The ALMA Survey of 70 μm Dark High-mass Clumps in Early Stages (ASHES). III. A Young Molecular Outflow Driven by a Decelerating Jet

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Abstract

We present a spatio-kinematical analysis of the CO (J = 2 → 1) line emission, observed with the Atacama Large Millimeter/submillimeter Array (ALMA), of the outflow associated with the most massive core, ALMA1, in the 70 μm dark clump G010.991–00.082. The position–velocity (PV) diagram of the molecular outflow exhibits a peculiar S-shaped morphology that has not been seen in any other star-forming region. We propose a spatio-kinematical model for the bipolar molecular outflow that consists of a decelerating high-velocity component surrounded by a slower component whose velocity increases with distance from the central source. The physical interpretation of the model is in terms of a jet that decelerates as it entrains material from the ambient medium, which has been predicted by calculations and numerical simulations of molecular outflows in the past. One side of the outflow is shorter and shows a stronger deceleration, suggesting that the medium through which the jet moves is significantly inhomogeneous. The age of the outflow is estimated to be τ ≈ 1300 yr, after correction for a mean inclination of the system of ≈57°.

Unified Astronomy Thesaurus concepts: Radio astronomy (1338); Submillimeter astronomy (1647)

1. Introduction

The jet phenomenon is ubiquitous in the universe, as it is found in many astrophysical contexts over a wide range of spatial scales. Particularly, in star-forming regions jets can drive massive molecular outflows that reveal the presence of young protostellar objects that are still accreting material from their parent clouds (see, e.g., Arce et al. 2007; Bally 2016; Lee 2020). Molecular outflows in high-mass star-forming regions have been found from the earliest stages of evolution in infrared dark clouds (IRDCs; Sanhueza et al. 2010; Wang et al. 2011; Sakai et al. 2013; Lu et al. 2015; Zhang et al. 2015; Kong et al. 2019; Li et al. 2019b; Svoboda et al. 2019) to later stages with evident signs of star formation (e.g., Beuther et al. 2002; Zhang et al. 2005; Qiu et al. 2008; Yang et al. 2018; Li et al. 2019a; Nony et al. 2020; Li et al. 2020). The study of jets and molecular outflows in the context of star formation is important since they provide crucial information on the accretion history of the central object. In addition, jets are thought to facilitate the accretion process by removing angular momentum from the disk, and, eventually, they may also play a role in quenching the accretion by dispersing the material of the parent cloud. Furthermore, the study of the physical processes behind the launching and collimation of jets in star formation is important in itself since it can contribute to better understanding the jet phenomenon in other astrophysical contexts.

A powerful tool that is commonly used to study the spatio-kinematical characteristics of jets and their associated molecular outflows is the position–velocity (PV) diagram. The PV diagrams of the outflows of low- and high-mass star-forming regions have revealed the presence of different components with specific kinematical signatures. Particularly, it has been found that many outflows exhibit components whose velocity increases with distance (so-called Hubble law). The Hubble law may appear associated with several components in such a way that they form a jagged profile, which is referred to as the Hubble wedge. The tips of the spurs of such a Hubble wedge are sometimes identified as discrete components, called knots, whose velocity decreases with distance from the central source (e.g., L1448, HH 211, CARMA-7, W43-MM1(#67); Bachiller et al. 1990; Palau et al. 2006; Hirano et al. 2006; Plunkett et al. 2015; Nony et al. 2020). These particular velocity profiles are explained in terms of internal shocks, within a collimated outflow or jet, produced by variations in the mass-loss rate, which in turn are thought to be due to variations in the mass accretion rate of the central source. Arce et al. (2007) summarized the morphologies of the spatial distributions and PV diagrams obtained from models of different types of outflows. In general, the morphology of the outflows and the shape of their corresponding PV diagrams depend on the specific details of the geometry and physical conditions of the jet, as well as those of the ambient medium. Thus, it is important to
carry out observations of molecular outflows to characterize their physical conditions and constrain the values of the input parameters of the models.

In the ALMA Survey of 70 μm Dark High-mass Clumps in Early Stages (ASHES; Sanhueza et al. 2019) we investigate the early stages of high-mass star formation using the Atacama Large Millimeter/submillimeter Array (ALMA). In a pilot survey, we carried out high angular resolution observations toward 12 massive 70 μm dark clumps. The sample was selected by combining the ATLASGAL survey (Schuller et al. 2009; Contreras et al. 2013) and a series of studies from the MALT90 survey (Foster et al. 2011; Sanhueza et al. 2012; Foster et al. 2013; Jackson et al. 2013; Guzmán et al. 2015; Rathborne et al. 2016; Contreras et al. 2017; Whitaker et al. 2017). The source selection and fragmentation properties of the sample are described in detail by Sanhueza et al. (2019).

One of the ASHES targets is the clump G10.991−00.082 (hereafter G10.99−0.08), which is located at the distance of 3.7 kpc (Pillai et al. 2006; Henning et al. 2010; Kainulainen et al. 2013; Wang et al. 2016; Sanhueza et al. 2019; Pillai et al. 2019, and references therein). This clump has no point sources detected in the near- or mid-infrared either in the GLIMPSE or in the MIPS Galactic Plane Survey (Churchwell et al. 2009; Carey et al. 2009).

Neither does it have point sources detected at 70 μm in the HiGAL survey (Molinari et al. 2010), indicating that this clump is at a very early stage of its evolution (e.g., Sanhueza et al. 2013; Tan et al. 2013; Sanhueza et al. 2017). A spectral energy distribution fitting for G10.99−0.08 gives a dust temperature of 12 K and a mass of 1810 M_☉ (Sanhueza et al. 2019). Recently, Pillai et al. (2019) presented SMA observations toward G10.99−0.08 and identified structures that seem to be molecular outflows driven by low-mass protostars. Li et al. (2020) confirmed the presence of blue- and redshifted CO emission associated with the brightest core (ALMA1; M ∼ 10 M_☉), suggesting that it is indeed driving a bipolar outflow, although, given the complexity of the emission in the region, it was not possible to characterize in detail the observed structures. Nevertheless, since G10.99−0.08 is a relatively young star-forming region, it is an attractive target that deserves further investigation to study the first stages of development of molecular outflows in a relatively massive core that has the potential to form a high-mass star in the future.

