Protostellar jets: a statistical view with the CALYPSO IRAM-PdBI survey

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Protostellar jets: A statistical view with the CALYPSO IRAM-PdBI survey

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Abstract. In the context of the CALYPSO IRAM-PdBI Large Program we performed the first statistical survey of protostellar jets by analysing molecular emission in a sample of 21 protostars covering a broad range of internal luminosities ($L_{\rm int}$ from 0.035 $L_\odot$ to 47 $L_\odot$). We find that the outflow phenomenon is ubiquitous in our sample of protostars, with wide-angle outflows detected in CO (2 – 1) in all sources, and high-velocity collimated jets detected in SiO (5 – 4) in 80% of the sources with $L_{\rm int} > 1$ $L_\odot$. The protostellar flows have an onion-like structure, with the SiO jet (opening angle, $\alpha \sim 10°$) nested into a wider angle SO ($\alpha \sim 15°$) and CO ($\alpha \sim 25°$) outflows. Interestingly, protostellar jets show several properties in common with the atomic jets associated with more evolved sources (10^6 yr), e.g. one third of the jets show velocity asymmetry of $\sim 1.3 - 2$ between the two lobes, and the mass-loss rates are $\sim 1\% - 50\%$ of the mass accretion rates. This suggests that the same launching mechanism is at work and that the correlation between mass ejection and mass accretion holds along the star-formation process from 10^4 yr up to a few Myr.

1 Introduction

Supersonic collimated jets are believed to be launched from the disk due to a magneto-centrifugal mechanism. Theoretical studies suggest that they are a key ingredient for the formation of Sun-like stars, as they can remove the excess angular momentum from the disk thus allowing accretion onto the central star [see, e.g., 1].

Despite their importance, their formation mechanism is still very debated, in particular it is not clear if they are launched from the inner star-disk region [e.g., 2], or instead from a larger range of disk radii out to tens of au [e.g., 3]. While there have been a number of detailed studies of a few prototypical protostellar jets, such as, e.g., HH 212 [4, 5], there has been a lack of statistical studies devoted to characterize the protostellar jet properties on a large sample. Observational surveys of CO low-J transitions at intermediate resolution ($3'' - 4''$) [e.g., 6] have shown that large-scale outflow emission is commonly associated with protostellar objects. Are these outflows accelerated by high-velocity collimated jets launched from the disk?

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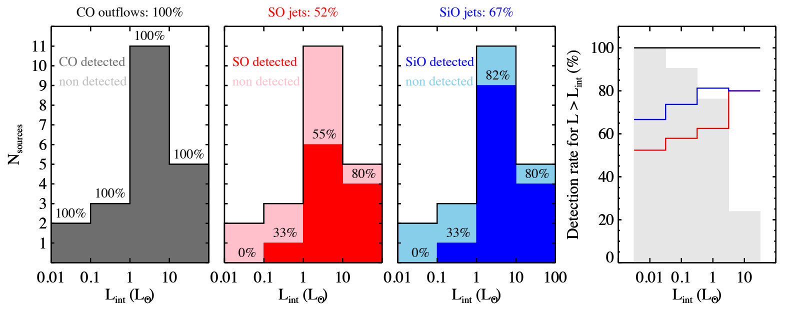

Figure 1. Number of sources associated with outflows and jets as traced by CO (2 – 1) (black, *left*), SO ($5_6 - 4_5$) (red, *middle-left*), and SiO (5 – 4) (blue, *middle-right*) as a function of the internal luminosity, L_{int}, of the 21 Class 0 protostars in the CALYPSO sample. The detection rate for each L_{int} bin (in logarithmic scale) is reported above the histogram, while the detection rate for the whole sample is labeled on top of each panel. The detection rate of jets and outflows for $L > L_{int}$ is shown in the right panel, with the same colour coding. The grey histogram shows the fraction of sources for $L > L_{int}$.

