A Ringed Pole-on Outflow from DO Tauri Revealed by ALMA

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Received 2019 January 29; revised 2020 February 20; accepted 2020 February 24; published 2020 March 23

Abstract

We present new Atacama Large Millimeter/submillimeter Array (ALMA) Band 6 observations including the CO(2–1) line and 1.3 mm continuum emission from the surroundings of the young stellar object DO Tauri. The ALMA CO molecular data show three different series of rings at different radial velocities. These rings have radii around 220 and 800 au. We make individual fits to the rings and note that their centers are aligned with DO Tauri and its optical high-velocity jet. In addition, we notice that the velocity of these structures increases with the separation from the young star. We discuss the data under the hypothesis that the rings represent velocity cuts through three outflowing shells that are possibly driven by a wide-angle wind, dragging the environment material along a direction close to the line of sight (i = 19°). We estimate the dynamical ages, the mass, the momentum, and the energy of each individual outflow shell and those of the whole outflow. The results are in agreement with those found in outflows from Class II sources. We make a rough estimate for the size of the jet/wind launching region, which needs to be of \(\lesssim 15\) au. We report the physical characteristics of DO Tauri’s disk continuum emission (almost face-on and with a projected major axis in the north–south direction) and its velocity gradient orientation (north–south), indicative of disk rotation for a 1–2 \(M_\odot\) central star. Finally, we show a Hubble Space Telescope [S II] image of the optical jet and report a measurement of its orientation in the plane of the sky.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Protoplanetary disks (1300); Stellar jets (1607); Young stellar objects (1834)

1. Introduction

In the heart of the Taurus molecular cloud lies the young stellar object DO Tauri, located at 139.4° \(\pm\) 0.2° pc from Earth (as measured by the Gaia DR2 catalog Gaia Collaboration et al. 2018). It has a spectral type M0.3 with an effective temperature of 3830 K and a stellar luminosity of \(0.2–1.2 L_\odot\) (Kenyon & Hartmann 1995; Herczeg & Hillenbrand 2014). From these properties and the assumed theoretical evolutionary tracks, the stellar mass is estimated as \(0.5–0.7 M_\odot\) and its age as \((0.8–9) \times 10^7\) yr (Kitamura et al. 2002; Pallà & Stahler 2002; Herczeg & Hillenbrand 2014). DO Tauri is one of the T Tauri stars with highest accretion and wind ejection rates (Kenyon et al. 1995; Gullbring et al. 1998; Alonso-Martínez et al. 2017), with estimates ranging two orders of magnitude around an average value of \(\dot{M}_{\text{acc}} = 10^{-7} M_\odot\) yr\(^{-1}\) for the accretion rate and 1% of that value for the wind ejection rate. These large values indicate that this source is among the most active accreting class II stars in Taurus. DO Tauri is surrounded by a dusty disk discovered by Beckwith et al. (1990) using IRAM 30 m observations at 1.3 mm. Koerner et al. (1995) detected it at a range of centimeter and millimeter wavelengths using Owens Valley Radio Observatory and Very Large Array observations. The dusty disk has not been clearly resolved until this year, and its size, inclination, and position angle (PA) were uncertain for a long time (Koerner et al. 1995; Kitamura et al. 2002; Kwon et al. 2015; Tripathi et al. 2017). Recently, Long et al. (2019) resolved the dusty disk (with a 95% radius of 0°25), reporting a low inclination of 28° \(\pm\) 0°3 and a PA of 170° \(\pm\) 1°. Its mass has been estimated to be in the range 0.004–0.014 \(M_\odot\) (Kitamura et al. 2002; Andrews & Williams 2005; Kwon et al. 2015). Koerner & Sargent (1995) observed an asymmetric CO(2–1) profile toward the disk position showing high-velocity blueshifted emission that did not match the disk rotation expectations. They concluded that the CO was not only tracing the disk but possibly part of an outflow. The morphology of the CO emission did not exactly match the expectations for the emission of an outflow either, suggesting the possibility of circumstellar infalling motions. The disk is polarized at near-IR (NIR) wavelengths, showing a scattering PA of \(170^\circ–180^\circ\) (Bastien 1982, 1985; Tamura & Sato 1989), or a more recent value of \(166^\circ ± 1^\circ\) inside a 6° region (Pereyra et al. 2009). At high-angular resolution, both an H-band Subaru coronagraphic and optical Space Telescope Imaging Spectrograph Hubble images, reveal an asymmetric arc-like structure about 2″–3″ north of the star, running from PA = 45° to PA = 320° and the presence of a faint (but doubtful) companion at \(\sim 3.5''\) (Itoh et al. 2008). The interpretation of the former arc structure is complicated, although it could be related to the high-velocity bipolar jet driven by DO Tauri, found through the study of the [S II] forbidden line spectra (Hirth et al. 1994). The optical jet (associated with the object HH 230) reaches larger velocities in the redshifted part of the spectra (+220 km s\(^{-1}\) against −90 km s\(^{-1}\)) and has a total size of about 8° (although its optical image has never been published). The PA of its blueshifted lobe is \(250^\circ ± 10^\circ\) (Hirth et al. 1997), roughly perpendicular to the NIR polarized scattered emission from the dust.

At larger scales (thousands of au), DO Tauri is associated with an optical arc-like reflection nebula extending northwest. At about 91° east of DO Tauri is located another classical T-Tauri star: the triple system HV Tauri. Both young stars are connected by a bridge structure preferentially seen through Herschel observations at 100 and 160 \(\mu m\) (Howard et al. 2013). This bridge (or common envelope) has been recently
proposed as the imprint of a tidal tail structure produced by the disintegration of a putative multiple system formed by DO Tauri and the current HV Tauri triple system, about 0.1 Myr ago (Winter et al. 2018).

In this work, we analyze new Atacama Large (sub)Millimeter Array (ALMA) archive observations toward DO Tauri at 1.3 mm and focus mainly on the analysis of the large-scale molecular emission from the pole-on outflow associated with this young star. In Section 2, we describe the observations and explain the calibration procedure. Section 3 presents the results obtained from the continuum and CO emission associated with the disk, the optical jet observed by the Hubble Space Telescope (HST), and the extended CO(2−1) emission associated with the outflow. We discuss our findings in Section 4 and present an outline with the main ideas extracted from this work in Section 5. We also include a table summarizing our fit to the outflow emission in the 2.1.

2. Observations

2.1. ALMA observations

We present ALMA Cycle 4 archive observations (Project 2016.1.01042.S; P.I. Claire Chandler) toward the surroundings of the young stellar object DO Tauri. During the observations carried out on 2016 November 28, 47 antennas (with baselines from 16 to 626 m) were on duty and the weather was good (average precipitable water vapor column 2.05 mm and average system temperature ~120 K) to operate at Band 6. The array was pointed at NGC 2264 = 04:38:28.600, and α122000.0 = 26°10′49″20, and the primary beam of the 12 m antennas corresponds to about 26″ at the observing frequency. Time on source was 1.22 minutes.

The correlator setup included eight spectral windows comprising about 6800 MHz, which we used to generate a continuum image after removing the emission from the line channels (mainly from the bright CO(2−1) transition). The spectral windows were centered at 232.366 GHz (spw0), 216.994 GHz (spw1), 231.193 GHz (spw2), 230.703 GHz (spw3), 218.878 GHz (spw4), 219.256 GHz (spw5), 219.725 GHz (spw6), and 220.194 GHz (spw7). For our study, we are particularly interested in spectral window 3, which contains the CO(2−1) emission at a spectral resolution of 0.488 MHz (about 0.63 km s^{-1} at 230.538 GHz).

The ALMA data were calibrated using the data reduction scripts provided by ALMA for the Common Astronomy Software Applications (CASA) package (McMullin et al. 2007), which we use in its version 4.7.0. The atmospheric phase noise was reduced using radiometer measurements. The quasar J0510 + 1800 was used as bandpass and absolute flux calibrator, assuming a model with a flux density of 2.139 Jy at 232.366 GHz and a millimeter spectral index of −0.393,5 produced by the ALMA monitoring of quasars. Typically, the uncertainty in the ALMA flux measurements is estimated to be of the order of ~10% for Band 6. The quasar J0438 + 3004 was used to track and correct the phase variations.

