ALMA Observations and Modeling of the Rotating Outflow in Orion Source I

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Abstract

We present 29SiO (J = 8–7) ν = 0, SiS (J = 19–18) ν = 0, and 28SiO (J = 8–7) ν = 1 molecular line archive observations made with the Atacama Large Millimeter/Submillimeter Array (ALMA) of the molecular outflow associated with Orion Source I. The observations show velocity asymmetries about the flow axis that are interpreted as outflow rotation. We find that the rotation velocity (∼4–8 km s⁻¹) decreases with the vertical distance to the disk. In contrast, the cylindrical radius (∼100–300 au), the expansion velocity (∼2–15 km s⁻¹), and the axial velocity vz (∼10 km s⁻¹) increase with the vertical distance. The mass estimated of the molecular outflow Moutflow ∼ 0.66–1.3 M⊙. Given a kinematic time ∼130 yr, this implies a mass-loss rate Moutflow ∼ 5.1 × 10⁻³ M⊙ yr⁻¹. This massive outflow sets important constraints on disk wind models. We compare the observations with a model of a shell produced by the interaction between an anisotropic stellar wind and an Ulrich accretion flow that corresponds to a rotating molecular envelope in collapse. We find that the model cylindrical radii are consistent with the 28SiO(J = 8–7) ν = 0 data. The expansion velocities and the axial velocities of the model are similar to the observed values, except for the expansion velocity close to the disk (z ∼ ±150 au). Nevertheless, the rotation velocities of the model are a factor of ∼3–10 lower than the observed values. We conclude that the Ulrich flow alone cannot explain the rotation observed and other possibilities should be explored, like the inclusion of the angular momentum of a disk wind.

Unified Astronomy Thesaurus concepts: Stellar winds (1636); Protostars (1302); Stellar accretion (1578)

1. Introduction

Molecular outflows and protostellar jets are present in the star formation process and appear to be more powerful and collimated during the earliest phases of young stellar sources (e.g., Bontemps et al. 1996); however, their origin is debated. Two scenarios are proposed to explain the formation of the molecular outflows. In the first case, several authors (e.g., Pudritz & Norman 1986; Launhardt et al. 2009, and Pech et al. 2012) propose that the molecular outflows are ejected directly from the accretion disk. Other authors suggest (e.g., Shu et al. 1991; Cantó & Raga 1991, and Raga & Cabrit 1993) that the molecular outflows are a mixture between the entrained material from the molecular cloud and a fast stellar wind.

The magnetocentrifugal mechanism (Blandford & Payne 1982) is the principal candidate for producing jets and stellar winds (see reviews by Königl & Pudritz 2000 and Shu et al. 2000). In this mechanism, the rotating magnetic field anchored to the star-disk system drives and collimates these winds (Pudritz et al. 2007; Shang et al. 2007). Nevertheless, it is not clear where the magnetic fields are anchored to the disk. The magnetocentrifugal mechanism has two different origins: X wind (Shu et al. 1994) and disk winds (Pudritz & Norman 1983). In the first model, these winds are launched close to the star, from the radius where the stellar magnetosphere truncates the disk. In the second model, these winds come from a wider range of radii. Anderson et al. (2003) found a general relation between the poloidal and toroidal velocity components of the magnetocentrifugal winds at large distances and the rotation velocity at the ejection point. Therefore, the observed rotation velocity of the jet could provide information about its origin on the disk.

In recent years, evidence of the rotation in protostellar jets and the molecular outflows has been found. For example, the jets HH 211 (Lee et al. 2009) and HH 212 (Lee et al. 2017) show signatures of rotation of a few km s⁻¹. Molecular outflows with signatures of rotation are as follows: CB 26 (Launhardt et al. 2009), Ori-S6 (Zapata et al. 2010), HH 797 (Pech et al. 2012), DG Tau B (Zapata et al. 2015), Orion Source I (Hirota et al. 2017), HH 212 (Tabone et al. 2017), HH 30 (Louvet et al. 2018), and NGC 1333 IRAS 4C (Zhang et al. 2018).

Zapata et al. (2015) argued that slow winds ejected from large disk radii do not have enough mass, thus these winds cannot account for the observed linear and angular momentum rates of the molecular outflow of DG Tau B. Their argument assumed that the mass-loss rate of the wind is a small fraction f ∼ 0.1 of the disk mass accretion rate (Mw ∼ fMd). Nevertheless, recent non-ideal magnetohydrodynamic simulations of magnetized disk winds show that this fraction can be very large, f ∼ 1–2 (e.g., Bai & Stone 2017; Wang et al. 2019). However, massive disk winds could pose a problem for the disk lifetime. The mass of the disk of DG Tau B is Mw ∼ 0.068M⊙ (Guilloteau et al. 2011). Given the observed outflow mass-loss rate 1.7–2.9 × 10⁻⁷M⊙ yr⁻¹ (de Valon et al. 2020), the disk lifetime is t = Mw/Md, where fMw/Md, where f ∼ (2 – 4) × 10⁵ yr. Depending on the value of f, the disk lifetime could be smaller than the age of DG Tau B, which has been catalogued as a Class I/II source (Hartmann et al. 2005; Luhman et al. 2010).

The large masses of the molecular outflows can be explained if the outflow is formed mainly by entrained material from the parent cloud. López-Vázquez et al. (2019; hereafter LV19) modeled the molecular outflow as a thin shocked shell, formed by the collision between an anisotropic stellar wind and a rotating molecular cloud in collapse, as described by Ulrich (1976). They found that the mass of the molecular outflow probably comes from the parent cloud, but the angular
momentum could come from both the stellar wind and the parent cloud.

