMA archival observations from project 2013.1.00366.S, made on June 4th, 2014. Their spatial resolution, ~0.7 arcsec (85 au), is the best currently available, the data used by Isella et al. [1], with a spatial resolution of 25 au, being inaccessible to the public. Three line emissions, CO(2-1), C$^{18}$O(2-1) and DCO$^+$ (3-2), were observed in Cycle 2 of ALMA operation with spectral resolution of 0.04 km s$^{-1}$. The data were reduced by the ALMA staff into data-cubes consisting of 300×300 pixels, each 0.1×0.1 arcsec$^2$, and 800 bins of velocity, each 0.04 km s$^{-1}$ wide. Table 2 below lists the main parameters of relevance. The noise distribution is well behaved in each of the three lines and in what follows we apply a 3-$\sigma$ cut to each data-cube element unless otherwise specified, as was done for the study of continuum emission.

Table 2. Information of relevance to the line emissions.

| Line       | CO(2-1)  | C$^{18}$O(2-1) | DCO$^+$ (3-2) |
|------------|----------|---------------|---------------|
| Beam Size (arcsec$^2$) | 0.69×0.53 | 0.70×0.55 | 0.70×0.57 |
| Beam Position Angle | −80.9° | −80.3° | −79.4° |
| Noise (σ, mJy beam$^{-1}$) | 5.6 | 3.6 | 3.0 |
| Right Ascension (J2000) | 17h 56m 21.2 s |
| Declination (J2000) | −21° 57′ 22″ |
| Systemic Velocity | 5.80 km s$^{-1}$ |
| Pixel Size | 0.1×0.1 arcsec$^2$ |
| Velocity Bin Size | 0.04 km s$^{-1}$ |
Fig. 6. From left to right: Integrated spectra of CO(2-1), C$^{18}$O(2-1), and DCO$^+$ (3-2) emissions integrated over the ellipses shown in Figure 7. The blue histograms display spectra obtained by mirror symmetry about the origin.

### 3.2 Main features

In what follows we normally limit the analysis to ellipses where the signal is well above noise; they have semi-major and minor axes $(a, b)=$(4.8, 3.8) arcsec, (3.5, 2.4) arcsec and (3.3, 2.4) arcsec for CO(2-1), C$^{18}$O(2-1), and DCO$^+$ (3-2) respectively, with a common position angle of 135°. Figure 6 displays the Doppler velocity spectra of CO(2-1), C$^{18}$O(2-1), and DCO$^+$ (3-2) emissions integrated over these ellipses. They are symmetric about the systemic velocity of 5.80 km s$^{-1}$ taken as origin. We limit the present analysis to Doppler velocities not exceeding 6 km s$^{-1}$ in absolute value.

Figure 7 displays sky maps of the integrated intensity and of the mean value and standard deviation of the Doppler velocity spectra. The mean Doppler velocity is seen to display a characteristic rotation pattern about the disc axis while the rms deviation from the mean is nearly isotropic. As was observed earlier by Isella et al. [1] the intensity maps show no sign of a ring/gap structure but their common orientation and aspect ratio are, at least qualitatively, the same as observed in continuum emission. Accordingly, in what follows, we use the same disc plane coordinates $(x', y')$ as was done in the study of continuum emission. However, as the gas disc is expected to be significantly thicker than the dust disc, the thin disc hypothesis is no longer valid and the transformation of coordinates from $(x, y)$ to $(x', y')$ should no longer be strictly identified with de-projection, the disc thickness possibly causing significant smearing along the $y'$ axis.

Repeating for the C$^{18}$O and DCO$^+$ lines the same geometry analysis as was done for the continuum, we obtain respectively semi-minor axes of 1.15 and 1.07 arcsec, semi-major axes of 1.64 and 1.46 arcsec, corresponding to respective inclinations with respect to the sky plane of 45° and 43° (see Figure 8) in excellent agreement with the continuum results. Similar results, but less accurate, are obtained for the optically thick CO(2-1) emission (39°).

