Launching protostellar jets from finite-radius accretion disks

Matthias Stute[1], José Gracia[2], Nektarios Vlahakis[3], Kanaris Tsinganos[3]

[1]Eberhard Karls Universität Tübingen, [2]HLRS Stuttgart, [3]University of Athens

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

MATHEMATISCH-NATURWISSENSCHAFTLICHE FAKULTÄT

Institut für Astronomie & Astrophysik

Introduction

- Astrophysical jets, i.e. highly collimated high-velocity gas outflows, are ubiquitous phenomena in Astrophysics, occurring in a variety of objects on very different size and mass scales: AGN, XRBs, Symbiotic Stars and YSOs.
- In all known cases, jets and disks seem to be interrelated. Disks provide the jets with the ejected plasma and magnetic fields and jets are possibly the most efficient means to remove excess angular momentum in the disk (e.g. Ferreira 2007) making accretion possible in the first place.
- The magnetic model of a disk-wind seems to explain simultaneously acceleration, collimation as well as the observed high jet speeds (Königl & Pudritz 2000).

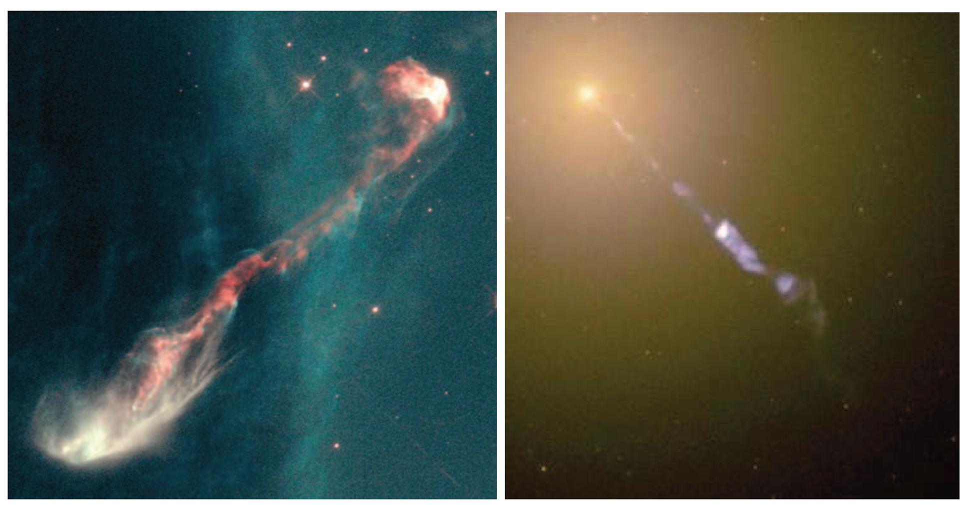

Figure 1: the protostellar jet in HH 47 (left); the AGN jet in M87 (right). (Courtesy: Hubble Heritage)

Self-similar jet formation models

- The first analytical work studying magneto-centrifugal acceleration along magnetic field lines threading an accretion disk was done by Blandford & Payne (1982).
- Numerous semi-analytic models extended the work of Blandford & Payne (1982) along the guidelines of radially self-similar solutions of the full magnetohydrodynamics (MHD) equations (Vlahakis & Tsinganos 1998).
- The model of Blandford & Payne (1982) and most self-similar models in general have serious limitations:
  1. The outflow speed at large distances does not cross the corresponding limiting characteristic, with the result that the terminal wind solution is not causally disconnected from the disk.
  2. Singularities exist at the jet axis in radially self-similar models.
  3. Self-similar models extend to infinite radius due to the absence of an intrinsic scale.
- Solutions to these problems:
  1. Vlahakis et al. (2000) showed that a terminal wind solution can be constructed which is causally disconnected from the disk.
  2. Numerical simulations are necessary to extend the analytical solutions close to the jet axis.
  3. Numerical simulations of truncated analytical solutions are necessary.

