Physical properties of the DG Tau jet on sub-arcsecond scales with HST/STIS

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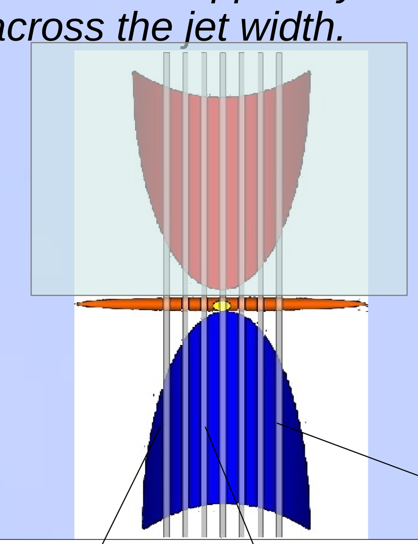
Aim Stellar jets are believed to play a key role in the formation of a new star, but the question of how they originate is still under debate [1]. To get a better understanding of the launch process we derive the physical properties at the base of the blue-shifted jet from the Classical T Tauri star (CTTS) DG TAU, from spectra taken with the *Hubble Space Telescope Imaging Spectrograph (HST/STIS)* at optical wavelengths. The analysis provides information on the jet physics (kinematics, density, excitation) at 0."1 angular resolution in two dimensions (along and across the jet), and as a function of velocity. Mass outflow and angular momentum rates can be estimated for different velocity components, giving indications on the validity of the proposed models for the jet generation [2, 3].

Figure 1. *HST/STIS slit positions stepped by 0."07 across the jet width.*



Method We analysed a set of seven HST/STIS spectra of the first 5" of the DG Tau jet, taken in January 1999 with spectral and spatial resolution of 50 km/s and 0"1. The spectra were obtained by placing a long-slit parallel to the jet axis, and stepping it across the jet width (Fig 1). The grating used was G750M covering from 6254 Å to 6906 Å. Previously published results based on this extraordinary dataset include a study of the basic morphology of the jet in the first 2" from the star [4] and the first indications of rotation of the jet [5].

In the present study we form Position Velocity (PV) plots of the forbidden emission lines (Fig. 2) and of their ratios (Fig. 3).
From the line maps we derive information on the structure and kinematics of the flow with unrivalled detail, revealing new features useful for a correct understanding of the nature of the flow and of its excitation. From the line ratios we derived PV plots of the gas physical quantities with an updated version of the so-called *"BE technique"* [6, 7, 8]. The technique is based on the strong link created by the charge-exchange mechanism between the ionisation fraction of O , N with the one of H. The main advantage of the new version (HDL-BE) is the extension to regions with electron density higher than the high density limit of the standard [SII] diagnostics (which is about 2 10^4 cm^{-3}) [9].