2 The CALYPSO Large Program

The CALYPSO Large Program[1] is a survey of Class 0 protostars located in the most active star-forming regions in the northern hemisphere with the IRAM Plateau de Bure Interferometer. The aim of the survey is: (i) to identify continuum and line emission from protostellar disks [7, 8]; (ii) to investigate the hot corino chemistry [9]; and (iii) to investigate the occurence and properties of protostellar jets by targeting CO (3 – 2), SiO (5 – 4), and SO ($5_6 - 4_5$) lines [10]. The first goal of the survey of protostellar jets performed by [10] is to answer a crucial question, i.e. whether jets, and, in general, mass ejection phenomena are commonly observed in protostars. The second goal is to derive the jet properties (velocity, width, mass loss rates), and the molecular abundances, which are crucial for understanding what region of the disk-protostar system jets are launched from. Finally, a third goal is to obtain a large database for follow-up observations at an extremely high-spatial resolution. The obtained results on protostellar jets are summarized in the following sections.

3 Jets ubiquity at the protostellar stage

The detection rate of outflows and jets emission in the molecular tracers as a function of the protostellar internal luminosity, L_{int}, is shown in Fig. 1. Outflows in CO (2 – 1) are detected in 100% of the 21 Class 0 protostars in the CALYPSO sample, indicating that ejection phenomena are ubiquitous at the protostellar stage. Collimated high-velocity jets traced by SiO (5 – 4) are detected in 67% of the sources and 79% of these also show jet emission in SO ($5_6 - 4_5$). The detection rate of jets increases with L_{int}, which is a probe of the mass accretion rate onto the protostar. This confirms the expected correlation between the mass accretion and the mass ejection rate (which, in turn, is proportional to the brightness of the emission lines). Hence, the non-detection of jet emission associated with the less-accreting sources could be an observational bias and deeper observations could demonstrate that jets are ubiquitous in our sample.

[1] http://irfu.cea.fr/Projects/Calypso
https://www.iram-institute.org/EN/content-page-317-7-158-240-317-0.html

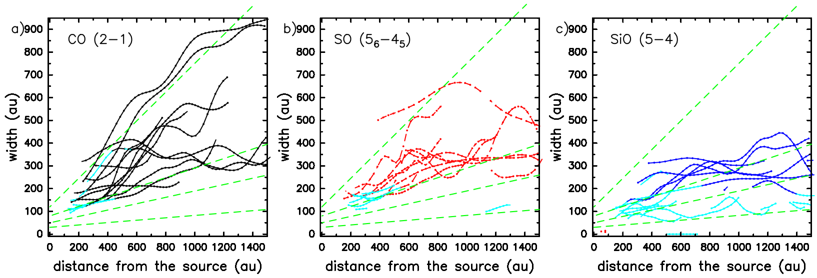

Figure 2. Flow widths ($2R_{\rm jet}$) estimated from the CO (a), SO (b), and SiO (c) emission from ∼ 200 up to 1500 au distance from protostars. Cyan lines indicate widths that are smaller that the transverse beam and consequently considered as inclusive upper limits. The green dashed lines correspond to full opening angles of $\alpha = 3°, 8°, 12°$, and 35° and initial widths of 30, 50, 80, and 120 au, and outline the collimation properties of the flow in different tracers.

4 Protostellar jets: spatio-kinematical properties

The observed protostellar flows have an onion-like structure: SiO (5 − 4) emission is more collimated than SO ($5_6 - 4_5$) emission, which in turn is narrower than CO (2 − 1), with median opening angles of 10°, 15°, and 25°, respectively (Fig. 2). High-velocity CO emission is as collimated as SiO indicating that low-velocity CO probes entrained material, while high-velocity CO traces the collimated jet. At scales larger than 300 au, most of the high-velocity SiO jets are broader (∼ 4° − 12°) than Class I and Class II atomic jets (∼ 3°). This could be due to projection effects as well as to contamination by the bow-shock wings.

The median radial velocity of the SiO protostellar jets is 30 km s^{-1}, that is, about two times smaller than that of atomic jets driven by Class II sources [11]. Assuming that the velocity of the jet scales with the Keplerian velocity at the launching point, the increase of the jet velocity with age is consistent with a jet launched from the same region of the disk around a central object of increasing mass. At least 33% of the SiO bipolar jets show a velocity asymmetry between the two lobes by a factor of 1.3 − 2.1, in agreement with what was found for atomic jets from T Tauri stars [12]. The similarity in knot spacings and velocity asymmetries suggests that the jet launching mechanism in protostars of 10^4 yr might be similar to that in Class II sources (10^6 yr). Finally, we find that 50% of the SiO jets are precessing or wiggling.