After the standard calibration, the continuum data was imaged using CASA version 5.4.0. We set the robust parameter to 0.5 and obtained a synthesized beam of 0.71 × 0.47 (PA = 149°). We made three iterations of self-calibration, reducing the final rms of the image by 60% (from 0.2 to 0.07 mJy beam^{-1}) and improving the signal-to-noise ratio from 80 to 350. The final solutions found during the continuum self-calibration stage were applied to the CO(2−1) spectral window and a velocity cube was constructed using robust = 0.5. This yielded an image with a synthesized beam of 0.78 × 0.53 (PA = 145°) at the native velocity resolution of 0.63 km s^{-1}. The rms of the velocity cube in one channel is about 13 mJy beam^{-1} (0.72 K).

To better spatially resolve DO Tauri’s dusty disk, we construct the final continuum image using a second day of observations within the same ALMA project 2016.1.01042.S, taken on 2017 August 2 with the array in a more extended configuration (with baselines from 32 to 2620 m). These data have higher-angular resolution and, therefore, are not as sensitive as the former observations in tracing the molecular extended emission. In the second track, ALMA had 46 available antennas, and the weather conditions were better, yielding a median system temperature of about 70 K. The correlator setup and the pointing were similar to the first track of observations. J0510+1800 was used as the bandpass calibrator and J0423-0120 as the flux calibrator (assuming it has 0.835 Jy at 223.670 GHz and a millimeter spectral index −0.437, values extracted from the ALMA monitoring of quasars). The phase was corrected using intertwined observations of J0426+2327. The time spent on DO Tauri was 3.7 minutes, and after three rounds of self-calibration, we end up with a signal-to-noise ratio enhancement rising from 85 to more than 400. The synthesized beam of the resulting image is 0.017 × 0.012 (PA = 16°) when using robust 0.5, and the final rms noise level is 0.06 mJy beam^{-1} (or 0.067 K, see Figure 1).

In the following, we use the high-angular resolution data set for imaging and analyzing the continuum emission due to its finest resolution. For imaging and analyzing the molecular gas emission, we prepared a data set combining both configurations, which yields a synthesized beam of 0.021 × 0.016 (PA = 7°) and an rms noise level of 4.6 mJy beam^{-1} (3.1 K) as measured in the empty channels of the velocity cube.

2.2. HST Archive Observations

To further investigate the optical jet of DO Tauri, we downloaded the available images of this source in the HST Legacy Archive (P.I. C. Dougados; HST proposal ID8215, New clues to the ejection process in young stars: Forbidden line imaging of TTauri microjets). The data comprises forbidden line observations, in particular, and we took two images. The first one was obtained in a deep (about 2 hr) integration using a narrowband filter (47 Å bandwidth) centered at 6732 Å (the emission of the [S II] 6717 and 6731 Å lines, characteristic of optical jets, are then included in the imaged wavelength range). The other image was taken with a filter of 483 Å bandwidth centered at 5483 Å, which does not include the characteristic emission lines, and is, thus, useful for mapping the continuum emission. Figure 2 present these HST data from which we could measure the PA of the optical jet.

3. Results

3.1. The Disk around the Young Star DO Tauri

The main focus of this paper is on the study of the large-scale molecular gas emission near DO Tauri, but we also report the characteristics of the disk dust emission, spatially resolved here, and its associated CO(2−1) emission (see also the recently reported ALMA results by Long et al. 2019, analogous to these simultaneously derived here). The disk is detected at 1.3 mm

5 Here, we define the spectral index α as S_ν ∝ ν^α, where S_ν is the flux density and ν the observed frequency.
continuum (Figure 1) with an intensity peak of 24.55 ± 0.06 mJy beam⁻¹ and a flux density of 116.8 ± 0.1 mJy, consistent with the 125.4 ± 3.5 mJy reported by Kwon et al. (2015) at a similar frequency. These authors derived a disk mass of 0.014 ± 0.001 M☉ by using a sophisticated disk modeling. We have fit DO Tauri’s disk emission in the u-plane after using a 2D-Gaussian model implemented in the task uvmodelfit in CASA. The disk is centered at (α, δ)2000 = (04h38m28s,5935, 26° 10′ 49″ 272) with a positional uncertainty of 0′′001. The estimated major and minor axes of the disk are 0′′3447 ± 0′′0004 × 0′′3251 ± 0′′0005 (these are statistical uncertainties). Note that this is roughly a circular disk, with a 47 au radius and the uncertainty of its PA and inclination may be larger than that provided by the statistical procedure. Therefore, we estimate the uncertainty of the disk PA and inclination as the difference with the same quantities derived by Long et al. (2019). For a circular disk, this fit implies an inclination of 19° ± 9° with respect to the plane of the sky. Plus, its derived PA is 150° ± 20°, not exactly perpendicular to the optical jet axis (with PA = 260° ± 1°, see Section 3.2), for it is deviated by about 20° from this configuration. Let us note here that an independent 2D-Gaussian fit to the continuum emission in the image plane, gives a similar result but with a different PA of 175° ± 6°. Taking this latter result and considering the uncertainties, the orientation of the disk is consistent with being perpendicular to the jet direction.

The CO(2–1) molecular image of Figure 1 (left panel) shows the emission integrated in the velocity ranges [5.0, 0.6] km s⁻¹ (blueshifted) and [12.7, 6.9] km s⁻¹ (redshifted) emission. A north–south velocity gradient is evident at the disk position. We measured the PA of the blue- redshifted velocity gradient in the disk. The PA between the blue- and redshifted peaks of the CO(2–1) emission (which are apart 0″22, i.e., the size of one beam approximately) is 1° ± 4°. This PA does not coincide with the disk PA derived from the Gaussian fit to the continuum emission implemented in the u-v-plane. We note that our PA measurement using the CO emission could be affected by contaminating extended emission most present at blue-shifted velocities. In any case, this PA is not exactly perpendicular to the jet axis. If real, the PA discrepancies could be the result of a tilt or warp in the disk but only through more sensitive and higher-angular-resolution observations can the PA be more accurately measured. Figure 1 (right panel) shows a position–velocity diagram along the velocity gradient of the DO Tauri’s CO disk. The molecular emission is separated in two parts by a cloud absorption feature centered at 5.7 km s⁻¹. Close to the central star (zero offset), the emission is at larger absolute velocities, which steeply decreases with the distance to the star. This is suggestive of a Keplerian rotation pattern with a velocity gradient of about 3–4 km s⁻¹ between the red- and blueshifted emission at a fiducial radius of about 0″3 (about 40 au). The presence of extended emission and the spectral resolution of the current data hampers a more accurate measurement of this gradient, which we very roughly estimate to imply a dynamical mass ranging 1.1–1.9 M☉ (M = V_{rot}² r/(sin(i) G), using i = 19°), see also curves in the position–velocity diagram of Figure 1). At this point, the detection of the disk in the CO images and pv-diagrams is slightly speculative, and it does not merit more sophisticated modeling. Confirming and characterizing the disk will probably require to make isotope 13CO and/or C18O observations that are less confused with outflow emission.

3.2. The Optical Jet Seen by the HST

Microjets are usually associated with quite evolved young stars such as Class II objects. From an observational point of view, this implies: (a) a near-infrared jet counterpart is not usually detected (H₂ emission); (b) the jet emission is short as compared with classical optical jets, consisting of just a few knots close to its driving source; (c) the driving source can be
detected at optical wavelengths. (b) and (c) cause difficulties to detect microjets, being the dominant problem the pollution of the jet emission by the emission from the star and from the light scattered by the surrounding material. This is especially critical in deep (long time exposure) images, inevitable to detect the jet emission.