The position angles $\phi_0$ are best measured from the maps of the mean Doppler velocity, which is expected to be anti-symmetric with respect to the axis. The position angle obtained by maximizing the anti-symmetry is 135° for each of the three lines, close to the continuum value of 130°.
Fig. 7. Sky maps of velocity integrated intensity (left), of $<V_z>$ (middle) and of Rms($V_z$) (right) for CO(2-1) (upper panels), C$^{18}$O(2-1) (central panels) and DCO$^+$ (3-2) (lower panels) emissions. Ellipses indicate the regions of the sky plane generally retained in the analysis.

3.3 Gas morphology

Figure 9 shows maps of the de-projected intensity in the central region (both $|x'|$ and $|y'|$ smaller than 2 arcsec) and their projections on the $x'$ and $y'$ axes. The similarity between the $x'$ and $y'$ projections illustrates the validity of their description in terms of inclined circular discs, with nearly identical values of $\phi_0$ and $\theta$. To a good approximation, they are both centred and symmetric with respect to the origin and emission extends up to distances from the central star of ~5.0 arcsec for CO(2-1), ~3.5 arcsec for C$^{18}$O(2-1) and ~3.0 arcsec for DCO$^+$ (3-2).
Fig. 8. Dependence on $\phi$ of $<R>$ for CO (left), C$^{18}$O (middle) and DCO$^+$ (right). Black curves are fits to ellipses (see text).

Fig. 9. De-projected intensity, from left to right: CO(2-1), C$^{18}$O(2-1) and DCO$^+$(3-2) emissions. Upper panels show the maps ($y'$ vs $x'$) and lower panels their projections (Jy beam$^{-1}$ km s$^{-1}$) on the $x'$ (red) and $y'$ (blue) axes.

Figure 10 (left) shows the dependence of intensity on $r'$, averaged over $\phi'$. It displays decrement factors evaluated in the interval 1<$r'$<2 arcsec of $\sim$1.9 arcsec$^{-1}$ for CO(2-1), $\sim$2.3 arcsec$^{-1}$ for C$^{18}$O(2-1) and $\sim$2.7 arcsec$^{-1}$ for DCO$^+$(3-2) emissions, the latter dropping to small values near the star. As remarked by Isella et al. [1], who observe a similar drop, the DCO$^+$(3-2) and continuum intensities are similar at small distances from the star: an excessive continuum subtraction would wrongly cause a significant decrease of the line emission. However, the effect is too important to be an artefact of continuum subtraction. While both continuum subtraction and beam convolution contribute important uncertainties to the detailed morphology of the observed depression, its reality makes no doubt. Figure 10
(right) displays the dependence on $\phi'$ of the intensity averaged over $0.5<r'<2.0$ arcsec, corresponding to the dust rings. Significant modulations are observed, similar for the three lines, and reminiscent of what was observed for the outer dust ring (Figure 5 right). We underline that these modulations are unrelated to the disc inclination (we are dealing here with average intensity and not with average radius) but associated with real intensity modulations in the disc plane.

The maps of the mean Doppler velocity in the disc plane are shown in Figure 11. Contrary to the intensity, the Doppler velocity shows remarkably similar behaviour for each of the three lines (see next section).

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig10.png}
\caption{Dependence of the intensity on $r'$ (left) and $\phi'$ (right, averaged over $0.5<r'<2$ arcsec). Red is for CO(2-1), blue for C$^{18}$O(2-1), and magenta for DCO$^+$(3-2).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig11.png}
\caption{Disc plane maps of $<V_z>$ for CO(2-1) (left), C$^{18}$O(2-1) (middle) and DCO$^+$(3-2) (right). Ellipses surround the regions where data are retained for the analysis.}
\end{figure}

Finally, to reveal the finer structure of the gas morphology, we display in Figure 12 the difference between the measured intensity and its mean value at the corresponding disc radius, averaged over position angle. Fluctuations are observed at the $\sim10\%$ level. As CO(2-1) emission is optically thick and the two other lines optically thin, these fluctuations probe the disc at different depths and indeed display different structures: a north-south bipolar asymmetry for CO emission corresponding to the disc surface and a north-south/east-west quadripolar asymmetry for C$^{18}$O(2-1) and DCO$^+$(3-2) probing the whole disc thickness.
3.4 Gas kinematics

As remarked in the preceding section, the three line emissions display nearly identical kinematics. This is illustrated in Figure 13 that displays the distributions of the difference between the mean Doppler velocity measured in a given pixel for CO(2-1) and that measured in the same pixel for C$^{18}$O(2-1) (left) or DCO$^+$ (3-2) (right). The mean values are respectively 0.01 and 0.03 km s$^{-1}$ and the standard deviations 0.30 and 0.37 km s$^{-1}$.