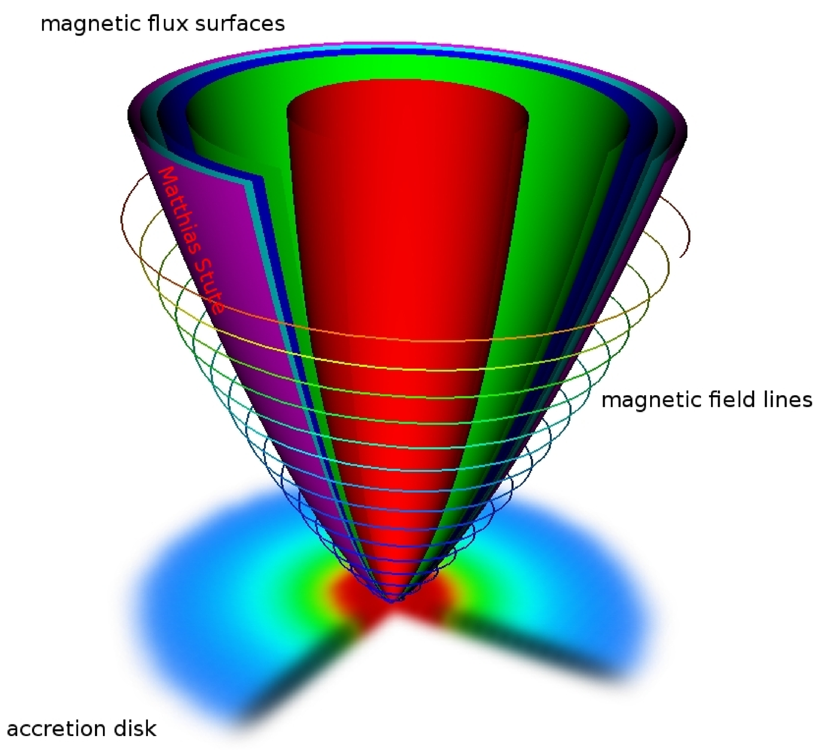

Figure 2: The hydrodynamic flow within jets is along magnetic flux surfaces whose shape is given by self-similar solutions of the axisymmetric stationary MHD equations

Models

We investigated numerically the effect of a finite radius of the jet launching region on the topology, structure, stability and ability of the final models to explain observations:

- We divided the computational domain in two regions separated by an arbitrary magnetic fieldline: the jet region and the ISM region. The jet region can be inside the ISM region (outer truncation) or outside the ISM region (inner truncation)
- The jet region is fully determined by the analytical solution of Vlahakis et al. (2000, ADO), while the ISM region is scaled down (reduced density, pressure, magnetic field and velocities)
- All quantities $\mathcal{Q}$ in both regions are matched with

$$\begin{aligned}\mathcal{Q} &= \mathcal{Q}_{\rm in}\, \exp[-(\alpha/\alpha_{\rm trunc})^2] \\ &\quad + \mathcal{Q}_{\rm out}\, \left(1 - \exp[-(\alpha/\alpha_{\rm trunc})^2]\right)\end{aligned}$$

- The initial conditions were then integrated with the time-dependent MHD code *PLUTO* (Mignone et al. 2007).
- We used OpenSESAMe to produce synthetic observations from our simulations in several steps:
  - approximation of the chemical composition of the plasma by locally solving a chemical network under the assumption of stationarity
  - calculation of the statistical equilibrium of level populations for each ion of interest as a function of temperature and density and the emissivity for individual transitions of interest
  - integration along the line-of-sight and projection
  - convolution with a Gaussian point-spread-function (PSF)
- We created synthetic observations from our simulations, i.e. synthetic emission maps of the [SII] λ6731 and [OI] λ6300 lines and position-velocity-diagramms.

