Physical information derived from the internal structure in jets

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Abstract. We present the first results on the analysis of the structures observed in the jet of the quasar 0836+710. We obtain the ridge lines of the jet at different epochs and several frequencies. We interpret the oscillatory structures obtained as waves that can be attached to the growth of instabilities. We explain how to derive information on the nature and origin of these structures by fitting together the ridge lines at different epochs and frequencies. Finally we show the predictive power of this approach: by generating an artificial wave and applying the corresponding relativistic and projection effects we show that apparent changes in the jet direction in the inner regions of jets can be attached to the transversal motion of structures.

1. Introduction

Understanding the nature of the structures and motions observed in jets is a crucial step in our knowledge of the physics of these objects. On parsec scales, this has become feasible only recently, using space VLBI (Very Long Baseline Interferometry) observations with the VSOP (VLBI Space Observatory Programme) (Lobanov & Zensus 2001). These observations revealed the presence of a double helical structure inside the jet of 3C 273, which can be attributed to a combination of the helical and elliptic modes of Kelvin-Helmholtz (KH) instability. Numerical simulations further support this interpretation (Perucho et al. 2006).

The luminous quasar S5 0836+710 at a redshift z = 2.16 hosts a powerful radio jet extending up to kiloparsec scales (Hummel et al. 1992). VLBI monitoring of the source (Otterbein et al. 1998) has yielded estimates of the bulk Lorentz factor $\gamma j = 12$ and the viewing angle $\theta j = 3^\circ$ of the flow. The presence of an instability developing in the jet is suggested by the kink structures observed on milliarsecond scales with ground VLBI (Krichbaum et al. 1990). Lobanov et al. (1998) observed the source at 5 GHz with VSOP and also reported oscillations of the ridge line. Identifying these structures with Kelvin-Helmholtz (KH) modes, they were able to derive the basic parameters of the flow. High dynamic range VSOP and VLBA (Very Long Baseline Array of National Radio Astronomy Observatory, USA) observations of 0836+710 at 1.6 GHz show the presence of an oscillation at a wavelength as long as $\sim 100$ mas (Lobanov et al. 2006), that cannot be readily reconciled with the jet parameters given in Lobanov et al. (1998). Perucho & Lobanov (2007) have shown that the presence of a shear layer allows
to fit all the observed wavelengths within a single set of parameters, assuming that they are produced due to KH instabilities growing in a cylindrical outflow. In this picture, the longest mode corresponds to a surface mode growing in the outer layers, whereas the shorter wavelengths are identified with body modes developing in the inner radii of the jet.

We report here on further progress of this investigation. We use different observations of the radio jet in the quasar S5 0836+710 with different VLBI networks (VSOP, global VLBI, VLBA and EVN) at several frequencies (1.6, 2, 5, 8, 15, 22 and 43 GHz) in order to obtain the ridge lines of the jet and compare their evolution in time at the different scales given by each frequency.

In Section 2. we present some of the ridge lines obtained from the different epochs and frequencies and explain the way in which the fits will be carried out. In this section we also show how this kind of functions can be used as a predictive tool for observations of sub-parsec scale jets. Finally, we present our conclusions in Section 3.

2. Ridge lines

The use of observations of the jet at different wavelengths and epochs is critical to our study. The different wavelengths can help to derive information on the different structures arising in different radial regions of the jet (Perucho & Lobanov 2007) and having different epochs can be useful for determining the motions of these ridge lines. We have thus used data from VLBA and VSOP at 1.6 and 5 GHz (Lobanov et al. 2006) at two different epochs, one epoch at 1.6 GHz from EVN (Perucho et al. in preparation), one epoch of simulataneous global VLBI (including VLBA) observations at 2 and 8 GHz (01/1997, Pushkarev & Kovalev, in preparation), and two epochs from VLBA at 8, 22 and 43 GHz (Perucho et al., in preparation). Finally, we have made use of 11 epochs between 1998 and 2007 from the 2 cm VLBA/MOJAVE database at 15 GHz.

At every observing frequency, different structure wavelengths are detected in the jet. When the different epochs are plotted together, a displacement of the ridge line is observed at all frequencies. Whether this displacement could be attached to experimental errors was tested by using a straight jet from the MOJAVE database. The results obtained showed that the differences observed between epochs in 0836+710 were much larger than the ones seen in the straight jet, which make us confident on the displacements being due to real or apparent motions.