As part of the series of papers derived from the ASHES survey, here we present an analysis of the CO (J = 2 → 1) line emission observed with ALMA toward G10.99−0.08 to study in detail the morphology and kinematics of the bipolar molecular outflow associated with core ALMA1, whose PV diagram exhibits a peculiar S-shaped morphology that has not been seen in other molecular outflows before. A summary of the details of the observations used in this work is presented in Section 2. The description of the analysis of the data and the presentation of a spatio-kinematical model that explains the observations are given in Section 3. In Section 4 we discuss the physical interpretation of the spatio-kinematical model and estimate the age and energetics of the molecular outflow. In this section we also discuss the nature of the driving jet. Finally, the conclusions of this work are presented in Section 5.

2. Observations

The observations used in the present analysis were carried out on 2016 January 28, using 41 antennas of the ALMA 12 m array with Band 6 receivers (∼224 GHz; 1.34 mm) as part of the project 2015.1.01539.S (P.I.: P. Sanhueza). The array was arranged in configuration C36-1, and the maximum and minimum baseline lengths were 330 and 15 m, respectively. The corresponding angular resolution and maximum recoverable scale are 0.95 and 8.8′′, respectively. The data were calibrated manually with CASA using J1924−2914 (3.05 Jy) and J1733−1304 (1.65 Jy) as bandpass and gain calibrators, respectively. The flux was calibrated using Titan. The continuum emission was produced by averaging line-free channels in visibility space (see additional details for the continuum in Sanhueza et al. 2019). Channel maps of the CO (J = 2 → 1) line with a spectral resolution of ∼1.3 km s⁻¹ were created after subtracting the continuum emission from the data cubes. The imaging of the channel maps was performed setting the multiscale option value to 0, 5, 15, and 25 times the size of the pixel of 0′′.2. The selection of masks for cleaning was done automatically using the cleaning algorithm YCLEAN developed by Contreras et al. (2018). The Briggs weighting robust parameter was set to 0.5, which resulted in a final angular resolution for the images of 1″38 × 0″95, PA = 76° (∼0.025 pc at 3.7 kpc). The typical channel rms noise level in the resulting channel maps is ∼4 mJy beam⁻¹.

3. Data Analysis and Results

The clump G10.99−0.08 is embedded in the IRDC G11.11−0.12, as is shown in Figure 1. Pillai et al. (2019) presented observations carried out with the SMA toward G10.99−0.08, with an angular resolution of ∼4″ (∼0.07 pc at 3.7 kpc), and found hints of the presence of a molecular outflow in this clump. Particularly, in their Figure 2 there is blue- and redshifted CO (J = 2 → 1) line emission distributed in a more or less bipolar fashion and centered at the position of the brightest 1.3 mm continuum peak (core ALMA1). Li et al. (2020) confirmed the presence of such a bipolar structure, which they identified as a bipolar outflow associated with core ALMA1. The ALMA observations of the CO (J = 2 → 1) line emission presented in this work clearly reveal two bright lobes located toward the north and south of core ALMA1 (see right panel of Figure 1).

The color map in the right panel of Figure 1 is a moment-0 image of the emission integrated over the velocity range −28 < v_{LSRK}(km s⁻¹) < +104, which, as is shown below, includes all the CO (J = 2 → 1) emission associated with the bipolar outflow, and the white contours indicate the 1.3 mm continuum emission. The moment-0 image was created using only pixels with a brightness in the range 4–250 mJy beam⁻¹ to enhance the emission of the bipolar outflow; nonetheless, some extended emission from the ambient medium is also visible in the image. The black and gray contours represent velocity-integrated emission in the velocity range −28 < v_{LSRK}(km s⁻¹) < +26 and +26 < v_{LSRK}(km s⁻¹) < +104, respectively. The derived systemic velocity of the bipolar outflow is v_{sys,LSRK} = 26.1 km s⁻¹ (see below). Thus, the gas of the northern lobe is moving toward us, while the southern lobe is moving away from us.

In order to scrutinize the spatial distribution and kinematics of the bipolar lobes, we created a PV diagram using the slit indicated with parallel pink lines in Figure 2(a). The resulting PV diagram is shown in Figure 2(b). The vertical axis is the LSRK radio velocity, 14 and the horizontal axis is the position offset with respect to the position of the 1.3 mm continuum peak, (J2000) R.A. = 18h10m06s736, decl. = −19°27′45″.88.

14 LSRK stands for the local standard of rest (LSR) as a kinematic (radio) definition (J2000) based on average velocity of stars in the solar neighborhood.
The PV diagram reveals an \textit{S}-shaped feature crossed by several horizontal components. Inspection of individual channels in the data cube shows that the horizontal components are due to extended emission of the ambient gas. On the other hand, the \textit{S}-shaped feature is associated with emission from the bipolar lobes seen in Figure 2(a). It is worth noting that there is emission that extends northward and southward of the two bright lobes, which is indicated in Figure 2(a) with a dashed and a solid oval, respectively. The corresponding emission in the PV diagram is also indicated with a dashed and a solid oval (see Figure 2(b)). It can be seen that such emission does not follow the \textit{S}-shaped pattern associated with the bright lobes, implying that it is most likely arising in the gas of the ambient medium.

Interestingly, the \textit{S}-shaped pattern in the PV diagram of Figure 2(b) resembles the PV diagram of the evolved star IRAS 16342–3814 (Sahai et al. 2017; Tafoya et al. 2019). Given the similarity of those two PV diagrams, we undertook an analysis of data of G10.99–0.08 adopting the approach taken by Tafoya et al. (2019), which is described in the following.