Located at the center of the Kleinmann-Low Nebula in Orion, at a distance ~418 ± 6 pc (Kim et al. 2008), the Orion Source I (Orion Src I) is a candidate high-mass ($M_\star > 8 M_\odot$) star (Hirota et al. 2014; Plambeck & Wright 2016; Hirota et al. 2017; Ginsburg et al. 2018). The central object of Orion Src I has a high luminosity ~$10^4 L_\odot$ (Menten & Reid 1995; Reid et al. 2007; Testi et al. 2010). The bipolar outflow presents low radial velocities (~18 km s$^{-1}$) along the northeast–southwest direction, with a size ~1000 au (Plambeck et al. 2009; Zapata et al. 2012; Greenhill et al. 2013). This source has a proper motion with respect to the nebula center of $\mu_\alpha \cos \delta = +2.9 \pm 0.4$ mas yr$^{-1}$ and $\mu_\delta = -5.4 \pm 0.4$ mas yr$^{-5}$, where the angle $\delta \sim -5^\circ$ (Rodríguez et al. 2017). In fact, the Orion Kleinmann-Low Nebula exhibits evidence of a violent explosive phenomenon (e.g., Bally & Zinnecker 2005; Gómez et al. 2008; Zapata et al. 2009; Bally et al. 2017; Zapata et al. 2017). The proper motions of the sources L, BN, and N reveal that this explosion appears to have taken place 500 yr ago (e.g., Luhman et al. 2017; Rodríguez et al. 2017).

We present archival $^{29}$SiO ($J=8−7$) $\nu=0$, SiS ($J=19−18$) $\nu=0$, and $^{28}$SiO ($J=8−7$) $\nu=1$ line observations, made with the Atacama Large Millimeter/Submillimeter Array (ALMA) of the molecular outflow associated with the young star Orion Src I. We also compare the observational results with the thin shell model of LV19. The paper is organized as follows. Section 2 details the observations. In Section 3 we present our observational results and compare with the outflow model. Finally, the conclusions are presented in Section 4.

2. Observations

The archival observations of Orion Src I were carried out with the Atacama Large Millimeter/Submillimeter Array (ALMA) in band 7 on 2016 October 31 and 2014 July 26 as part of the programs 2016.1.00165.S (P.I. John Bally) and 2012.1.00123.S (P.I. Richard Plambeck), respectively. At that time, the array counted with 31 (2014) and 42 (2016) antennas with a diameter of 12 m, yielding baselines with projected lengths from 33 to 820 m (41−1025 kλ) and 18 to 1100 m (22−1375 kλ), respectively. The primary beam at this frequency has an FWHM of about 20′, so that in both observations the molecular emission from the outflow of Orion Src I falls well inside this area.

The integration time on-source was about 25 min, and 32 min was used for calibration for the 2014 observations, while for the 2016 observations it was about 13 min on-source, and 37 min for calibration. The ALMA digital correlator was configured with four spectral windows centered at 353.612 GHz (spw0), 355.482 GHz (spw1), 341.493 GHz (spw2), and 343.363 GHz (spw3), with 3840 channels and a space channel of 488.281 kHz or about 0.4 km s$^{-1}$ for the 2014 observations and at 344.990 GHz (spw0), 346.990 GHz (spw1), 334.882 GHz (spw2), and 332.990 GHz (spw3) with 1920 channels and a space channel of 976.562 kHz, or about 0.8 km s$^{-1}$ for the 2016 observations. The spectral lines reported on this study were found in the spw2 ($^{29}$SiO) of the 2014 observations and the spw0 (SiO and SiS) of the 2016 observations (see Table 1).

For both observations, the weather conditions were reasonably good and stable for these high frequencies. The observations used the quasars J0510 + 1800, J0522−3627, J0527 + 0331, J0532−0307, J0607−0834, J0423−013 and J0541−0541 for amplitude, phase, bandpass, pointing, water vapor radiometer, and atmosphere calibration.

The data were calibrated, imaged, and analyzed using the Common Astronomy Software Applications (CASA Version 5.1). The resulting image rms noises for the spectral lines were about 10 mJy Beam$^{-1}$ (SiO and SíS) at an angular resolution of 0.199′ × 0.14′′ with a PA of −63° and about 20 mJy Beam$^{-1}$ ($^{28}$SiO) at an angular resolution of 0.30′′ × 0.24′′ with a PA of +58°. Self-calibration was attempted on the continuum; however, we did not obtain a relatively good improvement in the line maps.

3. Results and Discussion

Hirota et al. (2017) present observational results with ALMA at 50 au resolution from the emission of the $^{18}$O and H$_2$O molecular lines of the molecular outflow of Orion Src I. These lines trace the inner part of the molecular outflow. In contrast, the archive observations used in this work trace the outer part of the molecular outflow, because this improves an easy comparison with the thin shell model of LV19.

3.1. Results from the Observations

Figure 1 presents the first moment or the intensity-weighted velocity of the emission from the three molecular lines, $^{28}$SiO ($J=8−7$) $\nu=0$ (panel (a)), SiS ($J=19−18$) $\nu=0$ (panel (b)), and $^{28}$SiO ($J=8−7$) $\nu=1$ (panel (c)). These panels show that the east side of the molecular outflow presents blueshifted velocities, while the west side presents redshifted velocities. This difference in the velocity is interpreted as rotation around the outflow axis (Hirota et al. 2017). Moreover, Figure 1 indicates that the molecular outflow is not on the plane of the sky, i.e., the outflow has an inclination angle $i \neq 0^\circ$. At the lower edge of the outflow (left and middle panels), the molecular outflow has velocities of the order of 12 km s$^{-1}$; this high velocity with respect to the local standard of rest velocity $V_{LSR} = 5$ km s$^{-1}$ (Plambeck & Wright 2016) can be explained as the axial velocity. Here we assume an inclination for the outflow of $i = 10^\circ$, which is similar to the value reported by Plambeck & Wright (2016), Hirota et al. (2017), and Báez-Rubio et al. (2018). In addition, in panels (a) and (b), note that the size of the molecular outflow is ~1400 au. Panel (c) shows that the molecular line of $^{28}$SiO ($J=8−7$) $\nu=1$ traces the innermost part of the molecular outflow of Orion Src I. Figure 1 also shows the 1.3 mm continuum emission (in white contours) from Orion Src I. This continuum emission traces the disk surrounding this source; see Hirota et al. (2017) and Plambeck & Wright (2016).