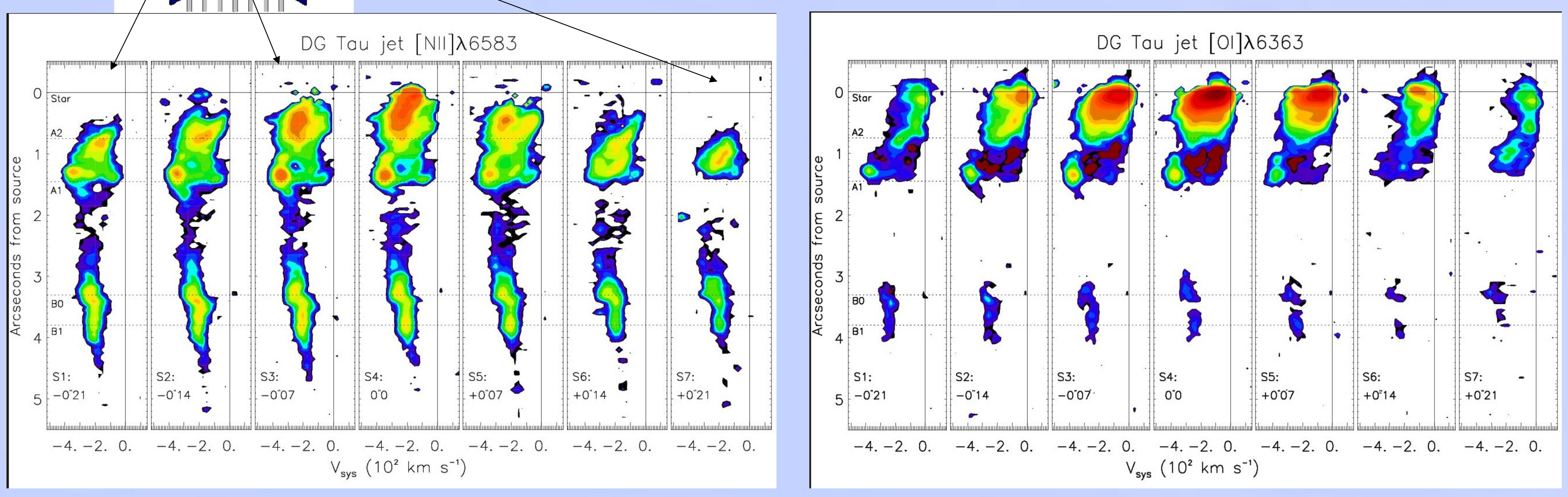


Figure 2. *Example of Position-Velocity (PV) plots of the emission, for the [NII]λ6583 (left) and the [OI]λ6300 lines. Dotted lines mark the position of recognised features in the images, while the vertical solid line is the systemic zero velocity.*