In each data-cube element, the Doppler velocity can be expressed as a function of rotation velocity, $V_{rot}$, and in-fall velocity, $V_{fall}$, as follows (Figure 14):

$$V_z = \sin(\theta) V_{rot} \sin(\phi' - \phi'_0) = V_0 \sin(\phi' - \phi'_0)$$

with $V_{rot} = V_0 \cos(\phi'_0)$ and $V_{fall} = V_0 \sin(\phi'_0)$ namely $V_0 = (V_{rot}^2 + V_{fall}^2)^{1/2}$ and $\phi'_0 = \tan^{-1}(V_{fall}/V_{rot})$.

Figure 15 shows the dependence of $<V_z>$ on $\phi'$ averaged over five different intervals of $r'$, for each of the three lines separately. A fit of the form $<V_z> = V_0 \sin(\theta) \sin(\phi' - \phi'_0)$ is made to the CO(2-1) data in each interval of $r'$ separately. The small values obtained for $\phi'_0$ show the dominance of rotation over in-fall. We estimate that the measured distributions can accommodate a maximal phase-shift of $\sim 5^\circ$ with respect to pure rotation, implying an upper limit of $\sim 9\%$ on the ratio between in-fall and rotation velocities. The results are summarized in Table 3.

In the limit of a thin and flat disc and neglecting a possible in-fall velocity, the rotation velocity can be calculated in each data-cube element as $V_{rot} = V_z (\sin(\theta) \sin(\phi'))^{-1}$ as long as $\sin(\phi')$ is not too small (in practice we require $|\sin(\phi')| > \sin(15^\circ)$). Figure 16 (left) shows the dependence on $r'$ of $V_{rot}$ calculated in this manner. Fits of the form $V_{rot} = V_0 r'^{-n}$ give the results listed in Table 3, providing evidence for approximate Keplerian motion. Clearer evidence is displayed in Figure 16 (right), showing the dependence on $r'$ of the Kepler factor, $V_{rot}^{0.5}$, which is constant for Keplerian rotation. It is indeed observed to be constant down to $r' \sim 0.8$ arcsec with a value of $\sim 4$ km s$^{-1}$ arcsec$^{1/2}$ in good agreement with the expectation of 3.9 km s$^{-1}$ arcsec$^{1/2}$ corresponding to a central mass of 2.3 solar masses.
Fig. 13. Distribution of the differences $<V_z^{\text{CO}}>-<V_z^{\text{CISO}}>$ (left) and $<V_z^{\text{CO}}>-<V_z^{\text{DCO}+}>$ (right) measured in a same pixel. Each pixel contribution is weighted by the geometrical mean $(I_1 I_2)^{1/2}$ of the velocity integrated intensities $I_1$ and $I_2$ measured in the pixel for each of the two lines. The black curves show Gaussian fits to the peaks with $\sigma$’s of 0.16 and 0.18 km s$^{-1}$ and mean values of 0.004 and 0.010 km s$^{-1}$ respectively.

![Graph showing distribution of differences](image)

Fig. 14. Velocity and trajectory of gas molecules in the disc plane.

