Velocity fields of parsec scale jets

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The project

Radio-loud AGN typically manifest powerful relativistic jets extending up to millions of light years and often showing superluminal motions organised in a complex kinematic pattern. A number of physical models are still competing to explain the jet structure and kinematics revealed by radio images using the VLBI technique. Robust measurements of longitudinal and transverse velocity field in the jets would provide crucial information for these models. This is a difficult task, particularly for transversely resolved jets in objects like 3C273 and M87. To address this task, we have developed a new technique for identifying significant structural patterns (**SSP**) of smooth, transversely resolved flows and obtaining a velocity field from cross-correlation of these regions in multi-epoch observations.

Wavelet-based image structure evaluation (WISE)

The WISE algorithm comprises three main constituent parts:

- Detection of structural information is performed using the segmented wavelet decomposition (**SWD**) (Mertens & Lobanov 2015).
- The multiscale cross correlation (**MCC**) algorithm combines structural information on different scales of the wavelet decomposition, providing a robust and reliable identification of related SSP in multi-epoch images (Fig. 1).
- A stacked cross correlation (**SCC**) is introduced to recover multiple velocity components from partially overlapping emitting regions (see inset in Fig. 4).

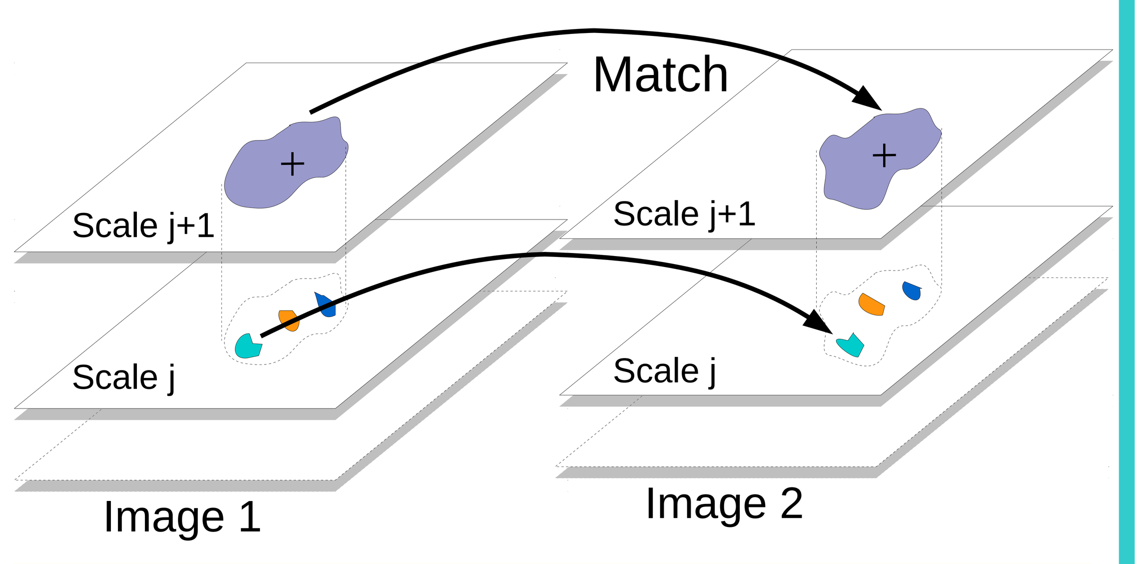


Figure 1: *Illustration of the MCC method. A coarse-to-fine strategy is used. Significant structural patterns are detected at each scale of the wavelet decomposition. The calculated displacement at a higher (larger) scale is used to constrain the determination of the feature displacements at a lower (smaller) scale*