Assuming thus that the observed differences between ridge line positions in time, for a given frequency, are due to motions of structures in the jet, and that these structures are due to pressure enhancements produced by any type of instability, we can try to fit them to a helix and derive its properties. The equations that determine the shape of helix in three dimensions, depending on the $z$ coordinate and time are $x(z, t) = A(z) \cos(2\pi (z + v_w t)/\lambda + \phi)$ and $y(z, t) = A(z) \sin(2\pi (z + v_w t)/\lambda + \phi)$, where $v_w$ is the wave speed, $\lambda$ is the wavelength, $\phi$ is the initial phase and $A(z)$ is the amplitude that depends on the growth rate of the instability $l_i$. The amplitude is fixed to 0 at origin, as the position of the wave does not change at the core: $A(z) = A_0 \exp(z/l_i) \sin(2\pi z/\lambda)$. The expressions given above for the $x$ and $y$ coordinates have to be corrected
for projection and relativistic effects and rotated in order to align it with the
direction of the observed jet. This depends on the viewing angle to the jet and
the position angle of the jet, which are known, but also on the wave speed.

The fits depend on five parameters: $A_0$, $l_i$, $\lambda$, $v_w$ and $\phi$, that will determine
the properties of the wave and can thus help in obtaining information about the
jet flow itself, via linear stability analysis of KH or current driven instabilities.
The different epochs are taken into account via the time parameter, so all epochs
are to be fitted at a time to a single moving structure.

At 43 GHz, we observe a lateral displacement of the ridge line, similar
to that reported by Agudo et al. (2007) and references therein for the jet in
NRAO 150. Using the equations given in the previous section as a model for a
short arbitrary mode with reasonable properties of a short body mode, we can
produce an artificial helix and use the time dependence to check its apparent
motion for an observer. The results, displayed in Fig. 1, show that the regular
wave motion of a pressure enhancement in a jet can result in an apparent
transversal motion of the jet itself if the observed region corresponds only to
this pressure maximum. This latter statement has to be considered in the frame
of the high frequency at which these motions are observed, which may result in
only a small part of the jet—that with the highest energies—being seen. The
superluminal nature of this transversal motions remains to be explained.

3. Summary

We are able to explain the structures observed in the jet at several frequencies
assuming that a shear layer exists between the jet and the ambient medium.
The observed structure of jets changes with frequency, but also do the hydro-
dynamics (Perucho et al. 2006; Perucho & Lobanov 2007). The fits to the ridge
line at different epochs and frequencies can give insight on the basic properties
of the instabilities, identify modes and provide better estimates of the physical
parameters of jets. At the same time this can help testing the KH and current
driven instability scenarios for the parsec and kiloparsec scales, depending on
the studied frequencies. We observe helical structures at all frequencies in the
jet in 0836+710. We claim that they cannot all be due to precession of the
same object. The periods for these waves range from several years to $10^7$ years.
The origin of these motions has to be addresses in the future and on the light
of the results of this work. The rotation of a structure, such as a wave pattern
produced by an instability can generate the observed radial motion of jets at
the highest frequencies. Superluminal velocities remain to be explained (from
observations or theory). High resolution observations like those planned in the
VSOP-2 project will be critical in this effort.

Acknowledgments. This work was supported in part by the Spanish Di-
recci´ on General de Ense˜ nanza Superior under grants AYA-2001-3490-C02 and
AYA2004-08067-C03-01. M.P. is supported by a postdoctoral fellowship of the
Generalitat Valenciana (Beca Postdoctoral d’Excellència). Y.K. is a research
fellow of the Alexander von Humboldt Foundation. This research has made
use of the data from the MOJAVE (Lister & Homan 2003) and 2cm Survey
(Kellermann et al. 2004) programs.
Figure 1. The top panel shows the ridge lines of the 43 GHz images in epoch 07/1998 (solid) and 11/1999 (dashed). The two bottom panels show the apparent motion of a short-wavelength structure ridge line seen at the same scales as the observations at this frequency. The dash-dot lines indicate possible real boundaries of the flow.

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