# Two epoch Fabry-Perot observations of FS Tau B

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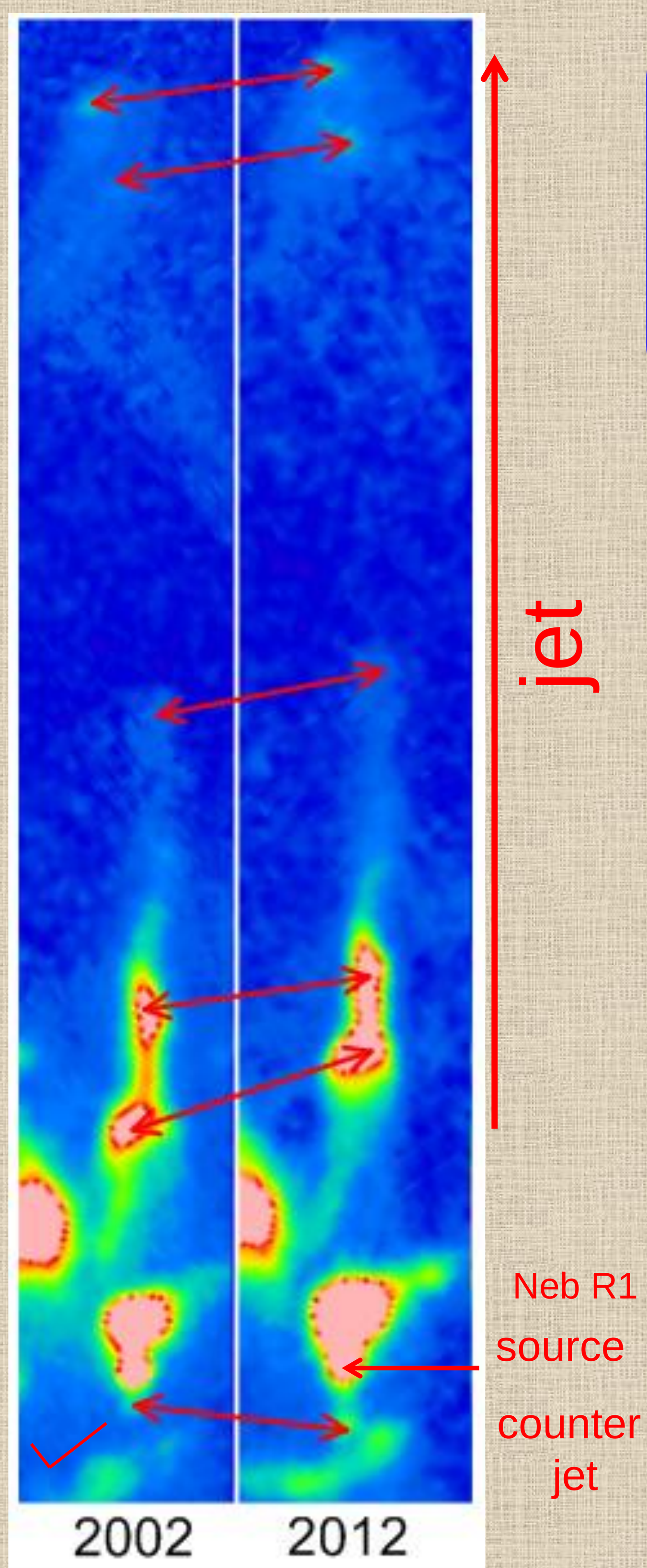



Fig. 2. Two epoch monochromatic images of FS Tau B outflow system.

## ABSTRACT

We present the observational results obtained with a 6 m telescope (Russia) using the SCORPIO camera with scanning Fabry-Perót interferometer. Two epochs of the observations of the FS Tau B region in Hα emission (2001 and 2012) allowed us to measure the proper motions (PM) for the spectrally separated inner structures of the jet. Unlike of the other knots, the bar-shaped structure NE from the source does not have any perceptible proper motion and represents stationary deflecting shock region. In the jet working surface two different radial velocity structures were found. Proper motions of these structures indicate the presence of two separate knots with different velocities in this region.