WISE analysis of MOJAVE sources

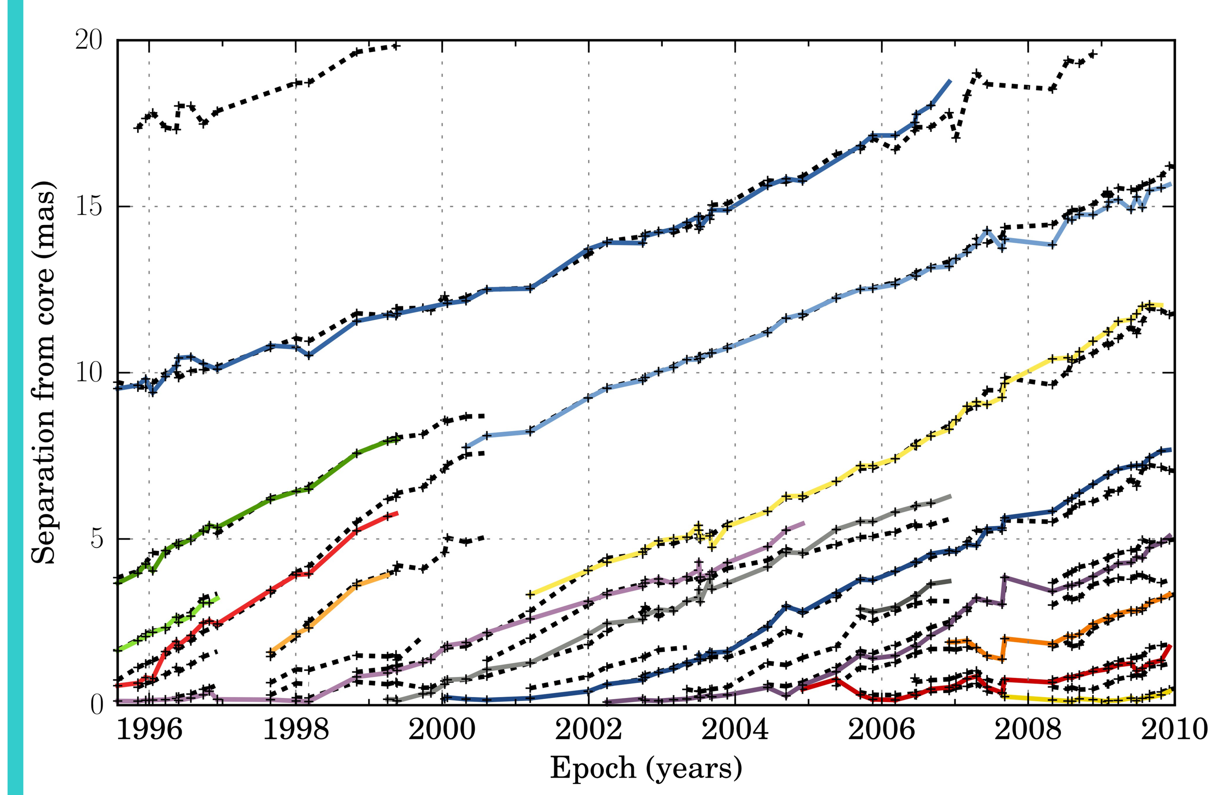


Figure 2: *Core separation plot of the most prominent features in the jet of 3C 273. The model-fit based MOJAVE results (dashed lines) are compared with the WISE results (solid lines).*

- WISE analysis was used to obtain the kinematics of two prominent AGN jets observed as part of the MOJAVE project.
- The results show excellent agreement with results from the supervised model fitting (Lister et al. 2009), demonstrating the ability of WISE for providing an objective and robust decomposition and tracking of two-dimensional structure in astronomical images (Fig. 2, 3).
- WISE is highly efficient: it takes only a few minutes to recover the same structural information which required weeks of model fitting efforts.
- Additional analysis of the tracks observed in the jet of 3C 120 (Fig. 3) reveals a helical morphology consistent with the patterns predicted from modeling with linearly growing Kelvin-Helmholtz instability (Hardee et al., 2005).