The position–velocity diagrams of the emission from the molecular line of $^{28}$SiO ($J=8−7$) $\nu=0$ are shown in Figure 2. This figure presents parallel cuts at different distances from the cloud. The data were calibrated, imaged, and analyzed using the Common Astronomy Software Applications (CASA Version 5.1). The resulting image rms noises for the spectral lines were about 10 mJy Beam$^{-1}$ (SiO and SíS) at an angular resolution of 0.199′ × 0.14′′ with a PA of −63° and about 20 mJy Beam$^{-1}$ ($^{28}$SiO) at an angular resolution of 0.30′′ × 0.24′′ with a PA of +58°. Self-calibration was attempted on the continuum; however, we did not obtain a relatively good improvement in the line maps.

![Image](image_url)
disk midplane; these cuts were made from $z = 480$ au to $z = -480$ au with intervals of 80 au (see the dashed lines in panel (a) of Figure 1). Note that in regions near the disk, this molecule fills the molecular outflow, while for regions far from the disk, this molecule presents a thin shell structure in expansion. In addition, one can observe that all position–velocity diagrams present signatures of the rotation (see panel (a) of Figure 5).

In Figure 3 we present an analysis similar to that of Figure 2 for the emission from the molecular line of SiS ($J = 19–18$) $\nu = 0$. The position–velocity diagrams show a thin shell structure where the emission from this molecule is very prominent. The width of the shell is $\Delta r \sim 120$ au, which is $\sim 1/3$ of the distance to the central star. This molecule shows that the outflow is in expansion because the size of the thin shells increases with the distance from the disk. In these
the excitation temperature. With these values, we obtain

\[ T_{\text{ex}} = \frac{h\nu/k}{\ln(1 + \frac{hv/k}{T_{\text{bg}} - T_{\text{ex}}})} \]  \hspace{1cm} (1)

where \( h \) is the Plank constant, \( k \) is the Boltzmann constant, \( \nu \) is the rest frequency in GHz (see Table 1), \( T_{\text{ex}} \) is the observed antenna temperature of \( ^{28}\text{SiO} \), and \( T_{\text{bg}} \) is intensity in units of temperature at the background temperature \( T_{\text{bg}} = 2.7 \text{ K} \). Using the value of \( \nu \) given in Table 1, we obtain \( T_{\text{ex}} \) for \( ^{29}\text{SiO} \). Assuming that the \( ^{28}\text{SiO} \) and \( ^{29}\text{SiO} \) molecules coexist and share the same excitation temperature, \( T_{\text{ex}} \) is the intensity in units of temperature at the background temperature \( T_{\text{ex}} \) for the same heights and the same velocities. The horizontal dashed line shows the value of the LSR velocity of the source. The vertical dashed lines represent the cylindrical radius \( r_{\text{cyl}} \) defined in Figure 6. The solid line in each panel indicates the rotation signature.

diagrams the rotation of the molecular outflow is confirmed. The biggest rotation velocity corresponds to height of \( z = 80 \text{ au} \) (see panel (b) of Figure 5).

Figure 4 shows the position–velocity diagrams of the emission from the molecular line \( ^{28}\text{SiO} \) (\( J = 8–7 \) \( \nu = 1 \)) for the same distances from the disk midplane of Figures 2 and 3. In contrast to the other two molecules, in this molecular line the thin shell structure does not appear. This figure confirms the presence of rotation in the molecular outflow (see panel (c) of Figure 5). The absence of the emission for distances of \( z \geq 320 \text{ au} \) means that this molecule is only tracing the inner part of the molecular outflow. This may be due to excitation conditions.

Hirota et al. (2017) measured the rotation velocities for heights between \( z = 200 \text{ au} \) and \( z = 200 \text{ au} \), and they found that these velocities decrease with the height and have values between \( \sim 3–9 \text{ km s}^{-1} \). In this work, we reported rotation velocities for the same heights of the order of \( 4–8 \text{ km s}^{-1} \), these values are similar to those reported by these authors.

Finally, Figure 5 clearly shows evidence of the rotation and the expansion in Orion SFC. In this figure, we zoom into the position–velocity diagrams of Figures 2–4 at a distance of \( z = 80 \text{ au} \) from the disk for the molecular lines of \( ^{28}\text{SiO} \) (\( J = 8–7 \) \( \nu = 0 \) (panel (a)), \( ^{29}\text{SiO} \) (\( J = 19–18 \) \( \nu = 0 \) (panel (b)), and \( ^{28}\text{SiO} \) (\( J = 8–7 \) \( \nu = 1 \) (panel (c)), respectively.

3 If the gas is expanding and rotating, the position–velocity diagrams show an elliptical structure with the semimajor axis inclined with respect to the position axis (see, e.g., panel (d) of supplementary Figure 1 of Hirota et al. (2017)).

3.2. Mass of the Outflow

Assuming that the \( ^{28}\text{SiO} \) (\( J = 8–7 \) \( \nu = 1 \)) emission is optically thick, the excitation temperature is (e.g., Estalella & Anglada 1996)

\[ T_{\text{ex}} \left( ^{28}\text{SiO} \right) = \frac{h\nu/k}{\ln(1 + \frac{hv/k}{T_{\text{ex}} - T_{\text{bg}}})} \]  \hspace{1cm} (1)

where \( h \) is the Plank constant, \( k \) is the Boltzmann constant, \( \nu \) is the rest frequency in GHz (see Table 1), \( T_{\text{ex}} \) is the observed antenna temperature of \( ^{28}\text{SiO} \), and \( T_{\text{bg}} \) is intensity in units of temperature at the background temperature \( T_{\text{bg}} = 2.7 \text{ K} \). Using the value of \( \nu \) given in Table 1, we can estimate the optical depth of the emission of the \( ^{29}\text{SiO} \) molecule as (e.g., Estalella & Anglada 1996)

\[ \tau_{0} \left( ^{29}\text{SiO} \right) = -\ln \left[ 1 - \frac{T_{\text{ex}} \left( ^{28}\text{SiO} \right)}{J_{\text{c}}(T_{\text{ex}}) - J_{\text{c}}(T_{\text{bg}})} \right] \]  \hspace{1cm} (2)

where \( T_{\text{ex}} \) is the observed antenna temperature of \( ^{29}\text{SiO} \) and \( J_{\text{c}}(T_{\text{ex}}) \) is the intensity in units of temperature at the excitation temperature. With these values, we obtain \( \tau_{0} \left( ^{29}\text{SiO} \right) = 1.3 \), which is not optically thin. Thus, assuming

Figure 4. Position–velocity diagrams parallel to the disk midplane from the emission of the \( ^{29}\text{SiO} \) (\( J = 8–7 \) \( \nu = 1 \)) transition for the same heights and the same description as Figure 2.