Figure 1. Locations of the IRDC G11.11–0.12, the clump G10.99–0.08, and the core ALMA1. Left panel: three-color view of the vicinity of the IRDC G11.11–0.12 obtained with Spitzer IRAC and MIPS data with 5.8 \(\mu\)m (blue), 8.0 \(\mu\)m (green), and 24.0 \(\mu\)m (red) from the GLIMPSE and MIPS GAL surveys (Churchwell et al. 2009; Carey et al. 2009). Right panel: moment 0 of the CO \((J = 2 \rightarrow 1)\) emission integrated over the velocity range \(-28 < \nu_{\text{LSRK}} (\text{km s}^{-1}) < +104\). The image includes only pixels with a brightness in the range \(4 \text{–} 250 \text{ mJy beam}^{-1}\). The white contours indicate the 1.3 mm continuum emission. The contours are \(\text{rms} \times 2 \times i\), with \(\text{rms} = 1.5 \times 10^{-3} \text{ Jy beam}^{-1}\) and \(i = 3, 4, 5, \ldots\). The black and gray contours represent velocity-integrated emission in the velocity range \(-28 < \nu_{\text{LSRK}} (\text{km s}^{-1}) < +26\) and \(+26 < \nu_{\text{LSRK}} (\text{km s}^{-1}) < +104\), respectively. The contours are \(\text{rms} \times 2 \times i\), with \(\text{rms} = 1.8 \times 10^{-3} \text{ Jy beam}^{-1}\) and \(i = 3, 4, 5, \ldots\).

Figure 2. ALMA observations of the CO \((J = 2 \rightarrow 1)\) emission in G10.99–0.08. (a) Same as the right panel of Figure 1. (b) PV diagram of the CO \((J = 2 \rightarrow 1)\) emission obtained by using the slit indicated with parallel pink lines shown in panel (a). The horizontal axis is the position offset with respect to the position of the continuum peak of the core ALMA1, \((J2000)\) R.A. = 18\(^{h}\)10\(^{m}\)06\(^{s}\).736, decl. = −19\(^{\circ}\)27\(^{\prime}\)45\(^{\prime\prime}\).88. The ellipses indicate emission aligned in the direction connecting the northern and southern lobes but that does not follow the \textit{S}-shaped pattern associated with the bright lobes (see main text).
First, from the data cube of the CO \((J = 2 \rightarrow 1)\) line we measured the flux density and peak position of the emission associated with the bipolar lobes in every single channel within the velocity range \(-28 < v_{\text{LSRK}}(\text{km s}^{-1}) < +104\), which includes all the emission of the \(S\)-shaped pattern of the PV diagram, except the channels with significant contamination from extended emission. Given that the emission in individual channels is not well resolved, we fitted a 2D Gaussian function to obtain the peak positions. Subsequently, we calculated the separation of the emission peak positions from the peak positions of the 1.3 mm continuum, which is defined as the reference position. In Figure 3(a) we plot the decl. and R.A. offsets of the emission peak positions with respect to the reference position. The points appear clustered in two elongated structures that correspond to the northern and southern lobes. A linear fit to the distribution of points in each of the lobes reveals that while the points of the northern lobe lie on a line with P.A. \(= -8^\circ\), the points of the southern lobe lie on a line with P.A. \(= -2^\circ\). In Figure 3(b) we plot the distance of the emission peak from the reference position, \(r = \pm (\text{decl. offset}^2 + \text{R.A. offset}^2)^{1/2}\), as a function of the velocity offset with respect to the reference velocity. We took the negative solution of the square root for data points whose decl. offset is negative. Initially, the systemic velocity reported in previous works (Sanhueza et al. 2019; Pillai et al. 2019) was used as the reference velocity to calculate the velocity offsets. However, the reference velocity was later redefined in such a way that a linear fit of the green points in Figure 3(b) (see below for the definition of the coloring code) passes through the origin of the plot. The resulting reference velocity has a value of \(v_{\text{sys LSRK}} = 26.1 \text{ km s}^{-1}\), and it is defined as the systemic velocity of the outflow. The physical justification for interpreting the reference velocity in this manner is further discussed in Section 4.

In a similar way to the results obtained by Tafoya et al. (2019), the data points shown in Figure 3(b) reveal two kinematical components: one with intermediate velocity offsets, in the range \(-41 < |v_{\text{offset}}| < +48\), and whose velocity gradient is positive, i.e., \(d|v|/dr| > 0\); and another component with higher velocity offsets, in the ranges \(-54 < |v_{\text{offset}}| < -41\) and \(+48 < |v_{\text{offset}}| < +78\), and whose velocity gradient is negative. The data points in Figure 3(b) are color-coded according to their velocity gradient: green for \(d|v|/dr| > 0\) and blue-red for \(d|v|/dr| < 0\). In accordance with Tafoya et al. (2019), the kinematical component with positive velocity gradient is referred to as the “low-velocity component” (LVC), since it has relatively lower velocity offsets, and the component with negative velocity gradient, which has higher velocity offsets, is referred to as the “high-velocity component” (HVC). It is worth noting that although the LVC is represented with green color, it contains material that is both blue- and redshifted with respect to the systemic velocity. From Figure 3(a) it can be seen that, similarly to IRAS 16342–3814 (see Figure 1 of Tafoya et al. 2019), despite the different kinematical signatures of the LVC and HVC, they appear aligned in the same direction on the sky. On the other hand, the distribution of the data points in Figure 3(b) exhibits a morphology that resembles the \(S\)-shaped pattern of the emission in the PV diagram of Figure 2(b), although rotated \(90^\circ\). This is because the emission peak

\footnote{The color-coding adopted here is the same as the one used by Tafoya et al. (2019). The blue and red colors of the component with \(d|v|/dr| < 0\) indicate that the emission is blue- and redshifted with respect to the reference velocity. However, for the component with \(d|v|/dr| > 0\) only green color is used.}

**Figure 3.** Spatial and velocity distribution of the CO \((J = 2 \rightarrow 1)\) emission in G10.99–0.08. (a) Peak positions of the CO \((J = 2 \rightarrow 1)\) emission for each individual velocity channel obtained by fitting a 2D Gaussian function. The origin corresponds to the peak position of the continuum emission (see main text). The negative R.A. offsets are on the right side of the plot. (b) Position offsets from peak position of the continuum as a function of the velocity offset from the systemic velocity \(v_{\text{LSRK}} = 26 \text{ km s}^{-1}\). For both panels, the colors of the data points are coded according to their velocity gradient, \(d|v|/dr| > 0\) and blue-red for \(d|v|/dr| < 0\). The negative distance offsets correspond to data points with negative decl. offsets. The error bars represent the nominal errors from the 2D Gaussian fit.
positions lie basically along one single direction, which makes the plot of Figure 3(b) equivalent to a PV diagram.

