Episodicity in accretion-ejection processes associated with **IRAS 15398-3359**

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ABSTRACT

Context. The protostar IRAS 15398-3359 is associated with a bipolar molecular outflow ejected in an nearly northeast-southwest (NE-SW) direction which has been extensively studied. It has been suggested previous episodic accretion events by this source. Furthermore, the analysis of the morphology and kinematics of the molecular outflow revealed the presence of four ¹²CO (2-1) bipolar elliptical shock-like structures identified in both lobes. These structures seem to trace different ejections inclined $\sim 10^{\circ}$ on the plane of the sky from each other. This led to the hypothesis that the outflow axis likely precesses and launches material episodically. Aims. Since several authors reached the conclusion of the same episodicity scenario by independent observations, IRAS 15398-3359 has become an ideal target to empirically analyze the relationship between accretion and ejection processes.

Methods. We analyze ALMA archive observations in Band 6, revealing the presence of low-velocity ($< 3.5 \text{ km s}^{-1}$) emission from the 12 CO (2-1) line to the south and north of the protostar. We study the morphology and kinematics of the gas, which seems to support the hypothesis of a precessing episodic outflow.

Results. The ALMA observations reveal a north-south (N-S) outflow most likely associated with the IRAS 15398-3359 protostellar system. This outflow could be older than the well-studied NE-SW outflow. The orientation of the N-S outflow is 50° - 60° on the plane of the sky away from that of the NE-SW outflow. We also analyze the Spectral Energy Distribution of a far away young star and preliminary discard it as the driver of the SE outflow remnants.

Conclusions. The new observations support the hypothesis of strong episodic accretion-ejection events in IRAS 15398-3359, accompanied by dramatic changes in the orientation of its ejection axis, implying that all the outflows in the region may have been driven by the same protostar.

Key words. star formation - outflows - individual object: IRAS 15938-3359

Young stellar outflows are believed to extract angular momentum in protostellar disks, allowing material accreting onto the central protostar. However, the link between accretion and ejection is difficult to reach observationally due to the confusion among disk, envelope, outflow and accretion processes, the small scales within the disk, and the inaccuracies of mass estimates. Hence, accretion processes are far from being understood (although see a few empirical work connecting accretion and ejection processes Ellerbroek et al. 2013; Kim et al. 2023) and, at the same time, many outflows show perturbations moving them away from the traditional view of the well-behaved bipolar outflow (Cunningham et al. 2009a; Vazzano et al. 2021).

In this regard, the precession in outflows has usually been related to dynamical interactions of binaries or multiples. However, this effect can be caused in several ways, such as: (1) the orbital motion of a binary system, (2) the tidal effect in the disk by a non-coplanar companion, (3) the warp of the inner disk from which the jet is launched, (4) the misalignment between the spin of the disk and the axis of outflowing ejection (see e. g. Kwon et al. 2015; Young et al. 2022, and references therein). Precession has been reported in outflows from low-mass protostars such as HH30, HH46-47, or L1157 (Anglada et al. 2007; Arce et al. 2013; Kwon et al. 2015).

Multiple outflows arising apparently from a single young stellar system have been found mostly toward high-mass starforming regions (e.g., Cepheus A HW2 Cunningham et al. 2009a). The so-called binary jets have also been reported associated with low-mass young stars (e.g., Murphy et al. 2008), with L1551 IRS5 as a striking example of two jets ejected by two protostars separated by 50 au (e.g., Rodríguez et al. 2003). Although the most straightforward explanation for the multiple outflows is to have as many driving objects as bipolar ejections, in certain cases it has been speculated that two outflows can be driven from the same young star (Kwon et al. 2015; Cunningham et al. 2009a). This can be possible if the outflows are sequentially ejected in time and in different directions. The change of direction could be due, for instance, to the tidal interaction of a non-coplanar companion (as in the case of Cepheus A HW2, Cunningham et al. 2009a; Zapata et al. 2013). Other plausible scenarios could also explain such extreme systems.