Figure 2 shows the [S II] optical emission from the microjet in the HST images of DO Tauri. Although difficult to visualize due to the contamination from the source emission and the spikes produced by the saturation of the image, the emission from the microjet is clearly distinguished west of the young stellar emission. The maximum of the emission of the jet has a PA of 260° ± 1° with respect to the peak emission toward the central object, and is 1°9 ± 0.1 (270 au) away from it. In addition, Figure 2 reveals two possible knots further from the protostar due southwest. These two knots are not exactly aligned with the PA of the inner jet (260°), which may suggest it is wiggling. However, a more clear detection of these knots is needed to confirm the hints of wiggling. The measured PA of the inner part of the optical jet is roughly consistent with the previously value of 70° ± 10° (or its corresponding 250° ± 10°) reported by Hirth et al. (1997), but the difference (10°) is of the order of the uncertainty in Hirth’s et al. long slit spectra measurements.

In an attempt to look for the counterpart of the microjet, we subtract the continuum emission contribution to the line emission image (right panel in Figure 2). The resulting image still contains remainders of the saturation spikes and the rings of the diffraction pattern. However, it is possible to identify some bright pixels 0°9 due northeast of the star (PA = 42°) that may belong to the eastern lobe of the jet. The PA between this bright feature and the southwestern jet is 71°, which matches the expected orientation of the jet. The problem is that the line joining both features goes north of the peak emission of the central object. At this moment, we cannot be certain whether this northeast emission is part of the counterjet, and we refrain ourselves from further analyzing it.

3.3. The Molecular Environment Surrounding DO Tauri

3.3.1. Three Sets of CO Rings

Figure 3 shows the velocity cube of the CO(2−1) emission surrounding DO Tauri from 8.2 to −10.2 km s⁻¹. From −10.2 to −12.7 km s⁻¹, the emission is weak (see also figures in the 2.1), and at velocities larger than 8.2 km s⁻¹, there is only emission from the disk. The cloud velocity is centered at 5.7 km s⁻¹, and the corresponding channel shows the typical interferometer emptiness due to the presence of extended emission and some absorption spatially coincident with the disk position (both are seen also in channels at 5.0 and 6.3 km s⁻¹). The redshifted emission spans ∼5 km s⁻¹ while the blueshifted emission spans ∼18 km s⁻¹. This asymmetry in the CO line profile was already noticed by Koerner & Sargent (1995) in a spectrum toward the young stellar disk. The CO emission surrounding the disk shows some elliptical structures of different sizes. To understand these CO structures, we split them in three sets of elliptical rings spanning different velocity ranges.⁶

A small scale set of 17 rings of average geometrical mean radius 1°6 (225 au) and width between 0°6 and 1°0 (80–140 au) can be identified in velocity channels from −8.3 to 1.9 km s⁻¹. From here on, we refer to these rings as set of Small Blueshifted rings or SB rings. For instance, these rings are prominent in the −3.2 km s⁻¹ channel (the brightest CO structure at this velocity, Figure 4), in which the disk of DO Tauri is outside of the SB ring, although it is close to its easternmost rim. The SB rings are the brightest features seen in CO at blueshifted velocities. Their northeast rim is brighter compared to their southwest rim, which fades (and is undetected) at more blueshifted velocities (v_{rad} < −2.6 km s⁻¹), making the rings incomplete.

In channels where v_{rad} > −2.6 km s⁻¹, we identify a second set of 17 rings, which we name “Medium-size rings” or M rings, hereafter. These rings surround the smaller SB rings from −2.6 to 1.9 km s⁻¹, velocities at which both structures are present simultaneously (see, for instance, channels at 0.6, 1.2 and 1.9 km s⁻¹ in Figure 4). Between 1.9 and 4.4 km s⁻¹, the M rings encompass the emission from the DO Tauri disk and are filled with some extended emission. At redshifted velocities, two simultaneous (and equal) M rings explain the emission distribution morphology better (Figure 4). These two rings spatially coincide with the northeast and northwest arcs

⁶ Note, however, that some of the rings appear incomplete, with a crescent-like structure. These rings show their northeast side brighter than their southwest side in a consistent manner with velocity.
observed by Itoh et al. (2008) using NIR and optical images. The M rings have an average geometrical mean radius of 2.3 ± 0.320 au and a width ranging between 0.60 and 1.1 ± 0.80–1.50 au. In general, M rings are oriented northwest–southeast and show brighter emission toward their northern rim.

Figure 3 also shows a third set of rings that encompass the M and SB sets of rings at larger scales, from −10.8 to 1.9 km s⁻¹. We name them set of Large Blueshifted rings (LB rings). The 23 LB rings have an average geometrical mean radius of 5.7 ± 0.5’’7 (about 800 au) and a width between 0.8’’8 and 1.6’’ (110–220 au). They show stronger emission and are seen as complete rings between 1.2 and −4.5 km s⁻¹. At more blueshifted velocities they fade and only their northeast rims are detected.

3.3.2. Ring-fitting Procedure

In order to make a more comprehensive analysis of the three sets of rings present in the data, we fit 2D-ellipses to the emission of each ring channel by channel. We use an automatic fit (see below) only for those rings with a clear morphology, not blended or confused with other structures. For those rings
with emission mixed up or complicated for our automatic procedure, a manual fitting was carried out trying to follow the brightest ridge of the rings. The results of such fits are summarized in Table A1 and can be seen in Figure 4 and in the 2.1, in Figures A1 and A2. Automatic and manual fits are distinguished by a letter code in the mentioned table and by dashed or solid lines in the figures.

For the automatic fits, we used a Perl-PDL script with the Minuit tool (James & Roos 1975) that maximizes the product between the channel image and the equation of an elliptical ring with a negligible width compared with the synthesized beam size (we do not attempt to fit the width of the rings because it is variable along a single one). In order to determine proper uncertainties, we used a normalization factor proportional to the rms of the velocity cube and to the length of each ring. Hence, Minuit derives an error for each parameter (coordinates center, major and minor axis of the ring, and PA) as the value that makes the fit deviating one times the value of the standard deviation of the merit function evaluated in noise regions. This procedure gives positional and size errors typically of the order of half the size of the synthesized beam (∼0″1). These automatic fits were not possible in channels with more complicated emission distributions. In those channels, we perform manual fits to the emission trying to keep the fits as simple as possible (i.e., minimizing the number of rings). We estimate the uncertainties on the manual fitting empirically, by bringing the fits to the limit where the fitting ellipse escapes the boundaries of the emission ring. In general, these errors are no larger than ±0″3 for the central coordinates, ±0″3 for the major and minor axes, and ±15° for the PA of the ellipses. Finally, as a conservative estimate, we added 0″1 to the errors in position and sizes and 5° to the PAs. Furthermore, since some of the derived PAs have large uncertainties, we decided not to quote the PA of the rings when their eccentricity is less than 0.35 (i.e., we consider these rings are roughly circular).

3.3.3. Ring Properties as a Function of Radial Velocity

The ring fits show some general characteristic trends (some of them as a function of radial velocity) that are shown in Figure 5. First, let us notice that the centers of the elliptical rings with respect to the position of the disk peak continuum emission (we will refer to these as centers or ring centers from now on for simplicity) are linearly aligned with the position of DO Tauri (top left panel in Figure 5). A linear fit to the ring centers (taking only those rings with radial velocity lower than 5.7 km s⁻¹) gives a PA of 253°6 ± 0.1 and an alignment better than 0″1 with the DO Tauri’s disk position. This PA matches the orientation of the optical jet reported by Hirth et al. (1997).

Figure 4. CO(2−1) emission of the central velocity channels demonstrating the manual ellipse fitting carried out. A star marks the position of DO Tauri disk’s continuum peak, while the channel velocity and the synthesized beam are in the upper left and bottom right corners. Continuum/Dashed ellipses show manual/automatic fits carried out in the images.

http://pdl.perl.org/?page=credits
In addition to this trend, the centers of the SB and M rings are closer to the young stellar disk than those of the LB rings.

Second, the positions of the ring centers are also correlated with their corresponding radial velocities. The top right panel in Figure 5 shows that the larger the distance between the ring center and the young star, the bluer (the larger, or more negative) its velocity. Moreover, while a linear trend makes a reasonable fit for the LB data, the trends for the SB and M rings are not just linear correspondences. A closer look into these data shows that the velocity increases roughly exponentially with distance from the source, although more points (higher spectral resolution) would be needed to better sample these trends. For now, we can confidently say that the radial velocity increases with the distance from the young star and the increment is steeper further away from the star.