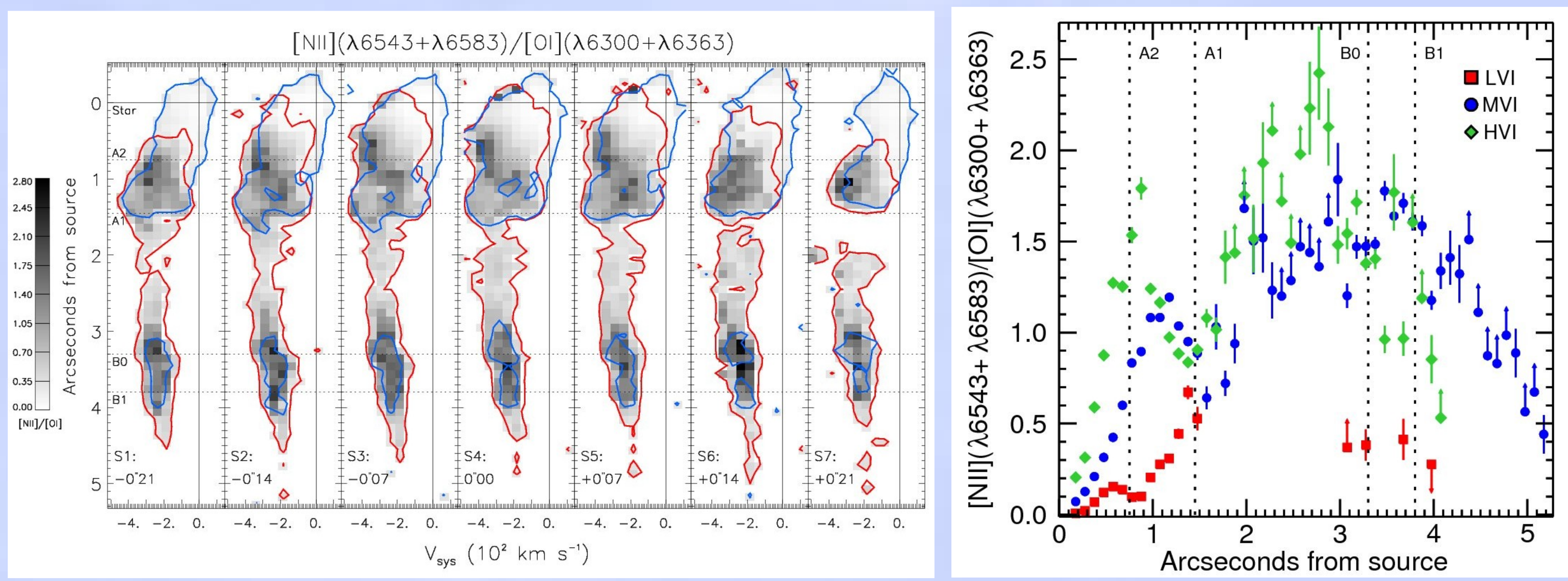


Figure 3. *Left: [NII]/[OI] line ratio as PV plots. The blue (red) contour indicates the regions where the [OI] line ([NII] line) is above 3 σ. Right: The same ratio as 1D profiles along the jet in three velocity intervals: LVI=[-120:+20] (red); MVI=[-270:-120] (blue); HVI = [-420:-270] (green) km /s*

Results The derived electron density n_e, hydrogen ionisation fraction x_e, and total hydrogen density n_H are displayed as PV plots (Fig. 4), which present the advantage of retaining all the spatio-kinematic information available. To assist with the interpretation, we also present 2-D images of the plasma parameters (Fig. 5), and 1-D profiles along the jet (Fig. 6) in each of the selected velocity intervals, applying the updated technique to binned data [9].

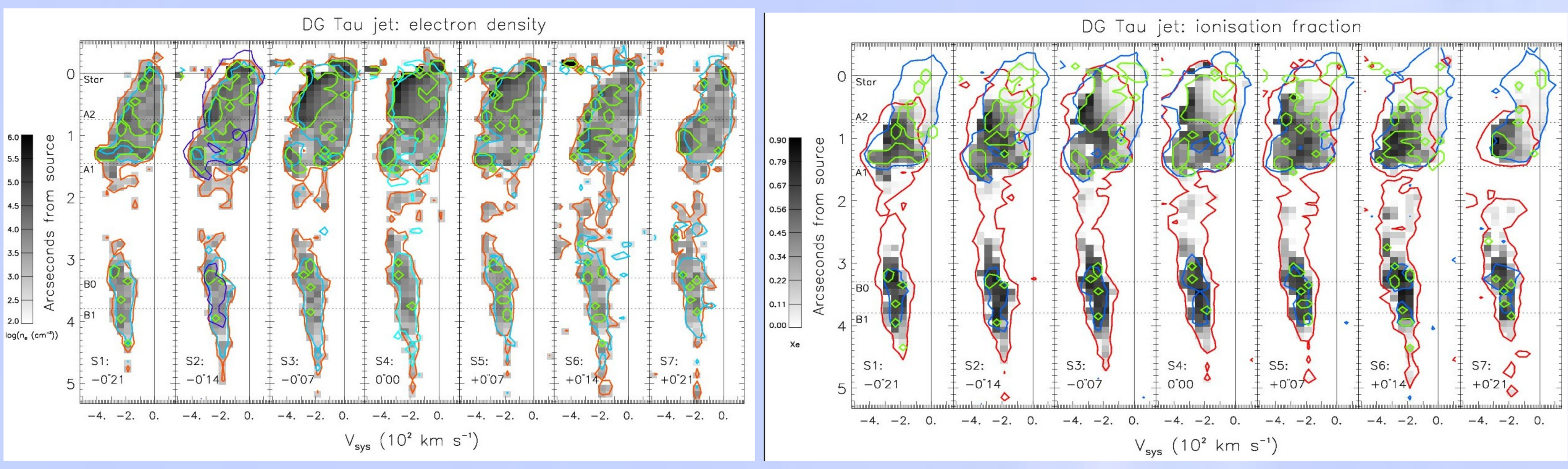


Figure 4. *Example of Position-Velocity (PV) plots for the derived physical quantities in the jet. Left: log of electron density n_e:. Contours : cyan - [SII] 6716 > 3 σ ; orange - [SII] 6731 > 3 σ ; green - [SII]6731/6716 ratio at the high density limit, inside which n_e is derived with the modified HDL-BE procedure. Right: hydrogen ionisation x_e. The blue (red) contour indicates the regions where the [OI] line ([NII] line) is above 3 σ. Green contour is as in the left panels.*