The protostar IRAS 15398-3359 and its associated molecular outflow has been extensively studied. It is a young low-mass Class 0 protostellar object located in the Lupus I star-forming region at RA, Dec (J2000) = 15:43:02, -34:09:07. Recent calculations of Lupus I distances based on Gaia DR2 data have revealed

that this cloud is located at 153 ± 5 pc (Santamaría-Miranda et al. 2021), in agreement with the distance derived by Sanchis et al. (2020).

IRAS 15398-3359 was first identified by Heyer & Graham (1989). Its associated outflow was first reported by Tachihara et al. (1996) and mapped in several CO transitions by van Kempen et al. (2009b) via single-dish observations.

From high angular resolution observations of H₂CO and CCH obtained with ALMA, Oya et al. (2014) detected the molecular outflow extending in the northeast-southwest direction (PA 220°), and derived an inclination angle of 20° with respect to the plane of the sky. They estimated an upper limit of 0.09 M_{\odot} for the protostellar mass. Using SO ALMA observations, Okoda et al. (2018) suggested the presence of a molecular gas disk, which has been recently resolved out by Thieme et al. (2023) into a 31.2 au radius structure. In this last work, the authors dynamically derived a protostellar mass of 0.022 M_{\odot} , in good agreement with that estimated by Yen et al. (2017) and Okoda et al. (2018). This lower mass value makes IRAS 15398-3359 an object between the proto-brown dwarf and the very lowmass regime. Furthermore, the reported envelope mass ranges from 0.5 (van Kempen et al. 2009a) to 1.2 M_{\odot} (Jørgensen et al. 2013), suggesting the protostellar growth in the future.

Jørgensen et al. (2013) and Bjerkeli et al. (2016) have suggested previous episodic accretion events by this source. Jørgensen et al. (2013) detected a H¹³CO⁺ ring structure of about 150-200 au around the protostar. The lack of H¹³CO⁺ inside the ring is not consistent with the current heating rate of the central protostar. These authors propose that the H¹³CO⁺ would have been removed by a chemical reaction with H₂O, sublimated from dust grains during an accretion burst that occurred $10^2 - 10^3$ years ago. Bjerkeli et al. (2016) also provided evidence for a past accretion event via the study of HDO $(1_{0,1}-0_{0,0})$. The authors found this molecule is only detected in the region closest to the protostar, and they suggest as a possible explanation that the water in the grains was released during a recent accretion burst. Furthermore, the analysis of the morphology and kinematics of the northeast-southwest molecular outflow revealed the presence of four pairs of counter-aligning elliptical shock-like structures identified in both lobes (Vazzano et al. 2021). These structures seem to trace different ejections inclined $\sim 10^{\circ}$ from each other. This led to the hypothesis that the outflow axis likely precesses and launches material episodically. Since several authors reached the conclusion of the same episodicity scenario by independent observations (Jørgensen et al. 2013; Bjerkeli et al. 2016; Vazzano et al. 2021), IRAS 15398-3359 has become an ideal target to empirically analyze the relationship between accretion and ejection processes.

From ALMA 12m array observations in Band 6, Okoda et al. (2021) detected the arc-like structure in H₂CO, SiO, CH₃OH and SO crossing the northeast-southwest molecular outflow in a direction roughly perpendicular. They proposed that the observed feature could be part of a relic outflow ejection, previously launched by IRAS 15398-3359. They interpret the difference in the ejection direction of this relic with respect to the direction of the northeast-southwest outflow as induced by variations in the angular momentum of the episodically accreting gas. These variations could produce a drastic change in the direction of outflow ejection. Alternatively, Vazzano et al. (2021) reveal a complex of ¹²CO (2–1) and SO ($J_N=6_5$, 5_4) arc-like structures, 10''-20'' southeast of the protostar's location. Some of these structures present bow-shock shapes with tips pointing toward IRAS 15398-3359, suggesting a possible origin linked to the emission of an outflow associated with the source 2MASS 15430576-3410004, placed about 1' southeast of IRAS 15398-3359, Okoda et al. (2021) interpreted these arc-like features as coming out from a possible second outflow associated with IRAS 15398-3359. In the present contribution we analyze recent ALMA archive observations, revealing the presence of red-shifted and blue-shifted low-velocity gas detected north and south of IRAS 15398-3359, respectively. This confirms the existence of a other outflow driven by this protostellar system. We study the morphology and kinematics of the gas, which seems to support the hypothesis of a precessing episodic outflow.