Investigation of Hα profiles toward the source and the bright reflection nebula R1 shows impressive differences. In fact, we observe the single peak profile in the direction of the source and the double peak profile in the direction of the reflection nebula. The reflection nebula works as a mirror located just on the axis of the flow and we observe the same object as edge-on system (source) and pole-on system (R1 nebula) simultaneously. We propose the scenario of formation of absorption component, which splits the emission profile, in a wide angle cool wind from the source.

## OBSERVATIONS

Observations were carried out at the prime focus of the 6m telescope with SCORPIO camera (Afanasiev & Moiseev 2005) in two epoches – 2001 & 2012 with scanning Fabry-Perot etalons.

**2001.** The detector was a Tektronix 1024×1024 pixel CCD array. A field-of-view of 4.8′ was observed with a scale of 0.56″ per pixel. We used an Queensgate ET-50 interferometer operating in the 501th order at the wavelength of Hα which provided a spectral resolution of FWHM ~0.8A. The number of spectral channel images obtained was 36 with the size of a single channel Δλ=0.36A (16 km $s^{-1}$).

**2012.** The detector was a 2K×2K CCD EEV 42-40 operated with 4×4 pixel binning to reduce the read-out time. The field of view of about 6′ was sampled with a scale 0.71″ per pixel. The ICOS interferometer operating in the 751th order at the wavelength of Hα provided a spectral resolution of FWHM ~0.4A. The number of spectral channel images obtained was 40 with the size of a single channel Δλ=0.22A (9.75 km $s^{-1}$).

We reduced our interferometric observations by using the software developed in SAO (Moiseev 2002), as well as ADHOC software package developed by J. Boulesteix (Marseille Observatory).

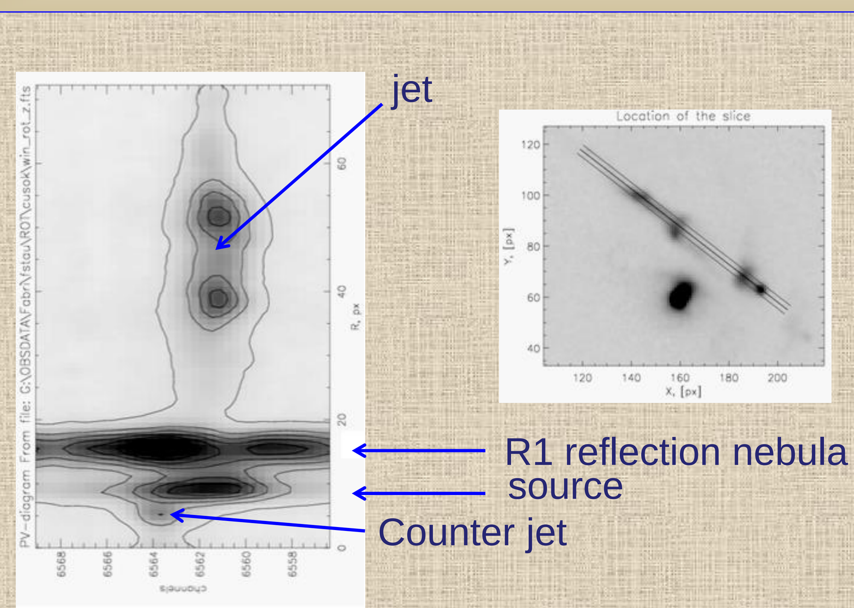



Fig. 6. Position-velocity diagram of FS Tau B system obtained from data cube. Split of emission in the position of R1 nebula is obvious.

## PROPER MOTION OF SPECTRALLY SEPARATED STRUCTURES

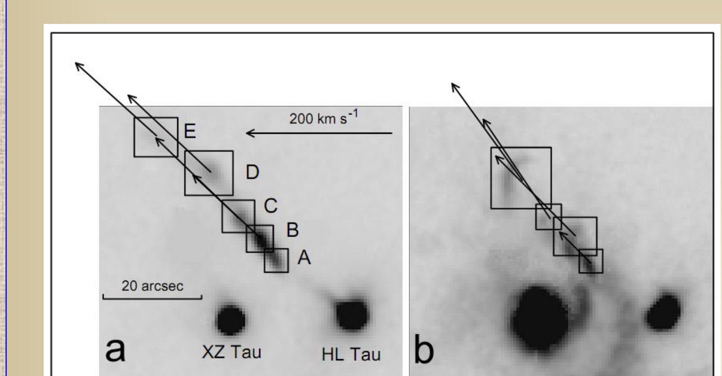



Fig. 1. . Proper motions of the structures in the A, B, C, D, and E knots of the HL Tau jet, corresponding to high a) and low b) radial velocities, are shown by vectors. Both images are obtained in Hα emission corresponding to the radial velocity of −150 km $s^{-1}$ and −50 km $s^{-1}$, respectively.

