ALMA Reveals a Collision between Protostellar Outflows in BHR 71

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Abstract

For a binary protostellar outflow system in which its members are located close to each other (the separation being smaller than the addition of the widths of the flows) and with large opening angles, the collision seems unavoidable regardless of the orientation of the outflows. This is in contrast to the current observational evidence of just a few regions with indications of colliding outflows, which could also suggests that the average distance between protostars is larger than the width of the flows. Here, using sensitive observations of the Atacama Large Millimeter/Submillimeter Array, we report resolved images of carbon monoxide (CO) toward the binary flows associated with the BHR 71 protostellar system. These images reveal for the first time solid evidence that their flows are partially colliding, increasing the brightness of the CO, the dispersion of the velocities in the interaction zone, and changing part of the orientation in one of the flows. Additionally, this impact opened the possibility of knowing the three-dimensional geometry of the system, revealing that one of its components (IRS 2) should be closer to us.

Key words: stars: formation

1. Introduction

Jets and outflows are ubiquitous in star-forming regions and their propagation through the interstellar medium has been studied in detail and is reasonably well understood (e.g., Lee et al. 2001; Bally 2007, 2016). The interaction between jets and dense parts of clouds or clumps has received also some attention (Raga & Cantó 1995), as well as the interaction with side-winds (Cantó & Raga 1995) or the interaction of jets of runaway protostars with the quiescent Interstellar Medium (Cantó et al. 2008). Precession effects of a single jet due to the orbital motion of a binary companion or the misalignment of the ejection mechanism with the system rotation axis has also been the subject of several observational and theoretical work. However, interactions between jets or outflows themselves, remain quite unexamined. In spite of being likely occurring in typical star-forming regions (Cunningham et al. 2006), interactions between two or more outflows have not been clearly observed.

As it is mentioned before, there is little evidence of colliding protostellar outflows. One of the best cases presented of this phenomenon is found in the IR-dark “tail” that crosses the IC 1396N globule (Beltrán et al. 2012). CO observations show two well collimated protostellar outflows associated with young stars at the northern part of the globule, these outflows are located close to the plane of the sky and probably are colliding (the blueshifted lobes) with each other toward the position of a strong 2.12 μm H2 line emission feature. This H2 feature is recognized as being excited by the impact of the two protostellar outflows. A less clear case of colliding outflows is the one found in the massive infrared dark cloud clump, G028.37+00.07-C1 (Kong et al. 2017). In that case, the collimated outflows emanating from the massive protostellar objects C1-Sb and C1-Sa seem to collide, but it is not clear if this involves a real physical interaction or is simply a projection effect as discussed throughout their study.

There is also some evidence of outflow collision but with dense parts of their natal molecular clouds (Raga et al. 2002; Choi 2005). The interaction between the protostellar outflow and the dense cloud causes an abrupt deflection on the orientation of the flow. This effect has been observed in both cases, the HH210 and NGC 1333 IRAS 4A molecular flows (Raga et al. 2002; Choi 2005).

The bipolar molecular outflows emanating from BHR 71 are powered by two young stars separated by about 15″ or 3500 au (at an assumed distance of 200 pc) called IRS 1 and IRS 2 (Bourke et al. 1997). IRS 1 is classified as a Class I/0 protostar with a bolometric luminosity of 13.5 ± 1.0 L⊙, a dust temperature of 25 K, and a mass of the dusty envelope of 2.1 ± 0.4 M⊙, while IRS 2 (which is classified as a Class 0 protostar) has a bolometric luminosity of 0.5 ± 0.1 L⊙, a dust temperature of 26 K, and a mass of the dusty envelope of 0.05 ± 0.02 M⊙ (Chen et al. 2008). More recently, using Herschel observations, it has been estimated for BHR 71 (which includes the binary, IRS1 and 2) an envelope mass of 19 M⊙ inside a radius of 0.3 pc and a central luminosity of 18.8 L⊙ (Yang et al. 2017). The outflow from IRS 1 is larger in extent, more massive, and dominates the CO emission (Garay et al. 1998; Bourke 2001). The IRS 2 bipolar outflow was revealed by the APEX telescope using the 12CO(4–3), 12CO(3–2), 13CO(3–2), C18O(3–2), and CH3OH(7–6) lines given its better angular resolution and sensitivity compared with other single dish telescopes (Parise et al. 2006). Contrary
to the outflow from IRS 1 its blueshifted emission is found to the northwest, while its redshifted emission is found to the southeast (Parise et al. 2006). The temperature in the outflow lobes from the two sources is very different. For IRS 2, the temperature ranges between 30 and 50 K, while for IRS 1 it rises up to 300 K. This again suggests the large energetics of the outflow from IRS 1 compared with the outflow from IRS 2, as observed in other studies (Gusdorf et al. 2015; Yıldız et al. 2015; Benedettini et al. 2017). It is important to mention that the temperature measurements on these studies were obtained far from the “colliding zone” that will be discussed on the next sections.

