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THE HH30 T-TAURI STAR

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Abstract. A prerequisite to understanding the formation of stars is the comprehension of the processes linking the collapsing molecular core, the setting of the circumstellar disk, and the accretion from this disk to the protostar. Together, these processes regulate the mass that the star will acquire. The critical point of these stages is the extraction of the angular momentum, that allows the matter to be accreted from the large scale down to the protostar. It has been proposed that the extraction of angular momentum in the disk could be through the jets and outflows, that are observed in proto-stellar objects of all mass. In this proceeding, we present the recent results we obtained with ALMA observations toward the HH30 T-Tauri star. By studying the gas dynamics we could show that the outflow is transporting angular momentum away from the system disk-protostar.

Keywords: ISM, Star formation, Protostar, Accretion, Ejection, Outflow, Jets, Precession

1 Introduction

A necessary prerequisite to understand the formation of stars is the comprehension of the complex processes that permit to a particle in the molecular cloud to end up in the protostar. The major issue in the aspect is the law of the conservation of the angular momentum: $r \times v_\phi = constant$. A particle collapsing toward the potential well (r decreases) will spin faster and faster (v_ϕ increases) and reach equilibrium when v_ϕ equals the Keplerian velocity at the distance r from the proto-star. It is believed that the magnetic field permit to extract a fraction of the angular momentum from the collapsing gas before it reaches the accretion disk. With such processes, the latest numerical simulations manage to form circumstellar disk in line with the observations (e.g. Tsukamoto et al. 2018; Hennebelle & Ciardi 2009). For long, the community thought that the extraction of the angular momentum in the disk itself was due to the *magneto-rotational-instability* (MRI, Balbus & Hawley 1991). This instability produces vigorous turbulence and efficiently transports angular momentum outwards in discs with effective viscosity $\alpha > 10^{-3}$ (Hawley et al. 1995). Nevertheless, it was shown recently that when non-ideal magneto-hydro-dynamical effects are taken into account, namely the Hall effect, the ambipolar diffusion, and the Ohmic dissipation, the MRI gets inefficient (e.g. Lesur et al. 2014). Another possibility to extract angular momentum from the disk could be trough the jets and outflows, hypothesis first stated by Pudritz & Norman (1983).

Outflows and jets seem to be ubiquitous in star-forming systems of all masses, that from the formation of brown-dwarves (Whelan et al. 2018) and up to massive star formation (Duarte-Cabral et al. 2014). Outflows are also witnessed at all stages of star formation, from the Class 0 stage (Bachiller & Pérez Gutiérrez 1997) and up to the T-Tauri stage (Burrows et al. 1996). Jets are also observed toward more extreme objects such as AGNs

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and X-binaries, where a compact object accrete material through an accretion disk. Therefore, it is possible that the physical process creating the outflows and jets is universal. Hence, studying the outflows arising from proto-stars could be a key path for understanding accretion in a broader context.

2 About the accretion-ejection processes

Using the interferometer ALMA, we observed the disk and the outflow of the HH30 T-Tauri star (Louvet et al. 2018). HH30 is a very well characterized proto-star of the Taurus molecular cloud, located at $\sim$140 pc. The left panel of the Fig. 1 summarizes our observations of the gas around HH30. The disk appears perpendicular to the plan of the sky and display a clear Keplerian rotation when traced in ^{13}CO (color scale in Fig. 1-left). The outflow of HH30 is well traced in ^{12}CO and extends in the plan of the sky up to several hundreds of au above the disk plane (grey scale in Fig. 1-left). Since the outflow develops in the plane of the sky, each cut above the mid-plane (e.g. such as the green arrow in Fig. 1) is at the same altitude, whereas in an inclined system different altitudes get mixed in a given line of sight. The middle panel of the Fig. 1 shows the position-velocity diagram (pvd) at the altitude where the green arrow is overlaid on the left panel. A pvd is basically a collection of spectra stuck one next to each over and where the flux in a given channel is levels of grey. In Fig. 1-middle one can see that at each position, two peaks are present in the spectrum. These two peaks show the red-shifted and blue-shifted faces of the outflow. Since the intermediate velocities have a very low flux (the pvd is 'empty') the best representation of the outflow is an empty cone with the gas flowing along the edges of the cone. In a more quantitative way, it is possible to derive the dynamical parameters of the gas at a given altitude (see Fig. 2-right) by fitting an ellipse to its pvd – the parameters of the ellipse being correlated to the dynamical parameters by:

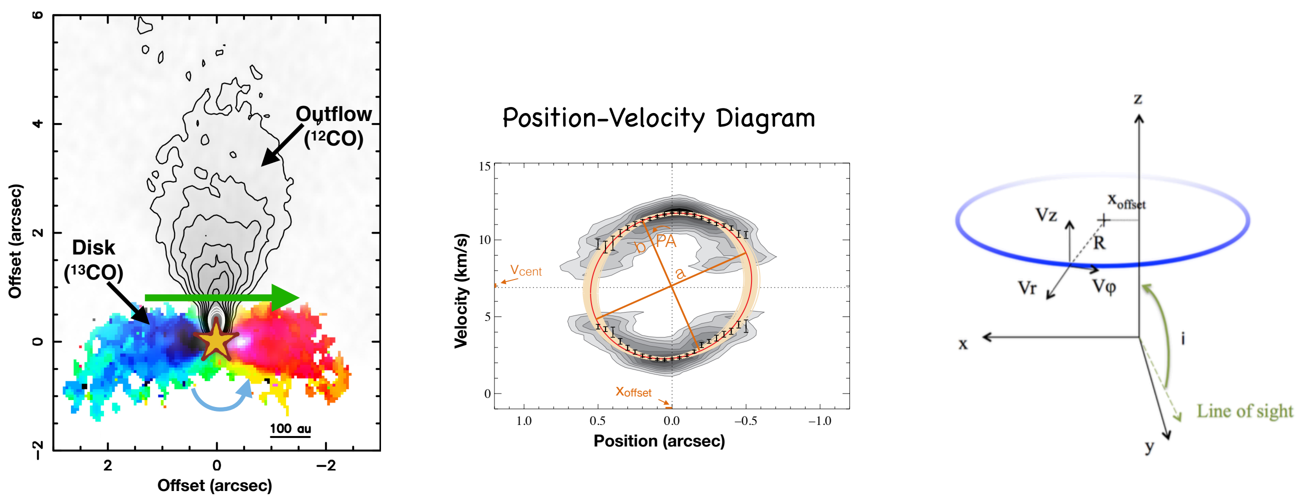

Fig. 1. Left: The figure displays in greyscale the integrated ^{12}CO(2-1) emission that traces the outflow, the colors display the moment 1 map of the ^{13}CO(2-1) emission showing the extent of the disk and its sense of rotation. **Middle:** Position-velocity diagram of the ^{12}CO(2-1) emission at the altitude $z = 0.7''$ (or 100 au at the distance of HH30), highlighted by the green arrow in the left panel. PA, a, and b design the parameters of the ellipse that best fit the CO emission. $v_{\rm cent}$ and $r_{\rm cent}$ are the offsets with respect to the $v_{\rm lsr}$ and to the center of disk as seen in continuum, respectively. **Right:** The sketch illustrates the different dynamical parameter of a cut at a given altitude above the mid-plane. For $i = 90°$, V_r is the radial velocity toward the observer, V_z is the velocity along in the plane of the sky, V_ϕ is the rotation velocity, $x_{\rm offset}$ is the offset of the cut with respect to the central position of the disk, and R is the radius of the cone at this altitude. All these parameters can be derived from the fit of an ellipse on the position-velocity diagram at the corresponding altitude z (see the central panel) through the equations (2.1)-(2.5).