4. A Molecular Outflow Driven by a Decelerating Jet from Core ALMA1

The simplest spatio-kinematical model that, in principle, can explain the morphology of the S-shaped seen in the PV diagram of Figure 2(b) considers a single outflow of material expanding with constant velocity and a large precession angle. In this model, the S-shaped pattern results from the projection effect of the material expanding along different directions. The resulting morphology of the outflow is also an S-shaped bipolar structure with some material moving in directions near the line of sight and some other material moving nearly on the plane of the sky (e.g., Sahai et al. 2017). However, Figure 3(a) shows that the HVC and LVC are aligned along narrow, linear structures. Thus, in order to simultaneously explain the morphologies of the PV diagram and the spatial distribution of the emission, the constant-velocity model would require a precession angle of ~90°, i.e., the outflow would need to be precessing on a plane that is oriented almost perfectly perpendicular to the plane of the sky, which is very unlikely. Furthermore, this model neglects the fact that the velocity of the gas in the outflow would depend on the hydrodynamic interaction with ambient gas.

Other typical outflow models, such as the unified wind-driven model that includes a collimated and wide opening angle wind (e.g., Shang et al. 2006; Banerjee & Pudritz 2006; Machida et al. 2008), predict PV diagrams that do not resemble the S-shaped pattern seen in Figure 2(b) (see, e.g., Hirano et al. 2010). Similarly, spatio-kinematical models such as biconical outflows (e.g., Cabrit & Bertout 1986, 1990) and expanding bipolar bubbles (e.g., Shu et al. 1991; Masson & Chernin 1992) can be easily ruled out since the resulting morphologies of their PV diagram differ from the ones seen in Figure 2(b).

Tafoya et al. (2019) demonstrated that it is possible to explain the spatial distribution and S-shaped PV diagram of the CO ($J = 2 \rightarrow 1$) line emission of the evolved star IRAS 16342−3814 with a spatio-kinematical model that includes two components: (i) a collimated high-velocity component that decelerates with distance from the central source, and (ii) a coaxial slower and less collimated component whose velocity increases with distance from the central source. As mentioned in Section 3, the outflow of core ALMA1 has components with the same kinematical characteristics as those of the evolved star IRAS 16342−3814. In addition, the morphologies of the spatial distributions and the PV diagrams of both sources exhibit remarkable similarities. Thereby, we propose that the CO ($J = 2 \rightarrow 1$) line emission of the outflow of core ALMA1 can be explained by the spatio-kinematical model presented by Tafoya et al. (2019).

The physical interpretation of the spatio-kinematical model that Tafoya et al. (2019) proposed for IRAS 16342−3814 is given in terms of a jet-driven molecular outflow in which the HVC corresponds to molecular gas entrained along the sides of the jet (steady-state entrainment; De Young 1986; Chernin et al. 1994), and the LVC is associated with entrained material that carries momentum transferred through the leading bow shock (prompt entrainment). This interpretation is supported by the results of Smith et al. (1997), who carried out numerical simulations of jet-driven bipolar outflows and obtained two kinematical components that correspond to the HVC and LVC seen in IRAS 16342−3814 and G10.99−0.08 (see their Figure 4). However, it should be noted that in their simulations the speed of the HVC remains constant across the outflow; thus, the PV diagram has a Z-shaped, instead of an S-shaped, morphology. Another piece of evidence that is consistent with the jet-driven outflow interpretation is the profile of the mass spectrum, $m(v)$, since it has been found that such outflows exhibit a power-law variation of mass with velocity, i.e., $m(v) \propto v^{-\gamma}$ (Raga & Cabrit 1993; Lada & Fich 1996; Cabrit et al. 1997, and references therein). We obtained the mass spectrum of the outflow of core ALMA1, and it is shown in Figure 4. The molecular mass was calculated using the measured flux density of the CO ($J = 2 \rightarrow 1$) emission from the outflow in channels with no contamination by emission of the ambient material. Since the blueshifted lobe seems to be suffering more contamination by emission of the ambient material, Figure 4 shows only the mass spectrum of the redshifted lobe. Optically thin emission, LTE conditions, an excitation temperature of $T_e = 12$ K (Sanhueza et al. 2019; Li et al. 2020), and a fractional abundance of CO relative to H$_2$ of $(CO)/10^{-4}$ were assumed in the calculations. The points exhibit significant spread, but they indicate that the data can be described by a double power law, $m(v) \propto v^{-\gamma}$, with $\gamma = 1.15 \pm 0.03$ (Pearson’s correlation coefficient $r = -0.78$) for $v_{\text{offset}} < 50$ km s$^{-1}$ (LVC) and $\gamma = 1.75 \pm 0.20$ ($r = -0.40$) for $v_{\text{offset}} > 50$ km s$^{-1}$ (HVC). This double power law is predicted by the numerical simulations of jet-driven bipolar outflows (Smith et al. 1997). The slopes of the power law of the outflow of core ALMA1 are slightly shallower than those of other sources (e.g., Rodriguez et al. 1982), but it has been found that the slope steepens with age and energy in the flow (Richer et al. 2000). Thus, the shallower slopes in Figure 4 would agree with the values expected for a young outflow embedded in a 70 $\mu$m dark massive clump at the early stages of high-mass star formation. Moreover, Solf (1987) proposed a similar model to explain the spatio-kinematical properties of the jet associated with the source HH24-C in the low-mass HH24 complex. As Solf (1987) mentions, the shape of the PV diagram of HH24-C, obtained from one half of the outflow, resembles that of the Greek capital letter Λ. This is exactly the shape of the PV diagram for each of the lobes of core ALMA1 (see Figure 3(b)). In addition, from Figure 3(b) it can be seen that the velocities at the tips of the lobes are the same for both HVC and LVC, strongly suggesting that there is a common mechanism that drives them simultaneously. Given all these arguments, we conclude that the bipolar lobes seen in core ALMA1 are very likely due to the presence of a young jet-driven molecular outflow.