Figure 5. Position–velocity diagrams parallel to the disk midplane at height \( z = 80 \text{ au} \). (a) Emission from the molecular line of \( ^{29}\text{SiO} \) (\( J = 8–7 \) \( \nu = 0 \)). (b) Emission from the molecular line of \( ^{28}\text{SiO} \) (\( J = 8–7 \) \( \nu = 1 \)). The horizontal dashed line shows the value of the LSR velocity of the source. The vertical dashed lines represent the cylindrical radius \( r_{\text{cyl}} \) defined in Figure 6. The solid line in each panel indicates the rotation signature.
local thermodynamic equilibrium, we calculate the mass of the outflow as a function of the $^{29}\text{SiO}$ optical depth as

$$\frac{M_{\text{outflow}}}{M_*} = 5 \times 10^{-3} (d^2 \Delta \Omega) \left[ \frac{m(H_2)}{X^{^{29}\text{SiO}}/H_*} \right]$$

$$\times \exp \left[ \frac{58.6}{\tau_{\text{SiO}}} \right] \frac{T_{\text{ex}} \tau_{0}^{(29)\text{SiO}} \Delta \nu}{1 - \exp \left[ \frac{-16.7}{\tau_{\text{SiO}}} \right]},$$

(3)

where $m(H_2)$ is the mass of molecular hydrogen, and $X^{^{29}\text{SiO}}/H_*$ = 6 - 12 \times 10^{-9} is the fractional abundance of $^{29}\text{SiO}$ with respect to H$_2$.$^4$ To obtain this value, we assumed a relative abundance of $^{29}\text{SiO}$ with respect to H$_2$ of 1.2-2.4 $\times$ 10$^{-7}$, obtained by Ziurys & Friberg (1987) in OMC1 (IRc2), and a relative abundance of $^{29}\text{SiO}$ with respect to 28SiO of 5 $\times$ 10$^{-5}$, obtained by Soria-Ruiz et al. (2005) toward evolved stars. The distance d is (418 ± 6 pc), $\Delta \nu$ is the velocity width of the line (≈30 km s$^{-1}$), and $\Delta \Omega$ is the solid angle of the source (≈1.33 $\times$ 10$^{-9}$ sr). With these values, the estimated mass of the outflow of Orion Src I is $M_{\text{outflow}}$ $\sim$ 0.66-1.3 $M_\odot$. This is a mass lower limit because the $^{29}\text{SiO}$ abundance could be lower by up to two orders of magnitude due to the uncertainty in the molecular hydrogen column densities (Ziurys & Friberg 1987).

In addition, for an expansion velocity $v$ $\sim$ 18 km s$^{-1}$ (Greenhill et al. 2013) and a size $z$ = 480 au, the kinematic time is $t_{\text{kin}}$ $\sim$ 130 yr. Then, the mass-loss rate of the molecular outflow is $M_{\text{outflow}}/t_{\text{kin}}$ $\sim$ 5.1-10 $\times$ 10$^{-5}$ $M_\odot$ yr$^{-1}$.

Hirota et al. (2017) proposed that the molecular outflow of Orion Src I is produced by a slow magnetocentrifugal disk wind. The observed values of the rotational velocities of the outflow can be reproduced by this model, which predicts that the wind is ejected from footpoints in the disk at radii $r$ $\sim$ 5-25 au.

A disk wind requires a very large mass-loss rate to account for the mass observed in the outflow. As mentioned in the introduction, recent MHD simulations show that disk winds around T Tauri stars can have $M_\text{w}$ = $fM_{d,a}$, where the fraction can be $f$ $\sim$ 1-2 (e.g., Bai & Stone 2017; Béthune et al. 2017; Wang et al. 2019). If the outflow is a disk wind, $M_{\text{outflow}} = M_\text{w}$.

In the case of Orion SrcI, this implies a very large disk accretion rate, $fM_{d,a}$ $\gtrsim$ (5.1-10) $\times$ 10$^{-3}$ $M_\odot$ yr$^{-1}$. Then, massive disk winds face two problems. The first problem has to do with the fact that the mass flux in the disk will eventually fall into the star. Assuming that the disk rotates with Keplerian speed $v_K$, the material accreted to the star has to dissipate its energy, $1/2M_{d,a}v_K^2$. Thus, the accretion luminosity at the stellar surface is given by $L_a = \eta - GM_{d,a}/R_*$, where $G$ is the gravitational constant, $M_*$ is the stellar mass, $R_*$ is the stellar radius, and $\eta$ is ~ 0.5. Assuming $M_\text{w} = 15M_\odot$ (Ginsburg et al. 2018) and $R_* = 7.4\;R_\odot$(Testi et al. 2010), the accretion luminosity is $L_a \sim (1/f) \times 10^4L_\odot$. This value is higher than the observed source luminosity $L_\text{ex} \sim 10^4L_\odot$ (e.g., Menten & Reid 1995; Reid et al. 2007), unless $f$ $\sim$ 2. Note that a factor $f$ $\sim$ 15 implies that (locally) 94% of the mass the mass escapes into the wind and only 6% accretes toward the star. Disk wind models would have to produce these high f values in the case of winds around massive stars. The second problem, which was already mentioned in the case of DG Tau B (Section 1), is the short disk lifetime. For a maximum disk mass $M_d \lesssim M_\text{w}/3 = 5M_\odot$, necessary for gravitational stability (Shu et al. 1991), and an accretion rate such that $fM_{d,a} \lesssim 5.1-10^3$ $M_\odot$ yr$^{-1}$, the disk lifetime is very small, $\tau = M_d/M_{d,a} \lesssim f \times 980$ yr (see also the short disk lifetimes in Figure 33 of Béthune et al. 2017 for disks around low mass stars). This estimate of the disk lifetime assumes that the disk mass is not replenished. Nevertheless, Orion Src I has a massive accreting envelope that could replenish the disk. The disk wind models would have to explore if the disk mass could be replenished on short timescales ($\lesssim 10^4$ yr) by the infalling envelope. Both the accretion luminosity and the disk lifetime are important constraints on the disk wind models.