2. Observations

The archive observations of the BHR 71 protostellar binary system were carried out with Atacama Large Millimeter/Submillimeter Array (ALMA) at Band 6 in 2015 January 17 as part of the Cycle 2 program 2013.1.00518.S. The observations used 35 antennas with a diameter of 12 m, yielding baselines with projected lengths from 15 to 348.5 m (11–268 kλ). The primary beam at this frequency has a full width at half-maximum of about 27″. In order to cover the central part of the outflows emanating from BHR 71, it was made a small mosaic of fourteen centers distributed in a Nyquist-sampled grid. The integration time on-source was 14.1 minutes, approximately 1 minute for each pointing in the mosaic. The continuum image was obtained averaging line-free channels from six spectral windows (of 0.059 and 2.000 GHz width) centered at rest frequencies: 219.563 GHz (spw0), 220.402 GHz (spw1), 217.998 GHz (spw2), 230.548 GHz (spw3), 231.332 GHz (spw4), and 232.332 GHz (spw5). The total bandwidth where we obtained the continuum emission is 4.236 GHz. These windows were centered to observe different molecular species as the 13CO(2–1), C18O(2–1), and 15CO(2–1). In this study, we concentrate in the 12CO(2–1), which is well known to be an excellent outflow tracer. This line was centered in the spectral window spw 3 (at 230 GHz) and has a channel spacing of 0.08 km s⁻¹. Strong CO emission is detected, see Figure 1.

The weather conditions were reasonably good for this frequency and stable with an average precipitable water vapor of about 3.4 mm and an average system temperature of 125 K. The ALMA calibration included simultaneous observations of the 183 GHz water line with water vapor radiometers, used to reduce atmospheric phase oscillation. Quasars J1107–4449, J1229–6003, and J1229–6003 were used to calibrate the bandpass, the atmosphere and the gain fluctuations, respectively. Ganymedes was used for the flux amplitude. The data were calibrated, imaged, and analyzed using the Common Astronomy Software Applications CASA (McMullin et al. 2007). We did self-calibration in phase and amplitude using the resulting mm continuum image as model. We then applied the solutions for self-calibration in the continuum to the spectra. Imaging of the calibrated visibilities was done using the task CLEAN. The resulting image rms noise for the continuum was 0.4 mJy beam⁻¹ at an angular resolution of 1″2 × 1″1 with a PA = −63°6. The ALMA theoretical rms noise for this configuration, integration time, and frequency is about 0.3 mJy beam⁻¹, which is very close to the value we obtain in the continuum images. We used the ROBUST parameter of CLEAN in CASA set to zero. For the line emission, the resulting image rms noise was 50 mJy beam⁻¹ km s⁻¹ at an angular resolution of 1″6 × 1″4 with a PA = −77°2, and a bandwidth of 0.084 km s⁻¹. A mild outer taper (140 kλ) was applied to avoid the sparseness of the longest baselines. The ALMA theoretical rms noise for this configuration, integration time, and frequency is about 40 mJy beam⁻¹ km s⁻¹, which is again very close to the value we obtain in the line images. The resulting 1.3 mm continuum and 12CO(2–1) line emission images are presented in Figure 1. In Figure 1, the range of velocities where we detected CO emission is from −25 to +20 km s⁻¹.