In third place, the bottom left panel in Figure 5 shows the geometrical mean radius of the rings as a function of the radial velocity. The three sets of rings are clearly segregated from each other. SB rings are below 1''9 (260 au), M rings are between 1''9 and 3'' (560 au), and LB rings are larger than 4''. Despite the fact that the size of the rings within each set does not change much, the M rings slightly decrease their size monotonically toward bluer velocities, and the LB rings monotonically decrease their radii from 6'' to 4'' and then increase them again monotonically up to more than 6''.

The fourth plot (bottom right panel) in Figure 5 shows the change on the ring orientations as a function of radial velocity. Most of the PAs of the SB rings are in a range of 40° around PA = 140° (note that a quarter of these rings are quite circular and just a few of them are closer to PA = 25°), while those of the M rings seem to linearly vary from 120° (blueshifted velocities) to 180°. The orientation of the LB rings is more uncertain since these rings are quite round; in any case, their PAs do not change more than 20° overall.

4. Analysis and Discussion

In this section, we try to interpret the ALMA CO(2−1) observations toward DO Tauri. Although more information is needed to fully understand the origin of these molecular structures, we discuss the possibility of an outflow entrained by an episodic wide-angle wind or jet from the young star. The usual appearance of protostellar outflows is that of a biconical parabola, but the geometry of an outflow seen almost pole-on should reveal the cavity walls of the outflow as a ringed structure when imaged in a velocity cube, in a similar manner to the present CO observations from the surroundings of DO Tauri. This hypothesis has further support when taking into account the very inclined orientation (almost face-on) of DO Tauri’s circumstellar disk (Section 3.1) if, as expected, it is perpendicular to the jet/outflow direction.

The interaction between the interstellar medium and DO Tauri itself, which may be moving supersonically in the molecular cloud after a close encounter with HV Tauri in the past (Winter et al. 2018), could somehow account for some of the observed features, but we underweight this possibility as DO Tauri seems to be roughly co-moving with the Taurus molecular cloud (the cloud velocity coincides with the
kinematic center of the DO Tauri disk, Figure 1), and its
GaIA DR2 proper motions are similar to those of the stars
from its vicinity.8

In this section, we add more support to the outflow
hypothesis, extending it to analyze the correlations between
the velocity and the physical characteristics of the rings and to
estimate the dynamical age of the outflow shells traced by the
rings, as well as their mass and energetics.

4.1. An Outflow from DO Tauri

CO is known to be a good outflow tracer in star-formation
regions, although it can be also encountered as part of the disk,
the envelope, and the parental cloud. In DO Tauri, however, the
CO(2−1) emission is both spatially extended (spreading much
further than the size of the disk) and extended in velocity (over
about 20 km s−1), so it seems at least plausible that the SB, M,
and LB rings seen in the vicinity of DO Tauri are part of the
material dragged by the high-velocity jet reported in the
literature (Hirth et al. 1994) and detected in the HST images
presented here. Indeed, the sets of elliptical rings seen in CO
have their centers aligned with the position of DO Tauri (with
the smaller rings closer to the young star than the larger ones)
and the PA of the optical jet (260° ± 1°) roughly coincides the
PA of the aligned ring centers (253°6 ± 0.1).

Usually, outflows show a parabolic biconical shape because
they are seen close to the plane of the sky, but in the case of DO
Tauri, we do not see this parabola. We interpret the three
families of elliptical rings as three different shells of entrained
material seen at different radial velocities. In this scenario, we
see the outflow from an almost pole-on perspective. Indeed, if
the jet and outflow are launched perpendicular to the
circumstellar disk plane, the inclination of the jet with respect
to the line of sight would be the same as that of the disk,
i = 19°. From now on, we will assume this is the case, and we
use this inclination to correct for the estimated physical
properties when adequate. Taking this inclination into account,
the dimensions of the outflow would be 4070 au × 1960 au
from the young star to the further ring detected by the ALMA
observations. This implies an opening angle of 27° (a
collimation factor of 2.1). The size of the CO structure, its
opening angle, and the radial velocity extent all agree with the
usual measures of CO outflows from protostars and young stars
(from a few thousands au to a few pc in length, opening angles
typically between 20° and 60° and radial velocity spreads
between 10 and 100 km s−1, Arce & Sargent 2006; Bally 2016).
When compared with one of the most recent paradigmatic
outflows from Class 0 objects such as HH 46/47 (about
60,000 au long and more than 10,000 au in width Arce et al.
2013), this one would be a small (young?) outflow, but in the
event that we are only detecting the inner shells of the DO
Tauri outflow, then the sizes match better, as the outflow from
DO Tauri is still more collimated; for HH 46/47, the inner
shells fit in a box of about 5000 au side (Zhang et al.
2016, 2019).

Class I/II young star, DG Tau B (see, e.g., Zapata et al. 2015),
both have sizes of the same order of magnitude (DG Tau B’s is
2550 au long and about 1400 au wide). It is also significant that
the outflow from DO Tauri would not have a clear redshifted
lobe. This is not a huge obstacle for the outflow hypothesis
since other monopolar outflows (probably due to environ-
mental inhomogeneities) have been reported in regions such as
GGD 27 or HH 30 (Fernández-López et al. 2013; Louvet et al.
2018).

Finally, let us show a reconstruction of a spatial cut parallel
to the outflow major axis based on this scenario (Figure 6).
First, we rotate the (R.A., decl.) coordinates of the ring centers
into the (x, z′) plane, where the projected z′ axis is oriented with
the outflow axis taking positive values southwest of the young
star. We used an outflow PA of 253°6 to rotate the coordinates.
Second, we correct for the inclination of the outflow with
respect to the line of sight, considering it as perpendicular to
the disk, to get the unprojected coordinates along the z-axis.
After this, we assume that the rings are perfect circumferences
with radii equal to the semimajor axis of the fitted ellipses. That
is how we build the left panel of Figure 6. The morphology
outlined by the points in this figure reminds the shape of
protostellar outflows. In the left panel two cylinder-like
structures are outlined: one with smaller radius composed of
the SB and M rings extending up to ~1200 au, and a second
one with a larger radius that doubles this size reaching
~4000 au (lower sideband (LSB) rings). The right panel of
Figure 6 has a further step in the reconstruction, by forcing
the position of the rings to lie in the z-axis (i.e., we force them to
be at x = 0). This way, we remove any wiggling of the outflow or
errors in measuring the ring center positions. The result is a
symmetric outflow, but here, we can notice additional
interesting details. On one side, the inner part of the outflow
(<1200 au) comprises two concentric structures: one with a
roughly constant width (mostly formed by the SB rings) and a
wider one whose width seems to decrease smoothly with the
distance to the star (the M rings). In contrast, the widest LSB
shell (>1200 au) smoothly decreases its aperture up to 3000 au
from the star and from this point increases it again.

4.2. Velocity Gradients and Dynamical Ages from Different
Shells

In Figure 5, each set of rings shows a different velocity
gradient (SB, M, and LB). These velocity gradients show an
increase in velocity with distance, sometimes steeper than a
simple linear trend. Although the gradients are not linear, they
show a similar trend to the Hubble-law behavior found in the
cavity walls of some molecular outflows (see for instance
Zhang et al. 2016, 2019). Radial wide-angle winds can account
for such Hubble-laws provided they have an angular dependent
force (e.g., ∝1/sin2θ, where θ is the polar angle and θ = 0°/180°
correspond to the direction perpendicular to the disk
plane) and sweep-up gas in a medium with a specific density
structure (e.g., ∝ sin2θ/rr2). Under this model, the resulting
outflow walls have a roughly parabolic morphology that expands
radially with a constant speed, independent of the
outflow shell size. The velocity V (θ) is different for each
direction θ, but constant in time. As a result, at any given age
τdyn, the shell shows an apparent Hubble-law, with patches of
the shell closer to the source being slower than further ones
with V (θ) = R (θ)/τdyn (Shu et al. 1991, 2000; Li & Shu 1996;
Lee et al. 2000).

