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Inner structure of the jets from YSO's

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In this paper we summarise main results of our investigations of Herbig–Haro jets and especially focus on the different type of the inner structures. Observations were carried out with 2.6 m telescope of Byurakan Observatory and 6 m telescope of SAO RAS using scanning Fabry–Perot etalon. The new method to measure proper motions of spectrally separated structures using two epoch observations with Fabry–Perot was developed. This method allows us to separate inner structures of various physical nature as bow-shocks, Mach disks and deflection shocks. We suppose that characteristic knotty structures in the jets represent internal working surfaces formed by the episodic velocity variations in the flows from young stellar objects.

Keywords: ISM: Herbig–Haro objects, jets and outflows, stars: pre-main sequence

1 Introduction

Jets from young stellar objects often are called Herbig–Haro jets and not only because of the same spectral properties but because already known HH objects represent brightest parts of the jets. Before discoveries of highly collimated jets the detail investigations of HH objects formed the basis of the concept that these objects represent an optical manifestation of bipolar outflows from young stars. Great advances in formation of this concept were done by G. Herbig in the earlier 1980s, after measuring the proper motions and revealing high tangential velocities in HH objects. Moreover, orientations of proper motion vectors precisely indicate the sources of HH objects and, in some cases, provide evidence of their bipolar nature. This concept was fully confirmed after the discovery of highly collimated jets. In some cases HH systems consist of a well-collimated jet ending in a bright symmetric bow shocks. However, such fine morphologies which we called "grand design jets" (e.g. HH34) are rare.

HH jets typically appear as linear or gently wiggling chains of compact knots, sometimes connected by fainter emission. The mechanisms of formation of these knots are the subject of discussion during many years. The first suggestion that jets might consist of a series of stationary shocks of the kind seen in laboratory jets (e.g.,

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Falle et al., 1987; Canto et al., 1989) had to be abandoned when it was recognized that the knots in many jets exhibit large proper motions. Two competing theories for the origin of the knotty structure of jets remained now. On the one hand, a series of oblique, traveling shocks may be excited in the jet by different type of instabilities (Hardee and Stone, 1997; Micono et al., 1998; Ouyed and Pudritz, 1997). On the other hand, variations in the velocity of the flow may generate internal working surfaces that propagate along the jet and have shock velocities comparable to the amplitude of the velocity perturbation (e.g., Raga et al., 1990; Kofman and Raga, 1992; Hartigan and Raymond, 1993; Raga and Noriega-Crespo, 1998). These two models predict very different internal structures for the knots (e.g.,compare Micono et al., 1998; Raga and Noriega-Crespo, 1998).

Detailed investigation of working surfaces (WS) revealed their complex nature. Narrow band imagery allows us to separate high and low excitation structures, which are completely different by morphology. Usually WS represents two shock structures: compact with low excitation and bow shape with high excitation. In the WS two principal shock regions (Blandford and Rees, 1974) are formed, consisting of a reverse shock (Mach disk), which decelerates the supersonic flow, and a forward shock (bow-shock), which accelerates the gas in the ambient medium with which it collides (e.g., Hartigan, 1989). The forward shock may take the form of a bow shock whose surface is normal to the flow direction on axis, but which becomes increasingly oblique away from the axis in the swept-back wings.

Position-velocity diagrams obtained by long-slit spectroscopy indicate two radial velocity components in the WS. But, unfortunately, slit spectroscopy does not give a possibility to investigate their morphological properties. The only way to study the morphology of spectrally separated structures is provided by various methods of panoramic spectroscopy. Here we will present data obtained by scanning Fabry–Perot etalon, using 2.6 and 6 m telescopes. Detailed description of the methods and technique of the observations are presented in our previous papers (Movsessian et al., 2000, 2007, 2012).

2 Observational results

2.1 Separation of Mach disk and bow-shock structures in terminal working surfaces

Scanning Fabry–Perot data show that the WS is divided into two distinct velocity components, which are well separated spectrally as well as morphologically (Movsessian et al., 2000, 2009). On Fig. 1 the superposition of high and low radial velocity components of HH 7 and HH 83 WS are presented. Monochromatic images in HH7 corresponding to -125 km s^{-1} (high) and -18 km s^{-1} (low) and -295 km s^{-1} (high) and -68 km s^{-1} (low) in HH 83. In both cases the low radial velocity component has bow shape morphology and high velocity component is more compact. This picture strongly supports the classical WS concept where an advancing bow shock is followed by a Mach disk through which the jet flow is halted by a reverse shock.