3. Results

Figure 1 shows the moment zero or integrated intensity map of the 12CO(2–1) line emission (CO from now on, unless otherwise is indicated) overlaid with the 1.3 mm continuum emission as revealed by the ALMA observations. The 1.3 mm continuum emission traces the dust from the envelopes and protoplanetary disks surrounding IRS 1 and IRS 2. For the case of IRS 1, the ALMA observations reveal a small cavity present in the northern part of its dusty envelope, likely carved by the redshifted part of its bipolar outflow. From the observations, IRS 1 has a deconvolved size of 0.078 ± 0.037 × 0.062 ± 0.039 with a Position Angle⁹ (PA) of 94° ± 15° and a flux density of 547 ± 10 mJy. For IRS 2, we estimated a deconvolved size in the uv-plane of 0.089 ± 0.004 × 0.084 ± 0.0099 with a PA of 120° ± 70° and a flux density of 44 ± 5 mJy. The continuum density flux for IRS1 is 0.545 ± 0.008 Jy and for IRS2 is 0.056 ± 0.002 Jy. Here the uncertainties in the deconvolved sizes and flux densities are only statistical, the true uncertainties are larger than these values.

⁹ Measured as usual from north to east.
The corresponding physical sizes of these deconvolved values are between 120 and 180 au. Assuming that the dust emission is optically thin and isothermal, the dust mass \( (M_d) \) is directly proportional to the flux density \( (S_p) \) as:

\[
M_d = \frac{D^2 S_p}{\kappa_p B_p(T_d)},
\]

where \( D \) is the distance to the object, \( \kappa_p \) the dust mass opacity, and \( B_p(T_d) \) the Planck function for the dust temperature \( T_d \). Assuming a dust mass opacity \( (\kappa_p) \) of 0.015 cm\(^2\) g\(^{-1}\) (taking a dust-to-gas ratio of 100) appropriated for these wavelengths (1.3 mm) for coagulated dust particles with no ice mantles (Ossenkopf & Henning 1994), a typical opacity power-law index \( \beta = 1.5 \), as well as a characteristic dust temperature \( (T_d) \) of 25 K, we estimated a lower limit (because the emission is probably not optically thin) for the mass of the most compact part (i.e., not interferometrically filtered) of the disk and envelope system associated with IRS 1 of about 0.215 \( \pm 0.004 \) M\(_{\odot} \), and of 0.017 \( \pm 0.002 \) M\(_{\odot} \) of the most compact part of the disk and envelope system associated with IRS 2. Note that the level of uncertainty in the given lower limits are only statistical, and thus proportional to the flux density estimates. The actual uncertainty could be very large (a factor of two or three) given the uncertainty in the opacities. Comparing the estimated masses to the masses given in Chen et al. (2008) it seems that a large fraction of the more extended envelope mass is filtered by the ALMA observations, thus revealing the youth of the two protostars that have just a fraction of their surrounding mass into more compact structures (i.e., disks). A mass ratio of the order of \( M_{\text{star}}/M_{\text{disk}} \approx 10 \) is frequently found in sources where the masses of the disks and the stars have been estimated (Guilloteau & Dutrey 1998; Rodríguez et al. 1998). However, recent numerical hydrodynamical simulations of protostellar disks have shown that for young disks the ratio varies from 1 to 10 (Bate 2018). This might suggests that the central sources in IRS 1 and IRS 2 are low mass.

The CO emission reveals the innermost parts of the two molecular outflows already reported to be associated with BHR 71. A wide-angle structure in both bipolar outflows is exhibited, with the outflow from IRS 1 being more widely open (open angle of about 44°, versus 29° for the outflow of IRS 2). These wide-angle structures are likely created by the molecular material being entrained by a collimated jet-like outflow as observed in many other outflows (e.g., Zapata et al. 2014, 2015).