Finally, we point out that, under this interpretation, the green points in Figure 3(b) would correspond to the entrained material whose velocity field follows a Hubble law, as is seen in several other molecular outflows. Thus, the velocity offset at the origin of the outflow is expected to be close to zero, which justifies the definition of the velocity reference given in Section 3.

4.1. Timescale of the Molecular Outflow

Figure 3(b) shows the current configuration of positions and velocities for the different parts of the molecular outflow of core ALMA1. As Tafoya et al. (2019) pointed out, this type of plot not only provides an instantaneous picture of the velocity field in the outflow at the present time and cannot be used to trace
the velocity history of the gas, unless the deceleration law as a function of time is known for each part of the outflow. Nonetheless, despite this limitation, important information of the kinematics of the outflow can be extracted by making some reasonable assumptions, which we describe in the following. From Figure 3(b) it can be seen that the blue- and redshifted parts of the HVC have material moving with a maximum velocity, \(v_{\text{max}, \text{B}, \text{R}}\), at the minimum position offset, \(r_{\text{min}, \text{B}, \text{R}}\), where the subscripts \([\text{B, R}]\) stand for the blue- and redshifted part, respectively. Correspondingly, the minimum velocity, \(v_{\text{min}, \text{B}, \text{R}}\), is reached at the maximum position offset, \(r_{\text{max}, \text{B}, \text{R}}\). This means that if one assumes that the driving jet has been launched with a constant velocity throughout its life, the material located at the tip of the jet has suffered a deceleration. Thus, using the size of the HVC and assuming a constant deceleration, the age of the outflow can be estimated. However, before attempting to estimate the age of the outflow, some considerations on its geometrical characteristics are necessary.

One characteristic of the outflow of core ALMA1 that is readily seen from Figure 3 is that the northern and southern lobes have different spatial extents, as well as different velocity offsets. While the maximum position offset for the southern lobe is \(3\text{"}7\), it is only \(2\text{"}9\) for the northern lobe. Similarly, the maximum velocity offsets for the southern and northern lobes are \(78\) and \(54\text{ km s}^{-1}\), respectively. However, these values are only projections of the position offset onto the plane of the sky and the velocity offset onto the line-of-sight direction, respectively, implying that the difference of size and velocity offset between the northern and southern lobes could be due to projection effects, i.e., one lobe may be more inclined than the other. Consequently, the inclination angles of the lobes, \([\theta_{\text{B}}, \theta_{\text{R}}]\), with respect to the plane of the sky are needed to calculate the intrinsic values of the size and velocity offset (see Figure 5(a)). In the Appendix we show that it is possible to constrain the relative inclination of the lobes, \(\theta_{\text{B}} - \theta_{\text{R}}\), which can then be used to further constrain their absolute inclination, by assuming that the launch velocity of the driving jet is the same for both lobes, i.e., \(v_{\text{LB}} = v_{\text{LR}} = v_{1}\), and that the blue- and redshifted parts of the jet have the same age, i.e., \(\tau_{\text{jet,B}} = \tau_{\text{jet,R}} = \tau\). In the following subsection, Section 4.2, we provide arguments that support these assumptions.

Using the observed values of the projected sizes and line-of-sight velocities of the lobes, it is found that their relative inclination angle is restricted to the range \(0^\circ < (\theta_{\text{B}} - \theta_{\text{R}}) < 9^\circ.5\). Furthermore, for each given value of \((\theta_{\text{B}} - \theta_{\text{R}})\), there are only two pairs of inclination angles for the lobes. For example, if \((\theta_{\text{B}} - \theta_{\text{R}}) = 1^\circ\), the inclination angles of the northern and southern lobes are either \([\theta_{\text{B}} = 85^\circ, \theta_{\text{R}} = 84^\circ]\) or \([\theta_{\text{B}} = 3^\circ, \theta_{\text{R}} = 2^\circ]\) (see Table 2). This means that if we assume that the lobes are almost aligned with each other, their axis would lie basically either on the line-of-sight direction or on the plane of the sky. However, this is an unlikely configuration since it would imply either unrealistic initial velocities and extremely short kinematical timescales or too large sizes for the lobes (see Table 2). On the other hand, if one considers an average inclination of the lobes equal to the mean inclination angle, \((\theta_{\text{B}} + \theta_{\text{R}})/2 = 57^\circ.3\) (e.g., Bontemps et al. 1996; Beuther et al. 2002; de Villiers et al. 2014), Equation (2) gives a relative angle of \((\theta_{\text{B}} - \theta_{\text{R}}) \approx 6^\circ\), and the resulting age and size of the outflow are \(\approx1300\text{ yr and }\approx0.2\text{ pc, respectively (see Figure 5(b)).}

### 4.2. Energetics of the Molecular Outflow

From Table 2 it can be seen that, regardless of the relative inclination between the lobes, the final velocity of the northern lobe, \(v_{\text{LR}}\), is lower than that of the southern lobe, \(v_{1,\text{LR}}\). This difference could simply be indicating that the southern part of the jet is intrinsically faster than the northern part, or it could be indicating that the latter is preferentially decelerated by ambient material. One way of investigating whether the initial velocities and ages for both parts of the jet are indeed equal or not is by means of comparing the momentum and mechanical force carried by the lobes. If the launch velocities and ages are the
same for both parts of the jet, the momentum and mechanical force for both lobes should be the same too.

