Connection between jets, winds and accretion in T Tauri stars

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1. *Rationale*

Mass accretion and ejection are intimately connected during stellar formation, and they both play a role in circumstellar disk evolution. In particular, it is commonly assumed that ejection of matter in the form of jets is an ubiquitous phenomenon during the active phase of protostellar accretion. Such a statement is supported by the high detection frequency of high velocity CO outflows in young embedded protostars. However the occurrence frequency of jets in accreting T Tauri stars has not yet been investigated on large samples of sources. Here we present a statistical analysis performed on a sample of active T Tauri stars observed with VLT/X-shooter. The [OI]6300 Å forbidden line has been used to spot the presence of high velocity jet emission and correlate it with accretion and stellar parameters. In addition, we compare the luminosity and kinematics of the [OI] jet emission with those of wind indicators (low velocity [OI] and He I at 1.08µm) to infer the connection between different mass loss phenomena.

2. *The sample*

- The sample includes 36 T Tauri in Lupus, 39 in Chamaeleon I/II and 8 in σ Ori, for a total of 83 sources.
- Observations were performed with VLT/X-shooter (300-2500nm) at resolution *R*(6300Å)=8800 (Δv = 35 km/s) for the Lupus and σ Ori sources, and 18000 (Δv = 17 km/s) for the Chamaeleon sources.
- Source accretion and stellar properties have been well characterized from the same X-shooter spectra or from the literature (Antoniucci et al. 2011, Alcalà et al. 2014, Manara et al. 2015, Rigliaco et al. 2012).
- Range of physical parameters: 0.03 <M_*< 2 $M_\odot$, 0.02 <L_*<1 $L_\odot$, -11.5 <log($\dot{M}_{acc}$)<-7 $M_\odot$/yr

3. *The [OI]6300Å HVC and LVC*

- The [OI]6300Å line has been used as tracer of stellar mass ejection. Two different components can be identified: one peaking close to systemic velocity (Low Velocity Component, LVC) and one peaking at velocities between 50 and 150 km/s (High Velocity Component, HVC) (Hartigan et al. 1995).
- The HVC can be unambiguously associated with the presence of a high velocity jet. The LVC is suggested to originate from slow velocity winds (photo-evaporated or magnetically driven), from bound gas in keplerian rotation in the inner disk, or from a combination of the two (Natta et al. 2014, Rigliaco et al. 2013)
- Natta et al. (2014) identify the HVC and LVC in the Lupus and σ Ori sample and compute the intensity and velocity of each component through Gaussian fitting. The same procedure has been applied on the ChaI/II sample.
- **In our sample, the LVC is detected in 85% of the sources, while the HVC is detected in 36% of the sources. No source shows a HVC without the LVC.**