5 The correlation between accretion and ejection

The mass loss rates of the protostellar jets range from 7×10^{-8} M$_\odot$ yr^{-1} up to values of $\sim 3 \times 10^{-6}$ M$_\odot$ yr^{-1} for internal luminosities of the driving protostars of ∼ 1 − 50 L$_\odot$ (see Fig. 3). These values are larger by up to five orders of magnitude than those measured for atomic jets driven by Class II sources (from ∼ 10^{-11} to a few 10^{-8} M$_\odot$ yr^{-1}, [e.g., 13, 14]). Moreover, we find that $\dot{M}_{\rm jet} \sim 0.1 - 0.5\dot{M}_{\rm acc}$ for most of the jets, with the exception of the "CO-poor" and monopolar jets for which $\dot{M}_{\rm jet} \sim 0.01 - 0.1\dot{M}_{\rm acc}$. These $\dot{M}_{\rm jet}/\dot{M}_{\rm acc}$ ratios are similar to those found for atomic Class II jets ($\dot{M}_{\rm jet} \sim 0.01 - 0.3\dot{M}_{\rm acc}$, [13, 14]) and indicate that the correlation between ejection and accretion holds over the whole star-formation process, from protostellar objects of 10^4 years to pre-main sequence stars of 1 Myr. The total jet power ($L_{\rm jet}$) is 10%-50% of the source internal luminosity for ∼ 60% of the jets in the sample (Fig. 3-right). This indicates that the gravitational energy released by accretion onto the protostar could be efficiently extracted and converted into mechanical energy in the jet.

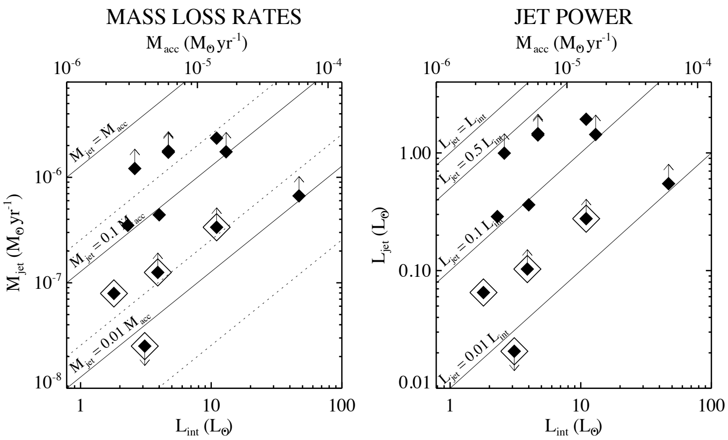

Figure 3. Protostellar jet mass-loss rates ($\dot{M}_{\rm jet}$ in $M_\odot\,{\rm yr}^{-1}$, *left*), and mechanical luminosities ($L_{\rm jet}$ in $L_\odot$, *right*) versus the source internal luminosity ($L_{\rm int}$ in $L_\odot$). Lower and upper limits are indicated by upward and downward arrows. The jet knots where no CO is detected (the "CO-poor" jets) are indicated by larger empty diamonds. The black lines in the left panel indicate $\dot{M}_{\rm jet} = [0.01, 0.1, 1] \times \dot{M}_{\rm acc}$, with $\dot{M}_{\rm acc}$ estimated from $L_{\rm int}$, assuming a protostellar mass, M_*, of 0.05 $M_\odot$ or 0.25 $M_\odot$ (solid and dotted lines, respectively). The $\dot{M}_{\rm acc}$ values labeled on the upper x-axis correspond to $M_* = 0.05$ $M_\odot$. The black solid lines in the right panel indicate $L_{\rm jet} = [0.01, 0.1, 0.5, 1] \times L_{\rm int}$.

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