2. ALMA molecular data

This work is mainly based on archival data obtained with the 7m Atacama Compact Array (ACA) of ALMA. We also use higher angular resolution images obtained with ALMA, previously presented in Vazzano et al. (2021). These images were not combined and we analyzed them independently. New archival data presented in this work consist of a mosaic done with the ACA 7m-antennas array in Band 6 centered on IRAS 15398-3359 (project 2019.1.01063.S, P.I: Jinshi Sai). The mosaic contained 28 pointings covering an area of 2.4×2.6 . The data were taken on December 19, 2019. Maximun and minimum baselines were 8 and 48 meters, then the angular resolution is 8''. With respect to the weather conditions, the precipitable water vapour (PWV) values ranged between 1.6 and 1.95 mm during the observations. The correlator was configured to use four spectral windows and one continuum window. The continuous window at 1.3 mm (233.999 Ghz) has 128 channels and a bandwidth of 2.0 Ghz. The spectral windows were centered on the transitions of $C^{18}O(2-1)$, ¹³CO(2-1), CO(2-1) and $N_2D^+(3-2)$ at 219.561, 220.399, 230.539 and 231.323 Ghz, respectively. The number of channels and the bandwidth of the first two windows were 2048 and 0.125 GHz each, while for the remaining two windows, 1024 channels were observed with a bandwidth of 0.062 GHz (equivalent to a velocity resolution of 0.08 km s^{-1}). Calibration of the raw visibility data was performed using the standard reduction script for the Cycle 6 data provided by the ALMA Observatory. This pipeline ran within the Common Astronomical Software Application (CASA 5.6.1 McMullin et al. 2007) environment. The on source integration time was 2.55 hours and the calibrators used to correct for instrumental and atmospheric disturbances (flux, phase, and bandpass) were J1337-1257, J1534-3526, and J1337-1257 respectively. The self-calibrated interferometric free-line continuum data were cleaned in CASA to produce continuum images. The spectral line cubes were produced by subtracting the continuum and applying a standard cleaning with primary beam correction. The continuum was subtracted in the uv-plane using the uvcontsub task. The ACA calibrated visibilities were Fourier transformed and cleaned with the CASA task tclean. We set the Briggs weighting parameter robust= 0.5 for both the continuum and 12 CO (2-1) images as a compromise between angular resolution and signal-to-noise ratio (beam of $7''.7 \times 4''.2$, PA=86°). The rms noise level in the continuum image is around 2 mJy/beam. The rms noise level for the ¹²CO (2-1) cube is $\sim 100 \text{ mJy beam}^{-1}$ per one channel of 0.16 km s⁻¹ of the line velocity cube. In this work we only report ¹²CO (2-1) data.

3. Results

Fig. 1 shows the blue-shifted and red-shifted integrated ¹²CO (2-1) intensity images, considering a systemic velocity v_{sys} = 5.1±0.1 km s⁻¹ (Mardones et al. 1997; van Kempen et al.