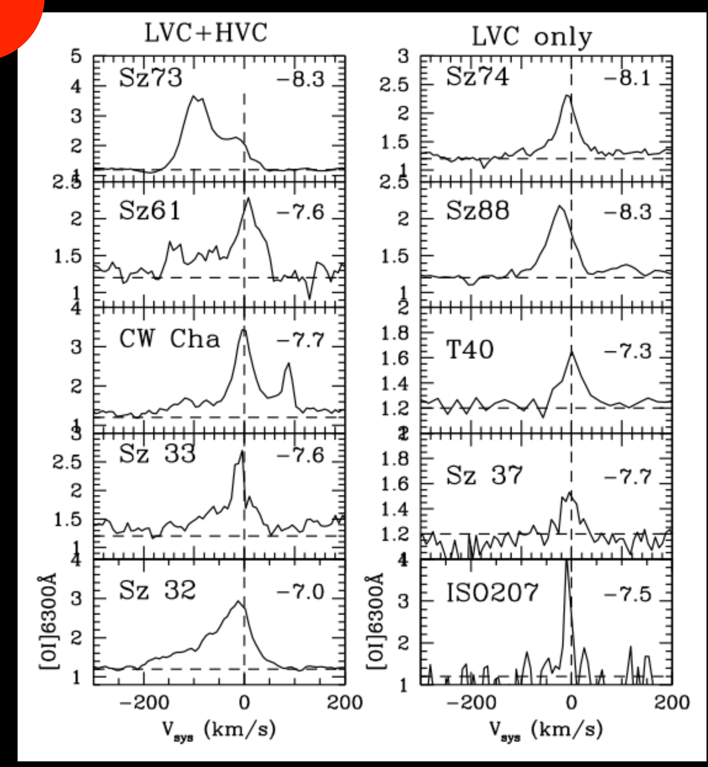


Fig. 1: Examples of spectra around the [OI]6300Å line: sources are divided among those showing both the HVC and LVC emission, and those with a LVC only. The log of $\dot{M}_{acc}$ (in $M_\odot$/yr) is indicated in each panel.

4. *HVC and source parameters*

When detected, the luminosity of the HVC correlates with the accretion luminosity and mass accretion rate (L_{acc}, $\dot{M}_{acc}$), the stellar luminosity (L_*), and the stellar mass (M_*). However, upper limits for undetected sources are often located well below the correlation lines.

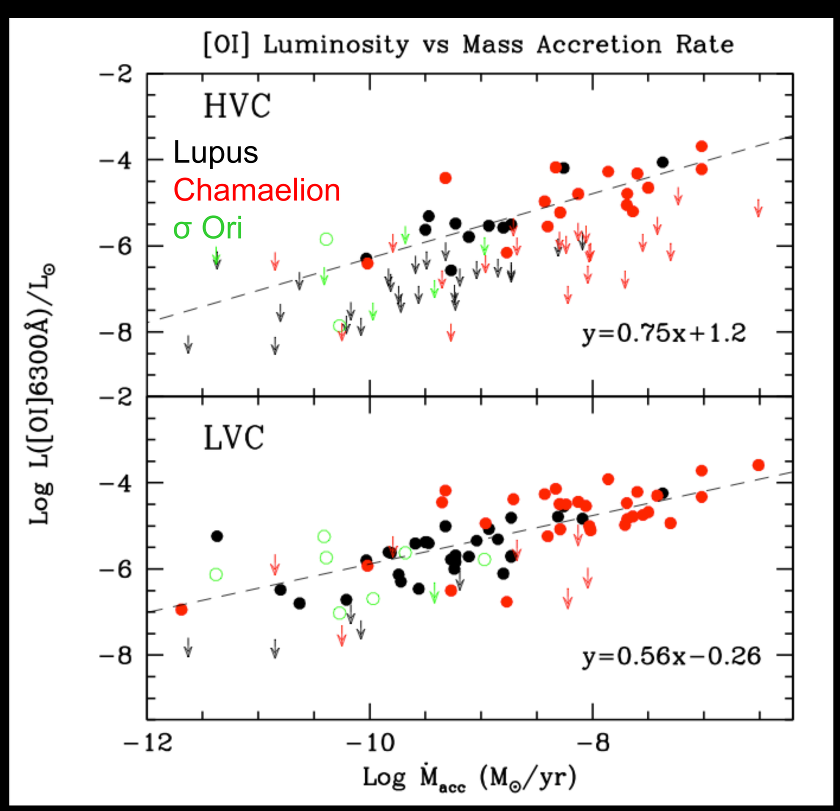


Fig. 2: Correlation between the [OI]6300Å lumonosity, relative to the LVC (bottom) and HVC (top), and the mass accretion rate ($\dot{M}_{acc}$). Arrows indicate upper limits. The linear fit through the detected data points is presented in each plot. The HVC luminosity has a dependence on $\dot{M}_{acc}$ steeper than the LVC.

