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X-Shooter Survey of Jets and Winds in T Tauri Stars



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1 Introduction

It is a common paradigm that collimated jets are an ubiquitous phenomenon during the active phase of accretion, as they are able to efficiently extract angular momentum accumulated in the disc, allowing disc matter to accrete onto the star (e.g. [1]). Powerful optical jets are indeed commonly observed in young protostars and very active Classical T Tauri (CTT) stars. However, the frequency of the jet phenomenon among the general population of young stellar objects is still far from

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being settled. The question on how common jets are in active accreting stars has a major relevance in the context of disc evolution, as jets can significantly modify the structure of the disc region involved in the launching, impacting its evolution and the formation of planetary systems.

A direct way to infer the presence of jets and winds in CTT stars is through observations of atomic forbidden lines (e.g. [2, 3, 5]), and of the [OI]6300Å transition in particular, being the brightest among the optical lines. The [OI]6300Å line commonly exhibits two distinct components: a Low Velocity Component (LVC), peaking at velocities close to systemic one or only slightly blue-shifted, and a High Velocity Component (HVC) observed at velocities up to $\sim \pm 200 \text{ km s}^{-1}$. The HVC is directly connected with the extended collimated jets, while the origin of the LVC is still unclear. It comes from a compact and denser region with respect to the HVC [2, 3] and it is usually associated to an atomic photo-evaporated or magneto-hydro-dynamic (MHD) slow-wind (e.g. [6, 7]). In this contribution, we summarise the results obtained with a statistical study on the [OI]6300Å emission in a sample of 131 T Tauri stars in the Lupus, Chamaeleon and σ Orionis star-forming regions [4] observed with the X-shooter instrument at the VLT. These observations are part of a project aimed at characterizing the population of young stellar objects with discs in nearby star-forming regions [8, 9]. As part of this project, the stellar and accretion properties of the sample have been measured in a uniform and self-consistent way, providing a unique database where the properties of the [OI]6300Å emission can be analysed and correlated with the other derived parameters in a homogeneous fashion.

2 The Sample and [OI]6300Å Decomposition

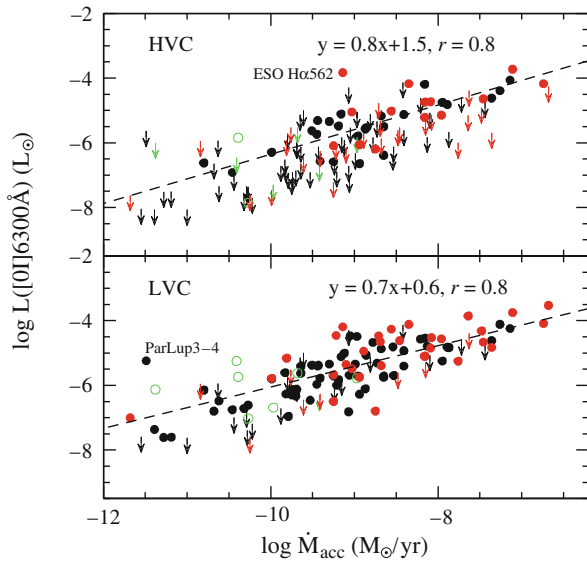
The adopted sample consists of 131 Young Stellar Objects (YSOs) observed with the X-shooter instrument. In particular, the sample includes sources in the Lupus (82 sources), Chamaeleon (41 sources) and σ Orionis (8 sources) star forming regions, whose stellar and accretion properties have been already analysed in previous papers ([8, 10] for Lup; [11] for σ Ori; [9] for Cha). We focus our analysis on the [OI]6300Å line which is the brightest among the class II forbidden lines in the spectral range of our data. As discussed in the introduction, the [OI]6300Å profile can be decomposed in a LVC, close to systemic velocity, and a blue- or red-shifted HVC. To separately derive line center and width of the different components we fitted the [OI] line profile with one or more gaussians. We define the velocity that separates the LVC from the HVC as 40 km s^{-1} , which roughly corresponds to the resolution attained for most of our objects. Line fluxes have been then converted into intrinsic luminosities adopting the A_V derived from the stellar parameters fitting procedure (see e.g. [10]).

3 Statistics and Correlation with Stellar and Disc Properties

The [OI]6300Å line is detected in 101 out of the 131 sources of our sample (i.e. 77% rate of detection). In all detections the LVC is identified, while the HVC is observed in 39/131 objects (i.e. 30% rate of detection). The $L_{[OI]HVC}$ spans a wide range of values, i.e. between 0.01 and $3 L_{\odot}$ for the detections. In the majority of the sources the $L_{[OI]HVC}$ is typically fainter than the $L_{[OI]LVC}$ by a factor of two/three, which partially explains the higher number of LVC detections with respect to the HVC. However sensitivity alone is not the only reason for a difference in detection rate between the LVC and HVC, as the signal-to-noise ratio in the LVC line is often larger than 10. We also estimate that orientation effects could misclassify emission at high velocity with a LVC in about 20% of sources (see discussion in [4]). The HVC detection rate does not depend on stellar luminosity, while a slightly larger detection rate is observed in sources with higher accretion luminosity (39% in sources with $\log(L_{acc}/L_{\odot}) > -3$). Our sample comprises also 11 transitional discs (TD) sources. The detection rates in these objects is roughly in line with the overall statistics of our sample (i.e. 80% LVC, 20% HVC), which confirms that TD have characteristics similar to other CTTs with a full disc, not only for what accretion properties concern [12], but also regarding the properties of the inner atomic winds.