Moreover, if there is an accreting envelope around the Orion Src I, a stellar or disk wind will necessarily collide against it, driving a shell of entrained material. For this reason, in this work we explore a model where the molecular outflow is a shell produced by the interaction of a stellar wind and an accretion flow as the scenario first proposed by Snell et al. (1980). The shell is fed by both the stellar wind and the accretion flow. The latter can have very large mass accretion rates, as observed in the case of young massive stars (e.g., Zapata et al. 2008; Wu et al. 2009). We will verify under which conditions this shell model can acquire the observed mass.

### 3.3. Comparison with the Outflow Model

The position–velocity diagrams, presented in Figures 2–4, show the detailed structure of the outflow velocity as a function of the distance from the disk midplane. With these diagrams, we can also obtain information about the kinematic and physical properties of the outflow and compare with the outflow model of LV19.

Goddi et al. (2011) suggested that this source is a binary system with a stellar mass of $\sim 20 M_\odot$ and a separation of the stars $< 10$ au. Since this separation is very small compared to the size of the outflow, even if each star has its own stellar wind, a single stellar wind emanating from the center is a good approximation.

The proper motion of the Orion Src I with respect to the center of the explosive event that occurred 500 yr ago (Rodríguez et al. 2017) will change the environment of the central star. Its envelope will not be a gravitational collapsing envelope of the Ulrich type since the freefall time of a gas parcel starting at an outflow distance $\sim 1000$ au from star is of the order of twice the crossing time. Nevertheless, we will apply the models of LV19 and see how well the observational properties of the outflow can be reproduced.

The model of LV19 assumes that the molecular outflow is a thin shell formed by the collision between a stellar wind and a molecular rotating cloud in gravitational collapse. The thin shell assumption is adequate because the width of the shell is $\Delta r \sim 1/3$ of the distance to central star (see Section 3.1). For our comparison we assume a stellar mass $M_\text{w} = 15M_\odot$ (Ginsburg et al. 2018) and a centrifugal radius of $R_{\text{en}} = 40$ au, within the range of 21 au–47 au reported by Hirota et al. (2017).
This model depends on two parameters associated with the properties of the stellar wind and the accretion flow. The first parameter is the ratio between the wind mass-loss rate $M_w$, and the mass accretion rate of the envelope $M_a$:

$$\alpha = \frac{M_w}{M_a}$$  \hspace{1cm} (4)

for this case, we assume a value of $\alpha = 0.1$, a typical value the molecular outflows (Ellerbroek et al. 2013; Nisini et al. 2018). The second parameter is the ratio between the stellar wind and the accretion flow momentum rates

$$\beta = \frac{M_w v_w}{M_a v_0} = \alpha \frac{v_w}{v_0},$$  \hspace{1cm} (5)

where $v_w$ is the velocity of the stellar wind, and $v_0$ is the freefall velocity at the centrifugal radius, given by

$$v_0 = \left( \frac{GM_a}{R_{\text{cen}}} \right)^{1/2}. \hspace{1cm} (6)$$

For inferred values $M_w = 15 M_\odot$, and $R_{\text{cen}} = 40$ au, the freefall velocity is $v_0 = 19$ km s$^{-1}$. Assuming a stellar wind velocity $\sim$800 km s$^{-1}$, of the order of the escape speed for a star with $R_s \sim 7.4 R_\odot$ (Testi et al. 2010), implies that $\beta \approx 4$.

We assume a density profile of the stellar wind given by

$$\rho_w = \frac{M_w}{4\pi R^2 v_w f(\theta)}, \hspace{1cm} (7)$$

where $f(\theta)$ is the anisotropy function given by

$$f(\theta) = \frac{A + B \cos^2 \theta}{A + B/(2n + 1)}. \hspace{1cm} (8)$$

The physical properties of the shell model that will be compared with the observations are the cylindrical radius $\varpi$, the opening angle $\theta_{\text{opening}}$, expansion velocity $v_{\text{exp}}$, the axial velocity $v_z$, and the rotation velocity $v_{\text{rot}}$. Figure 6 presents a schematic diagram of the molecular outflow that shows the cylindrical radius, the height over the disk midplane, and the opening angle. The procedure used to measured these quantities is described in the Appendix.

We considered two models, a shell formed by an isotropic stellar wind with $B = 0$, and a shell formed by a very anisotropic stellar wind, with $A = 1$, $B = 35$, and $n = 5$. The parameters of the anisotropic stellar wind model are chosen to reproduce the shape of the most extended outflow emission observed by the $^{29}$SiO $(J = 8–7)$ transition. We choose the parameters that minimize $\chi^2$, defined as

$$\chi^2 = \frac{1}{N} \sum (\varpi_{\text{obs}} - \varpi_{\text{model}})^2,$$

where $\varpi_{\text{obs}}$ is the observed cylindrical radius, $\varpi_{\text{model}}$ is the model cylindrical radius, and $N$ is the number of observed values along the $z$ axis. This analysis is shown in Figure 7. We integrate in time the shell model from a small initial shell radius $r_0(0) \simeq R_s/R_{\text{cen}} \sim 10^{-3}$, close to the stellar surface, until the cylindrical radii of the model $\varpi_{\text{model}}$ reaches the observed cylindrical radii $\varpi_{\text{obs}}$ at different heights, as shown in panel (a) of the Figure 9, which happens at $t = 65$ yr. The shell model $R_s(\theta)$ is shown in Figure 8. Because the shell decelerates with time, the dynamical time (65 yr) is half the kinematic time (130 yr) calculated in Section 3.2. Figure 8 shows a shell produced by the isotropic wind (dashed line) and the anisotropic stellar wind (solid line) model superimposed on the ALMA first moment of the line emission $^{29}$SiO $(J = 8–7)$ $\nu = 0$ transition (panel (a)), SiS $(J = 19–18)$ $\nu = 0$ (panel (b)), and $^{29}$SiO $(J = 8–7)$ $\nu = 1$ (panel (c)).