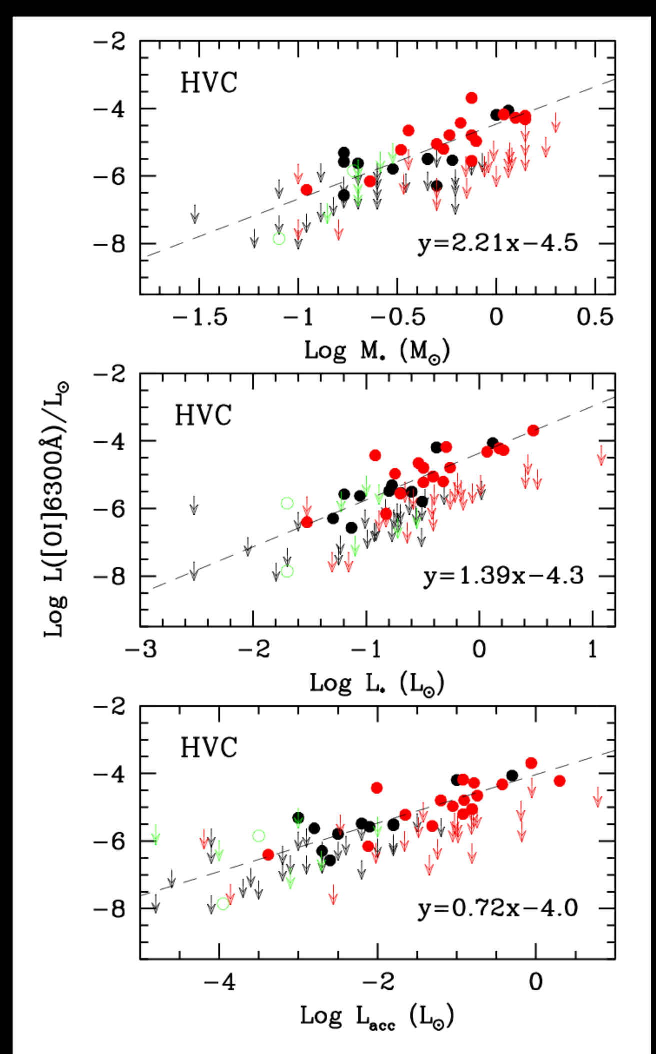


Fig. 3: Correlation between the [OI] 6300 Å luminosity of the HVC and source parameters. Note that sources with undetected HVC (the upper limits) do not segregate in any particular range of the above parameters. Similar correlations were found by Natta et al. (2014) for the LVC of the Lupus and sigma Ori samples.

5. $\dot{M}_{jet}/\dot{M}_{acc}$ *ratio*

- Jet formation models predict that mass accretion and mass ejection rates are correlated and that $\dot{M}_{jet}/\dot{M}_{acc}$ should be in the range 0.01-0.5 (e.g. Konigl & Pudritz 2000).
- We confirm these expectations on the sub-sample with detected HVCs.
- However, we found about 40% of sources with a $\dot{M}_{jet}/\dot{M}_{acc}$ ratio significantly lower than 0.01. This could be indicative that jet evolution proceeds with timescales shorter than accretion, so that jets are switched off while sources are still accreting mass.