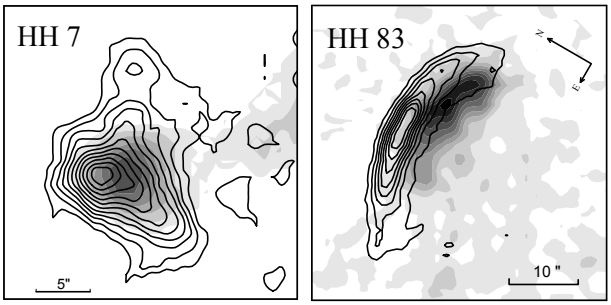


Figure 1 Superposition of two monochromatic images for HH 7 and HH 83 working surfaces, which corresponds to high-velocity (grey scale) and low-velocity (contoured) structures.

2.2 The nature of the knotty structures in the HL Tau jet

As was already described in our previous paper (Movsessian et al., 2007), the HL Tau jet consists of the high-velocity narrow jet with knotty morphology and the low-velocity bows, which are visible only in Hα and cross the jet axis, being located in front of the high-velocity knots. They exhibit the greater transverse widths at the greater distances from HL Tau and are not axisymmetric, being elongated in the SE direction. Their morphology is also evident from HST images (Krist et al., 2008).

These structures differ not only by their radial velocity but also by excitation, because bow-shape structures are visible only in Hα emission and high-velocity knots are much brighter in [S II] (Movsessian et al., 2007; Krist et al., 2008). This picture strongly resembles the separation of bow-shock and Mach disk structures in the terminal WS of the jets. But, for the jet knots even the doubtless splitting of two shocked structures both by radial velocity and by excitation leaves some uncertainty in choosing between the theoretical mechanisms of the knot formation. Here, in our opinion, the proper motion values combined with the radial velocities can play the crucial role in clarifying of this situation.

To measure proper motion (PM) of spectrally separated structures we use two epochs scanning Fabry–Perot observations separated to 6 years (2001–2007). The results of our PM measurements are presented in Fig. 2, where the two images of the HL Tau jet, corresponding to low and high radial velocities, with the vectors of PM of the knots, are shown. The most obvious and interesting result is that the structural components with low and high radial velocity both have very similar values of proper motions (Movsessian et al., 2012).

To analyse this picture we suggest to consider the knots as the internal WS formed in a time-dependent flow, i.e. in the same way as the terminal WS with formation of two principal shock regions. These data allow us to obtain pattern and fluid speeds (Eisloeffel and Mundt, 1992) of the structures in the jet. The pattern speed of these two structures should be the same, in contrast to the fluid speed of emitting particles.

As was shown by Hartigan (1989), the ratio of radial velocities in shocked structures depends on the flow and ambient medium densities as well as on the jet velocity itself. From the same model, it follows that the relative surface brightness of a Mach disk and a bow-shock also depends on the ratio of the jet and ambient medium densi-

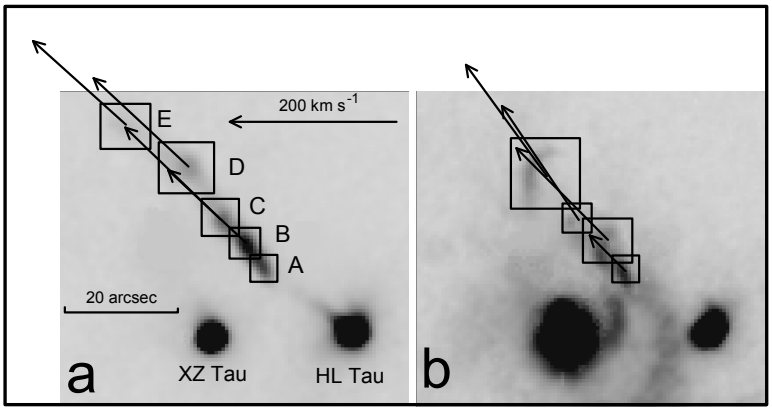


Figure 2 Proper motions of the structures in the A, B, C, D, and E knots of HL Tau jet, corresponding to high (a) and low (b) radial velocities, are shown by the vectors, plotted on the images in Hα emission, which correspond to -150 km s^{-1} and -50 km s^{-1}, respectively. The scale of the vectors is indicated by the arrow at the top of the left panel. Rectangles show the areas used for the cross-correlation.

ties (n_j and n_a correspondingly), and brighter bow-shocks are formed in denser jets. For knots within the HL Tau jet, the relative surface brightness of bow-shock and Mach disk is nearly equal, so the ratio n_a/n_j is a little more than unity.