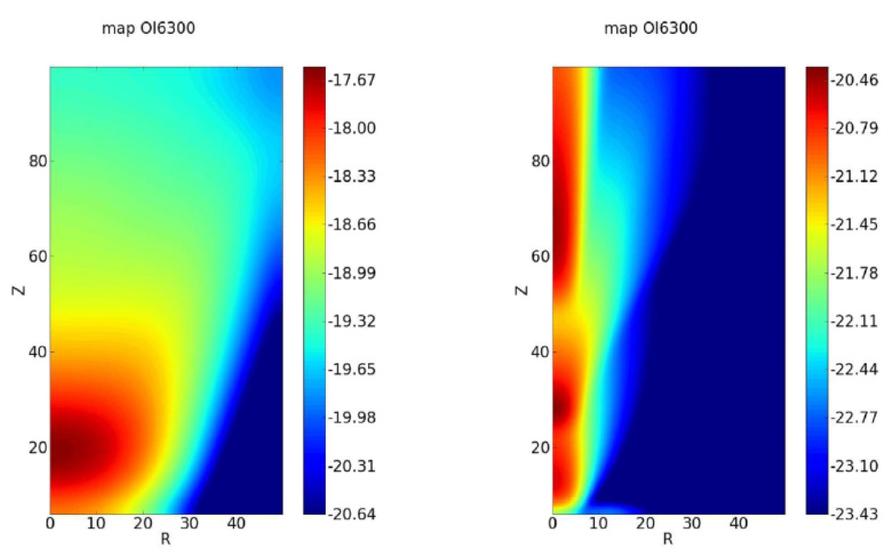

Figure 3: Synthetic [OI] images in the untruncated model ADO (left) and the truncated model SC1e (right). The emission is much more collimated than the density structure in Fig. 5 (Stute et al. 2010).

- From the emission maps, we measured the width of the jet as the FWHM and compared it with observations.

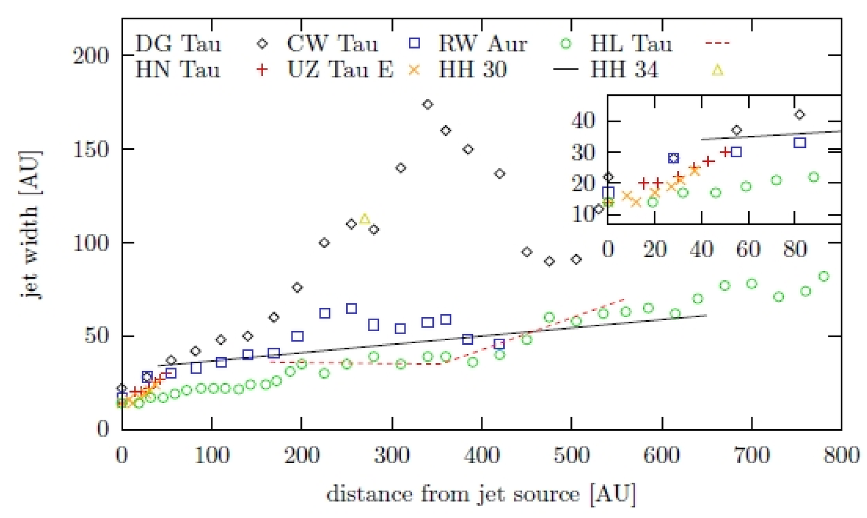

Figure 4: Variation of observed jet widths derived from [SII] and [OI] images as a function of distance from the source; data are taken from Ray et al. (2007) and references therein.

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Stability of truncated jet formation solutions

- The flow in the jet region always expands towards the ISM region due to reduced thermal and magnetic pressure in the latter.
- In all studied cases, we find eventually steady two-component solutions.