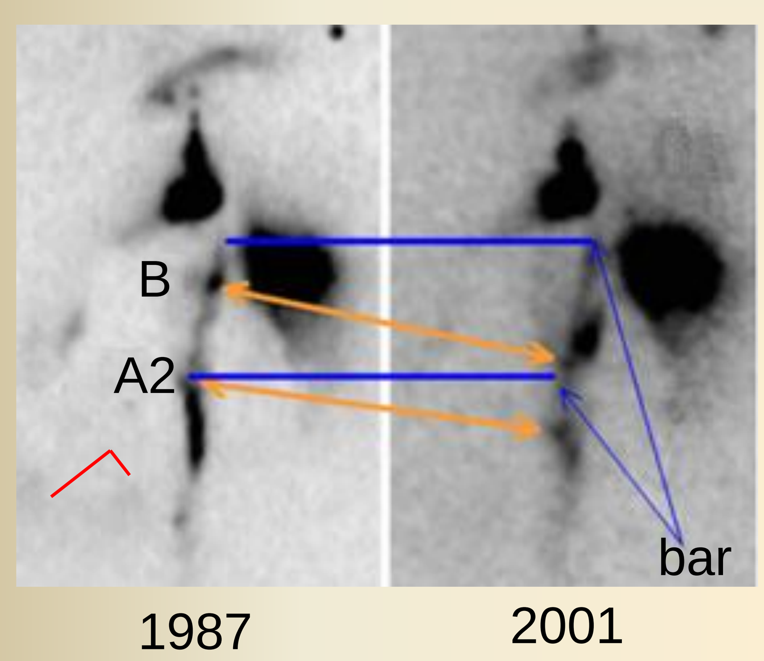



Fig. 4. Comparison of the narrow band image (Eisloffel & Mundt, 1998) and the Fabry-Perot image (corresponding to 0 km $s^{-1}$), obtained in 2001. High PM of two knots B and A2 is obvious, but PM of bar-like structure is near 0.

Although long-slit spectroscopy indicates split of emission lines into high and low velocity components in the working surfaces of jets, only spectra-imagery revealed the morphology of different kinematical structures. So, working surfaces are divided into “reverse shock” and “forward shock” regions, which are split by excitation (Reipurth & Heathcote 1992, Reipurth et al. 1992) as well as by radial velocities (Morse et al. 1990, Movsessian et al. 2000, 2009). Morphologically, the first one is represented by a high radial velocity compact knot and the second one – by low velocity bow shape structure in front of the first. Scanning Fabry-Perot observations of jets from YSOs revealed also the complex morphology of the inner structures with high and low radial velocities. To understand the physical nature of those structures it is very important to combine the radial velocity data with PM.

We developed a new method of PM measurement for the various radial velocity structures in jets using two epoch scanning Fabry-Perot observations, which allow both to separate the structures with various radial velocities and to measure PM for the spectrally separated structures. Firstly it was tested on HL Tau jet, were we revealed internal structures with surprisingly different radial velocities (Movsessian et al. 2007). Second epoch observations show the same PM for these structures (Fig. 1). It is an evidence in favor of formation of internal working surfaces by the episodic velocity variations (Movsessian et al. 2012) and not by the various types of instabilities.