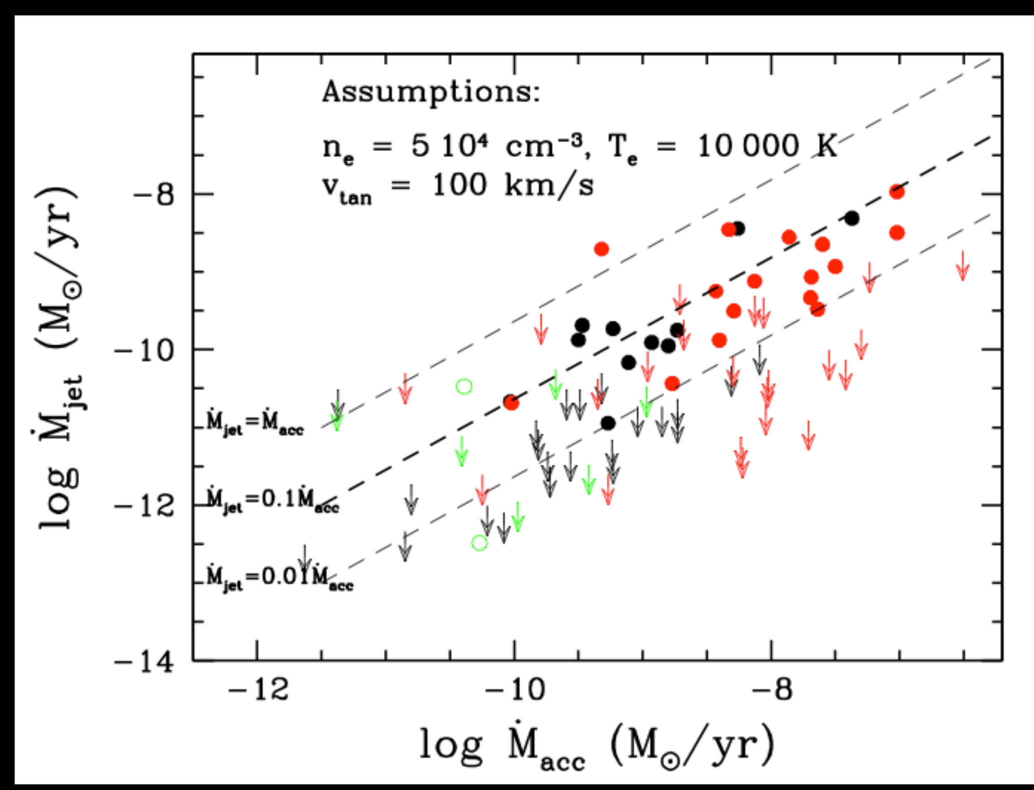
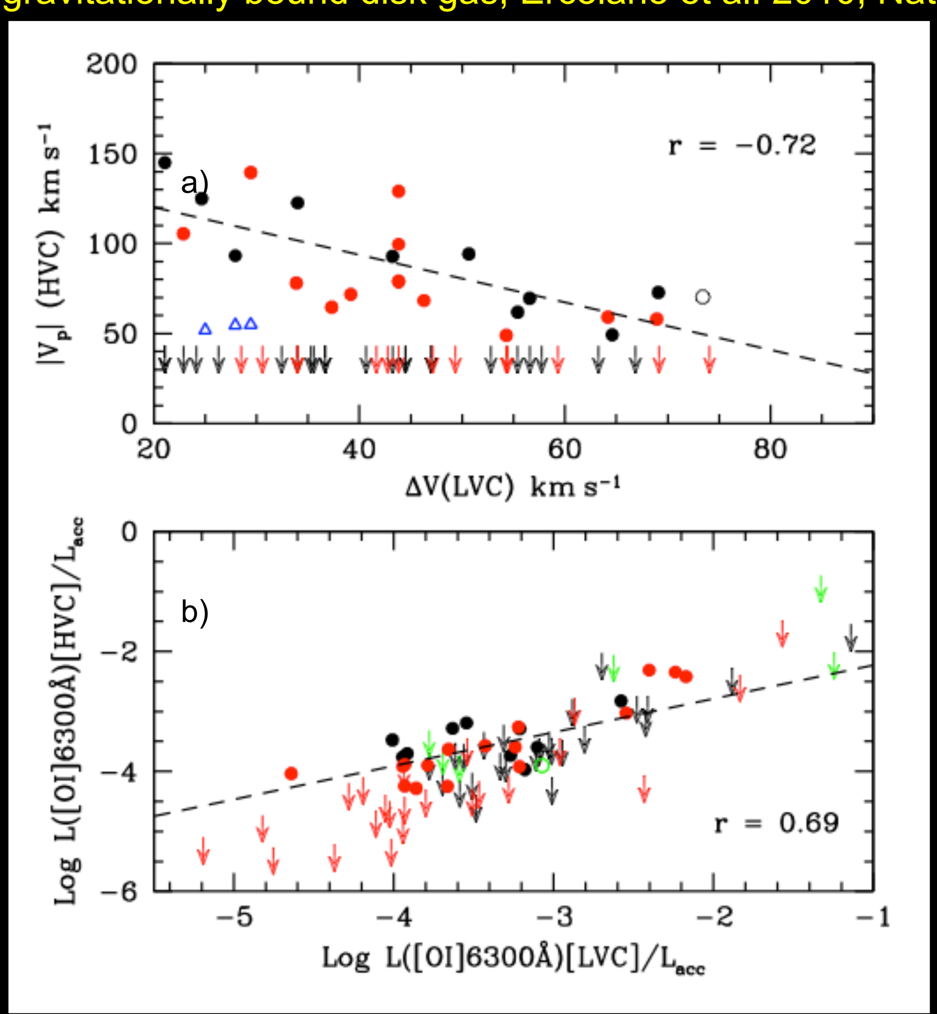