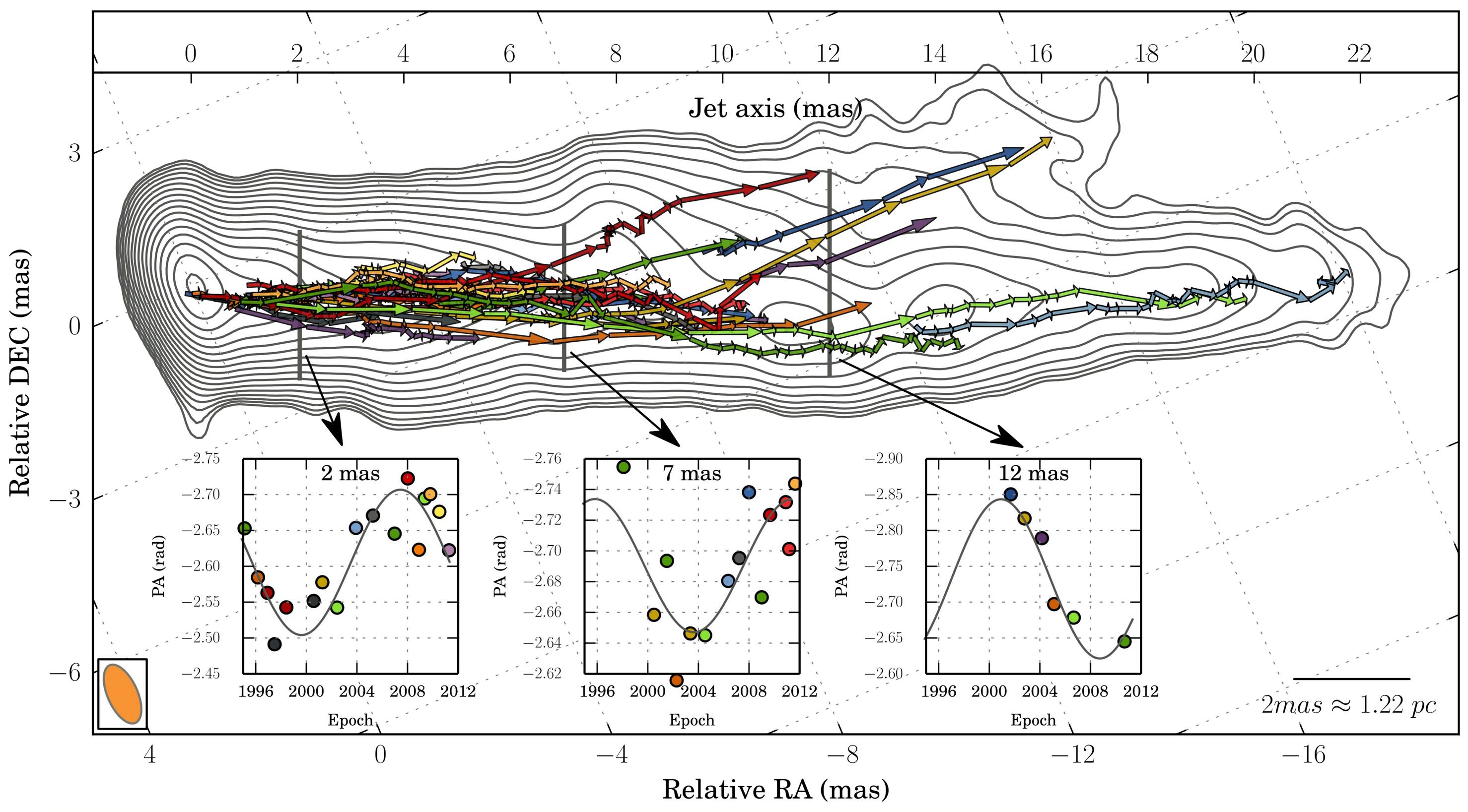


Figure 3: *Two-dimensional tracks of SSP detected in 3C120 overplotted on a stacked-epoch image of the jet. Colors distinguish individual SSP continuously tracked over several epochs. The three insets show the time and PA of each components crossing a distance from the core of 2 mas, 7 mas and 12 mas respectively. The PA change can be fitted by a sinusoid and is associated with the helical mode of the Kelvin-Helmholtz instability evolving in the jet with an apparent pattern speed β_W ~ 2 c, and an apparent wavelength λ_W ~ 15 mas.*