Now we apply this method for the study of the jet in FS Tau B system, which is a nearly edge-on system with wiggling jet with complex inner structures and terminal working surface. Two epochs (2001-2012) of observations with scanning Fabry-Perot etalon were carried out with 6-m telescope. The radial velocities of the bipolar outflow are close (within ±10 km $s^{-1}$) to the previously determined values (Eisloeffel & Mundt, 1998). In the terminal working surface two kinematically separated knots were revealed (Fig. 2). Besides of knots and bright bow-shape structures in the jet, there is a strange bar-like structure to SW from the source. Using two epoch observations we measure PM of these knots and structures (see Table and Fig. 3). Two knots in the terminal working surface have different PM and represent two separate episodic ejections; they are not the “reverse shock” and “forward shock” regions. PM of bar-like structure is very low (Fig. 4) and presumably it represents the shocked wall or deflection shock as in the case of HL Tau (Movsessian et al. 2012) and HH46/47 (Hartigan et al. 2011).

Table

| knot | PM (km $s^{-1}$) | PA(degr) |
|---|---|---|
| L | 232 | 58 |
| K | 317 | 55 |
| B | 431 | 46 |
| I | 286 | 50 |
| A | 240 | 56 |
| E | 163 | 239 |
| H | 155 | 237 |

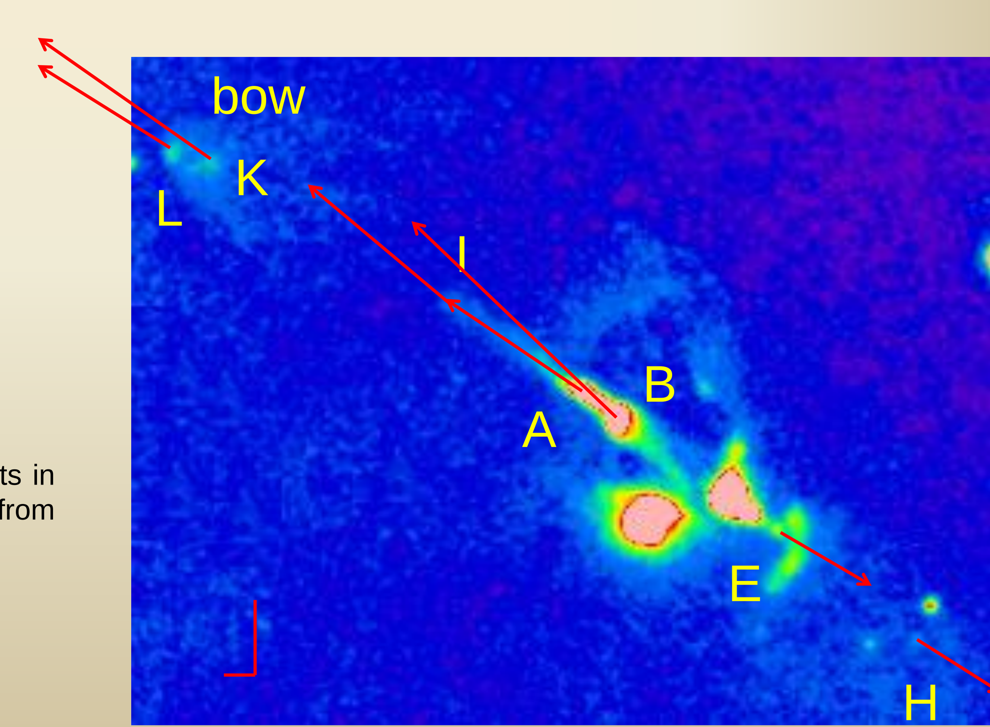



Fig. 3. Proper motion vectors of the bright knots in FS Tau B outflow system. The nomenclature from Eisloffel et al. (1998) is used .

## VARIATIONS OF THE EMISSION LINE PROFILES NEAR THE SOURCE

Our data cubes allow to study the Hα emission profiles not only in the spectrum of the star itself and of its directed outflow, but in the reflected light of the triangular nebula R1 as well. To be more precise, one should note that the star FS Tau B is totally obscured, as was shown by Eisloeffel & Mundt (1998), and its optical light cannot be observed directly. The bright northeastern stellar-like knot probably represents the upper surface of the seen edge-on circumstellar disk. HST images show that the source of a bipolar jet is not visible directly, but appears to illuminate a compact, bipolar nebula which assumed to be a protostellar disk similar to HH 30 (Krist et al. 1998). By the axis of outflow in NE direction the bright triangular reflection nebula is located. Emission profiles, observed at the positions of the circumstellar disk and R1 reflection nebula, show striking changes.