8 For DO Tauri, GaIA DR2 proper motions are μα = 6.1 ± 0.1 and
μδ = −21.34 ± 0.09 mas yr−1; the average proper motions of the objects
observed by GaIA DR2 toward a region inside a 40° radius centered at DO
Tauri, with parallaxes ranging between 6.2 and 8.3 mas (±0.2 pc from
DO Tauri’s distance of ≈140 pc) and with parallax errors of less than 0.25 mas are
μα = 6 ± 1 and μδ = −21 ± 2 mas yr−1 (note that we removed a few outliers
with large proper motions for this estimate); this results in DO Tauri
having a tangential velocity with respect to these objects of 1 ± 3 km s−1
(PA = 162° ± 120°).
Assuming the wide-angle wind model, we estimate the dynamical age of each shell by computing the dynamical time of each ring composing it as $t_{\text{dyn}} = R/V$, where $R$ is the deprojected distance from the young star to the edge of a ring ($R = \sqrt{z^2 + B_{\text{maj}}^2}$; where $z$ is the distance from the star to the center of the ring, and $B_{\text{maj}}$ is the ring’s major axis) and $V$ is an averaged value of the deprojected velocity of the molecular gas of the rings, respectively. We take $V \sim V_{\text{radial}}/\cos i$ ($i = 19^\circ$ is the inclination of the outflow) as the averaged value of the deprojected velocity of the gas in an individual ring. Figure 7 shows graphically the spatial distribution of dynamical times along each shell surface in the reconstructed sketch of the outflow (see also Figure 6). There is a notorious dynamical age segregation between the SB and LB outflow shells (see right panel on Figure 8), indicating that there are at least two different events of outflow entrainment (Zhang et al. 2019). We also consider the M rings as a third outflow shell that partly encompasses the SB shell.

While the dynamical ages of the rings composing the LB and SB shells are mostly distributed in a 300 yr lapse, the dynamical ages of the M rings are quite spread (due to low velocities and relatively larger sizes). Among them, the more well-delineated M rings between $-1.9$ and $1.2 \text{ km s}^{-1}$ have dynamical ages ranging 600–1100 yr ($700 \pm 100 \text{ yr}$ on average). These M rings comprise a shell that surrounds part of the the SB outflow shell, which appears $\sim$300 yr younger. In contrast, the M rings closer to the cloud velocity and those that are redshifted show extended emission inside$^{10}$ and have dynamical ages from 600 to 5000 yr, with deprojected gas-velocities as low as $1.3 \text{ km s}^{-1}$ with respect to the cloud velocity. These rings subtend the largest angles from DO Tauri in projection.

Within the individual shells, not all of the rings have the same dynamical time, unlike one would expect in the wind-driven model (Lee et al. 2000). These differences can be accounted for if there are any inhomogeneities in the ambient cloud that may decelerate the outflow material at different rates in different directions $\theta$. Moreover, deviations from the model are also expected if the outflow is not steady (Lee et al. 2001) as is the case for DO Tauri, where multiple shells are observed.

An interesting alternative scenario for the DO Tauri outflowing shells is that they are generated by successive jet-driven bowshocks (Ostriker et al. 2001). In this model, a narrow jet produces an expanding bowshock when bumping into the ambient medium. The velocity of the outflow thus created increases as a power law with increasing distance to the source. This model implies shorter dynamical times at larger distances from the source, which is the trend observed along the LB and SB shells (Figure 7). The rings with the largest $^9$ Note that, assuming that the shell expands purely in a radial direction, the deprojected velocity of the gas in a ring varies from $V_{\text{radial}}/\cos i + \epsilon$ and $V_{\text{radial}}/\cos i - \epsilon$, where $\epsilon$ is the semi-opening angle of the ring when viewed from the source.

$^{10}$ Whether this extended emission is part of the most inner part of the outflow or is part of the remains of a circumstellar envelope cannot be decided with the present data.
dynamical times in these shells show the largest opening angles too and have gas with lower projected velocities.

Finally, from the left panel of Figure 8, it can be inferred that within each shell, the dynamical times increase very steeply at lower velocities. This strongly suggests a slowing down of the shells close to the star where a more dense ambient material is expected. In particular, it should be noted that due to possible outflow deceleration, the measured dynamical times are upper limits to the true age. Hence, the best estimate of each shell age is obtained by measuring the dynamical time at large distances, where t_{dyn} is almost constant and the deceleration does not seem to be too severe. We, therefore, estimate the dynamical age of the observed outflow in 1090 ± 90 yr, considering the dynamical time of the furthermost LB shell. The mean averaged dynamical times of the three shells are gathered in Table 1 (error bars for these values are derived from rms times).

4.3. CO Masses, Momentum, and Energy of the Rings

Measuring gas masses using CO(2−1) has several problems (Arce & Goodman 2001; Dunham et al. 2014; Zhang et al. 2016) because this molecule is sometimes contaminated with emission from the disk and the natal cloud and can be optically thick. Here, we make an attempt to estimate the mass, linear momentum, and kinetic energy of the molecular ringed structure found in DO Tauri, to compare these quantities with those of young stellar outflows.

Since we do not possess observations of any optically thick tracer, we assume an excitation temperature of 25 K as a proxy for the mass, momentum and energy estimates. Similar values have been used for outflows of other Class II young stars (usually T_{ex} < 30 K, see, e.g., CB 26 and HH 30, Launhardt et al. 2009; Louvet et al. 2018). Using this T_{ex}, we found that some channels are optically thick at the peak emission. This choice sets a lower limit to the mass derived from now on.

Despite the existence of CO(2−1) optically thick emission at the brightest parts of the rings in several velocity channels (mainly in the SB and M rings), large areas have brightness temperatures between 3 and 8 K, which translate into optical depths ranging between 0.2 and 0.5. Therefore, we can just make a crude estimate of the mass, momentum, and energy of the outflow by assuming local thermodynamic equilibrium and optically thin CO emission. Note, in addition, that it is also possible that the ALMA observations are filtering out part of the extended material of the outflow. With these caveats in mind, we estimate first column densities as well as the shell masses, momenta, and kinetic energy, using an analog procedure to that in Pineda et al. (2008) and Zhang et al. (2016), with expressions adapted to the CO(2−1) transition following Mangum & Shirley (2015). In particular, we use the following equation to derive the column density for the optically thin case:

\[ N_{\text{rot}}(CO) = \frac{3h}{8\pi^2}\mu S \cdot \frac{Q_{\text{rot}} e^{E_e/kT_{\text{ex}}}}{g} \cdot \frac{\int T_B dv}{[I_e(T_{\text{ex}}) - J_e(T_{bg})]} \]

which, for the particular transition CO(2−1), can be expressed as

\[ N_{\text{rot}}(CO) = \frac{1.196 \times 10^{14} (T_{\text{ex}} + 0.921) e^{16.596/T_{\text{ex}}}}{e^{1.085/T_{\text{ex}}} - 1} \cdot \frac{T_B}{[I_e(T_{\text{ex}}) - J_e(T_{bg})]} \]

To obtain the latter expression, we used the line strength \( S = J/(2J + 1) = 2/5 \), the dipole moment \( \mu = 1.1011 \times 10^{-19} \) StatC cm, the partition function \( Q_{\text{rot}} = kT_{\text{ex}}/(\hbar B_0) + 1/3 \) with a rigid rotor rotation constant \( B_0 = 57.635968 \text{ GHz} \), the degeneracy \( g = 2J + 1 = 5 \), the \( T_B \) in K, and the \( \Delta v \) velocity interval in km s\(^{-1}\). From this, we estimate the mass by doing \( M = \mu m_H \Omega N_{\text{rot}}/X_{\text{CO}} \), using a mean molecular weight \( \mu = 2.8 \) times the atomic hydrogen mass and a CO abundance of \( X_{\text{CO}} = 10^{-4} \) (\( \Omega \) is the area of the rings). We further correct the momenta and kinetic energy by the adopted outflow inclination (we use \( i = 19^\circ \) in \( v_{\text{outflow}} = v_{\text{rad}}/\cos(i) \), where \( v_{\text{rad}} \) is the line-of-sight or radial velocity). The results for each of the three outflow shells are summarized in Table 1, considering the M shell as the part with \( V < -4 \text{ km s}^{-1} \), thus excluding the redshifted emission and the emission close to the cloud velocity contaminated by the DO Tauri circumstellar disk. The LB shell has approximately twice the mass of the SB shells. The three shells carry out a comparable
amount of energy and momentum. Globally, the lower limits for
the total mass of the blueshifted outflow, the total linear
momentum, and the total kinetic energy are $1.3 \times 10^{-4} M_\odot$, $1.1 \times 10^{-3} M_\odot$ km s$^{-1}$, and $1.1 \times 10^{41}$ erg, respectively.