Kinematic of the innermost jet in M87

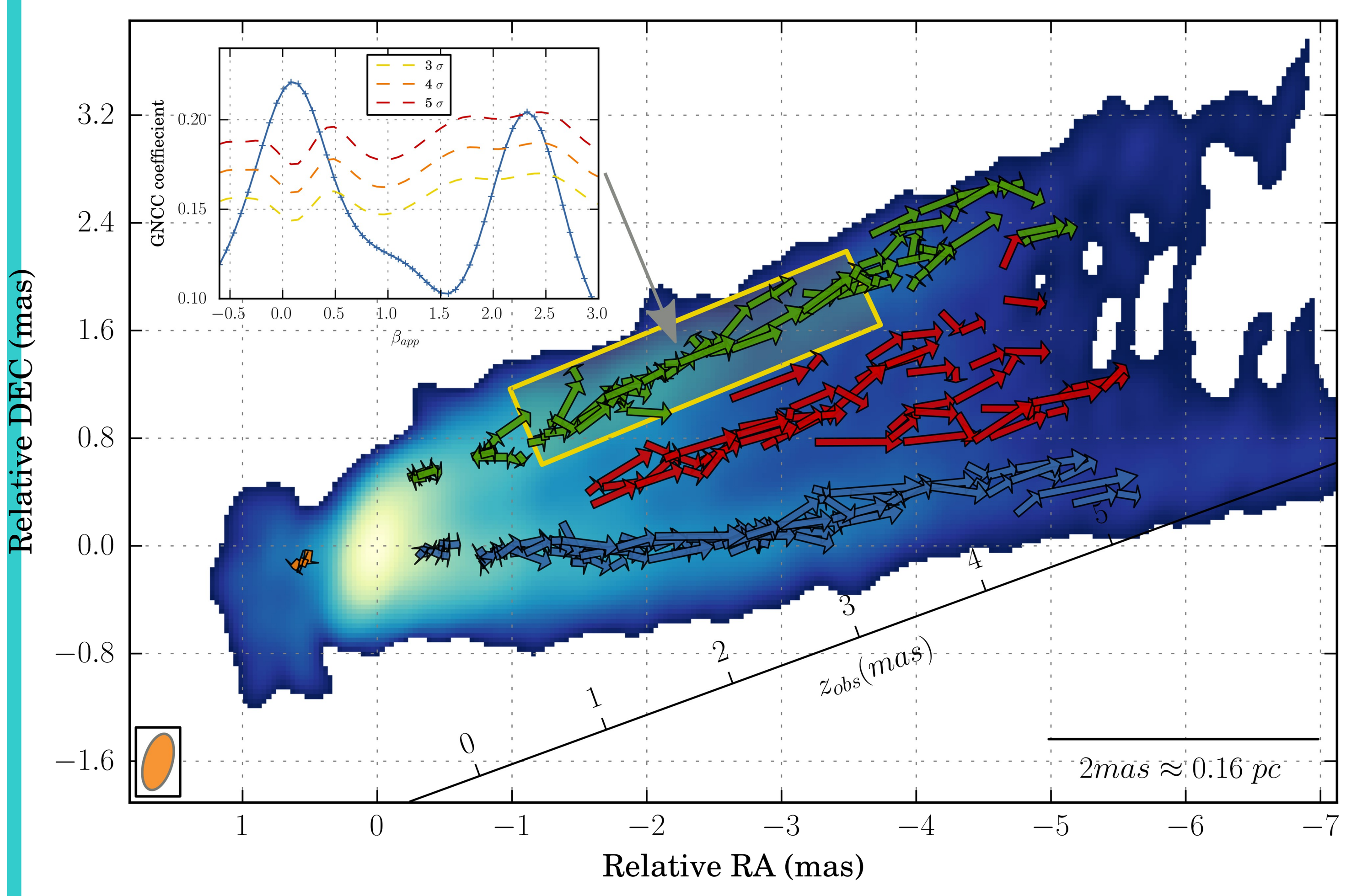


Figure 4: *Velocity field in the jet of M87. Three main flow patterns are detected in a southern (blue) and northern (green) rail and a central region (red). The component found in the inner part of the counter jet (orange), is used to constraint the viewing angle (θ ~ 18°). SCC analysis (inset) reveals velocity stratification with two main velocity components present in all three regions of the jets: a slow mildly relativistic speed (β ~ 0.5 c) and a faster relativistic speed (γ ~ 2.5). The spine in the center of the jet is deboosted and a maximum Lorentz factor can be estimated using the intensity ratio between the sheath and the spine (γ ~ 6).*