$$x_{\rm offset} = r_{cent} \tag{2.1}$$
$$V_{\rm z} = -(V_{cent} - V_0)/\cos i \tag{2.2}$$
$$(V_{\rm r} \sin i)^2 = \left((\cos PA)^2/a^2 + (\sin PA)^2/b^2\right)^{-1} \tag{2.3}$$

$$(V_\phi \sin i)/R = 0.5 \times (V_{\rm r} \sin i)^2 \times \sin 2PA \times (1/b^2 - 1/a^2) \quad (2.4)$$
$$1/R^2 = \left((\cos PA)^2/b^2 + (\sin PA)^2/a^2\right) - (V_\phi/R)^2/V_{\rm r}^2. \quad (2.5)$$

In Louvet et al. (2018) we derived these parameters all along the extent of the outflow. From this analysis, two major results were obtained:

- The outflow rotates. We found that v_ϕ reaches values of $\sim$0.75 km s^{-1} at 50 au above the disk plane and decreases with the altitude.

- The specific angular moment, defined as the product $R \times v_\phi$ is conserved all along the outflow with a value of $\sim$40 au km s^{-1}.

If we further assume that the specific angular momentum is conserved down to the disk-plane, we can infer a launching radius for the outflow between 1 and 7 au. The association of such ejection radius with the mass ejection rate of $\sim 9\times10^{-8}$ M$_\odot$ yr^{-1} that was infer by Louvet et al. (2018) best favour the magneto-centrifugal disk-winds to explain the outflow of HH30. Interestingly, among all the models that explain for the ejection of material through jets and outflows, the magneto-centrifugal disk-winds are the only ones that extract angular momentum from the disk – and could consequently explain for the accretion in circumstellar disks.

3 About the precession of jets and outflows

Numerous jets arising from proto-stellar systems are observed to wiggle. This is the case for the jet of HH30 (Anglada et al. 2007), but also for instance in V1331 Cyg located at 550 pc from the Sun (Mundt & Eislöffel 1998), or in RNO 15-FIR located at 350 pc from the Sun (Davis et al. 1997). It is largely believed that the wiggling of jets is caused either by orbital motions in coplanar binary system or by tidal interactions in non-coplanar binary system (e.g., Terquem et al. 1999). These two configurations are illustrated in Fig. 2. Anglada et al. (2007) computed the two solutions that reproduce the wiggling of the jet of HH30. They showed that if orbital motions is causing the wiggling of the jet of HH30 the separation of the binary shall be of $\sim$18 au, which should truncate the disk at an inner radius of $\sim$40 au. If the wiggling is due to precession of the jet, they showed that the separation of the binary would be very small, of $\sim$1 au. Later, Guilloteau et al. (2008) observed the disk of HH30 in continuum with the PdBI interferometer. They reported a possible truncation of the disk at 37$\pm$4 au, giving credit to the orbital motion scenario. Nevertheless, we could not find a sign for disk truncation in HH30 when we re-observed the system with ALMA at an angular resolution two times better than that of Guilloteau et al. (2008). The image of the continuum emission as seen with ALMA is shown on the left panel of Fig. 3. That result casts doubt on the existence of a wide binary explaining for the wiggling of HH30. Also, by studying the dynamical parameters of the outflow (see Sect. 2) we could constrain the amplitude of the wiggling of the outflow, as shown on the right panel of Fig. 3. We adapted the two solutions found by Anglada et al. (2007) so they would correspond to the dynamics of the outflow*. These solutions, over-plotted on the right panel of Fig. 3 clearly show that the orbital-motion solution predicts displacement of the outflow order of magnitudes bigger than the observed one, while the precession solution is much more in line with the observations.

4 Conclusions

In the one hand, Louvet et al. (2018) showed that the outflow of HH30 is rotating, and that the angular momentum is conserved as the outflow extends. Assuming that the angular momentum is also conserved all the way down to the disk (i.e. below our angular resolution) we could infer launching radius in between 1 and 7 au. These launching radii together with the mass ejection rate of $\sim 10^{-7}$ M$_\odot$ best favour the MDH disk wind models. In the other hand the study of the continuum, that shows no gap in the inner part, together with the very small wiggling of the outflow best favour precession to explain for the wiggling of the jet and outflow in HH30.