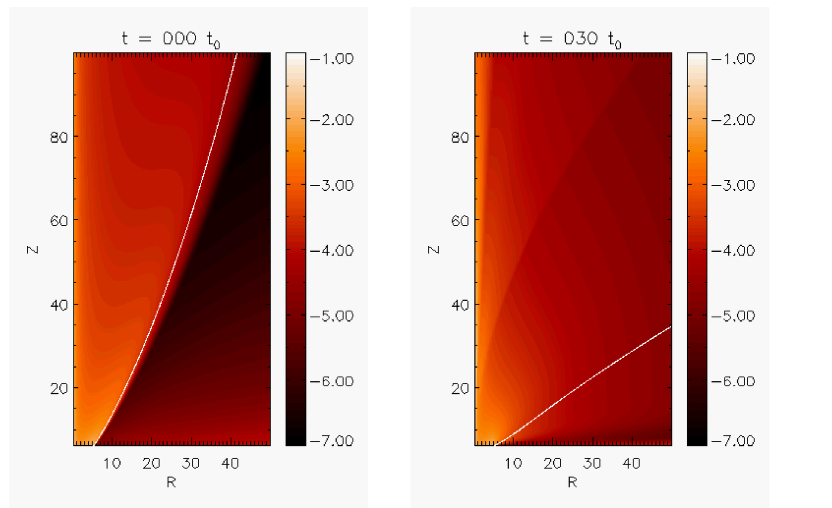

Figure 5: Structure of the jet (density) for a model with outer truncation, i.e. the jet region is inside the ISM region; left: initial conditions, right: the stationary final state; the white line denotes the position of the truncation field line separating the jet from the ISM region. (Stute et al. 2008)

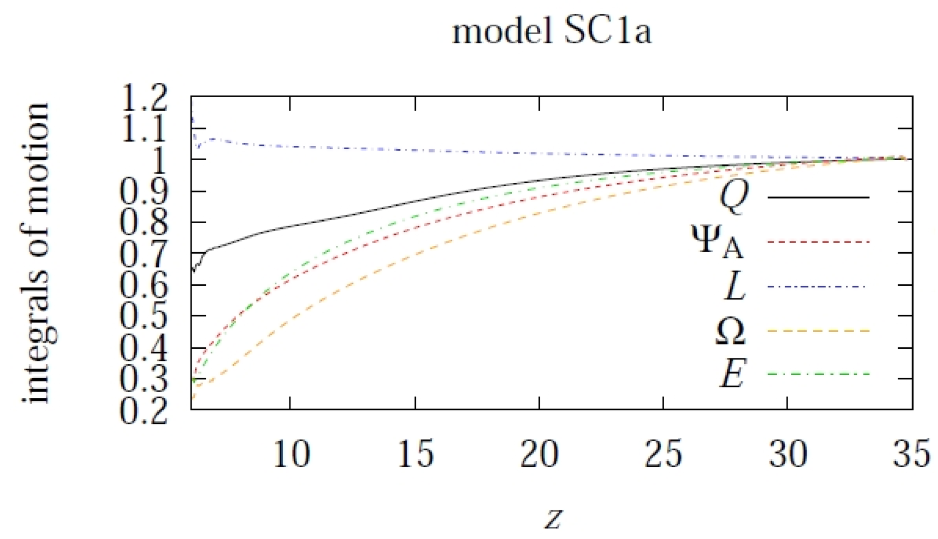

Figure 6: Integrals of motion showing that models reach a steady state. (Stute et al. 2008)

Comparison with observations of YSO jets

- We found that the untruncated solution cannot account for the small jet widths found in recent optical images taken with HST and AO.
- Our results can be used to infer the "real" value of the truncation radius in the observed sample of jets.
- Except for RW Aur, the derived truncation radii are consistent with earlier theoretical considerations and fit in our current picture of jet formation.