The [OI]6300Å line luminosity has been correlated with the stellar and accretion parameters for both the LVC and HVC. The line luminosity correlates well with all the considered parameters in both LVC and HVC, with a Pearson correlation coefficient r always between 0.7 and 0.8. Correlations with L_{*} present the larger scatter and in general we find that both the LVC and HVC show a better correlation with L_{acc} than with all the other parameters. The best fit linear regressions for all

Fig. 1 The [OI]6300Å line luminosity of the LVC (bottom) and HVC (top) is plotted as a function of the mass accretion rate. Arrows refer to 3σ upper limits. The dashed line indicates the linear regression whose parameters are given in the upper right corner of the figure, together with the correlation parameter. Black, red and green symbols indicate sources in Lupus, Chamaelion and σ Orionis clouds, respectively. (From [4])



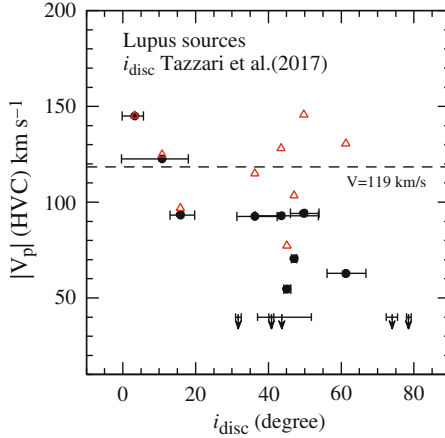


Fig. 2 The absolute value of the peak velocity in the HVC ($V_{peak}(\text{HVC})$) is plotted as a function of the disc inclination angle for a sub-sample of sources in Lupus with known disk inclination (i_{disc}). An upper limit of $V_{peak}(\text{HVC})$ of 40 km s^{-1} has been applied for sources with measured inclination angles that don't have a HVC component. Red triangles refer to the total jet velocity obtained by de-projecting the peak radial velocity by the corresponding inclination angle for the sources with a detected HVC. The dashed line indicates the average jet total velocity of the sample. (Figure adapted from [4])

the correlations can be found in [4], while in Fig. 1 we show the correlation between the $[\text{OI}]6300\text{\AA}$ luminosity and the mass accretion rate \dot{M}_{acc} . The $\log(L_{[\text{OI}]HVC})$ vs $\log \dot{M}_{acc}$ correlation is particularly useful to indirectly estimate the mass accretion rate in moderately embedded sources driving jets, where the permitted lines or the LVC emission region might be subject to large extinctions or scattering (e.g. [4]).

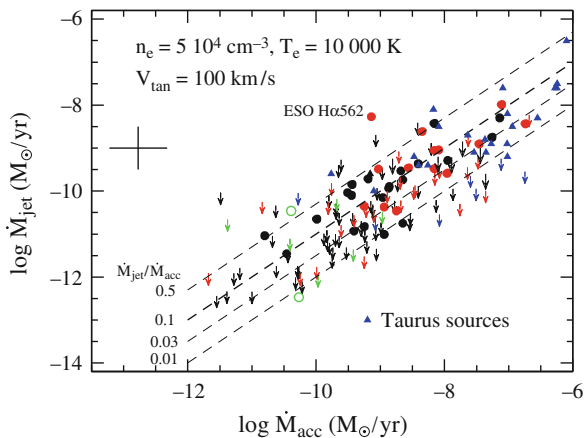
Figure 2 shows the HVC peak velocity ($V_{peak}(\text{HVC})$) plotted as a function of the disc inclination angle for the 13 sources of the Lupus cloud where this parameter has been measured from ALMA images [13]. The absolute value of V_{peak} is anti-correlated with i_{disc} , as expected in the working hypothesis that the HVC traces collimated jets ejected in a direction perpendicular to the disc. If we de-project the peak velocities adopting the corresponding inclination angle, we find total velocities ranging between ~ 100 and 150 km s^{-1} (red triangles in Fig. 2), with an average value of 119 km s^{-1} . A similar correlation has been derived by [14] in a sample of T Tauri of Taurus with known inclination angle, showing a jet mean velocities of the order of 200 km s^{-1} , thus higher than typical values found by us. This can be explained by a larger mass, on average, of the sources in Taurus with respect to the Lupus sources, as the jet poloidal velocity is proportional to the Keplerian velocity v_K in the disc at the launching radius r_0 ($v_K = \sqrt{GM_*/r_0}$). Our derived jet velocities are in fact more in line with the velocities found from proper motion analysis in a sample of jets of the Cha II cloud [15], driven by sources more similar to those investigated here in terms of stellar parameters.

