Jets at all Scales
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On the time variability of the HH jet ejection process

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Abstract. Two-dimensional emission line images of the HH30 jet were recently used (De Colle *et al.* 2010) to recover the three-dimensional structure of the jet by applying standard tomographic technique ("Tikhonov regularization techniques"). In this paper I show that it is possible to determine the ejection history of the HH30 jet by directly comparing the outcome of numerical simulations with the results of the tomographic inversion. In particular, it is shown that the HH30 jet electron density map is best reproduced by assuming a velocity variation at the base of the jet with a large scale periodicity (with a period of ~ 3 yrs) added to small scales velocity variation (with periods $\lesssim$ months).

Keywords. hydrodynamics, methods: data analysis, methods: numerical, stars: winds, outflows, ISM: Herbig-Haro objects, ISM: jets and outflows.

1. Introduction

Herbig-Haro (HH) jets play a crucial role in the star formation process (e.g. Reipurth & Bally 2001). For instance, they are important in the angular momentum evolution of the star-disk system (e.g. Chrysostomou *et al.* 2008), and they produce an important feedback on the star formation process itself (e.g. Wang *et al.* 2010).

Collimated jets are present at different scales and around very different classes of objects, ranging from young stars to compact objects (neutron stars and black holes). Assuming that the jets at all scales share a common origin, the study of the HH jets is particular useful, as the amount of observational information available for HH jets is in several cases much larger than in any other jet-driving systems.

HH jets present a characteristic knotty structure with a typical periodicity of $\sim$ a few to several years, emitting a rich radiation spectrum ranging from radio wavelength to, in a limited number of cases, x-ray. While there are evidences indicating that the knots are due to velocity variations in the star-disk system, the origin of these velocity variations is unkown (see De Colle *et al.* 2008 for a discussion). From the ratios of forbidden emission lines, the electron density, temperature and hydrogen ionization fraction can be easily determined down to a distance $\gtrsim 50$ AU from the star.

Recently, observations with information on emission profiles across the jet have been presented by several authors (e.g. Beck *et al.* 2007, Hartigan & Morse 2007). One example is the largely studied HH30 jet. The HH30 jet moves nearly on the plane of the sky, has a clear side-to-side symmetry in the region close to the central star, and the cooling region is resolved spatially with Hubble Space Telescope (HST) observations (e.g. Burrows *et al.* 1996, Ray *et al.* 1996, Bacciotti *et al.* 1999, Hartigan & Morse 2007). Assuming that the HH30 jet is axisymmetric, we showed in a previous work (De Colle *et al.* 2010) that standard tomographic techniques may be employed to recover the three-dimensional structure of the jets.

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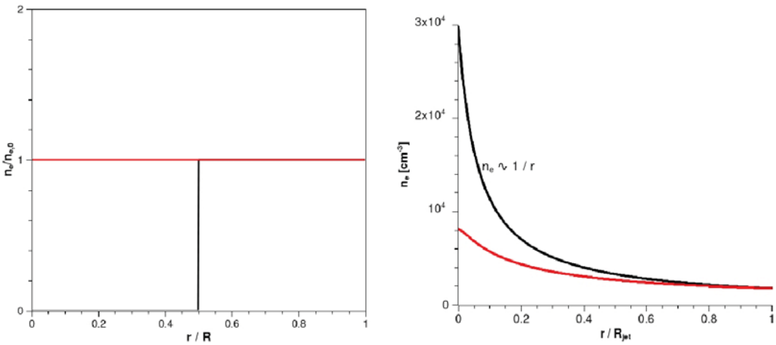

Figure 1. Effect of the hypothesis of homogeneity on the electron density determination. Assuming a certain n_e profile (black curves), [SII]$\lambda6716, 6731$ emission coefficients were determined solving the 5-levels atom problem (assuming a constant temperature $T_e = 10^4$ K). These are later integrated along the line of sight, and from the ratio of the intensities the electron density (equivalent to the one obtained directly assuming a jet homogeneous along the line of sight) is recovered (red curves). *Left panel*: the density profile is taken as $n_e = n_{e,0}$ for $r > 0.5$ and 0 otherwise. The resulting n_e strongly overestimate the real n_e. *Left panel*: the density profile is taken as $n_e \propto 1/r$. The resulting n_e in this case underestimate the real n_e.

These results, together with a brief discussion of the error introduced in the determination of the physical parameters when assuming a jet as homogeneous along the line of sight, are reviewed in Section 2, while Section 3 present a comparison between the results of the inversion technique and the prediction obtained by running detailed hydrodynamics simulations, showing that the data are best fitted by a model assuming a velocity variation at the base of the jet with a large scale periodicity (with a period of ~ 3 yrs) added to small scales velocity variation (with periods $\lesssim$ months).

2. Observations

Usually, observations can be used to extract two-dimensional electron density, temperature and ionization fraction images. The resulting maps of the physical parameters are accurate (assuming that the effect of the instrumental response is negligible) is the jet is homogeneous along the line of sight, and the the presence of dishomogeneity can introduce large errors in the determination of the physical parameters (see De Colle *et al.* 2008). Furthermore, the examples of Figure 1 illustrate that the density profile determined from the homogeneity assumption may over- or under-estimation the correct profile. In a previous paper (De Colle *et al.* 2010) we showed that, actually, replacing the homogeneity hypothesis with that of axisymmetric medium, standard tomographic techniques may be employed to recover the three-dimensional structure of the jets. The main result was that the reconstructed density, temperature, and ionization fraction present much steeper profiles than those inferred using the assumption of homogeneity. In particular, the HH30 jet shows a much more fragmented and irregular jet structure with several small scale knots present along the main jet axis, together with large scale knots.