*The solutions of Anglada et al. (2007) depend on the jet velocity along the z-scale. We simply replaced that velocity by that of the outflow that is $\sim$10 times slower.

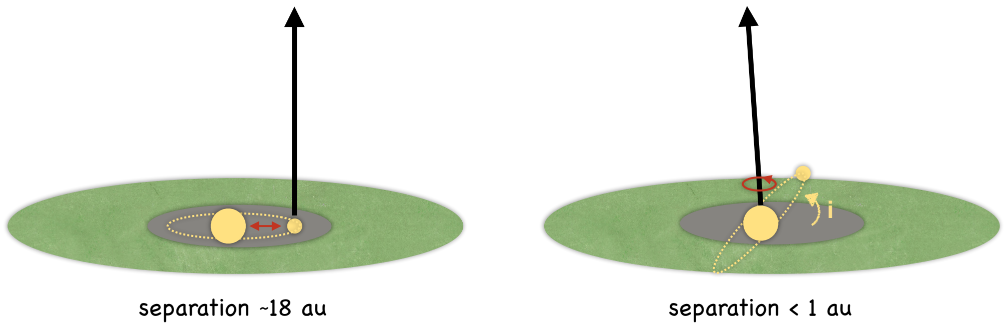

Fig. 2. Left: Sketch of the *orbital motion* scenario. In this scenario, the outflow arises from the circumstellar disk of the secondary. **Right:** Sketch of the *precession scenario*. With this hypothesis the secondary orbits out of the plane of the primary's disk. This provokes the disk of the primary to precess, a precession that gets imprinted onto the outflow. The angle i is exaggerated to ease the illustration – a few degrees are sufficient to induce precession.

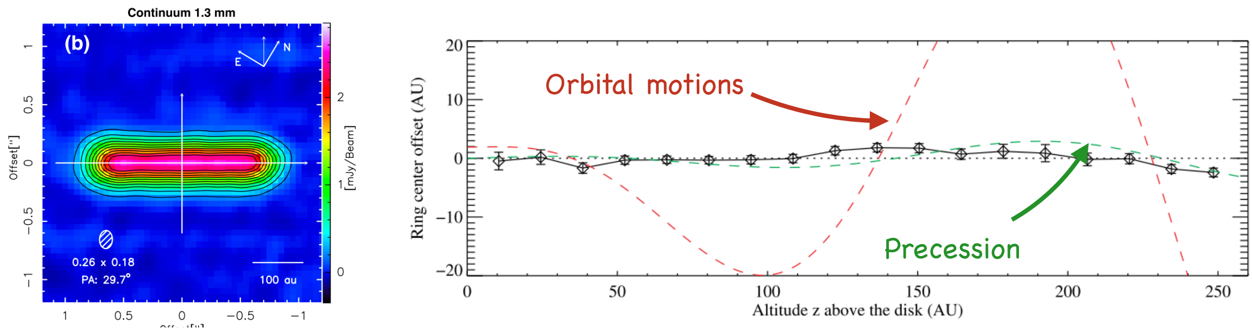

Fig. 3. Left: Continuum emission at 1.33 mm of HH30. Contrary to Guilloteau et al. (2008) no gap is seen in the continuum, casting doubts on the presence of a wide-binary as necessary in the *orbital motion* scenario (see Fig. 2-left). **Right:** The plot displays the radial offset position (see Fig. 1) of the gas as a function of altitude above the disk (hence along the outflow) with respect to the central position of the disk as seen in continuum. The red curve presents the predicted offset if the displacement in the outflow were due to orbital motion. The green curve presents the predicted offset of the outflow if due to precession. The figures were extracted from Louvet et al. (2018).

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