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	Δv_{rad} (km s ⁻¹)	PA (°)	Size (au)
NS outflow			
Blue lobe	3.4 ± 0.08	182 ± 4.0	10030 ± 570
Red lobe	2.9 ± 0.08	355 ± 4.0	10100 ± 570
NE-SW outflow			
Blue lobe	15.3±0.08	232.0±0.2	2550 ± 50
Red lobe	11.6 ± 0.08	64.9 ± 0.2	1800 ± 50

Table 1. Outflow parameters. $\Delta v_{rad} = |v_{sys} - v_{max}|$ is the outflow spread in radial velocity, where v_{sys} is the systemic velocity and v_{max} is the velocity up to which it is possible to detect outflow emission over the 3σ threshold.

2009b). This systemic velocity is consistent with the recent ALMA study (Yen et al. 2017). In the center of the figure there is strong emission corresponding to the well-known molecular flow associated with the northeast-southwest direction. Moreover, there is a second lobe to the southeast, which was identified as an outflow relic by Okoda et al. (2021). In addition, we detected other blue-shifted and red-shifted gas emission to the south and north of IRAS 15398-3359, respectively. The morphology seems an additional molecular outflow. These structures of ¹²CO are aligned with respect to the location of the IRAS 15398-3359 protostar and their emission is fainter than that of the northeast-southwest outflow. In addition, their projected size in the plane of the sky is greater than the northeastsouthwest outflow. Hereafter, we further refer to the well-known outflow in the northeast-southeast direction as the 'NE-SW outflow', the southeast lobe reported by Okoda et al. (2021) as the 'SE lobe', and to the new one detected in the north-south direction as the 'N-S outflow'.

Table 1 lists the velocity ranges used to map the red-shifted and blue-shifted lobes of the NE-SW and N-S structures, the position angles (P.A.) measured from north (0°) to east (90°), and the size of lobes. We derive these quantities for the red- and blueshifted lobes of each outflow separately. $\Delta v_{rad} = |v_{sys} - v_{max}|$ is the outflow spread in radial velocity, where v_{sys} is the systemic velocity and v_{max} is the maximum velocity which it is possible to detect outflow emission over the 3σ threshold. The position angles are calculated from the source position to the peak emission in each lobe. Since the outflow inclination is unknown, the sizes are projected on the plane of the sky and should be treated as lower limits. The errors in the measured sizes are given by the angular resolution of the image ($\Delta Size = beam/2$). The parameters listed for the NE-SW outflow were taken from Vazzano et al. (2021).

In the top panels of Figure 2 we show three channels of the high-angular resolution ¹²CO (2-1) velocity cube (Vazzano et al. 2021). The emission in these channels is slightly blue-shifted with respect to the system velocity. The NE-SW outflow is very bright, and a fainter complex of several arc-shaped structures (that we have identified as the SE lobe) can be identified southeast of the protostar location, almost perpendicular to the NE-SW outflow. These arc-shaped structures are also detected in CO(2-1) by Vazzano et al. (2021), and other molecular tracers (H₂CO, SO, SiO and CH₃OH) in Okoda et al. (2021). We identify two main directions linking the protostar position with the tips of some prominent arc-shaped structures; we include a third direction pointing to the blue-shifted southern lobe of the N-S outflow. These three directions, marked with blue arrows in Fig. 2, have position angles 137° , 160° and 180° . They seem to be separated by $\sim 20^{\circ}$ each on the plane of the sky. The three



Fig. 1. Blue-shifted and red-shifted integrated emission of 12 CO (2-1) toward the IRAS 15398-3359 region. The blue-shifted and red-shifted emission were integrated over the velocity ranges from 2.3 to 4.7 km s⁻¹ and from 6.2 to 7.4 km s⁻¹. Blue-shifted and red-shifted contours are represented at 10, 20, 30, 40, 50, 60, 100, and 150 times the *rms* of 0.15 mJy beam⁻¹ km s⁻¹ and 0.1 mJy beam⁻¹ km s⁻¹, respectively. The stars indicate the position of IRAS 15398-3359 and 2MASS 15430576-3410004. The synthesized beam (7".7×4".2, PA=86°) is represented by the black ellipse in the bottom left corner.

panels in the bottom right of Fig. 2 present the mean integrated spectra taken toward three regions marked with the corresponding boxes in the bottom left panel. Spectra from boxes 1 and 2 show a single main peak blue-shifted at 4.1 km s⁻¹. The spectrum from box 3 shows a double peak structure at 3.8 km s⁻¹ and 3.2 km s⁻¹.