Assuming that the \(^{12}\)CO(2–1) line emission is optically thin and in Local Thermodynamic Equilibrium (LTE), we can estimate a lower limit for the mass of the bipolar outflows using the following equation (Scoville et al. 1986; Palau et al. 2007), which for the (2–1) transition is given by

\[
\frac{M_{\text{HI}}}{M_{\odot}} = 7.6 \times 10^{-16} T_{\text{ex}} e^{16.50 \frac{v}{c}} X_{\text{HI}} \times \left[ \frac{\int I_\nu d\nu}{Jy \text{ km s}^{-1}} \right] \left[ \frac{\theta_{\text{maj}} \theta_{\text{min}}}{\text{arcsec}^2} \right] \left[ \frac{D}{\text{pc}} \right]^2,
\]

where we used 2.8 as mean molecular weight, \( X_{\text{HI}} \) is the abundance ratio between the molecular hydrogen and the carbon monoxide (Scoville et al. 1986) \( \sim 10^4 \), \( T_{\text{ex}} \) is in units of K and assumed to be 30 K for IRS 2 and 100 K for IRS 1 (a conservative value for IRS 1, see the introduction). \( \int I_\nu d\nu \) is the average intensity integrated over velocity (here we take a range of integration of \( 10 \text{ km s}^{-1} \) for IRS 1 and \( 5 \text{ km s}^{-1} \) for IRS2, respectively), \( \theta_{\text{maj}} \) and \( \theta_{\text{min}} \) are the projected major and minor axes of the outflows, and \( D \) is the distance to the source (200 pc). We then estimate a lower limit for the gas mass for the outflows in IRS 1 of \( 5.0 \times 10^{-4} M_{\odot} \) and \( 5.0 \times 10^{-5} M_{\odot} \) for IRS 2. Both outflow masses are consistent with the fact that the energizing objects (IRS 1 and 2) are low-mass young stars, and that IRS 1 is about 10 times more massive than IRS 2. The resulting kinetic energy \( (E_k = \frac{1}{2} m v^2) \) is \( 5 \times 10^{41} \text{ erg} \) and the momentum \( (p = mv) \) is \( 6 \times 10^{-3} M_{\odot} \text{ km s}^{-1} \) for IRS1, and for IRS2 is \( 2.5 \times 10^{40} \text{ erg} \) and \( 3 \times 10^{-4} M_{\odot} \text{ km s}^{-1} \), respectively.

It is easy to appreciate in Figure 1 that in the southwest side of the bipolar outflow from IRS 1 there is a strong and abrupt increase of CO flux of about a factor of two or three times the average values within this side of the flow (we have marked this zone in the Figure 1). This position coincides very well with the intersection in the plane of the sky between the southwest cavity wall from the IRS 1 outflow and the southeast cavity wall of the outflow from IRS 2. One can also see that the continuation of this cavity wall (southeast of IRS 2’s outflow) along a PA of about 133° bifurcates and seems to be also redirected into a PA between 70° and 90°. The southwest cavity wall of the outflow from IRS 2 continues with the same orientation (PA = 133°) for a longer distance and crosses the IRS 1 outflow cavity close to the southern edge of the ALMA image, with a lower flux enhancement which is washed out in the momentum image due to the frequency averaging. Low angular-resolution \(^{12}\)CO(3–2) observations have shown that IRS 2’s outflow continues apparently unperturbed due southwest (Parise et al. 2006), but the field of view of the present ALMA CO observations does not show this clearly.

These results may suggest that both outflows are colliding or just overlapping in projection. In order to further interpret the data, we have made images for the moment 1 (intensity-weighted velocity, Figure 2) and moment 2 (velocity dispersion, Figure 3) of the CO emission.