As is seen from the Fig. 5 and the position-velocity diagram (Fig. 6), the Hα line profile, which corresponds to the scattered light in the circumstellar disk, shows a broad emission. In contrast, the averaged profile in the R1 reflection nebula is split into two components. If we fit these two emission profiles by one component, their FWHM will be the same. Presumably they are split by the blueshifted absorption formed in a cool wind from the source.

It should be noted, that emission profile in the position of the source is typical for the edge-on T Tau stars (Appenzeller et al. 2005) and the profile in the reflection nebula is similar to CTTS. In our opinion, the reflection nebula works as a mirror and we observe the same object as the edge-on and the pole-on systems (see sketch below) simultaneously.

FS Tau B becomes one more example of a source exhibiting the rare phenomenon known as “spectral asymmetry”. This was first reported in the observations of the R Mon + NGC 2261 system (Greenstein 1948; Stockton, Chesley & Chesley1975; Greenstein et al. 1976). This asymmetry was successfully explained in the work of Jones & Herbig (1982).

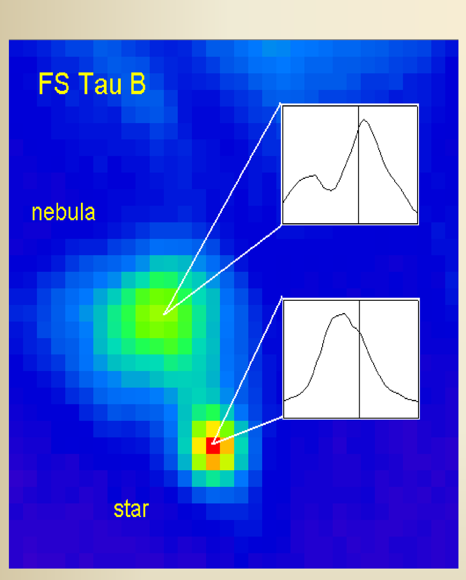
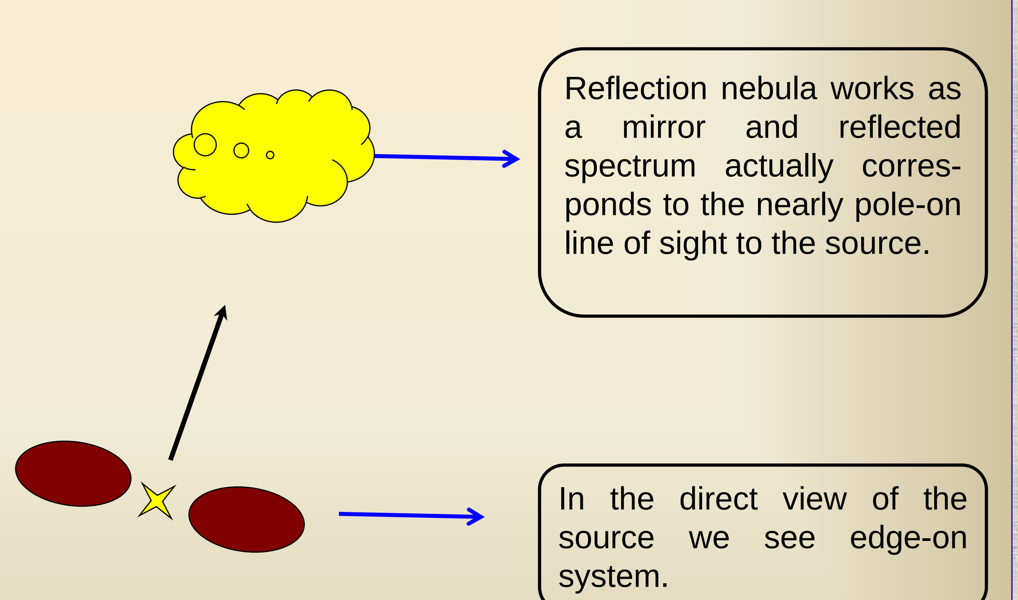



Fig.3. Averaged profiles of Hα emission line in the FS Tau B and the reflection nebula




## AKNOWLEDGMENT

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