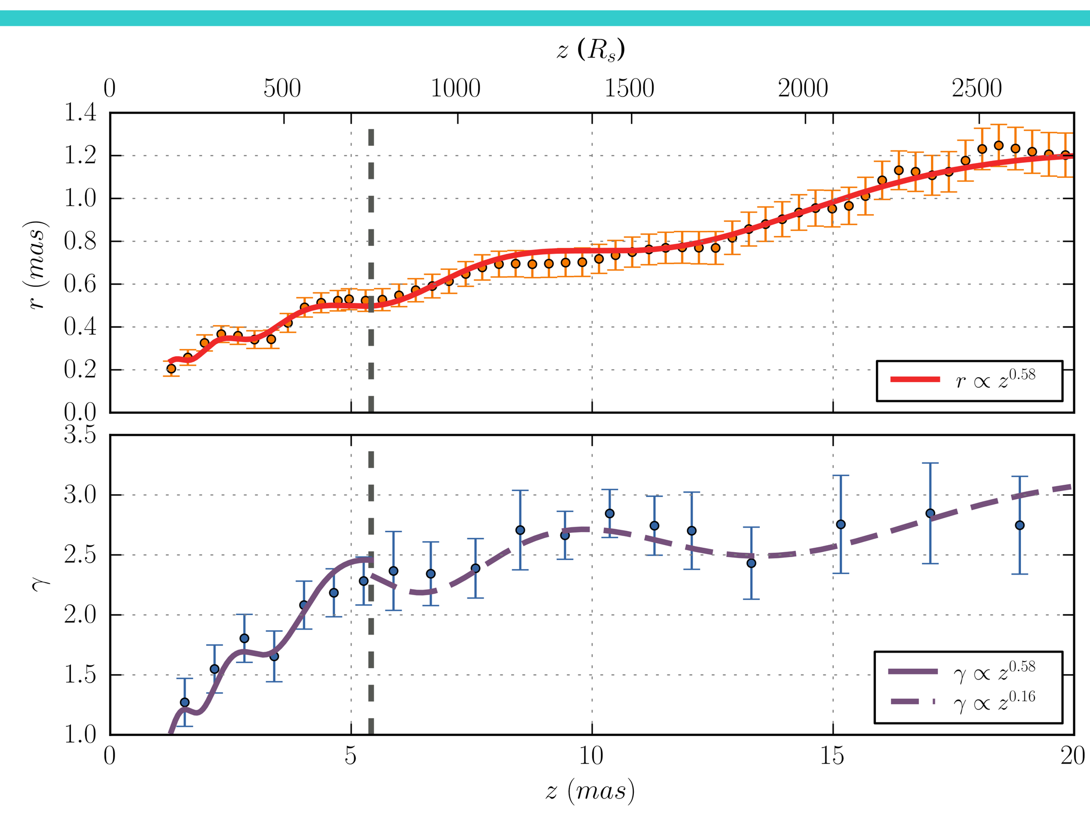
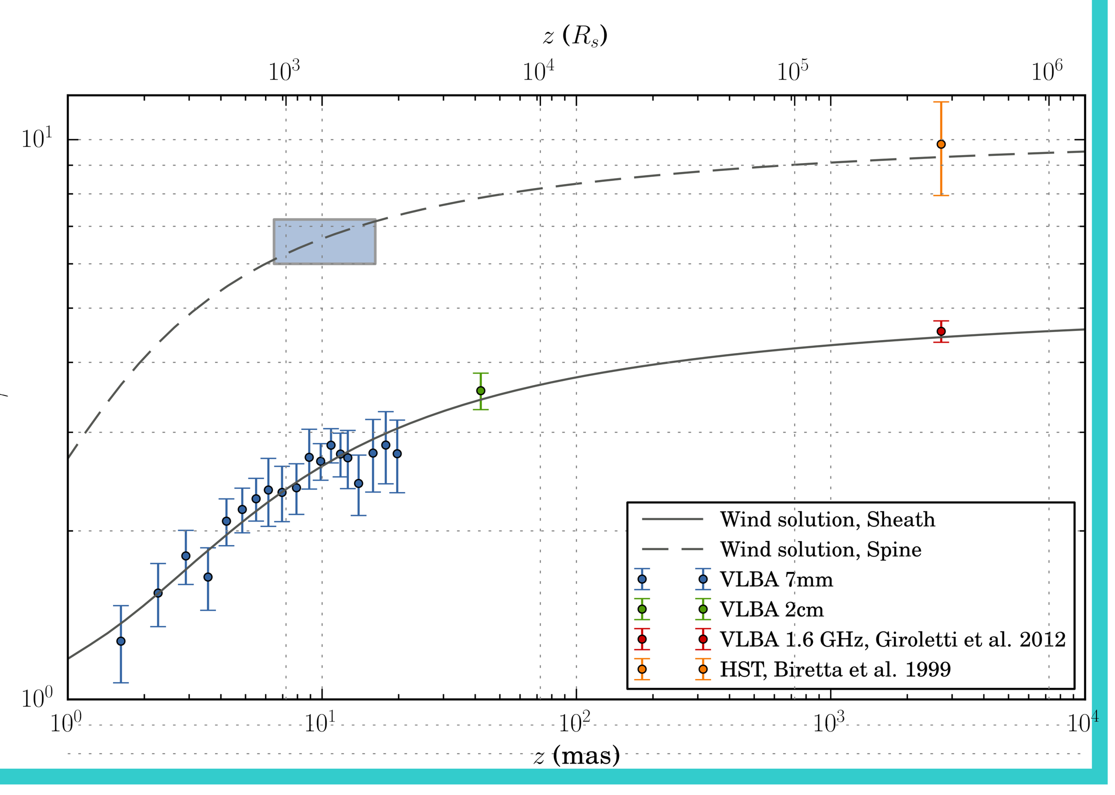