Figure 2 presents the moment 1 of the molecular gas of both bipolar outflows. The range of velocities where we integrated to construct this image is from \(-25 \text{ to } +20 \text{ km s}^{-1}\). The redshifted side of the outflow from IRS 1 is located to the north, while the blueshifted side is located to the south. This is contrary to the bipolar outflow from IRS 2, which has its blueshifted component toward the northwest, and its redshifted component to the southeast. This has been already observed in the APEX observations (Parise et al. 2006). Figure 2 clearly reveals the presence of redshifted gas inside the otherwise blueshifted cavity of the IRS 1 outflow, and also the abrupt change of orientation in the southeast side of part of the IRS 2 outflow. The redshifted gas from the outflow emerging from IRS 2 seems to get redder after crossing the southwest edge of the IRS 1 outflow, which maybe indicates a simple change of orientation of some of the material. The morphology and the east–west velocity gradient of this spatially coherent stream of CO emission can be better seen in Figure 4, where we have only integrated toward redshifted velocities from 0 to...
10% of the intensity peak. The CO intensity peak is 13.9 Jy Beam$^{-1}$.

The brown contours are starting from 2% to 90% in steps of 2% of the intensity peak. The 1.3 mm continuum intensity peak is 0.4 Jy Beam$^{-1}$.

The range of velocities where we integrated to construct this image is from $-25$ to $+20$ km s$^{-1}$.

Moreover, Figure 3 shows a velocity dispersion image of the CO emission. The range of velocities where we integrated to construct this image is from $-25$ to $+20$ km s$^{-1}$. Relatively broad-line emission is generally detected toward the cavity walls of the IRS 1 outflow and the northern lobe of the IRS 2 outflow (about 3 km s$^{-1}$ on average). Interestingly the cavity walls of the southern lobe of IRS 2 do not present such broad line-widths (about 1 km s$^{-1}$), which is not surprising, since many outflows present fainter redshifted lobes (Pech et al. 2012; Fernández-López et al. 2013). However, the most characteristic feature in Figure 3 is the very broad-lines (up to 7.5 km s$^{-1}$ wide) found along the path of the CO stream crossing the outflow cavity of IRS 1 (i.e., colliding zone).

4. Discussion

After inspecting the ALMA CO data, we found strong evidence supporting the existence of a change of orientation of the molecular material, which can easily explain the change of projected velocity along the stream of gas crossing the southern lobe of the IRS 1 outflow. Since this process is spatially coincident with the position where the two outflows of the region overlap, we hypothesize that they may be interacting physically, indeed. To strengthen this hypothesis we summarize here the main observational facts in line with it:

1. The emission from both CO outflows spatially overlap;
2. The stream of gas crossing the outflow cavity from IRS 1 appears as an extension of the southeast cavity wall from the IRS 2 outflow, as if it was deflected;
3. The stream of gas has also a velocity gradient to redder velocities from west to east;
4. There is an increase of the CO emission toward the collision zone as expected in region with strong shocks;

Figure 2. ALMA $^{12}$CO(2–1) intensity-weighted velocity (moment one) (color-scale), $^{12}$CO(2–1) integrated intensity (black contours), and 1.3 mm continuum (gray contours) images of BHR 71. The half-power synthesized beam size is shown in the bottom left corner. The radial velocity scale-bar is shown in the right. The black contours are starting from 10% to 90% in steps of 10% of the intensity peak. The CO intensity peak is 13.9 Jy Beam$^{-1}$ km s$^{-1}$. The brown contours are starting from 2% to 90% in steps of 2% of the intensity peak. The 1.3 mm continuum intensity peak is 0.4 Jy Beam$^{-1}$. The systemic velocity of the molecular cloud in BHR71 is $-4.6$ km s$^{-1}$ (Bourke et al. 1997). The range of velocities where we integrated to construct this image is from $-25$ to $+20$ km s$^{-1}$.