In order to calculate the energetics of the molecular outflow of core ALMA1, we followed the same procedure as Tafoya et al. (2019). First, we assumed that all the velocity vectors within each lobe are parallel to the outflow axis; thus, their de-projected magnitude is \( v = \frac{v_{\text{offset}}}{\sin \theta_{\text{inc}}} \). We adopted an inclination of the lobes \( \theta_{\text{N}} = 54^\circ \), \( \theta_{\text{S}} = 60^\circ \), which, as discussed in Section 4.1, results in an age of the outflow of \( \tau_{\text{jet}} = 1300 \) yr. Subsequently, we calculated the values of the physical parameters shown in Table 1 for each individual velocity channel, \( i \), assuming LTE conditions, optically thin emission, and an excitation temperature in the range \( T_{\text{ex}} = 10-30 \) K. Finally, we added the values of the channels that correspond to a particular component, namely, northern lobe, southern lobe, HVC, and LVC. The entrainment rate, \( \dot{M} \), mechanical force, \( F_m \), and mechanical luminosity, \( L_m \), were calculated using the times that it takes for the gas to move from \( r_{\text{min,B,R}} \) to \( r_{\text{max,B,R}} \), which are estimated to be 850 and 800 yr for the red- and blueshifted lobe, respectively. The resulting values of the physical parameters are listed in Table 1. The derived molecular mass for the outflow is lower than the one estimated by Pillai et al. (2019), but their observations had lower angular resolution and were more affected by contamination of emission of the ambient material. As a matter of fact, in our analysis we do not consider the emission at the base of the outflow because of contamination of emission of the ambient material (see Figure 2(b)). Thus, the values of the molecular mass shown in Table 1 should be considered as lower limits. Nevertheless, using the mass (\( M \sim 10M_\odot \); Sanhueza et al. 2019; Pillai et al. 2019) and bolometric luminosity (\( L_{\text{bol}} \sim 470L_\odot \))\(^{17} \) for core ALMA1, and taking our estimation of the total mechanical force from Table 1, which is a dynamical quantity that is not significantly affected by a poor sampling of the outflow, we find that core ALMA1 follows the mechanical force versus core mass and bolometric luminosity correlations obtained from molecular outflows in low- and high-mass star-forming regions (see Figure 6).

In addition, the values of the momentum and mechanical force for the northern and southern lobes listed in Table 1 are, within the uncertainty range, basically the same. Thus, we conclude that, even though the final velocities of the northern and southern lobes are different, they must have been ejected simultaneously and with the same initial velocity, as suggested in Section 4.1.

### 4.3. Nature of the Deceleration of the HVC

There are now a plethora of observations of molecular outflows in low- and high-mass star-forming regions that have revealed a rich variety of spatio-kinematical properties (e.g., Bachiller 1996; Arce et al. 2007; Kong et al. 2019; Zapata et al. 2019; Nony et al. 2020; Lee 2020; Li et al. 2020). As mentioned before, it is common that collimated molecular outflows exhibit components with a Hubble law velocity profile and/or complex Hubble wedges, some of which may contain decelerating knots (e.g., Bachiller et al. 1990; Plunkett et al. 2015; Nony et al. 2020). Nevertheless, to the best of our knowledge, there has not been reported in the literature any other molecular outflow in a star-forming region whose PV diagram has the \( S \)-shaped morphology seen in G10.99–0.08. Particularly, the part of the PV diagram that corresponds to the decelerating HVC, which we interpret as entrained material along the sides of the jet, is not seen in other outflows. One

\(^{17} \)The luminosity is derived following Equation (3) of Contreras et al. (2017).
may wonder what is the origin of the deceleration of the HVC and what are the particular physical conditions of the molecular outflow of core ALMA1 that result in such a peculiar PV diagram. The driving jet of the outflow, in principle, could be launched magnetocentrifugally, as is proposed in the unified wind-driven model (Shang et al. 2006), although without the wide opening angle component (or with one that is too weak to be detected). Given the short age of the outflow of ALMA1 (~1000 yr), it could be argued that the presence of the decelerating HVC occurs mainly at an early phase of the outflow when there is more material available to be entrained along the sides of the jet, i.e., the jet has not completely cleared out the inner parts of the lobes. However, similar timescales have been estimated for outflows of cores with a wide range of masses (1–100 \( M_\odot \); Nony et al. 2020), and they do not show the S-shaped morphology seen in the outflow of core ALMA1. Consequently, the short age of the outflow does not seem to be the only factor for having such a PV diagram. Chemin et al. (1994) found that a jet with Mach number \( \leq 6 \) slows down rapidly by delivering energy and momentum as it entrains ambient material along its sides, which would account for the deceleration of the HVC. We thus propose that the observed deceleration of the HVC is likely due to the presence of a jet with a low Mach number that decelerates as it interacts with the ambient material. We also note that, given that the energetics of the outflow of core ALMA1 do not deviate from the trend seen in other outflows (Bontemps et al. 1996; Beuther et al. 2002; Zhang et al. 2005), future observations with high angular resolution should reveal more outflows with characteristics similar to that of G10.99–0.08.

On the other hand, we have so far assumed that the driving jet has been launched with a constant velocity throughout its life. However, an alternative possibility that could explain the observed deceleration of the HVC is that the parts of the jet launched at earlier times (the ones farther away from the protostar) were ejected at a lower velocity than those launched at later times (the ones closer to the protostar). This interpretation would imply that the jet is not ejected at a constant velocity, possibly shedding some light on the mass accretion rate of the protostar, as we describe in the following. Since we do not know exactly the evolutionary stage of the protostar on the pre-main-sequence track, we assume that the accreting protostar is at zero-age main sequence (ZAMS) for the sake of estimating its mass. Considering the bolometric

![Figure 6](image.png)

Figure 6. Mechanical force as a function of bolometric luminosity. The plot has been adapted from Figure 7 of Maud et al. (2015), Figure 4 of Beuther et al. (2002), and Figure 4 of Zhang et al. (2005). The blue asterisk indicates the value for the outflow of core ALMA1.