The comparison between both outflow models with the observational data is shown in Figures 9 and 10. Since the isotropic wind model (dotted lines) does not reproduce the observations, hereafter we will only discuss the properties of the anisotropic stellar wind model.

Panel (a) of Figure 9 shows the cylindrical radius obtained from the three line observations and from the anisotropic stellar wind model. These radii are shown as vertical dashed lines in Figure 5. The cylindrical radius $\varpi$ increases with the height above the disk midplane; the model (black solid lines) agrees well with observational data.
For fixed centrifugal radius $R_{\text{cen}}$, the opening angle can be defined as

$$\theta_{\text{opening}} = \tan^{-1}\left(\frac{\varpi}{R_{\text{cen}}/z}\right).$$

This angle is shown in panel (b) of Figure 9. The observed values and the model (black solid lines) are consistent. The fact that the opening angle decreases with height above the disk indicates that the molecular outflow could close up at higher heights. Nevertheless, observations of a molecule that emits at higher disk heights are needed to establish the outflow shape.

The panel (a) of Figure 10 shows the expansion velocity for the three molecules indicated in the panel. This velocity increases with height above the disk midplane. The model expansion velocities (black solid lines) are similar to the observed values, except close to the disk ($z < \pm 150$ au).

Panel (b) of Figure 10 shows the measured axial velocity $v_z$. This velocity increases with height above the disk midplane. The axial velocity of the anisotropic stellar wind model corrected by the inclination angle $i = 10^\circ$ and a system velocity $V_{\text{LSR}} = 5$ km s$^{-1}$ (e.g., Plambeck & Wright 2016) fits the data well.

The rotation velocity is shown in panel (c) of the Figure 10. For the molecular line $^{28}\text{SiO} (J = 8-7) \nu = 0$ (blue points), the rotation velocity is in the range 5–8 km s$^{-1}$: at $z = \pm 80$ au above the disk the rotation velocity is $\sim 8$ km s$^{-1}$ and it decreases with height. The SiS ($J = 19-18$) $\nu = 0$ line (yellow points) has a similar behavior. The $^{28}\text{SiO} (J = 8-7) \nu = 1$ emission (red points) behaves in the same way but has slightly lower velocities, in the range 4–6 km s$^{-1}$. The observed rotation velocity is a factor of 3–10 larger than those of the anisotropic stellar wind model. Furthermore, the rotation velocity of the model decreases steeply with the height; the
observed rotation velocity slowly decreases. For reference, a polynomial function \( (v_{\text{rot}}/\text{km s}^{-1}) = a(z/\text{au})^\gamma + b \) with \( a = -1.5 \times 10^{-3}, \gamma = 1.2, \) and \( b = 8.3 \) is shown as a dashed dotted line in panel (e) of Figure 10.

One can also compare the model shell mass with the observed outflow mass (Section 3.2). The shell mass is given by

\[
M_{\text{outflow}} = \frac{M_\odot R_{\text{cen}}}{v_0} \int_0^{\pi/2} p_m d\theta, \tag{11}
\]

where \( p_m \) is the nondimensional mass flux (Equation [47] of LV19). For the anisotropic stellar wind model, \( \int_0^{\pi/2} p_m d\theta = 6.0, \) in nondimensional units. Therefore, for the values of the centrifugal radius and freefall velocity above, one requires a mass accretion rate of the envelope \( M_e = 1.1 -2.2 \times 10^{-2} \ M_\odot \text{yr}^{-1} \) to obtain the observed mass of the shell, \( M_{\text{outflow}} = 0.66 -1.3 M_\odot. \) Such large mass envelope accretion rates have been inferred in regions of high-mass star formation (e.g., Zapata et al. 2008; Wu et al. 2009.) This accretion rate corresponds a mass-loss rate of the molecular outflow corrected by the dynamical time \( T_{\text{dynamical}} = (0.66-1.3 \ M_\odot)/65 \text{ yr} = 1-2 \times 10^{-2} M_\odot \text{yr}^{-1}, \) which is very similar to \( M_e. \) Thus, the small fraction of mass that slides along the shell toward the equator does not increase the disk mass significantly.

In summary, the comparison between the anisotropic stellar wind model and the observations of the outflow from Orion Src I fits the outflow cylindrical radius very well. The opening angle is a function of the cylindrical radius, therefore it also fits the observations well. The expansion velocity and the axial velocity \( v_z \) behave similar to the observations, although the slope is somewhat different. Nevertheless, the model rotation velocity is much lower (3–10 times) than the observed velocity.

The smaller rotation velocity profile of the model indicates that the envelope of Ulrich (1976) cannot explain the rotation in molecular outflows. This problem could be alleviated if a stellar wind or disk wind with angular momentum is considered, or increases the angular momentum of the envelope.

For a representative height of \( z \sim 240 \text{ au}, \) the observed rotation velocity is a factor \( \sim 6 \) of the model rotation velocity. Thus, the model has only \( \sim 17\% \) of the observed specific angular momentum. The missing angular momentum could come from an accreting envelope with more angular momentum, or from an extended disk wind.\(^5\)

### 4. Conclusions

In this study, we present new and sensitive ALMA archive observations of the rotating outflow from Orion Snc I. In the following, we describe our main results.