Figure 3. ALMA $^{12}$CO(2–1) intensity-weighted square root velocity (moment two) (color-scale), $^{12}$CO(2–1) integrated intensity (black contours), and 1.3 mm continuum (brown contours) images of BHR 71. The half-power synthesized beam size is shown in the bottom left corner. The radial velocity scale-bar is shown in the right. The black contours are starting from 10% to 90% in steps of 10% of the intensity peak. The CO intensity peak is 13.9 Jy Beam$^{-1}$ km s$^{-1}$. The brown contours are starting from 2% to 90% in steps of 2% of the intensity peak. The 1.3 mm continuum intensity peak is 0.4 Jy Beam$^{-1}$. The range of velocities where we integrated to construct this image is from $-25$ to $+20$ km s$^{-1}$.

Figure 4. ALMA redshifted $^{13}$CO(2–1) intensity-weighted velocity (moment one) (color-scale) and 1.3 mm continuum (black contours) images of BHR 71. The half-power synthesized beam size is shown in the bottom left corner. The radial velocity scale-bar is shown in the right. The black contours are starting from 2% to 90% in steps of 2% of the intensity peak. The 1.3 mm continuum intensity peak is 0.4 Jy Beam$^{-1}$. The blue arrows trace the position of the blueshifted side of the flow from IRS 1. The systemic velocity of the molecular cloud in BHR 71 is $-4.6$ km s$^{-1}$ (Bourke et al. 1997). The range of velocities where we integrated to construct this image is from 0 to $+20$ km s$^{-1}$.
5. The collision zone shows much broader lines than the rest of the outflow, matching the expectation for an episode of outflow deflection;

All of these facts are well explained in a collision scenario. However, this explanation needs the outflow from IRS 1 to be more powerful and energetic than the outflow from IRS 2, so that the deflected outflow is that from IRS 2. Given that the IRS 2 protostellar system is less massive and has a lower luminosity, this requirement appears reasonable. Another evidence of the power of the outflow from IRS 1 comes with the optical and IR images that show it has already exit the natal cloud, digging its way out just south of the colliding zone.

The collision scenario has to explain also why the outflow from IRS 2 runs beyond the cavity of the outflow of IRS 1, apparently unperturbed, and roughly following its original trajectory (as seen, e.g., in low-angular resolution $^{12}$CO(3–2) observations in Parise et al. 2006). There is also traces in the ALMA CO emission confirming that the outflow from IRS 2 extends further than the colliding zone. All of this indicates that the two flows are only partially colliding. That is, part of the outflow from IRS 2 is kept intact and therefore it proceeds with its original trajectory, while another part physically collides with IRS 1’s outflow southern lobe, producing a strong shock and undergoing a deflection due east. Interestingly, and as a further indication of the strength of the IRS 1 outflow, part of the redshifted emission detected with ALMA appears due south from the collision zone. This emission may be only gas from the deflected material or maybe material from the IRS 2 outflow being dragged south by the more energetic IRS1’s outflow. Please see the above, where we have estimated the momentum and kinematical energy from the outflows.

Hence, assuming the collision scenario, a particular geometry is required for the protostars, since the redshifted lobe of the IRS 2 outflow may be impacting the blueshifted lobe of the IRS 1 outflow. The most probable layout is with IRS 2 closer to the observer than IRS 1, as shown in the sketch of Figure 5.

Although the collision between two outflows may not be surprising given the probability estimate by Cunningham et al. (2006), only three cases have been reported so far. In the Appendix, we make a statistical estimate based on the geometry of the collision of two outflows. Given the size of the outflows we let the problem have the separation between protostars as a variable. From our study, we conclude that impacting outflows may be more common than normally thought (as derived from the scarcity of the observational proof), and therefore they may be taken into account when estimating the energetic budget of the molecular clouds.

The ALMA maps presented here from the outflows in BHR71 suggest that probably the flows with a quadrupolar morphology, that is, the outflows which are constituted by two pairs of bipolar lobes with a common center (with one pair of lobes sometimes aligned perpendicularly to the other) are only two outflows arising from very close-by (proto)stars. This conclusion is also supported by recent millimeter and centimeter observations from, for example, the quadrupolar outflow L723, first studied in detail by Hirano et al. (1998). Using Submillimeter Array continuum observations at 1.35 mm, Girart et al. (2009) reported the presence of two cores SMA1 and SMA2 separated by some 900 au and that probably are powering the “quadrupolar outflow” in L723.