Moreover, with the mass and the dynamical age of the
blueshifted lobe of the outflow, we can now derive an estimate
(lower limits due to possible optically thick CO emission, $T_{\text{ex}}$
uncertainty and $t_{\text{dyn}}$ being an upper limit of the outflow age) of
its average mass-load rate ($1.1 \times 10^{-7} M_\odot$ yr$^{-1}$) and its average
rate of linear momentum injected by the wind/jet into the CO
outflow ($1.0 \times 10^{-9} M_\odot$ km s$^{-1}$ yr$^{-1}$). Table 1 contains these
quantities estimated for the three individual shells. There is
a striking good agreement of the $M$ and the $P$ among the three
shells, with average values $M_{\text{shells}} = 5.5 \times 10^{-8} M_\odot$ yr$^{-1}$ and
$P_{\text{shells}} = 4.7 \times 10^{-7} M_\odot$ km s$^{-1}$ yr$^{-1}$. These values may be
compared with the mass-loss rate and its associated momentum
rate extracted from the optical observations of the jet. Observing
forbidden lines and assuming a projected plane of the sky
velocity (150 km s$^{-1}$) and length (125), Hartigan et al. (1995)
derived a jet mass-loss rate of $3.1 \times 10^{-8} M_\odot$ yr$^{-1}$. We can
update this value using the inclination of the outflow ($i = 19^\circ$),
the line-of-sight blueshifted jet velocity of 95 km s$^{-1}$ (taking into
account the cloud velocity and the observations of Hirth et al.
(1994)), the blueshifted jet length from the HST observations
($\sim 2^{\prime\prime}$) and the equation A10 from Appendix A.1 in Hartigan et al. (1995). This way we obtain a jet mass-loss rate
$M_{\text{jet}} = 4.3 \times 10^{-9} M_\odot$ yr$^{-1}$. We can also make a rough
estimate of the jet mass-loss rate assuming that it is a fraction
of the accretion rate of the disk ($M_{\text{jet}} \approx 0.1 M_{\text{acc}}$, see, e.g.,
Pudritz & Banerjee 2005). $M_{\text{acc}}$ has been estimated as $1.4 \times 10^{-7} M_\odot$ yr$^{-1}$ and $3.0 \times 10^{-8} M_\odot$ yr$^{-1}$ (Gullbring et al. 1998;
Alonso-Martínez et al. 2017), yielding jet mass-loss rates
ranging $3 \times 10^{-9} - 10^{-8} M_\odot$ yr$^{-1}$, in good agreement with our
new estimate for the Hartigan et al. observations. In summary,
the average mass-load rate from the outflow shells is a factor
5–20 larger than the jet mass-loss rate. In the meantime, its
rate of injected momentum is comparable to that of the optical jet
($4 \times 10^{-7} M_\odot$ km s$^{-1}$ yr$^{-1}$). This may suggest that the outflow
shells mainly comprise swept-up gas from the original envelope/cloud, with only a small fraction of material incorporated from
the wind directly launched from the disk. The momentum of this
wind is apparently conserved when sweeping up the CO shells.

Figure 9 shows the mass distribution $dm/dV$ within the
shells as a function of velocity corrected by the outflow inclination. Symbols with three different colors designate the
three outflow shells. A usual analysis of a mass spectrum
diagram, such as this, consists of performing power-law fits of
the form $V_{\text{outflow}} \propto V^{-\gamma}$. We make individual fits to each of the
three shells, using only masses corresponding to larger outflow
velocities that show a clear power-law behavior. Table 1
collects the resulting slopes for each of the three fits. In the case

### Table 1

| Physical Properties of the Three Sets of Rings | SB  | $M^\ast$ | LB  | Total |
|----------------------------------------------|-----|---------|-----|-------|
| Mean geometrical radius (au)                 | 195–240 | 280–350 | 640–850 | ... |
| Distance from DO Tauri (au)                  | 530–1025 | 190–910 | 1140–3680 | ... |
| $T_{\text{dyn}}$ (yr)                        | 460 ± 70 | 700 ± 100 | 1090 ± 90 | 1090 ± 90 |
| $M$ ($10^{-9} M_\odot$)                      | 2.6 | 4.0 | 5.9 | 12.5 |
| $P$ ($10^{-4} M_\odot$ km s$^{-1}$)           | 2.1 | 2.5 | 6.5 | 11.1 |
| $E$ ($10^{48}$ erg)                          | 1.8 | 1.6 | 7.6 | 10.9 |
| $M$ ($10^{-9} M_\odot$ yr$^{-1}$)            | 5.6 | 5.7 | 5.4 | 11.4 |
| $P$($10^{-7} M_\odot$ km s$^{-1}$ yr$^{-1}$)  | 4.6 | 3.6 | 6.0 | 10.2 |
| $\gamma$                                    | 3.2 ± 0.3 | 2.2 ± 0.4 | 3.9 ± 0.7 | ... |

**Notes.**

- Magnitudes for the M shell are estimated taking into account only emission
  with $V_{\text{out}} < -4$ km s$^{-1}$.
- Corrected by outflow inclination ($\epsilon = d_{\text{observed}} / \sin(i)$).
of ambient shells driven by wide-angle winds, the expected slope of the mass–velocity relationship is about 2 (e.g., Masson & Chernin 1992; Li & Shu 1996; Matzner & McKee 1999). Inclination effects (e.g., Lee et al. 2001) and, most importantly, deviations from the canonical angle dependence on the wind thrust and the ambient density distribution (Matzner & McKee 1999) can modify these values. In the case of DO Tauri’s outflow, the slopes of the LB and SB shells are steeper than the slope of the M shell. The overall shape of the mass–velocity relations for the three shells matches quite well the expectations for the wide-angle wind scenario (which are not very different from those of the jet-driven bowshock model, Zhang & Zheng 1997; Downes & Cabrit 2003).

The resulting mass, momentum, and energy of the blueshifted lobe of the DO Tauri outflow are, in general, lower than those derived for some Class 0 or Class I molecular outflows (∼10−3 M⊙, 10−3–0.1 M⊙ km s−1, 1041–1043 erg, Arce 2003; Arce & Sargent 2004; Kwon et al. 2006; Lumbrañas & Zapata 2014; Zapata et al. 2014, 2015; Zhang et al. 2016). However, they agree better with the characteristics of the outflow from the Class II HH 30 (M = 1.7 × 10−5 M⊙, M = 8.9 × 10−8 M⊙ yr−1, Louvet et al. 2018). Thus, DO Tauri’s outflow mass and energetics roughly lie within the range of other young stellar outflow values, supporting the outflow interpretation for the nested ringed structures in the surroundings of DO Tauri.

4.4. Launching Region

The three CO shells of dragged gas have remarkably coherent and regular shapes several hundreds of au far away from the central source. In order to form structures with this degree of cohesion and shape, the launching zone of the outbursting wind or jet entraining these shells should be causally connected during the outburst period. Following Zhang et al. (2019), we constrain the dimensions of the launching area of the outbursts that entrained the outflow shells. We estimate the interval between the production of the SB and LB outflow shells in ~600 yr. Part of the M shell was intertwined between these two so we choose a shell interval time of 300 yr. Assuming that the ejection outburst lasts for just a fraction of the interval between the dynamical age of the shells (consider toutburst ≈ (0.2–0.3) × Δtshell as an upper limit to produce a coherent shell), we derive a length scale c2t · Δtoutburst using the disk sound speed c2 = 0.24/√T/10 expressed in km s−1. Although this procedure is very approximate, by taking a temperature of 100 K appropriate for the inner part of the disk, we obtain an upper limit for the size of the wind/jet outburst launching region of <10–15 au.