Table 3. Parameters describing the gas kinematics.

| $r'$ interval | CO(2-1) | C$^{18}$O(2-1) | DCO$^+$(3-2) |
|---------------|---------|----------------|--------------|
|               | $<0.5''$ | 0.5”-1.0”      | 1.0”-1.5”    |
| $V_0$(km s$^{-1}$) | 3.2     | 4.3            | 3.6          | 3.0          | 0.9          |
| $\phi_0$      | 1.3°    | -0.5°          | -2.4°        | -2.5°        | -2.9°        |
| $r'$ interval | 0.8”-3.5” | 0.8”-3.5”      | 0.8”-3.0”    |
| $V_0^*$       | 4.1     | 4.4            | 4.2          |
| $n$           | 0.46    | 0.49           | 0.40         |
1. $0 < r' < 0.5$ (arcsec) 

2. $0.5 < r' < 1.0$ (arcsec) 

3. $1.0 < r' < 1.5$ (arcsec) 

4. $0 < r' < 0.5$ (arcsec) 

5. $0.5 < r' < 1.0$ (arcsec) 

Fig. 15. Dependence on $\omega=90^\circ-\phi'$ of $<V_Z>$ for five intervals of $r'$ (see Table 3). The black curves are fits of the form $V_0\sin\theta\sin(\phi'-\phi'_0)$ to the CO(2-1) distributions. Red is for CO(2-1), blue for C$^{18}$O(2-1) and magenta for DCO$^+$(3-2).

3.5 Line widths

Figure 17 (left) shows the distributions of the difference between the Doppler velocity and its mean calculated in the same pixel, $\Delta V_z=V_Z-<V_Z>$, for each line separately (we recall that we require $|V_z|$ not to exceed 6 km s$^{-1}$). Gaussian fits to the central peaks (black curves) give standard deviations of 0.39, 0.32, and 0.31 km s$^{-1}$ for CO(2-1), C$^{18}$O(2-1), and DCO$^+$(3-2) respectively. The dependence on $r'$ and $\phi'$ of $Rms(V_z)$ (averaged over $\phi'$ and $r'$ respectively) is shown in Figures 17 (right) and 18, the latter separately in the five intervals of $r'$. They display similar shapes for each of the three lines but different amplitudes, significantly larger for CO than for the two other emissions. Apart from beam convolution effects, the velocity dispersion is a combination of: 1) instrumental resolution; 2) the range of velocities covered in each pixel because of disc thickness, disc inclination and Keplerian shear; 3) thermal broadening, having a standard deviation $\sigma_v=(2kT/\mu)^{1/2}$ where $k$ is Boltzmann constant, $T$ the gas temperature and $\mu=28m_H$, 30$m_H$, and 30$m_H$ for CO, C$^{18}$O and
DCO⁺ respectively; and 4) turbulence. All of these are expected to be significantly smaller than measured, never exceeding 0.1 km s⁻¹ for r'>1 arcsec. However, beam convolution, with FWHM values nearing 0.7 arcsec, seven times larger than the pixel size, is expected to dominate the line width. To evaluate its effect, we assume that the disc is thin and flat, that the orbits are circular and that other contributions to the line width can be neglected. Moreover, we assume pure Keplerian motion with \( V_{\text{rot}} r'/\sqrt{2} = 3.9 \) km s⁻¹ arcsec⁻¹, we use the \( r' \) dependence of the intensity displayed in Figure 10 (left) and we neglect its dependence on \( \phi' \). A same 3-σ cut is applied to the model as to the data.

Fig. 17. Left: distribution of \( V_Z - <V_Z> \) in each pixel and for each line separately. Right: dependence on \( r' \) of Rms(VZ). Red is for CO(2-1), blue for C¹⁸O(2-1) and magenta for DCO⁺(3-2).

Fig. 18. Dependence on \( \omega = 90^\circ - \phi' \) of Rms(VZ). Red is for CO(2-1), blue for C¹⁸O(2-1) and magenta for DCO⁺(3-2).
Fig. 19. From left to right: radial dependence of the Kepler factor $V_{\text{rot}} r^{0.5}$ as observed (red) and predicted by the model (blue) for CO(2-1), C$^{18}$O(2-1), and DCO$^+$ (3-2) respectively.

Fig. 20. Radial dependence of $\text{Rms}(V_Z)$ as observed (left) and predicted by the model (right). Red is for CO(2-1), blue for C$^{18}$O(2-1) and magenta for DCO$^+$ (3-2).