1. The Orion Snc I outflow has a mass-loss rate \( M_{\text{outflow}} = 5.1 -10 \times 10^{-3} \ M_\odot \text{yr}^{-1}. \) This massive outflow poses stringent constraints on disk wind models concerning the accretion luminosity and the disk lifetime.
2. We find that the opening angle (in a range of \( \sim 20^\circ -60^\circ) \) and the rotation velocity (in a range of \( \sim 4-8 \text{ km s}^{-1} \)) decrease with the height to the disk. In contrast, the cylindrical radius (in a range of \( \sim 100-300 \text{ au} \)) increase (in a range of \( \sim 2-15 \text{ km s}^{-1} \)) and the axial velocity \( v_z \) (in a range of \( \sim 1-10 \text{ km s}^{-1} \)) increase with respect to the height above the disk.
3. We compare with the outflow model of LV19, where the molecular outflow corresponds to a shell produced by the interaction of a stellar wind and an accretion flow.
4. We find that the observed values of the cylindrical radius, the opening angle, the expansion velocity, and the axial velocity \( v_z \) behave similar to the LV19 anisotropic stellar wind model. However, the rotation velocity of the model is lower (by a factor of 3–10) than the observed rotation velocity of the Orion Snc I outflow.
5. We conclude that the Ulrich flow alone cannot explain whether the rotation of the molecular outflow originated from Orion Snc I and other possibilities should be explored.

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\(^5\) An X wind comes from radii very close to the central star, so it has little angular momentum.
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Appendix

Measurement Procedure

The position–velocity diagrams in Figures 2–4 were analyzed to derive the following physical parameters as a function of height $z$: the cylindrical radius $\varpi_{\text{obs}}$, the expansion velocity $v_{\text{exp}}$, and the rotation velocity $v_{\text{rot}}$. These properties were compared with the physical properties of the thin shell model of LV19.

Figure A1 shows the intensity profiles at $V_{\text{LSR}} = 5 \text{ km s}^{-1}$ as a function of the distance to the outflow axis at height $z = -80 \text{ au}$ for the molecular lines $^{29}\text{SiO} (J = 8–7) \nu = 0$ (panel (a)), $\text{SiS} (J = 19–18) \nu = 0$ (panel (b)), and $^{28}\text{SiO} (J = 8–7) \nu = 1$ (panel (c)). These panels also show a Gaussian fit to the intensity profiles (red solid lines). The cylindrical radius $\varpi_{\text{obs}}$ is the width of the Gaussian profile and the error if given by the Gaussian fit. In panel (b), the three peaks correspond to the emission from three shells. For our measurements, we only consider the two most prominent peaks.

The cylindrical radius of the shell model is the projection of the spherical radius $R_z$ at a given height, $\varpi_{\text{model}} = R_z \sin \theta$, where $\theta = \cos^{-1}(z/R_z)$.

Figure A2 shows the intensity profiles at height $z = -80 \text{ au}$ at the outflow axis (angular offset = 0 au in Figure 5) as a function of velocity for the three molecular lines, $^{29}\text{SiO} (J = 8–7) \nu = 0$ (panel (a)), $\text{SiS} (J = 19–18) \nu = 0$ (panel (b)), and $^{28}\text{SiO} (J = 8–7) \nu = 1$ (panel (c)). The expansion velocity is calculated at the outflow axis as $v_{\exp} = (v_{r} - v_{r})/2$, where $v_{r}$ are the radial velocities corresponding to the width of the Gaussian profile. The axial velocity $v_{z}$ is calculated as

![Figure A1](image1.png)

Figure A1. Intensity profiles at $V_{\text{LSR}} = 5 \text{ km s}^{-1}$ of the position–velocity diagrams at height $z = -80 \text{ au}$, as indicated by horizontal dashed lines in panels (a)–(c) in Figure 5. The red line shows the best Gaussian fit to the intensity profile of (a) $^{29}\text{SiO} (J = 8–7) \nu = 0$, (b) $\text{SiS} (J = 19–18) \nu = 0$, and (c) $^{28}\text{SiO} (J = 8–7) \nu = 1$.

![Figure A2](image2.png)

Figure A2. Intensity profiles at the outflow axis of the position–velocity diagrams at height $z = -80 \text{ au}$ in Figure 5. The red line shows the best Gaussian fit to the intensity profile of (a) $^{29}\text{SiO} (J = 8–7) \nu = 0$, (b) $\text{SiS} (J = 19–18) \nu = 0$, and (c) $^{28}\text{SiO} (J = 8–7) \nu = 1$. For reference, the dashed lines indicate the $V_{\text{LSR}}$ velocity.
The errors are given by the Gaussian fit. In the case of the anisotropic stellar wind model, for a given inclination angle $i$, one calculates $v_z$ as the projection along the line of sight of the velocity of the two sides of the shell. The axial velocity is also corrected by the system velocity $V_{LSR}$.

Figure A3. Intensity profiles at the position of the cylindrical radii $\varpi_{\text{obs}}$ (left panels) and $-\varpi_{\text{obs}}$ (right panels) in Figure 5 at height $z = -80$ au. The red line shows the best Gaussian fits to the intensity profiles of $^{29}\text{SiO} (J = 8-7) \nu = 0$ (upper panels), SiS ($J = 19-18$) $\nu = 0$ (middle panels), and $^{28}\text{SiO} (J = 8-7) \nu = 1$ (lower panels).
(lower panels). The red solid lines show the Gaussian fits, some of which require 2 Gaussians.

The rotation velocity is given as the difference between the outer edges of widths of the intensity profiles at $\pm \sigma_{\text{obs}}$, indicated by the dashed line in each panel (see also the inclined solid lines in Figure 5). The error bars are given by the Gaussian fit. For the model, we use the rotation velocity $v_{\text{rot}}$.

Figures A1–A3 show, as an example, the analysis to obtain the observed quantities $\sigma_{\text{obs}}$, $v_{\text{exp}}$, and $v_{\text{rot}}$ at $z = -80$ au. The same analysis is performed for each height $z$ in Figures 9 and 10.