Figure 3 shows the position-velocity diagram obtained along the N-S outflow axis and centered at the continuum peak position and the systemic velocity (5.1 km s^{-1}) . The emission near the zero offset likely belongs to the IRAS 15398-3359 rotating molecular envelope/disk system. Further away, the redshifted and blue-shifted gas moves up to 70["] away from the protostar and reaches velocities as fast as 3 km s⁻¹ with respect to the systemic velocity. The two-branch morphology observed in the blue-shifted part of the diagram (positive offsets) could correspond to a shell structure typical of molecular outflows (see white arrows in the Figure 3). This agrees with the doublepeaked spectrum corresponding with box 3 in Figure 2.

Figure 4 shows the ¹²CO (2-1) velocity channel map of the NE-SW and NS outflows, and the SE lobe. The velocity of the blue-shifted emission from the NS outflow ranges from 2.3 to 4.2 km s^{-1} and its red-shifted emission ranges from 6.4 to 7.4 km s⁻¹. The SE lobe emission ranges from 3.6 to 4.4 km s^{-1} . The NE-SW main outflow spreads a range larger than that covered in the Figure.

From the ¹²CO map in Fig. 1 and the velocity gradients of the gas revealed in Fig. 3, we can infer the presence of two bipolar structures centred on the IRAS 15398-3359. The NE-SW outflow that has been extensively studied and the new N-S outflow



Fig. 2. *Upper panels*: High-angular resolution velocity channel maps taken with the 12-m array of the ¹²CO (2-1) emission near the cloud velocity. The blue arrows indicate possible relic ejections interacting with the gas in the vicinity of IRAS 15398-3359. The red star indicates the position of the continuum source. The synthesized beam (0''.57×0''.50) is represented in the bottom left corner and the radial velocity is indicated in the top left corner. *Bottom left panel*: The same arrows as in the figure above are shown on the integrated blue-shifted emission image covering from 2.3 to 4.7 km s⁻¹. The red boxes show the regions within which the spectra shown on the right-hand panels were taken. *Bottom right panels*: Average spectra obtained integrating the blue-shifted emission inside the three boxes from the left. The vertical red line in the spectra indicates the systemic velocity at 5.1 km s⁻¹.



Fig. 3. Position-velocity diagram of the 12 CO (2-1) emission along the north-south axis and centered at the continuum peak position with an angle position of and cut width of 1''.

presented in this work for the first time. A multiple outflow scenario supports the scenario proposed by Okoda et al. (2021), who revealed various outflows coming out from IRAS15398-3359 at different epochs (4). The position angles of the blue-shifted and red-shifted lobes of the N-S and NE-SW outflows differ by 173° and165°, respectively. In addition, the size projected on the plane

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Fig. 4. ¹²CO emission velocity channel maps toward IRAS 15398-3359 (grey scale). The upper/lower channel map shows the blue/red-shifted emission, avoiding the central channels around the 5.1 km s^{-1} cloud velocity. Contours are displayed at 2.0 and 5.0 mJy beam⁻¹. Radial velocities are indicated in the top left corner. Synthesized beam is shown in the bottom left corner on every channel.

of the sky of the N-S outflow is over four times greater compared with the NE-SW outflow, while its velocity extent is at least four times smaller without correcting for inclination angles.