4 The $\dot{M}_{jet}/\dot{M}_{acc}$ Ratio

In the assumption that the [OI]6300Å HVC traces the high velocity jet, its luminosity can be used to infer the jet mass flux rate (\dot{M}_{jet}) adopting a procedure similar to that applied in [2]. In particular, to estimate the mass of the flow from the line luminosity we have considered the [OI]6300Å emissivities computed considering a 5 level OI model, and assuming $T_e = 10,000$ K and $n_e = 5 \times 10^4$ cm $^{-3}$, which typically represent the values found in the region at the base of T Tauri jets, where the [OI] emission originates. The adopted values are also similar to those used by [2] to estimate the \dot{M}_{jet} of a sample of Taurus sources from their HVC [OI] emission. Hence, we can make a direct comparison between our derived mass flux rates and those estimated by [2].

In Fig. 3 the derived mass flux rates are plotted as a function of the source mass accretion rates. In this figure we also plot the data points relative to the sample of sources in Taurus whose \dot{M}_{jet} has been measured by [2] with a similar procedure as the one we adopt here. For these sources, we have estimated the \dot{M}_{acc} from the determination of the accretion luminosity given by [16], adopting the stellar masses and radii given in the same paper. The Taurus sources, which extend to higher mass accretion rates with respect to our sample, fall along the same trend as the rest of targets. The Figure shows that for most of the detections the $\dot{M}_{jet}/\dot{M}_{acc}$ ratio is between 0.01 and 0.5, confirming, on a large statistical bases, previous results found on individual objects. We note a significant number of upper limits pointing to a very low efficiency of the jet mass loss rate, even for objects with high accretion rates. In

Fig. 3 Mass accretion (\dot{M}_{acc}) vs mass ejection (\dot{M}_{jet}) rates. The \dot{M}_{jet} has been measured from the [OI]6300Å luminosity assuming a jet tangential velocity of 100 km s $^{-1}$ and gas temperature and density of $10,000$ K and 5×10^4 cm $^{-3}$ respectively. Black, red and green symbols are as in Fig. 1, while blue triangles indicate the values for the sample of Taurus sources (see text). (From [4])



particular, the average of the detections is at $\dot{M}_{jet}/\dot{M}_{acc} = 0.07$ but considering both detections and upper limits, we find that 57 sources, i.e. 44% of the entire sample, have $\dot{M}_{jet}/\dot{M}_{acc} < 0.03$.

The large scatter in the $\dot{M}_{jet}/\dot{M}_{acc}$ ratio is partially due to the uncertainty in the determination of the \dot{M}_{jet} , and in particular on the assumed parameters. However, given the remarkable similarity in the excitation conditions of jets from sources with different masses and mass accretion rates, it is likely that the scatter, of almost two orders of magnitude, reflects a real difference in the \dot{M}_{jet} efficiency among sources more than excitation conditions very different from what assumed here.

In conclusion, the analysis of $\dot{M}_{jet}/\dot{M}_{acc}$ ratio shows that there is a large spread of values for this ratio that does not depend on the mass of the driving source. From Fig. 3 we note, however, a tentative trend for sources with accretion rates $> 10^{-8} M_{\odot} \text{ yr}^{-1}$ to have on average a lower ratio. This trend needs to be confirmed/rejected on the bases of observations on a more complete sample of sources with high mass accretion rates.

5 Conclusions

We have summarised the results of a statistical work performed on the [OI]6300Å line in a sample of 131 young stars with discs in the Lupus, Chamaeleon and σ Orionis star forming regions, having mass accretion rates spanning from 10^{-12} to $10^{-7} M_{\odot} \text{ yr}^{-1}$, observed with the X-shooter instrument. The line has been deconvolved into a LVC, detected in 77% of the sources, and in a HVC, present in only 31% of the objects. The luminosity of the two line components correlates with different stellar and accretion parameters of the sources. The line luminosity correlates better (i.e. has a lower dispersion) with the accretion luminosity than with the stellar luminosity or stellar mass. We suggest that accretion is the main drivers for the line excitation and that MHD disc-winds are at the origin of both components. In the sub-sample of Lupus sources observed with ALMA a relationship is found between the HVC peak velocity and the outer disc inclination angle, as expected if the HVC traces jets ejected perpendicularly to the disc plane. Mass ejection rates (\dot{M}_{jet}) measured from the detected HVC [OI]6300Å line luminosity span from $\sim 10^{-13}$ to $\sim 10^{-7} M_{\odot} \text{ yr}^{-1}$. The corresponding $\dot{M}_{jet}/\dot{M}_{acc}$ ratio ranges from ~ 0.01 to ~ 0.5 , with an average value of 0.07. However, considering the upper limits on the HVC, we infer a $\dot{M}_{jet}/\dot{M}_{acc}$ ratio < 0.03 in more than 40% of sources. We argue that most of these sources might lack the physical conditions needed for an efficient magneto-centrifugal acceleration in the star-disc interaction region. Systematic observations of populations of younger stars, i.e. class 0/I, are needed to explore how the frequency and role of jets evolve during the pre-main sequence phase. This will be possible in the near future thanks to space facilities like JWST.

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