Fig. 4: Correlation between mass accretion and mass ejection rates. The latters have been estimated from the HVC [OI]6300Å luminosity assuming a jet density of 5 10^4 cm^{-3} , a temperature of 10^4 K and a tangential jet velocity of 100 km/s. We further assume that the jet emission fills the instrumental slit.

6. HVC vs LVC

We have searched for any correlation between the HVC and LVC, comparing their kinematics and luminosity. In particular, we are looking for any connection among the processes giving rise to the two components that could shed light on the debated origin for the LVC (i.e. whether photo-evaporative winds, MHD disk winds, gravitationally bound disk gas, Ercolano et al. 2010, Natta et al. 2014, Rigliaco et al. 2013).



In the assumption that the jet total velocity does not vary significantly in objects of similar mass, the HVC peak velocity should depend only on the orientation of the jet with respect to the line of sight.

In this hypothesis, the anti-correlation found between V_{peak}(HVC) and the LVC width (Fig. 5a) could be interpreted with an increase of the contribution to the LVC from gravitationally bound gas in the disk as the jet inclination angle with respect to the plane of the sky decreases.

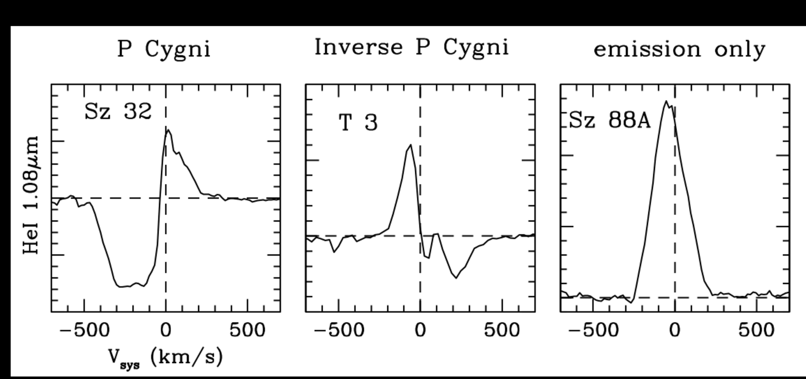
In the hypothesis that the bulk of the LVC originates in photo-evaporative winds, the jet should have an influence in obstructing the wind formation, as it would intercept the stellar UV photons responsible for the photo-evaporation.

We find instead a correlation between the HVC and LVC luminosities, normalized to the accretion luminosity (Fig. 5b). This is more consistent with a scenario in which the LVC originates in magnetically driven slow disk winds. Note that the upper limits on the HVC would suggest an even steeper correlation.

Fig. 5: a) Correlation between the HVC peak velocity and the FWHM of the LVC. The linear fit and correlation coefficient are estimated excluding the three data points indicated as blue triangles, for which the separation between HVC and LVC is uncertain. Upper limits indicate sources where the HVC has not been detected (i.e. V_{peak}(HVC) < 40 km/s). b) Correlation between the accretion normalized [OI]6300Å luminosities in the LVC and HVC.