4. Discussion

4.1. A north-south molecular outflow from IRAS 15398-3359

In addition to the well-known NE-SW molecular outflow associated with the protostar IRAS 15398-3359, Okoda et al. (2021) showed indications of the presence of a second molecular outflow probably ejected by the protostellar system, extending southeast up to 2'' (3000 au). The present 7m array ALMA observations reveals the existence of a third molecular bipolar outflow in the north-south direction. The projected sizes measured from the position of the protostellar system ($\sim 10^4$ au) and the radial velocities (up to $\sim 3 \text{ km s}^{-1}$) of the blue-shifted (south) and red-shifted (north) lobes are similar; their position angles match within the error bars. All of this supports the idea that these two lobes comprise a bipolar structure originated at the IRAS 15398-3359 position. Similar cases can be found in the literature where more than one outflow is observed. There is the case of Par-lup where two outflows were found associated with a young very low mass star (Santamaría-Miranda et al. 2020). In this source

the evidence points to a < 15 au packed binary driving the two outflows. Another example is given in L1157, where Kwon et al. (2015) observed two jets would be of different ages and would be triggered by a single Class 0 protostar (< $0.04 M_{\odot}$).

4.2. Origin and nature of SE lobe

Furthermore the 7m array ALMA observations show, although unresolved, the emission from the blue-shifted complex of arcshaped structures (the SE lobe), previously detected by Okoda et al. (2021) in several molecular shock-tracers between 1000 au and 3000 au southeast of the protostar (position angles ranging 137°-160°). The red-shifted counterpart of these arc-shaped structures is, however, not clearly seen with the current lowangular resolution data (but see the ¹³CO and C¹⁸O velocity cubes in Thieme et al. 2023). In the following, we discuss the origin and nature of the molecular emission of the SE lobe and its relationship with the two outflows apparently launched from IRAS 15398-3359 location.

Regarding IRAS 15398-3359, a first possible scenario could be the presence of another source to the southeast, launching an outflow that produces bow-shock arc-shaped structures when breaking into the quiescent gas surrounding IRAS 15398-3359 (Vazzano et al. 2021). Figure 1 shows the position of the southeastern infrared source 2MASS 15430576-3410004, about 9000 au away (~ 60''). However, the molecular gas from the arc-complex does not extend to this location. In addition, we have compiled and analyzed the SED of this 2MASS source. The SED can be fitted with a blackbody model of temperature 2200 K, which peaks at $\sim 10^5$ GHz (Figure 5; see also Table 2). The infrared spectral index from 2 to 24 μ m is $\alpha = \frac{dlog(\lambda F(\lambda))}{dlog\lambda} = -$ 2.27. The lack of strong millimeter emission, along with the derived infrared spectral index, indicates that this star is probably in a more evolved stage (Evans et al. 2003), and is not probably responsible for the ejection of a prominent outflow.

A second possible scenario, proposed by Okoda et al. (2021), suggests that the arc-complex originates from relic IRAS 15398-3359 ejections. In this scenario, the geometry of the arcs is showing the bottom part of bubble-shaped structures, instead of bowshocks tips. A variation of the SE lobe as a relic outflow scenario, would explain the arcs and the filamentary structure (upper panels in Figure 2) as the remnants of a side-way shock created by adjacent wakes of two separate ejections. This may explain the arcs pointing toward the protostar and the shock tracers found in this structure. Ejections with this type of morphology (cavities with parabolic shapes) are considered in the wind-driven shell model explained by Lee et al. 2000, and have already been detected in other outflows, such the northwest lobe of IRAS 16059-3857 (Vazzano et al. 2021) or the western lobe of HH 46/47 (Arce et al. 2013). Alternatively, the SE lobe could comprise the relics of two colliding side-way shocks from adjacent outflow ejections. The discovery of N-S outflow extending up to 10⁴ au supports this second hypothetical scenario, as it provides new evidence for the existence of older ejecta launched from the IRAS 15398-3359 location.

The difference in the position angles of the different arcs and the southernmost blue-shifted lobe ($\sim 20^{\circ} \cdot 23^{\circ}$) may indicate that the outflow axis was precessing. A similar set of ejections in slightly different directions have also been observed in the NE-SW outflow (Vazzano et al. 2021). We analyze this precessing behaviour in the Section 4.4.