5. Conclusions

We presented new 1.3 mm continuum and CO(2–1) ALMA observations, and [S II] HST archival observations toward the DO Tauri young stellar object. The DO Tauri 45 au disk is oriented north–south and is apparently close to face-on (i = 19°). It shows a velocity gradient with this same orientation indicative of rotation. A rough estimate assuming a Keplerian rotation pattern gives a central mass of 1–2 M⊙.

The molecular environment of the region appears in the ALMA velocity cube as a series of nested ring structures, separated in radial velocity. The rings are spatially aligned with the location of DO Tauri’s disk (lying along a line with PA = 253°) and the optical jet. We identify the individual rings and fit them with ellipses deriving their size, orientation and inclination. We found that there are three sets of rings with separate sizes (SB have radii <260 au, LB radii >560 au and M have radii between these two). They show an increase of their radial velocity as a function of their distance to the star.

Based on the alignment of the rings with the jet, their kinematics and the high inclination of the young stellar disk, we interpret these ringed structures to be part of a molecular outflow seen mostly pole-on (close to the line of sight) and, therefore, revealing an outflow from a different perspective. Instead of the typical parabolic biconical shape, DO Tauri’s outflow is seen as a collection of elliptical rings (possibly the cavity walls) displayed at different radial velocities. After correcting for the line-of-sight inclination (i = 19 ± 9°), we derive the dimensions of the blueshifted outflow (4070 au × 1960 au), its opening angle (27°), and its deprojected velocity (18 km s−1). From the observations, we identified three outflow shells. Knowing the outflow inclination and adopting the wide-angle wind model of Lee et al. (2000), we could derive that the dynamical ages of the SB, M, and LB shells lie around 460, 700, and 1090 yr, respectively. These shells may correspond to entrainment by separate wind/jet outbursts. The total dynamical time of the outflow is about 1090 ± 90 yr. We also estimated the mass (1.3 × 10−5 M⊙), the momentum (1.1 × 10−3 M⊙ km s−1), and the energy (1.1 × 1037 erg) of the blue lobe of the outflow and those of the individual shells (Table 1). The average mass-load rate of the three outflow shells is about 5.5 × 10−8 M⊙ yr−1 and that of the rate of injected momentum is 4.7 × 10−2 M⊙ km s−1 yr−1. A comparison between these quantities and those of the optical jet indicates that only a fraction of the outflow material comes directly from the disk wind and the jet carry enough momentum flux to drive each of the shells. All of the measurements agree with the outflow hypothesis within the wide-angle wind model, but a jet-driven bowshock scenario cannot be discarded, since the trend in velocity vs distance from source can be better explained by this model. Finally, we make a rough estimate of the dimensions of the wind/jet launching zone using the estimated elapsed time between the creation of each outflow shell. Our findings suggest a narrow (<15 au) launching zone.

![Figure 9. CO(2–1) shell masses per unit velocity interval as a function of the outflow velocity (corrected for inclination) for each of the three outflow shells. Power-law fits use only data corresponding to larger outflow velocities.](image-url)
New observations with deeper sensitivity will surely help to dig further into the complex molecular environment around DO Tauri, offering a unique perspective of this phenomenon.

We are very grateful to the anonymous referee for all of the comments and suggestions that helped a lot to improve the text and contents of this work.

M.F.L. has received funding from the European Union’s Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie grant agreement No 734374.

This paper makes use of the following ALMA data: ADS/ JAO.ALMA#2016.1.01042.S. ALMA is a partnership of ESO (representing its meMrR 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 Joint ALMA Observatory is operated by ESO, AUI/ NRAO, and NAOJ. L.A.Z. and L.F.R. acknowledge financial support from DGAPA, UNAM, and CONACyT, México.

It is also partially based on observations made with the NASA/ ESA Hubble Space Telescope, and obtained from the Hubble Legacy Archive, which is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESA), and the Canadian Astronomy Data Centre (CADC/NRC/CSA).

Facilities: ALMA, HST.

Software: DS9 (Joye & Mandel 2003), CASA (v4.7.0 and v5.4.0 McMullin et al. 2007), IRAF (Tody 1986), Astropy (Astropy Collaboration et al. 2013), Karma (Gooch 1995), PDL (Glazebrook & Economou 1997).

Appendix

This Appendix contains a table (Table A1) summarizing the main results of the fitting process of the outflow ellipses. It also contains the complete CO (2-1) velocity cube through Figures A1 and A2.

### Table A1

| Fit | Ellipse set | $V_{\text{rad}}$ (km s$^{-1}$) | R.A. offset (°) | Decl. offset (°) | $B_{\text{maj}}$ (°) | $B_{\text{min}}$ (°) | PA (°) |
|-----|-------------|-------------------|----------------|----------------|-------------------|-------------------|-------|
|     |             |                   |                |                |                   |                   |       |
| Set of Large Blueshifted Rings—LB |
| A   | LB          | −12.1             | −9.4 ± 0.2     | −2.3 ± 0.2     | 6.6 ± 0.3         | 5.7 ± 0.2         | 113 ± 19 |
| A   | LB          | −11.5             | −9.3 ± 0.2     | −2.7 ± 0.2     | 7.0 ± 0.2         | 5.6 ± 0.2         | 79 ± 6  |
| A   | LB          | −10.8             | −9.4 ± 0.2     | −2.5 ± 0.2     | 7.1 ± 0.2         | 5.8 ± 0.2         | 88 ± 8  |
| A   | LB          | −10.2             | −9.2 ± 0.2     | −2.9 ± 0.2     | 6.9 ± 0.2         | 6.0 ± 0.2         | 77 ± 8  |
| A   | LB          | −9.6              | −8.7 ± 0.3     | −2.8 ± 0.3     | 7.0 ± 0.3         | 5.5 ± 0.3         | 62 ± 7  |
| A   | LB          | −8.9              | −8.8 ± 0.2     | −2.6 ± 0.2     | 7.2 ± 0.2         | 6.0 ± 0.3         | 71 ± 11 |
| A   | LB          | −8.3              | −8.1 ± 0.3     | −2.5 ± 0.3     | 6.6 ± 0.3         | 5.7 ± 0.2         | 70 ± 15 |
| A   | LB          | −7.7              | −7.6 ± 0.2     | −2.3 ± 0.2     | 6.2 ± 0.2         | 5.7 ± 0.2         | 63 ± 32 |
| A   | LB          | −7.0              | −7.1 ± 0.2     | −1.8 ± 0.2     | 5.9 ± 0.2         | 5.6 ± 0.2         | ...    |
| A   | LB          | −6.4              | −5.4 ± 0.2     | −2.0 ± 0.3     | 4.9 ± 0.2         | 4.4 ± 0.3         | ...    |
| A   | LB          | −5.8              | −5.7 ± 0.3     | −1.8 ± 0.1     | 5.0 ± 0.4         | 4.9 ± 0.3         | ...    |
| A   | LB          | −5.1              | −5.0 ± 0.2     | −1.8 ± 0.1     | 4.9 ± 0.2         | 4.8 ± 0.2         | ...    |
| A   | LB          | −4.5              | −4.7 ± 0.1     | −1.8 ± 0.1     | 5.0 ± 0.1         | 4.9 ± 0.2         | ...    |
| A   | LB          | −3.9              | −4.4 ± 0.1     | −1.7 ± 0.1     | 5.1 ± 0.1         | 5.0 ± 0.1         | ...    |
| A   | LB          | −3.2              | −4.3 ± 0.1     | −1.6 ± 0.1     | 5.1 ± 0.1         | 5.1 ± 0.1         | ...    |
| A   | LB          | −2.6              | −4.2 ± 0.2     | −1.6 ± 0.1     | 5.3 ± 0.2         | 5.1 ± 0.2         | ...    |
| A   | LB          | −1.9              | −3.8 ± 0.1     | −1.5 ± 0.1     | 5.4 ± 0.2         | 5.2 ± 0.1         | ...    |
| A   | LB          | −1.3              | −3.5 ± 0.2     | −1.5 ± 0.1     | 5.6 ± 0.2         | 5.4 ± 0.1         | ...    |
| A   | LB          | −0.7              | −3.2 ± 0.2     | −1.3 ± 0.2     | 5.8 ± 0.2         | 5.6 ± 0.3         | ...    |
| A   | LB          | 0.0               | −3.0 ± 0.2     | −1.2 ± 0.2     | 6.1 ± 0.2         | 5.8 ± 0.2         | ...    |
| A   | LB          | 0.6               | −3.1 ± 0.2     | −1.1 ± 0.2     | 6.3 ± 0.3         | 5.9 ± 0.2         | 153 ± 14 |
| A   | LB          | 1.2               | −3.6 ± 0.6     | −0.7 ± 0.2     | 6.3 ± 0.3         | 6.0 ± 1.0         | ...    |
| A   | LB          | 1.9               | −3.6 ± 0.8     | −0.7 ± 0.2     | 6.3 ± 0.3         | 6.0 ± 0.4         | ...    |
| Set of Medium Blueshifted Ellipses—MR |
| M   | M           | −2.6              | −2.3           | −0.6           | 2.2               | 1.8               | 135    |
| M   | M           | −1.9              | −2.2           | −0.7           | 2.3               | 1.8               | 135    |
| M   | M           | −1.3              | −2.0           | −0.6           | 2.3               | 1.9               | 135    |
| M   | M           | −0.7              | −1.7           | −0.5           | 2.3               | 1.9               | 138    |
| M   | M           | 0.0               | −1.8           | −0.5           | 2.4               | 2.2               | 125    |
| M   | M           | 0.6               | −1.2           | −0.6           | 2.2               | 2.0               | 132    |
| M   | M           | 1.2               | −1.0           | −0.4           | 2.4               | 1.9               | 152    |
| M   | M           | 1.9               | −1.0           | −0.5           | 2.5               | 2.0               | 152    |
| M   | M           | 2.5               | −1.1           | −0.6           | 2.6               | 2.2               | 156    |
| M   | M           | 3.1               | −0.9           | −0.8           | 3.0               | 2.1               | 168    |
| M   | M           | 3.8               | −1.0           | −0.6           | 2.8               | 2.1               | 179    |
| M   | M           | 4.4               | −0.7           | −0.4           | 2.9               | 1.9               | 163    |
| Set of Medium Redshifted Ellipses—MR |
| M   | M           | 6.9               | −1.6           | −0.5           | 3.0               | 1.5               | 167    |
Table A1 (Continued)