5. Conclusions

1. The sensitivity ALMA CO observations reveal that the outflows in the BHR 71 region are probably colliding as indicated for an increasing of the brightness of the CO emission, in the dispersion of the velocities in the impacting zone, and a change in the orientation in one of the outflows (IRS 2). Additionally ALMA observations toward other outflows could reveal additional cases of collision and reveal that this phenomenon occurs more frequently, as we discuss in the Appendix.

2. Provided that the outflows are colliding in BHR 71, a certain geometry for the system is implied. One can see how the redshifted lobe of IRS 2 is impacting the blueshifted lobe from the outflow ejected from IRS 1 from Figure 2, and then derive that IRS 2 should be closer to us than IRS 1.

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Appendix

The Probability of Colliding Flows

How likely it is that two nearby flows collide? In this Appendix, we present a simplified discussion of this topic. We assume that the flows can be represented by circular right capsules of height $2h$ and radius $r$ (see Figure 6(a)) in the Cartesian plane in three dimensions $(x, y, z)$. A capsule is the set of points at a given distance $r$ from a segment AB. It can also be regarded as the union of all the spheres of radius $r$ with center in one of the points of the segment AB. In mathematics, this is also called a convex parallel set of points. The centers of these capsules are separated by a distance $d$. The axis of the first capsule is given by

$$x_1 = a_1(h - r)\delta_1; \quad y_1 = b_1(h - r)\delta_1; \quad z_1 = c_1(h - r)\delta_1.$$
where \( a_1, b_1, c_1 \) are positive numbers between 0 and 1 generated randomly and normalized such that
\[
a_1^2 + b_1^2 + c_1^2 = 1.
\]
\( \delta_1 \) is a discrete variable that goes from \(-1\) to \(+1\) in steps of 0.01.

The second capsule is given by
\[
x_2 = a_2(h - r)\delta_2 + d; \quad y_2 = b_2(h - r)\delta_2; \quad z_2 = c_2(h - r)\delta_2,
\]
where \( a_2, b_2, c_2 \) are positive numbers between 0 and 1 generated randomly and normalized such that
\[
a_2^2 + b_2^2 + c_2^2 = 1.
\]
By analogy with the first capsule, \( \delta_2 \) is a discrete variable that goes from \(-1\) to \(+1\) in steps of 0.01.

For every set of \( a_1, b_1, c_1, a_2, b_2, c_2 \) numbers (representing a given orientation of the capsules), we calculate the separation between the points of the axes running across the \( \delta_1 \) and \( \delta_2 \) discrete parameters. We consider that the two capsules overlap if \( s \), the separation between points, is less than twice the radius of the cylinder:
\[s < 2r.
\]

For each separation, we run a realization with \( 10^5 \) sets of \( a_1, b_1, c_1, a_2, b_2, c_2 \) values and the probability is calculated from these realizations. There are two limit cases. If \( d < 2r \) the probability of collision is 1, while if \( d > 2h \) the probability of collision is 0.

In the specific case of BHR 71, we adopt as values \( r = 10^\circ \), \( h = 20^\circ \), and \( d = 15^\circ \). Here we are making the assumption that the dimensions in the plane of the sky represent the true dimensions. The resulting probability plot is shown in Figure 6(b). As can be seen there, for a separation of \( d = 15^\circ \), the probability of collision is very close to 1, regardless of the orientation of the flows. This results from the fact that these flows are wide and close to each other.

In contrast, there are cases of binary flows reported in the literature where a similar analysis indicates that a change in the orientation of the flows could have avoided the collision. We
have modeled the colliding outflows reported by Beltrán et al. (2012) and Kong et al. (2017) with the parameters given in Figures 6(c) and (d). In these two cases, the probabilities of collision are 0.2 and 0.5, respectively. This means that a change of orientation in the flows could have avoided the collision.

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