

Signatures of helical jets

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Abstract

Observational signatures of helical jets can be found in some X-ray binaries (XRB), planetary nebulae, Herbig-Haro objects and in jets of active galactic nuclei (AGN). For the prototypical XRB SS433 a kinematic model of precessing jets has been applied very successfully and yielded a determination of its distance which is independent of conventional methods. In galactic jets precession appears to be the predominant mechanism for the production of observed helical signatures. In extragalactic jets other mechanisms seem to be similarly frequent. As a result of their strong dependence on the direction of motion with respect to the observer, special relativistic effects can be pronounced in helical jets. These have to be taken into account in AGN-jets and the newly discovered galactic sources which show apparent superluminal motion. Since the galactic superluminal jets are located in a binary system, jet precession is very likely in these sources. In this paper I review the main structural and kinematic signatures of helical jets and briefly mention the physical mechanisms behind them. I will present kinematic simulations of relativistic jets which are helically bent or have an internal helical flow field.

1 Introduction

Extragalactic jets show signatures of helical structures on all observed scales, way down from the sub-parsec up to the kiloparsec scale [15, 32, 35]. Similarly, some stellar jets appear to vary their direction of propagation in regular patterns. Precessing stellar jets can be associated with Herbig-Haro objects [3, 28, 29, 30] or planetary nebulae [24]. However, the prototypical precessing jet is found in the X-ray binary SS433 [22, 25]. The recent discovery of highly relativistic stellar jets in XRBs [20, 26] with indications of wiggling ridge lines has raised hopes that these could reveal important parameters like distance and precession period of the binary as it was possible for SS433 [19]. Precessing jets have also been invoked as an explanation for the elusive phenomenon of Gamma Ray Bursters [12].

The term ‘helical jet’ is used to describe at least three different types of jet structures (Fig.1). First we have *ballistic helical jets* in which the individual fluid elements flow along straight lines, but with the direction of ejection changing periodically for different elements such that the instantaneous overall structure is helical. The second type is that of *helically bent jets* which are twisted as a whole. In this case all fluid elements flow along a common twisted path delineated by

the curved jet axis. The third category consists of jets with an *internally helical* structure, which are straight as a whole, but with the fluid flowing along helical trajectories within the jet. A further case could be considered in which two or three helically bent jet branches are braided along a common axis (NGC4258 [7], ESO428-G14 [11]). But we shall consider these as special cases of helically bent jets.

In this paper I describe the main structural and kinematic signatures of the three categories of helical jets mentioned above. I will sketch the structural, kinematic, and variability signatures and will briefly mention some of the underlying physical models and complications arising from coupling between different processes and relativistic effects.

2 General structural and kinematic signatures

One general characteristic of helical structures is that they are not symmetric with respect to the axis of the helix. The tangential vectors of the helix on one side are always pointing closer to the line of sight than on the other. The observed properties like flux, optical depth, polarization, and others are likely to be different, especially if the jet plasma is moving at relativistic speeds. Of these properties the most straightforward to observe is the brightness, which is enhanced due to the larger column on the side with the tangent more aligned with the line of sight. We might find discrete regularly spaced knots on one side and only weak filaments, if any, on the other side. In case of a helical internal structure the column density is the same on both sides, but relativistic motion may boost the brightness on one side. Three main types of observation can reveal signatures of helical jets:

- a) The projected *spatial structure* determined by imaging observations;
- b) the *motion (kinematics)* deduced from imaging or spectroscopy;
- c) the *variability* of the object.

Useful quantities which can be deduced from these observations are e.g. the variation of wavelength and amplitude of the oscillations, knot positions, transverse and radial motions, and brightness variations, and regular variations of the whole source brightness. For the discrimination between different possible models the variation of the regular quantities with distance from the central object may be useful [36].

Relativistic effects can distort the simple geometric features mainly in two ways. These are light travel-time effects (like apparent superluminal motion) and differential Doppler-boosting of the emission. Both of these effects are highly dependent on the direction of motion with respect to the line of sight. The Doppler-boosting basically increases the brightness contrast of the knots in a helix, although the effects can be more subtle, like the brightening of one side