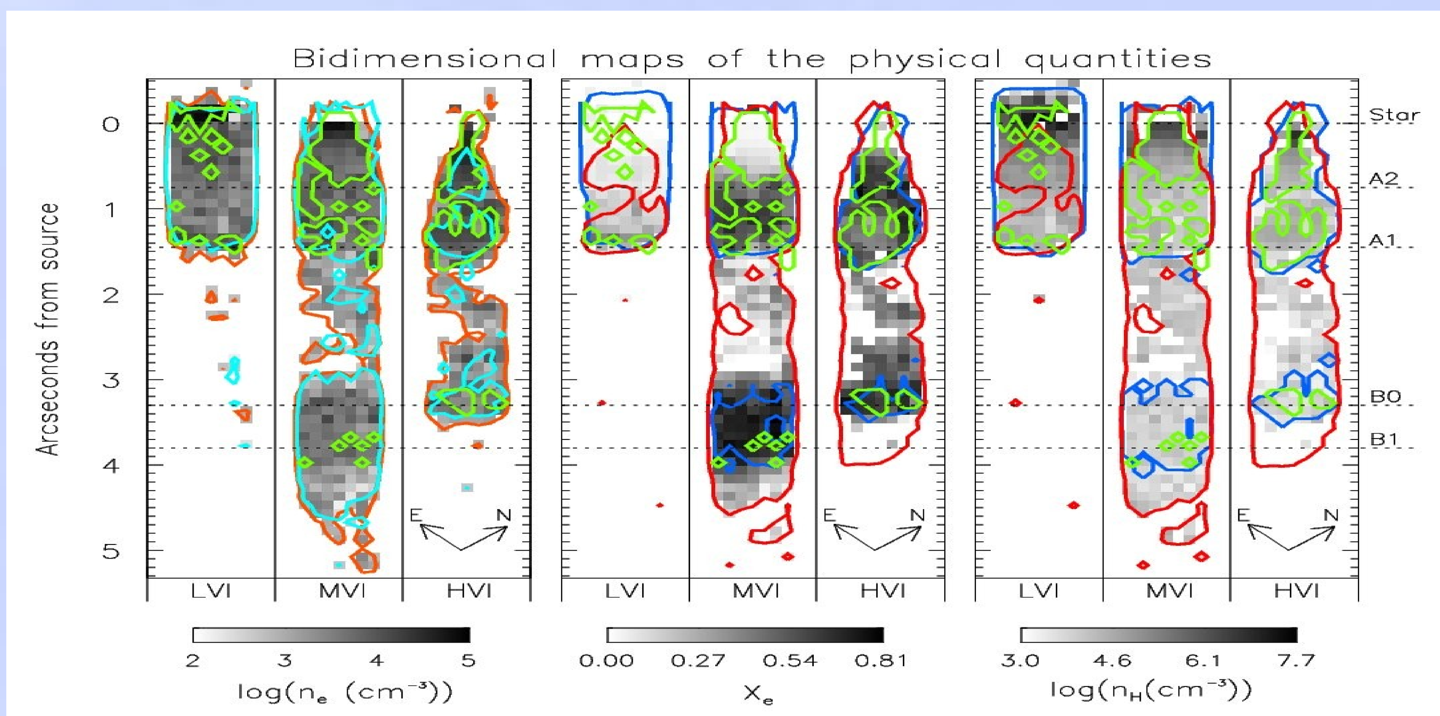


Figure 5. *2-D velocity channel maps of the log of the electron density (left), of the ionisation fraction (centre) and of the log of the total density (right). Greyscales are linear, velocity intervals and blue/red contours as in Fig. 3. Green contours as in Fig. 4 left.*