### Table 1

| Component Designation | \( M_p \) (\( M_\odot \)) | \( p \) (\( M_\odot \) km s\(^{-1}\)) | \( E_\nu \) (erg) | \( M_p \) (\( M_\odot \) yr\(^{-1}\)) | \( F_m \) (\( M_\odot \) km s\(^{-1}\) yr\(^{-1}\)) | \( L_m \) (\( L_\odot \)) |
|-----------------------|----------------|----------------|----------------|----------------|----------------|----------------|
| HVC                   | (1.7–2.0) \( \times 10^{-3} \) | (1.1–1.3) \( \times 10^{-1} \) | (7.1–8.5) \( \times 10^{31} \) | (1.9–2.3) \( \times 10^{-6} \) | (1.2–1.5) \( \times 10^{-4} \) | (6.9–8.2) \( \times 10^{-4} \) |
| LVC                   | (2.6–3.6) \( \times 10^{-3} \) | (0.9–1.2) \( \times 10^{-1} \) | (3.2–4.2) \( \times 10^{31} \) | (3.0–4.2) \( \times 10^{-6} \) | (1.0–1.4) \( \times 10^{-4} \) | (3.1–4.0) \( \times 10^{-4} \) |
| Northern Lobe         | (2.2–3.0) \( \times 10^{-3} \) | (1.0–1.2) \( \times 10^{-1} \) | (4.6–5.7) \( \times 10^{31} \) | (2.5–3.4) \( \times 10^{-6} \) | (1.1–1.4) \( \times 10^{-4} \) | (4.3–5.3) \( \times 10^{-4} \) |
| Southern Lobe         | (2.0–2.7) \( \times 10^{-3} \) | (1.0–1.2) \( \times 10^{-1} \) | (5.8–7.0) \( \times 10^{31} \) | (2.4–3.2) \( \times 10^{-6} \) | (1.2–1.5) \( \times 10^{-4} \) | (5.7–6.9) \( \times 10^{-4} \) |
| Combined              | (4.2–5.7) \( \times 10^{-3} \) | (2.0–2.4) \( \times 10^{-1} \) | (1.0–1.3) \( \times 10^{34} \) | (4.9–6.6) \( \times 10^{-6} \) | (2.3–2.9) \( \times 10^{-4} \) | 1.0–1.2 |

Note. The values were calculated assuming an inclination of the northern and southern lobes \( \theta_R = 54^\circ \) and \( \theta_B = 60^\circ \), respectively, and an excitation temperature in the range \( T_{ex} = 10–30 \) K. The physical parameters are computed as follows: \( M_p = \sum M_i \), \( p = \sum M_i v_i \), \( E_\nu = \sum (M_i v_i^2) / 2 \), \( M = \sum M_i / \Delta \tau \), \( F_m = p / \Delta \tau \), and \( L_m = E_\nu / \Delta \tau \), where the subscript \( i \) is the channel number and \( \Delta \tau \) is the time that it takes the gas to move from \( r_{min}[(B,R)] \) to \( r_{max}[(B,R)] \).
understand the physical characteristics of molecular outflows, and ignoring the contribution of the accretion luminosity $L_{\text{acc}}$, i.e., $L_{\text{acc}} < L_\star$, which is valid for more massive stars with typical accretion rates, the ZAMS mass of the star would be $M_{\text{ZAMS}} \approx 5 M_\odot$ (Schaller et al. 1992). This implies that the current mass of the protostar is $\lesssim 5 M_\odot$, assuming that all the luminosity from the clump is produced by a single protostar. Typically, one can consider that the initial velocity of the jet is comparable to the Keplerian velocity of the accretion disk at the jet launching location (Pelletier & Pudritz 1992). Therefore, the increase in jet speed over time would imply an increase in dynamical mass of the central object over time, if assuming that the jet is launched at the same location (see, e.g., Figure 6 from Rosen & Krumholz 2020). Based on the velocity differences seen in Figure 3, the increase of dynamical mass, which is proportional to $(v_{\text{max}}/v_{\text{min}})^2$, would be a factor of 2–3 times the initial mass. This would mean that there has been a significant increase in protostellar mass over the timescale of $\sim 1000$ yr, implying an upper limit for the mass accretion rate of $\lesssim 2 \times 10^{-3} M_\odot$ yr$^{-1}$. This value is rather large considering the physical parameters of the outflow listed in Table 1, which makes it unlikely that the increase of the jet speed over time is due only to the increase in dynamical mass of the central object. Nonetheless, the combined effect of not having a constant launch velocity together with deceleration of the jet by the entrained material may explain the $S$-shaped PV diagram of this source.

In order to further explore these possibilities and to better understand the physical characteristics of molecular outflows that exhibit a decelerating HVC, observations with higher angular resolution, together with new models and numerical simulations, will be crucial. Recently, Tafoya et al. (2020) obtained high-resolution images with ALMA of a jet-driven molecular outflow in the evolved star W43A, which also exhibits an $S$-shaped PV diagram. The sharp images allowed them to clearly disentangle the different components of the molecular outflow, revealing an extremely collimated decelerating HVC. Future observations with higher angular resolution may allow us to unveil the structure of the molecular outflow of core ALMA1 too.

5. Conclusions

In this work we have carried out a spatio-kinematical analysis of the CO ($J = 2 \rightarrow 1$) line emission of the molecular outflow associated with the relatively massive core ALMA1 embedded in G10.99–0.08. The PV diagram has a peculiar $S$-shaped morphology that is explained by means of two components with different kinematical characteristics: an inner axial high-velocity component that moves with high velocity but decelerates, and a coaxial component moving with lower velocity but whose velocity increases with distance from the central source. The spatio-kinematical model is interpreted as a jet-driven molecular outflow. The high-velocity decelerating component is associated with material moving near in the axis of the flow entrained by the underlying jet, or it could be the molecular component of the jet itself. The lower-velocity component is interpreted as material lying in zones farther away from the axis of the flow ambient, but because of the entrainment by the inner gas it appears as if it was being accelerated. This interpretation is supported by the mass spectrum derived from the emission of the molecular gas. From an analysis of the PV diagram profile we conclude that there is a relative angle between the axis of the blue- and redshifted lobes. Assuming an overall mean inclination angle of the outflow of $\approx 57^\circ$, the relative angle between the lobes is $\approx 6^\circ$. For such an inclination, the resulting age and size of the outflow are $\approx 1300$ yr and $\approx 0.2$ pc, respectively. Further calculations and numerical simulations are necessary to better understand the physical characteristics of molecular outflows that have $S$-shaped PV diagrams. In addition, higher angular resolution observations are necessary to better constrain the input parameters of the models.

Finally, we stress the fact that molecular outflows with very similar spatio-kinematical characteristics to those of the outflow of core ALMA1 are seen in evolved stars too. This shows that, despite being found in different astrophysical contexts, molecular outflows may be studied with a unified approach, which encourages us to develop more synergies between different fields of astronomy to broaden our knowledge on the physical processes underlying their formation and evolution.