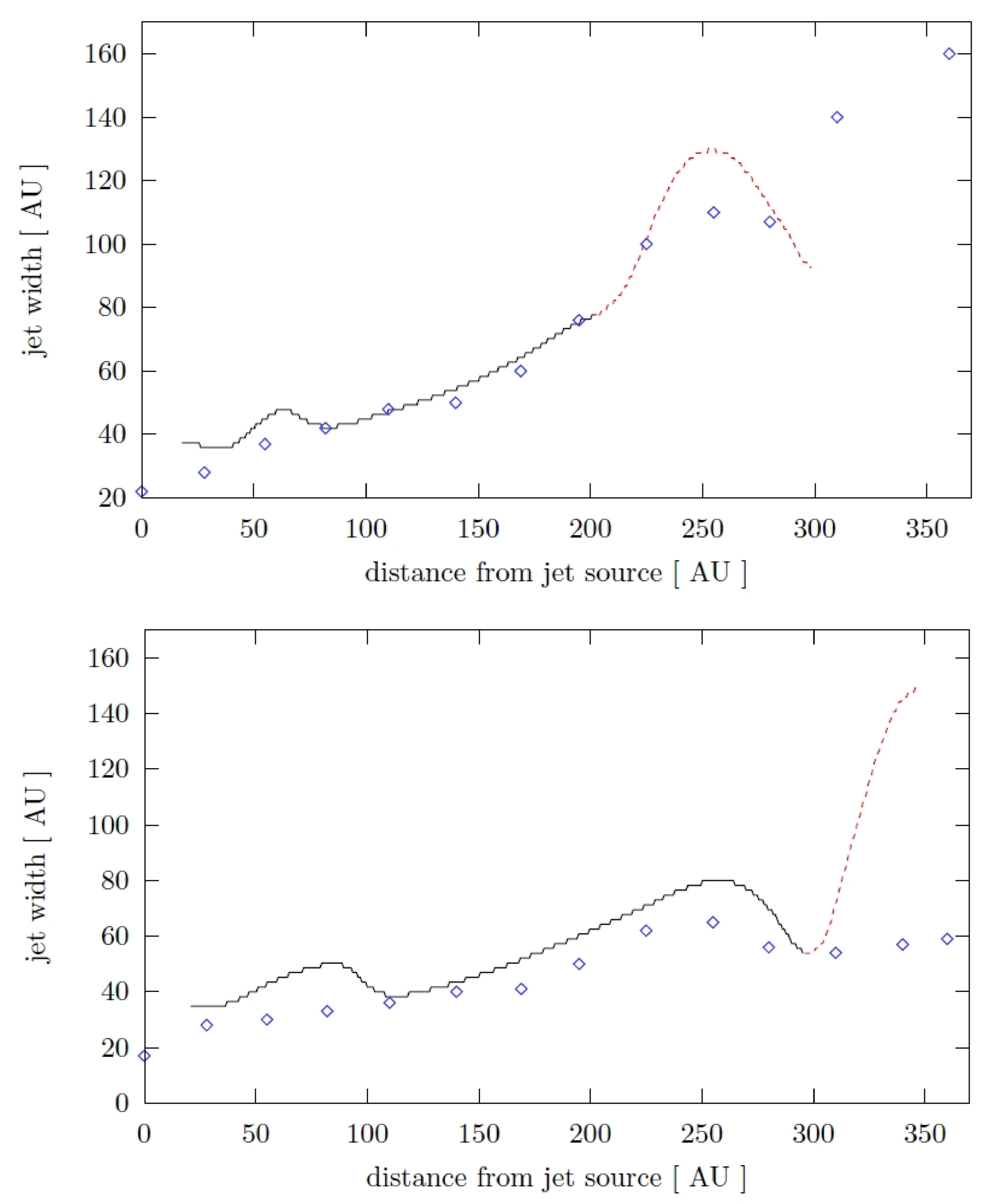

Figure 7: Jet widths in AU derived from our synthetic [OI] images as a function of distance from the source in our best-fit models of DG Tau and CW Tau. (Stute & Gracia 2012). The red part of the curve is unreliable due to the finite size of our computational domain.

source	$r_{\rm trunc}$ [AU]	$i_{\rm model}$ [°]
DG Tau	0.22	40
CW Tau	0.25	60
HN Tau	0.34	90?
UZ Tau E	0.26	90?