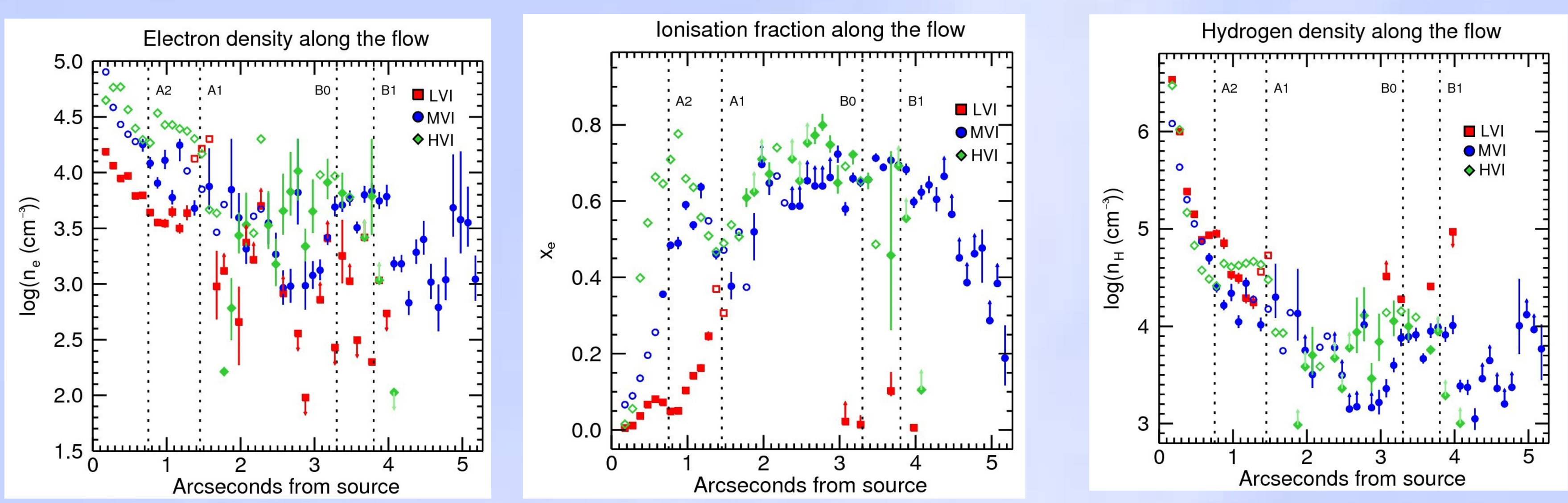


Figure 6 *1-D profiles of the physical quantities along the jet in the three velocity intervals of Fig. 3. Empty symbols indicate positions where n_e is above the high density limit for the standard [SII] diagnostics, and the derivation has been made through the modified HDL-BE technique.*

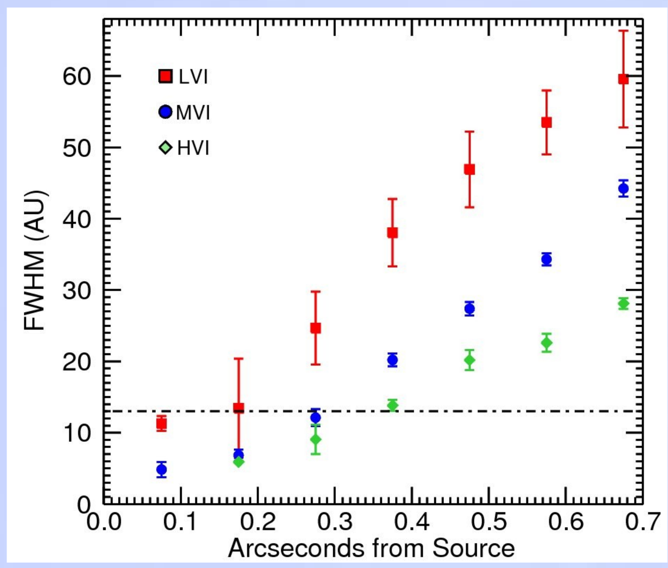


Figure 6 *Initial jet width as FWHM of the reconstructed brightness profiles across the jet. Dashed line: FWHM of the stellar continuum.*