To obtain the correct estimates for the jet absolute velocity and inclination (α angle) we need to use the structures where the fluid and pattern velocities have nearly the same values. For example, in a Mach disk by definition these velocities have nearly the same values. Thus, combining the tangential and radial velocities of high-velocity compact knots (which we assume to represent Mach disks), we find that $\alpha = 50^\circ \pm 10^\circ$ and the mean value of the absolute velocity of the jet is about 250 km s^{-1}.

2.3 Deflection shock structures

While most of the shock waves in stellar jets arise from velocity variations in the flow, shocks also occur when the jet deflects from an obstacle along its path. In this case the shock appears as a steady-state feature visible mainly in Hα emission. Using two epoch observations with scanning Fabry–Perot etalon such features were found in two HH jets: HL Tau and FS Tau B.

In the HL Tau jet the knot A shows very low tangential velocity in comparison with other ones. We are inclined to believe that the tail of knot A represents a so-called deflection shock. Both its stationarity and excitation of knot A have a great similarity to the feature that was recently discovered in the HH 46/47 jet by Hartigan et al. (2011) (compare their Fig. 14 and the Fig. 4 from Krist et al. 2008), which is considered by them as the deflection shock.

More striking example of the stationary structure in flow is the bar-like feature in the FS Tau B jet. On Fig. 3 two epoch images obtained with scanning Fabry–Perot etalon of the jet are presented. Shift of some structures between two epoch images are obvious especially for the knots B ($V_t = 430$ km s^{-1}), A2 ($V_t = 260$ km s^{-1}), I

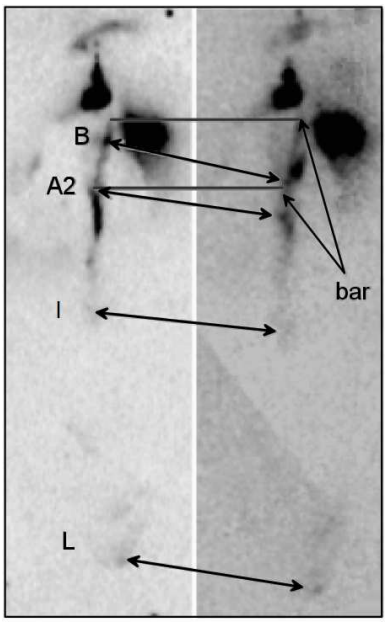


Figure 3 Two epoch (2001 and 2012) monochromatic images obtained with scanning Fabry–Perot etalon. Stationary bar-like structure is marked with black lines and the shift of knots is shown by arrows.

(V_t = 330 km s^{-1}) and L (V_t = 290 km s^{-1}). In the contrast of high values of PM in the knots of FS Tau B jet the bar-like structure, which is marked on the picture, does not show significant shift between two epoch images. As in the case of knot A in HL Tau jet and structure in HH 46 jet the bar-like structure is stationary over the period between two epoch of observations. This bar-like structure in FS Tau B jet is presumably formed in the region, where wide angle flow collides obliquely with the dense linear structures near the edge of an evacuated cavity.

Method of two epoch observations with scanning Fabry–Perot etalon is the powerful technique for discovery and separation of various type of structures in jets from young stellar objects as Mach disks, bow-shocks, deflection shocks, intersecting shock waves, Mach stems, clumps and sheets.

3 Conclusion

1. Using Fabry–Perot spectra-imagery we were able to separate bow-shock and Mach disk structures in the WS of HH flows.
2. Development of the new method of investigation of PM of spectrally separated structures allowed us to illuminate the physical nature of such structures as the internal working surfaces, formed by episodic velocity variations in the outflow.
3. Analysing the proper motion values we have found deflection shock structures in HL Tau and FS Tau B jets.

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