7. *Jets/winds vs He I 1.08µm line*

The HeI 1.08 µm line is a good probe of the acceleration region of hot stellar/disk winds, as it has favourable conditions for resonance scatter of stellar photons causing P-Cygni like profiles with deep blue-shifted absorptions (e.g. Edwards et al. 2006). In our sample, we observe sources with the HeI line having P-Cygni profiles, inverse P-Cygni profiles (signature of infall) or emission component only. We have searched for any connection between the HeI blue-shifted absorption and the jets/winds traced by the [OI] line.



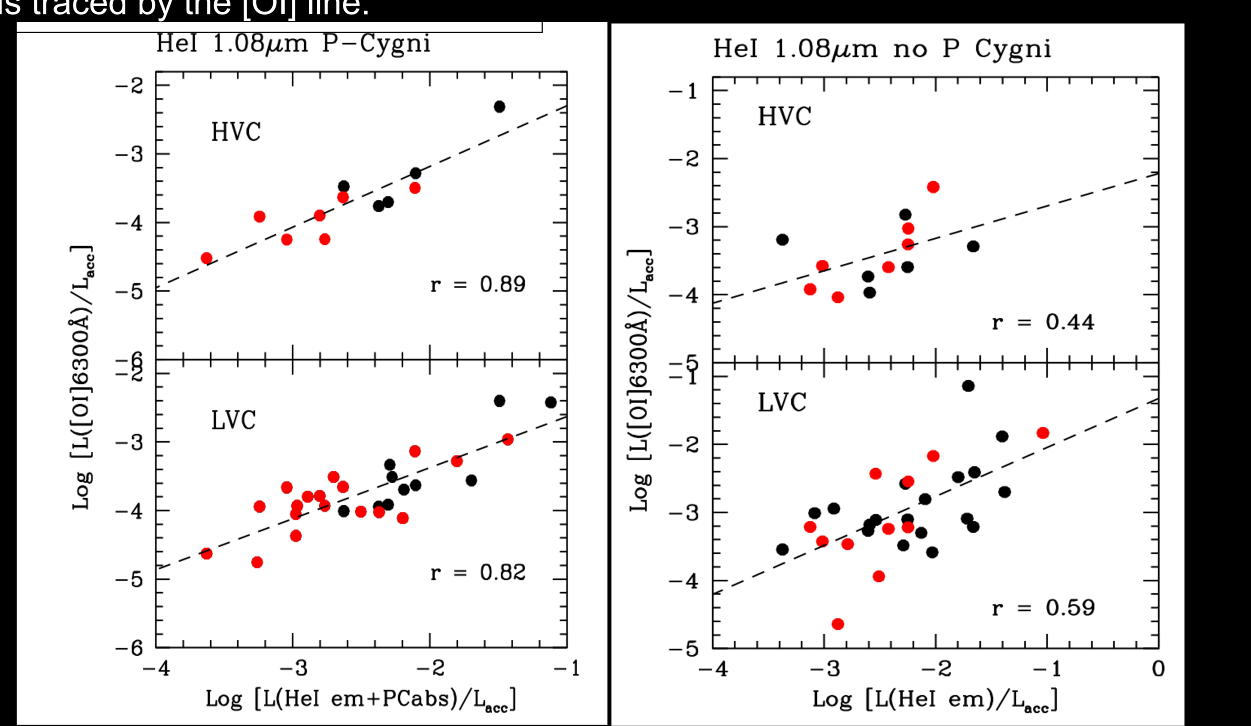


Fig. 6: Correlation between the [OI] luminosity (in the LVC and HVC) and the luminosity of the HeI 1.08 µm line, both normalized by L_{acc}. Sources with and without a HeI P-Cygni like profile are separately plotted in the left and right figure, respectively. We find that the [OI] luminosity better correlate with the HeI luminosity for sources showing the signature of hot winds. This indicates that the different forms of mass ejection are connected in spite of their very different kinematics and physical conditions.

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