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Appendix

Consider the jet of core ALMA1, traced by the emission of the HVC, moving along a direction that has an inclination angle $\theta_{B,R}$ with respect to the plane of the sky, where the subscripts B and R indicate the blue- and redshifted part of the jet, respectively (see Figure 7). If both parts of the jet were launched with the same initial velocity, $v_i$, and the material at the tip of the jet has slowed down with a constant deceleration to a final velocity, $v_{f,B,R}$, over a distance, $l_{B,R}$, then the travel time (i.e., the age for each part of the jet), $\tau_{\text{jet} [B,R]}$, is given by

$$\tau_{\text{jet}, [B,R]} = \frac{2 l_{B,R}}{v_i + v_{f,[B,R]}}. \quad (1)$$

Assuming that the blue- and redshifted parts of the jet were launched simultaneously, i.e., $\tau_B = \tau_R$, and considering from Figure 3 that $l_{B,R} = r_{\text{max},[B,R]}/\cos \theta_{B,R}$ and $v_{f,[B,R]} = v_{\text{min},[B,R]}/\sin \theta_{B,R}$, one obtains the following equation:

$$\frac{2 r_{\text{max},B}/\cos \theta_B}{v_i + v_{\text{min,B}}/\tan \theta_B} = \frac{2 r_{\text{max},R}/\cos \theta_R}{v_i + v_{\text{min,R}}/\tan \theta_R}. \quad (2)$$

Since the redshifted part of the jet seems to have suffered less deceleration, the launch velocity can be approximated as $v_i \approx v_{\text{max,R}}/\sin \theta_R$ and the inclination angle can be solved
Table 2

Inclination Angle and Spatio-kinematical Parameters of the Blue- and Redshifted Jets in Core ALMA1

| (θ_B − θ_R) (deg) | Solution | θ_B (deg) | θ_R (deg) | v_i (km s⁻¹) | v_min (B,R) (km s⁻¹) | v_max (B,R) (km s⁻¹) | l_B (10¹⁷ cm) | l_R (10¹⁷ cm) | τ (yr) |
|-------------------|----------|-----------|-----------|-------------|----------------------|----------------------|-----------------|----------------|-------|
| 1                 | Sol. 1   | 84        | 85        | 80          | 80                   | 48                   | 41              | 17.7           | 18.8  | 9240  |
|                   | Sol. 2   | 2         | 3         | 2292        | 1375                 | 783                  | 1.54            | 1.96           | 34    |       |
| 2                 | Sol. 1   | 78        | 80        | 82          | 49                   | 42                   | 8.86            | 9.43           | 4569  |       |
|                   | Sol. 2   | 2         | 4         | 2292        | 1375                 | 588                  | 1.54            | 1.96           | 34    |       |
| 3                 | Sol. 1   | 72        | 75        | 84          | 50                   | 42                   | 5.95            | 6.34           | 2989  |       |
|                   | Sol. 2   | 3         | 6         | 1529        | 917                  | 392                  | 1.55            | 1.96           | 51    |       |
| 4                 | Sol. 1   | 66        | 70        | 88          | 53                   | 44                   | 4.50            | 4.82           | 2181  |       |
|                   | Sol. 2   | 4         | 8         | 1147        | 688                  | 295                  | 1.55            | 1.96           | 68    |       |
| 5                 | Sol. 1   | 60        | 65        | 92          | 55                   | 45                   | 3.64            | 3.92           | 1682  |       |
|                   | Sol. 2   | 6         | 11        | 765         | 459                  | 215                  | 1.57            | 1.97           | 102   |       |
| 6                 | Sol. 1   | 54        | 60        | 99          | 59                   | 47                   | 3.08            | 3.33           | 1337  |       |
|                   | Sol. 2   | 7         | 13        | 656         | 394                  | 182                  | 1.58            | 1.97           | 119   |       |
| 7                 | Sol. 1   | 48        | 55        | 108         | 65                   | 50                   | 2.68            | 2.93           | 1079  |       |
|                   | Sol. 2   | 9         | 16        | 511         | 307                  | 149                  | 1.60            | 1.98           | 154   |       |
| 8                 | Sol. 1   | 41        | 49        | 122         | 73                   | 54                   | 2.35            | 2.60           | 844   |       |
|                   | Sol. 2   | 11        | 19        | 419         | 252                  | 126                  | 1.63            | 2.00           | 189   |       |
| 9                 | Sol. 1   | 33        | 42        | 147         | 88                   | 61                   | 2.07            | 2.34           | 631   |       |
|                   | Sol. 2   | 16        | 25        | 290         | 174                  | 97                   | 1.70            | 2.04           | 278   |       |

Note.

* For each value of (θ_B − θ_R) there are two possible combinations of solutions for θ_B and θ_R and the respective physical parameters derived from them.

Figure 7. Diagram of the configuration of the blue- and redshifted parts of the jet in the molecular outflow of G10.99-0.08. The initial velocity of the jet, v_i, is assumed to be the same for both parts. The observer is located on the left part of the diagram.

Numerically θ_B = θ_R(θ_B) from Equation (2). Using the numerical values of v_{max,B,R}, v_{min,B,R}, and v_{max,R} from Figure 3, it is found that Equation (2) has real solutions only for 0° < (θ_B − θ_R) < 9°5. Therefore, it can be concluded that the relative inclination angle of the northern and southern lobes is less than 9°5. Furthermore, for a given difference, (θ_B − θ_R), there are only two possible pairs of angles, θ_{R,B}, that solve Equation (2). The values of θ_{R,B} for given values of (θ_B − θ_R) are listed in Table 2. From Table 2 it can be seen that for (θ_B − θ_R) = 0°, both θ_{R,B} are close to either 0°, which would imply an initial velocity for the jet of ~2000 km s⁻¹, or 90°, which results in total length of the outflow of ~0.6 pc. It is worth noting that for the relative angle (θ_B − θ_R) ≈ 9°5 there is only one pair of angles that solves Equation (2), [θ_R = 20°, θ_B = 29°5], which would imply an age of the outflow of τ = 350 yr.

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