| Fit | Ellipse set | $V_{rad}$ (km s$^{-1}$) | R.A. offset ($^{\circ}$) | Decl. offset ($^{\circ}$) | $B_{maj}$ ($^{\circ}$) | $B_{min}$ ($^{\circ}$) | PA ($^{\circ}$) |
|-----|-------------|--------------------------|--------------------------|--------------------------|-----------------------|-----------------------|----------------|
| M   | M           | 6.9                      | 0.5                      | -0.6                     | 3.0                   | 1.5                   | 167            |
| M   | M           | 7.6                      | -0.9                     | -0.6                     | 3.1                   | 2.0                   | 158            |
| M   | M           | 7.6                      | 0.1                      | -0.5                     | 3.1                   | 2.0                   | 158            |
| M   | M           | 8.2                      | -0.9                     | -0.6                     | 3.0                   | 2.0                   | 158            |

Set of Small Blueshifted Ellipses—SB

| Fit | Ellipse set | $V_{rad}$ (km s$^{-1}$) | R.A. offset ($^{\circ}$) | Decl. offset ($^{\circ}$) | $B_{maj}$ ($^{\circ}$) | $B_{min}$ ($^{\circ}$) | PA ($^{\circ}$) |
|-----|-------------|--------------------------|--------------------------|--------------------------|-----------------------|-----------------------|----------------|
| A   | SB          | -8.3                     | -2.42 ± 0.07             | -0.75 ± 0.07             | 1.65 ± 0.08           | 1.46 ± 0.09           | 153 ± 9        |
| A   | SB          | -7.7                     | -2.50 ± 0.06             | -0.85 ± 0.1              | 1.6 ± 0.1             | 1.6 ± 0.1             | ...            |
| A   | SB          | -7.0                     | -2.61 ± 0.06             | -0.98 ± 0.09             | 1.6 ± 0.1             | 1.39 ± 0.09           | 36 ± 12        |
| A   | SB          | -6.4                     | -2.58 ± 0.07             | -0.70 ± 0.08             | 1.6 ± 0.1             | 1.4 ± 0.1             | 29 ± 23        |
| A   | SB          | -5.8                     | -2.57 ± 0.08             | -0.75 ± 0.07             | 1.61 ± 0.08           | 1.44 ± 0.07           | 12 ± 33        |
| A   | SB          | -5.1                     | -2.57 ± 0.06             | -0.75 ± 0.07             | 1.55 ± 0.09           | 1.42 ± 0.08           | 152 ± 24       |
| A   | SB          | -4.5                     | -2.51 ± 0.05             | -0.72 ± 0.06             | 1.61 ± 0.09           | 1.5 ± 0.1             | 145 ± 16       |
| A   | SB          | -3.9                     | -2.44 ± 0.06             | -0.69 ± 0.06             | 1.7 ± 0.1             | 1.48 ± 0.09           | 133 ± 10       |
| A   | SB          | -3.2                     | -2.45 ± 0.07             | -0.61 ± 0.05             | 1.72 ± 0.07           | 1.62 ± 0.05           | ...            |
| A$^a$ | SB      | -2.6                     | -2.4 ± 0.2               | -0.7 ± 0.2               | 1.6 ± 0.2             | 1.5 ± 0.2             | ...            |
| M$^b$ | SB       | -2.6                     | -2.2                     | -0.5                    | 1.6                   | 1.5                   | ...            |
| M   | SB          | -1.9                     | -2.2                     | -0.5                    | 1.6                   | 1.6                   | ...            |
| M   | SB          | -1.3                     | -2.1                     | -0.4                    | 1.7                   | 1.6                   | 133            |
| M   | SB          | -0.7                     | -2.1                     | -0.3                    | 1.7                   | 1.6                   | 128            |
| M   | SB          | 0.0                      | -2.0                     | -0.5                    | 1.8                   | 1.6                   | 79             |
| M   | SB          | 0.6                      | -1.6                     | -0.2                    | 1.6                   | 1.4                   | 135            |
| M   | SB          | 1.2                      | -1.6                     | 0.1                     | 1.6                   | 1.3                   | 141            |
| M   | SB          | 1.9                      | -1.4                     | -0.3                    | 1.6                   | 1.2                   | 159            |

Notes. Uncertainties for the manual fit are estimated in ±0.3 (3 pixels) for the R.A. and decl. coordinates, ±0.3 for the $B_{maj}$ and $B_{min}$ semi-axis of the ellipses, and ±15° for the PA of the ellipses. These uncertainties were estimated from pushing the fit on several ellipses up to the limit of reasonable ellipse boundaries and conservatively adding 0.1 to the errors in position and sizes and 5° to the PAs. We do not quote the PA of the ellipse when the eccentricity $e = \frac{1 - (B_{min}/B_{maj})^2}{2} < 0.35$

$^a$ This ring is fitted automatically and manually for comparison of the results.

Figure A1. Color-scale image of the ALMA CO [J = 2 → 1] radial velocity channels from 8.8 to 0.0 km s$^{-1}$. The position of the 1.3 mm continuum peak is marked with a white star. The white dotted ellipses represent the fits carried out automatically, while the white solid ellipses show fits carried out manually (Section 3.3.2). The velocity is indicated in the upper left corner and the synthesized beam is represented by a cyan ellipse in the bottom right corner of each channel, respectively. The emission from the channels at the cloud velocity is filtered by the interferometer.
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Figure A2. Same as Figure 10 but for the radial velocity interval between 0.0 and −12.1 km s⁻¹.

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