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References

Anderson, J. M., Li, Z.-Y., Krasnopolsky, R., & Blandford, R. D. 2003, ApJL, 590, L107

Báez-Rubio, A., Jiménez-Serra, I., Martín-Pintado, J., et al. 2018, ApJ, 853, 4

Bai, X.-N., & Stone, J. M. 2017, ApJ, 836, 46

Bally, J., Ginsburg, A., Arce, H., et al. 2017, ApJ, 837, 60

Bally, J., & Zinnecker, H. 2005, AJ, 129, 2281

Béthune, W., Lesur, G., & Ferreira, J. 2017, A&A, 600, A75

Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883

Bontemps, S., Andre, P., Terebey, S., & Cabrit, S. 1996, A&A, 311, 858

Cantó, J., & Raga, A. C. 1991, ApJL, 372, L64

Ellerbroek, L. E., Podio, L., Kaper, L., et al. 2013, A&A, 551, A5

Estalella, R., & Anglada, G. 1996, Introducción a la Física del Medio Interestelar (Barcelona: Univ. Barcelona)

Ginsburg, A., Bally, J., Goddi, C., Plancke, R., & Wright, M. 2018, ApJ, 860, 119

Goddi, C., Humphreys, E. M. L., Greenhill, L. J., et al. 2011, ApJ, 728, 15

Greenhill, L. J., Goddi, C., Chandler, C. J., Matthews, L. D., & Humphreys, E. M. L. 2013, ApJL, 770, L32

Guilloteau, S., Dutrey, A., Piolé, V., et al. 2011, A&A, 529, A105

Hartmann, L., Megeath, S. T., Allen, L., et al. 2005, ApJ, 629, 881

Hirota, T., Kim, M. K., Kurono, Y., & Honma, M. 2014, ApJL, 782, L28

Kim, M. K., Hirota, T., Honma, M., et al. 2008, PASJ, 60, 991

Königl, A., & Pudritz, R. E. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson, AZ: Univ. Arizona Press), 759

Königl, A., & Pudritz, R. E. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson, AZ: Univ. Arizona Press), 759

Lee, C.-F., Hirano, N., Palla, A., et al. 2009, A&A, 494, 147

Lee, C.-F., Hony, N., Palau, A., et al. 2009, ApJL, 699, L154

López-Vázquez, J. A., Cantó, J., & Lizano, S. 2019, ApJL, 874, 42

Louvet, F., Dougados, C., Cabrit, S., et al. 2018, A&A, 618, A120

Luhman, K. L., Allen, P. R., Esplandiel, C., et al. 2010, ApJS, 186, 111

Menten, K. M., & Reid, M. J. 1995, ApJL, 445, L157

Nisini, B., Antoniucci, S., Alcalá, J. M., et al. 2018, A&A, 609, A87

Pech, G., Zapata, L. A., Loinard, L., & Rodríguez, L. F. 2012, ApJ, 751, 78

Plancke, R. L., & Wright, M. C. H. 2016, ApJL, 835, 219

Plambeck, R. L., Wright, M. C. H., Friedel, D. N., et al. 2009, ApJL, 704, L25

Pudritz, R. E., & Norman, C. A. 1983, ApJL, 277, 674

Pudritz, R. E., & Norman, C. A. 1986, ApJL, 301, 571

Pudritz, R. E., Ouyed, R., Fedt, C., & Brandenburg, A. 2007, in Protostars and Planets IV, ed. B. Reipurth, D. Jewett, & K. Keil (Tucson, AZ: Univ. Arizona Press), 277

Raga, A., & Cabrit, S. 1993, A&A, 278, 267

Reid, M. J., Menten, K. M., Greenhill, L. J., & Chandler, C. J. 2007, ApJ, 664, 950

Rodríguez, L. F., Dzib, S. A., Loinard, L., et al. 2017, ApJ, 834, 140

Shang, H., Li, Z.-Y., & Hirano, N. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewett, & K. Keil (Tucson, AZ: Univ. Arizona Press), 261

Shu, F. H., Najita, J., Ostriker, E., et al. 1994, ApJ, 429, 781

Shu, F. H., Najita, J. R., Shang, H., & Li, Z.-Y. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson, AZ: Univ. Arizona Press), 789

Shu, F. H., Ruden, S. P., Lada, C. J., & Lizano, S. 1991, ApJL, 370, L31

Snell, R. L., Loren, R. B., & Plambeck, R. L. 1980, ApJL, 239, L17

Soria-Ruiz, R., Colomer, F., Alcolea, J., et al. 2005, A&A, 432, L39

Tabone, B., Cabrit, S., Bianchi, E., et al. 2017, A&A, 607, L6

Testi, L., Tan, J. C., & Palla, F. 2010, A&A, 522, A44

Ulrich, R. K. 1976, ApJ, 210, 377

Wang, L., Bai, X.-N., & Goodman, J. 2019, ApJ, 874, 90

Yu, W., Qin, S.-L., Guan, X., et al. 2009, ApJL, 697, L116

Zapata, L. A., Lizano, S., Rodríguez, L. F., et al. 2015, ApJL, 798, 131

Zapata, L. A., Palau, A., Ho, P. T. P., et al. 2008, A&A, 479, L25

Zapata, L. A., Rodríguez, L. F., Schmid-Burgk, J., et al. 2012, ApJL, 754, L17

Zapata, L. A., Schmid-Burgk, J., Ho, P. T. P., et al. 2009, ApJL, 704, L45

Zapata, L. A., Schmid-Burgk, J., Mudders, D., et al. 2010, A&A, 510, A2

Zapata, L. A., Schmid-Burgk, J., Rodríguez, L. F., Palau, A., & Loinard, L. 2017, ApJL, 836, L33

Zhang, Y., Higuchi, A. E., Sakai, N., et al. 2018, ApJ, 864, 76

Ziurys, L. M., & Friberg, P. 1987, ApJL, 314, L49

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