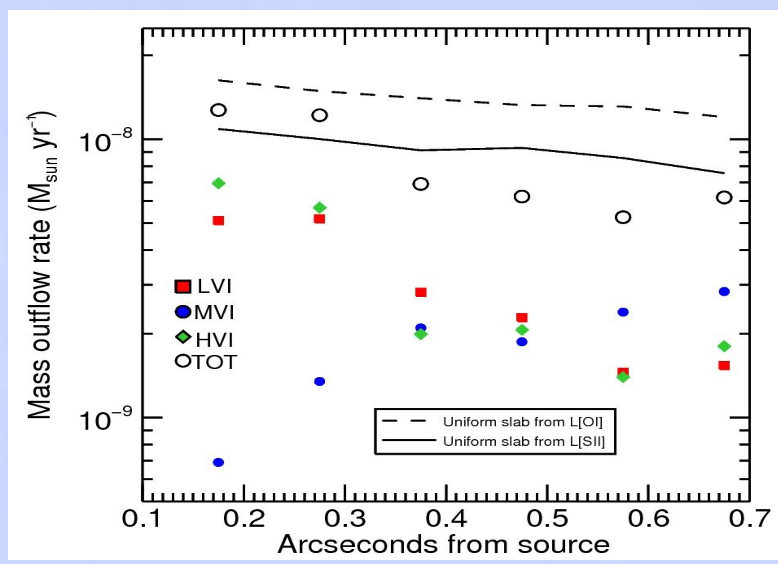


Figure 7 *Mass outflow rate calculated from (i) jet density traversing annuli of nested cones (data points broken down by velocity interval and also totalled;) (ii) jet density obtained via line luminosities from a uniform slab as in [10] (curves). Uncertainties are about 50% in every velocity channel.*

- Within the first arcsecond, the flow presents properties consistent with magneto-centrifugal launch. The jet is narrower at moderate-high velocity and has higher excitation than the slow velocity component. Nevertheless, the total density is similar in all components.
- Remarkably, our analysis shows absence of significant variations in the plasma parameters across the jet width in each velocity interval. Along the jet, we observe gradients in density and ionisation spatially coincident with sharp velocity jumps, and slightly downstream emission peaks. This is consistent with shock excitation producing the emission.
- The mass outflow rate (Fig 7) is on average 8± 4 10^{-9} Msun/yr, within the typical range for jets from CTTSs. Good agreement is found with values derived from the line luminosity method [10] and with the estimates from infrared lines by [11], taking into account derivation procedures. The ratio of mass ejection to mass accretion, for the supposedly symmetric bipolar jet , can vary between 0.03± 0.01 and 0.16± 0.08, which is compatible with the range predicted by Disk-wind models.
- The angular momentum transported by the LVI and MVI components turns out to be 3.5 ±1.7 10^{-6} Msun/yr AU km/s, allowing for a symmetric jet and a correction for asymptotic velocities. This value is of the same order of magnitude of the angular momentum lost by the disk to allow accretion, but the large uncertainties prevent further analysis in this direction for the time being.

Conclusions The physical structure of the DG Tau jet reveals patterns expected from magneto-centrifugal launch. However, other features like shock fronts formed on different temporal scales, seem to reach beyond this simple scenario. The presented maps constitute a powerful benchmark for testing new alternatives.

References
[1] Ray et al. 2007, PPV; [2] Pudritz et al. 2007, PPV; [3] Ferreira 2013, EES2011, EAS Publ. Series;[4] Bacciotti et al 2000, Apj, 537, L49; [5] Bacciotti et al 2002, Apj, 576,222; [6] Bacciotti & Eisloeffel, 1999, A&A 350, 917, [7] Podio et al. 2006, A&A 456, 189; [8] Coffey et al. 2008, ApJ 689, 1112; [9] Maurri et al 2013 A&A subm ; [10] Hartigan et al. 1995, ApJ, 452, 736; [11] Agra-Amboage et al., 2011 A&A, 532, 59 .