As a detailed description of the tomographic techniques and its application to the HH30 jet has been already presented previously (De Colle *et al.* 2010), we focus here on the consequences of those results on the ejection models. In the next Section, in particular, we show by using detailed numerical simulation that the best fit to the observations is obtained when assuming a chaotic variation in the velocity ejection from the star-disk system.

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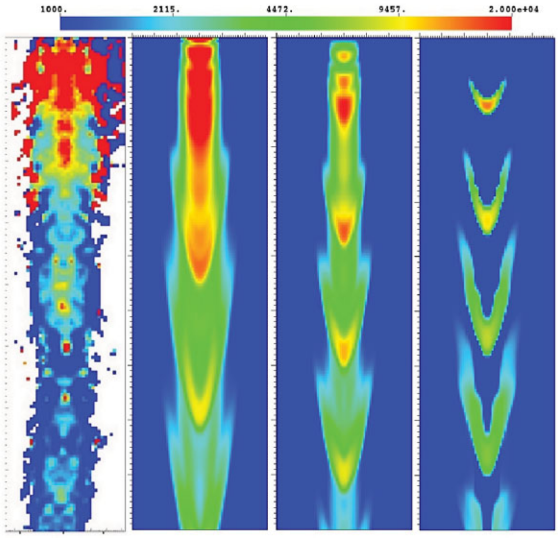

Figure 2. Electron density maps determined from the tomographic inversion of the HH30 observations (left panel) and from hydrodynamics simulations using four, two and a single variability (right three panels) in the injection velocity of the jet (see eq. 3.1) from the boundary of the computational grid (located on the upper $x-$axis; the jet is moving from up to down). The variabilities are on scales of years (for the three models) added to variabilities on scales of months (models shown in the II and III panels from the left) and days (model shown in the II panel from the left).

3. Numerical Simulations

We use the hydrodynamics version of the Mezcal code (De Colle 2010, in preparation). The code includes rate equations for the calculation of the ionization and recombination of a set of 17 atomic/ionic species: [HI], [HII], [HeI], [HeII], [HeIII], [NI], [NII], [NIII], [OI], [OII], [OIII], [OIV], [SII], [SIII], [CII], [CIII], [CIV]. The cooling term in the energy equation is calculated explicitly, as the sum of the contributions coming from the 17 species. The details of the implementation of the cooling term and the rate equations are given in Raga *et al.* (2007).

It is commonly accepted that the HH objects (the knots along the jet flow) are produced by supersonic velocity variations at the base of the jet. For instance, numerical simulations, using a velocity variations of about 10–20% of the average velocity, have been able to reproduce the morphology and the emission property of the knots in HH objects. Following the same recipe, the velocity at the boundary of the computational grid is changed periodically as

$$v_{jet} = v_0 + \sum_{i=1}^{N} A_i \sin \frac{2\pi t}{\tau_i} \, . \tag{3.1}$$

The jet density is 10^4 cm^{-3}, the jet temperature 1000 K, and the average velocity v_0 = 200 km/s (with a radial "top hat" profile). To reproduce the observed change in the FWHM (see De Colle *et al.* 2010), the jet is assumed to be conical, with an opening angle of 2°. The ambient medium values have been choose as $\rho_{amb} = 10^3$ cm^{-3}, and $T = 1000$ K. The jet is therefore slightly overpressure. This overpressure is likely to be matched by a strong toroidal component of the magnetic field (that collimates the jet). As in this study we are not interested in reproducing the observed HH30 jet in detail,

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but only to explore qualitatively the theoretical implications of the results obtained from the application of the tomographic reconstruction technique to the HH30 jet, we neglect the effect of the magnetic field.

We run a series of simulations changing N, τ_i, and A_i. In the first model, we use $N = 1$, $\tau_1 = 3$ yrs, and $A_1 = 0.5$. In the second model we add a second perturbation with $\tau_2 = 6$ months and $A_1 = 0.25$, $A_2 = 0.5$. In the third simulation we add other two sinusoidal component, with $A_{3,4} = 0.43, 0.59$ and $\tau_3 = 2$ months and $\tau_4 \approx 10$ days. As τ_4 is lower than the timestep of the simulation itself, the $i = 4$ periodic component represents substantially a chaotic contribution to the velocity variation.

The volumetric electron density map $n_e = n_e(r)$ determined from the tomographic inversion techniques and corresponding to the models with $N = 4, 2, 1$ is shown in Figure 2 (left to right panels respectively). In the model with $N = 1$ the electron density presents strong post-shock peaks, with large electron density drops between the shock traveling downstream. This is in clear contradiction with observations, where elongated structures with large electron density (and emission line intensities) are present also in the regions between the main knots. The observed substructures and the relatively high degree of ionization (of order of ~ 0.1) present in the observation are best matched by the model with $N = 4$.

These results imply that the mechanism responsible for the generation of a velocity variation at the base of the jet is producing a chaotic or at least a multi-component variation, with a typical large timescale of 3 yrs (necessary to reproduce correctly the position of the main knots) added to a low scale (less than 6 months) velocity variation.

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Discussion

L.F. Rodriguez: Is it understood why on larger scales uou see longer periodicities? Is it real or some observational bias?

De Colle: This can be explained by assuming a multi-periodic ejection from the source. The small scale knots present close to the source collide and leave, at larger distances, the knots with the larger periodicity.

de Gouveia Dal Pino: Can you use the same tomographic technique to reconstruct the 3D structure of light relativistic jets?

De Colle: Well, the necessary condition to apply the tomographic technique is to have high resolution images of a jet that is also located in the plane of the sky and is axisymmetric. Do we have a light relativistic jet with these characteristics?

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