Figure 5 (left): Modeling of the observed acceleration (blue) and collimation (orange) using asymptotic relations of MHD Poynting flux dominated jets (Lyubarsky 2009). Oscillations wave are superimposed on a parabolic expansion. Two different regimes are found for the acceleration.

Figure 6 (bottom): *Wind solution for the sheath (solid line) and the spine (dashed line) using a realistic flux function from Toma et al. 2013. The solution for the sheath fit the observed acceleration and the velocity at HST-1 in the radio band. The solution for the spine fits well the inferred velocity of the de-boosted structure in the M87 map (blue box) and the velocity observed at HST-1 in the optical band.*

- We analyzed 11 epochs of the M87 jet VLBA movie project observed at ~3 weeks interval (Walker et al. 2008). The analysis reveals a structured and stratified flow (Fig. 4).
- Using the velocity detected in the counter-jet, we constraint the viewing angle $\theta \sim 18°$.
- Differential rotation between the north and south sheath is detected. It can be explained by the jet rotation consistent with field line angular velocity $\Omega \sim 10^{-6} s^{-1}$.
- The corresponding launching location is at $r_0 \sim 4\, R_s$.
- Acceleration and collimation can be represented in the framework of MHD acceleration (Fig. 5).
- Wind solution for the sheath suggest $\mu \sim 6$ (Fig. 6) and an efficient, conversion of Poynting to kinetic energy with: $r_{eq} \sim 10\, r_{lc} \sim 200\, R_s$, $z_{eq} \sim 3000\, R_s$
- De-boosted structure in the spine suggests $\gamma_{spine} \sim 6$.



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Summary

- ➢ WISE provides an efficient objective and reliable reconstruction of the velocity field in transversely resolved flows.
- ➢ Evolution of the resolved structure in 3C 120 suggests a K-H helical mode with β_W ~ 2 c and λ_W ~ 15 mas.
- ➢ Analysis of the M87 innermost jet reveals a stratified flow with:
  - I. A slow mildly relativistic layer (β ~ 0.5 c) associated either with instability pattern speed or an outer wind.
  - II. A fast accelerating field line (sheath, γ ~ 2.5) connected with the velocities observed at HST-1 in radio.
  - III. A potentially faster inner field line (spine, γ ~ 6) connected with the velocities observed at HST-1 in optical.
- ➢ The wind solution of the sheath suggests an efficient conversion of magnetic to kinetic energy.
- ➢ Launching location is most likely disk for the sheath, but magnetosphere is not discarded.