Fig. 21. Dependence of $\langle V_z \rangle$ (km s$^{-1}$) on $\omega = 90^\circ - \phi'$ for six intervals of $r'$, 0.5 arcsec wide and covering between 0 and 3 arcsec. Red is for the observations and blue for the model.
The results are compared with observations in Figures 19, 20 and 21. The agreement is excellent in view of the simplicity of the model. The apparent departure from Keplerian motion observed at distances from the star smaller than 0.8 arcsec is found to be essentially due to beam convolution. The line width is reasonably well reproduced by the model down to \( r' \approx 0.5 \) arcsec, where temperature and turbulence effects are probably becoming important. Above this distance, other effects than beam convolution do not significantly contribute to the line width.

4. Summary and conclusions

Using ALMA observations of continuum emission at 0.9 mm wavelength and of molecular line emissions from CO(2-1), C\(^{18}\)O(2-1) and DCO\(^+\)(3-2), the morphology of the dust and gas disc of HD 163296 has been explored; the position and inclination with respect to the sky plane have been accurately measured and found identical for gas and dust. The ring/gap structure of the dust disc has been characterized with better precision than previously achieved [1] and no evidence has been found for a third gap at a distance of \( \approx 1.31 \) arcsec from the star as claimed by Isella et al. [1]. The outer gap and ring have been shown to display a significant modulation of their morphology and intensity. The disc thickness at \( \approx 80 \) au has been shown to be smaller than 10 au.

Small intensity fluctuations of the three line emissions that have been observed, CO(2-1), C\(^{18}\)O(2-1) and DCO\(^+\)(3-2), have been revealed and precisely located and measured; they explore different regions across the disc thickness and display clearly different structures. In particular, in the region of the dust rings, modulations of the intensity reminiscent of those displayed by the outer dust disc have been observed.

The three line emissions display remarkably identical kinematics dominated by Keplerian rotation. An upper limit of 9\% of the rotation velocity has been placed on a possible in-fall velocity. A Keplerian factor of 4.0 km s\(^{-1}\) arcsec\(^{1/2}\) has been measured consistent with the expectation of 3.9 km s\(^{-1}\) arcsec\(^{1/2}\) corresponding to a central mass of 2.3 solar masses. Apparent departure from Keplerian motion at distances from the star smaller than \( \approx 0.8 \) arcsec has been shown to be essentially due to beam size (\( \approx 0.7 \) arcsec FWHM). The observed line widths have been shown to be dominated by beam size effects over most of the radial range. A simple model accounting for the effect of beam convolution has been shown to very well reproduce the observations.

Recently, several new proto-planetary discs displaying a ring and gap structure have been discovered and imaged with high resolution by ALMA (for a review, see Reference 11). The complexity of their morphology, including spirals and clumps in addition to the rings has come as a surprise. This has triggered a surge of studies aiming at giving an interpretation of the gap forming mechanism, usually in terms of planet formation (see for example Reference 12). The present work has shown that the case of HD 163296 is particularly well suited to give important contributions to this domain of stellar physics. The present data, giving evidence for strong radial depletion of the dust disc, while no significant counterpart is observed in the gas disc, do not strongly support the presence of planets in formation. However, higher resolution observations of the molecular line emissions should shed better light on this issue.
ACKNOWLEDGEMENTS

We thank Nguyen Xuan Que for contributions to this work in its earlier phase and Pr. P. Darriulat for guidance and advice. This paper makes use of data from the following ALMA projects: ADS/JAO.ALMA#2013.1.00601.S and ADS/JAO.ALMA#2013.1.00366.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. We thank the ALMA staff for the reduction of the data and for help with understanding the origin of a spurious emission in the CO(2-1) data at Doppler velocities well above the line emission. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France, and of the NASA ADS Abstract Services. This research is funded by the Vietnam National Foundation for Science and Technology Development (NAFOSTED) (No. 103.99–2016.50). We acknowledge support from the World Laboratory, Rencontres du Viet Nam, the Odon Vallet fellowships, the Vietnam National Space Center, the Graduate University of Science and Technology and the Vietnam Academy of Science and Technology.

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