Fig. 5. 2MASS 15430576-3410004 spectral energy distribution. Black dashed line shows the black-body fitting derived from infrared emission (data listed in Table 2).

Band	Wavelength	Flux	Reference
	[µm]	[mJy]	
2MASS J	1.235	0.160 ± 0.033	Cutri et al. (2003)
2MASS H	1.662	0.426 ± 0.058	Cutri et al. (2003)
2MASS Ks	2.159	0.657 ± 0.065	Cutri et al. (2003)
Spitzer-IRAC1	3.6	0.353 ± 0.020	Evans et al. (2003)
Spitzer-IRAC2	4.5	0.255 ± 0.016	Evans et al. (2003)
Spitzer-IRAC3	5.8	0.202 ± 0.034	Evans et al. (2003)

Table 2. Data used to fit the 2MASS 15430576-3410004 spectral energydistribution.

4.3. The age of the relic N-S outflow

The inclination of the outflows with respect to the plane of sky is still undetermined. Given that the NE-SW outflow seems to change its direction in short time lapses, the inclination with respect to the plane of the sky derived may be different to the value at which the relic N-S outflow was ejected. Moreover, their dynamic times depend on the observed radial velocities, which are considerably lower in the N-S outflow than in the NE-SW outflow. Although the velocities of the outflows are not a robust indicator of their age, this could mean that the N-S outflow was ejected in a direction closer to the plane of the sky (i.e., $i \sim 0^\circ$), and/or that the gas has slowed down after some time. In any case, older outflows are expected to be longer and slower than younger ones which hints at a difference in the age of both outflows.

As a first approximation, we consider the inclination of both outflows to be the same ($i = 30^{\circ}$, from Yen et al. 2017). We also use the radial velocities listed in Table 1. The dynamical times for the blue-shifted and red-shifted lobes of the N-S outflow result in 24200 and 28600 years, respectively. This implies that the N-S outflow would be about 20 times older than the NE-SW outflow (with a dynamic time of ~ 1300 years). Alternatively, we could also speculate that the gas in the N-S outflow was ejected in the past at similar velocity to that observed in the NE-SW outflow (i.e., a radial velocity of 13.5 km s⁻¹ on average). Under this hypothesis, the N-S outflow would have an inclination of ~ 13° with respect to the plane of the sky, and an estimated dynamical time of ~3650 yr, about 4 times older than the NE-SW outflow.

To sum this up, the new observations suggest that the N-S may be a relic of an older outflow, while the NE-SW outflow, currently being ejected, may be younger.

4.4. Episodic accretion and ejection

Vazzano et al. (2021) identified four pairs of bipolar elliptical structures ending in bow-like structures in the NE-SW outflow associated with IRAS 15398-3359. Every identified ellipse-like structure would correspond to a bipolar ejection. These structures have slightly different sizes and position angles, which possibly indicates the presence of episodically ejected material outflowing from the protostellar system with a variable direction caused by the precession of the launching axis. Extending this scenario to the SE lobe, we speculate that both, the N-S outflow and the SE lobe, can be part of a series of ejections in slightly different directions with position angles separated by $\sim 20^{\circ}$ (see arrows in Fig. 2). Therefore, the NE-SW outflow on one hand, and the N-S outflow along with the SE lobe, on the other hand, may share a similar pattern of episodic precessing ejections.

Assuming that the NE-SW outflow, N-S outflow and SE lobe are driven by the same protostellar system in IRAS 15398-3359 (for an update about the multiplicity of this system based on the most recent observations see Okoda et al. 2021; Thieme et al. 2023), the present observations suggest that events would have drastically changed the outflow direction, while keeping memory of the precession of the system (or as a consequence of it). In this way, the system would present both, small ($< 20^{\circ}$) and large $(> 20^{\circ})$ orientation changes. While the small changes may be caused by precession of the outflow axis, the large changes may be triggered by cataclysmic accretion events (a sudden asymmetric accretion of large amounts of mass), the close encounter with an interloper, or by the presence of an undetected smallmass companion star with a nearby periastron (reorientation by gravitational tugging, as in Cepheus A HW2, Cunningham et al. 2009b). Another possibility is that the gravitational interactions of a putative unresolved multiple system may episodically tilt the system, with intertwined periods of quiescent and chaotic reconfigurations. However, as said before, at this moment there is no clear evidence supporting the presence of such multiple system. Recent continuous analysis of high-resolution ($\sim 40 mas$) IRAS 15398-3359 observations by Thieme et al. (2023) has revealed one small, compact (deconvolved size of $4.5 \times 2.8 au$) and very low-mass $(0.6 - 1.8 M_{jup})$ dust disk.

In any case, the data reveal that the IRAS 15398-3359 system has different episodic ejections, and these could be associated with events in which the accretion suddenly varies. Moreover, Vazzano et al. (2021) determined that the estimated dynamical times of the different ejections in the NE-SW outflow range from 33 to 268 years, while Jørgensen et al. (2013), based on the lack of H¹³CO⁺ at the center of the protostellar system's envelope, proposed that the system underwent a recent accretion burst 100-1000 years ago. Despite the rough agreement between the two timescales, more data should be collected to relate this accretion event with the sudden change of direction in the outflow.

Mosaic observations with better angular resolution, higher sensitivity (e.g., 12 m ALMA observations with a extended array) will be necessary to accurately describe the structure of the relic N-S outflow lobes and discover if there are more continuum sources in IRAS 15398-3359. It would also be necessary to observe new chemical tracers to study the accretion processes of the protostellar envelope. In addition, observations with a larger field, including the whole extension of the SE lobe, could help us to better determine its origin.

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5. Summary

From 7m array ALMA data we report the presence of a new molecular outflow (the N-S outflow) associated with the young protostar IRAS 15398-3359, in addition to the already wellstudied one projected into the sky in a northeast-southwest direction. The NE-SW outflow may undergo precessional motions, which result in ejections driven along slightly $\sim 10^{\circ}$ different orientations (Vazzano et al. 2021). The newly reported molecular outflow is almost in a north-south direction and its position angle differs by 50°-60° from the NE-SW outflow. The morphology and kinematics of the detected gas show that the north-south ejections are older and may be the relics of a past ejected bipolar outflow. In addition, we build up the Spectral Energy Distribution of the 2MASS 15430576/3410004, which shows a spectral index that momentarily discard it as the possible driver of the outflow remnants in the form of arc-shaped structures, previously detected southeast from IRAS 15398-3359 (Cutri et al. 2003; Evans et al. 2003). These remnants may be the outcome of the collision of wakes produced by side-way shock fronts.

We propose that the gas detected north and south of IRAS 15398-3359 in these new observations, together with the gas structures identified southeast of the same source (Vazzano et al. 2021; Okoda et al. 2021), are the remnants of several episodic outflow ejections driven by a possible precessing system.

The new observations suggest that one or more events could have drastically changed the direction of the outflow. This result supports the scenario proposed by Okoda et al. (2021). They propose strong events could be related with extreme anisotropic accretion events that may produce a tilt in the direction of the disk-protostar system. In the case of IRAS 15398-3359, both the disk and the protostar have a relatively low mass, hence this sort of perturbation may not be so difficult to reach. After the tilt, or as a consequence of it, the system seems to keep the memory of such events in the form of a small precession seen as multiple ejections in the NE-SW outflow. It would be expected that the rotation of the disk may dampen the precession in due time.

Finally, the results presented in this work, depict IRAS 15398-3359 as a key protostellar system to better understand the link between accretion and ejection, their episodic nature, and the origin of precession in very young jets and outflows.

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