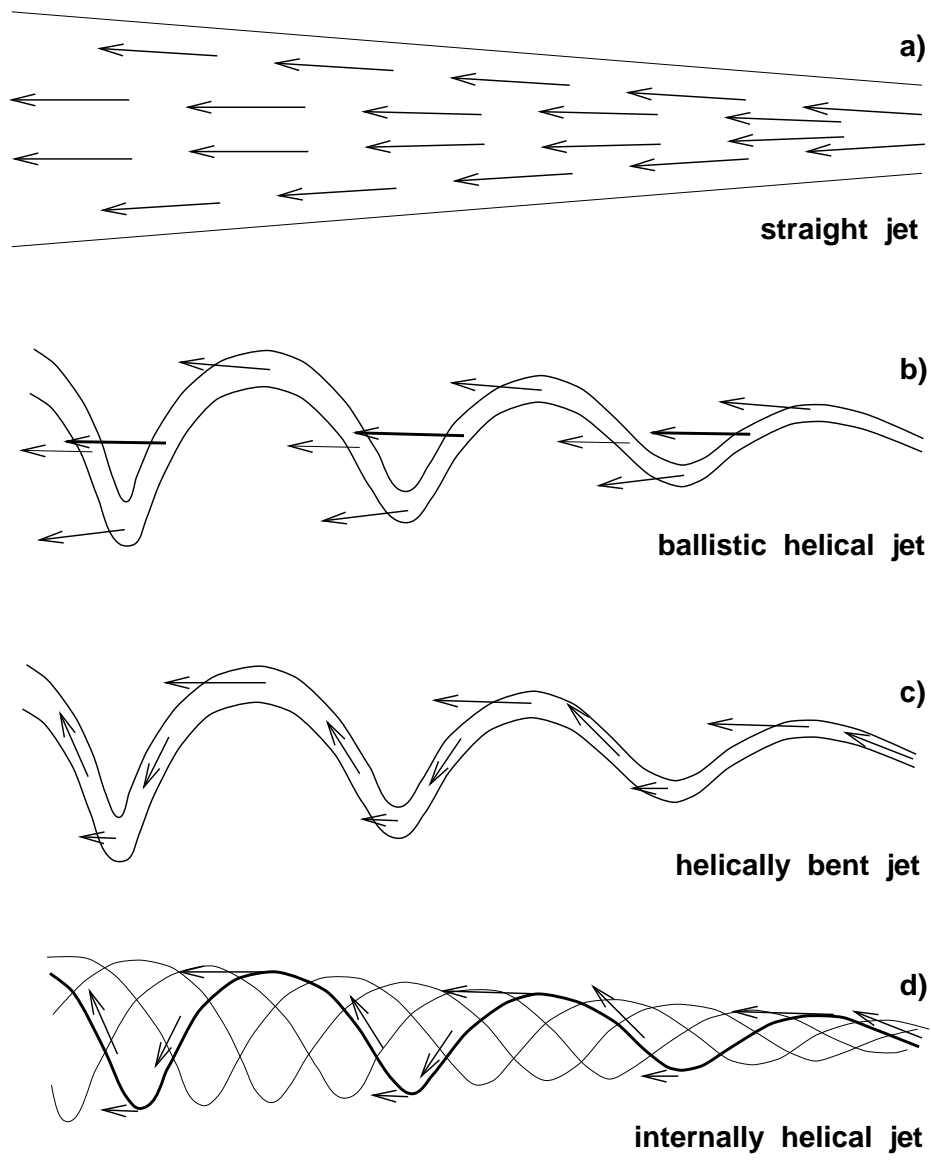


Figure 1: The proper motion vectors for a straight jet and different kinds of helical jets are shown schematically.

of a jet with an internal helical flow field (see Section 5).

In Figure 1 we summarize the observable structural and kinematic signatures in a schematic diagram. Figure 1a shows the case of conventional straight jet with the plasma moving on straight lines roughly parallel to the jet axis. There are no external or internal twisted structures nor bents, and the proper motion of all substructures has roughly the same magnitude and points to the same direction except for a possibly finite opening angle α .

The single most important parameter determining most of the kinematic properties of helical jets is the ratio η between the densities of the jet ρ_j and of the external medium ρ_x . “Heavy” jet elements with $\eta > 1$ propagate almost without resistance through the interstellar medium and are not deflected from a straight path in a homogeneous medium [28]. Observation of sinusoidal trajectories of *individual* knots is therefore a strong indication for a helically bent “light” jet with $\eta < 1$.

3 Ballistic helical jets

The case of a ballistic helical jet is illustrated in Figure 1b. This situation may exist for precessing high Mach number jets with densities higher than the environment or which are of lower density, but highly relativistic. Here the projected direction of ejection varies between two limits which define a certain opening angle of the precession cone ψ . This opening angle has to be distinguished from an intrinsic opening angle α which the jet itself may have.

This kind of jet is very much like the moving end of a water hose [28]: every drop of water moves independently and radially from the origin (if no gravity is present) at a velocity near the initial fluid velocity until it is stopped by the external medium far from the origin. Because of the opening angle the amplitude of the oscillating pattern increases with distance, but not the wavelength. The wavelength at best remains constant, but is more likely to decrease with distance, because the jet elements will slow down due to the interaction with the environment. Therefore, a constant or even decreasing wavelength combined with radially moving knots is a good indicator for a precessing jet.

The proper motion of the observed structures will be along straight lines radially away from the origin of the jet. If the initial ejection properties of the jet do not vary, the expansion speed at a given distance from the core will be roughly the same for all knots. However, because of the finite opening angle the projected proper motion near the axis of the precession cone may be noticeably different for the near and the far side. In Fig.1 this has been indicated by proper motion vectors of different lengths. The reverse is true for the velocity components along the line of sight, which may be determined from shifts of spectral lines in optical jets. Measurement of proper motions, line shifts, and opening angle of the precession cone allow to determine the true advance speed and distance to the source [37]. Cliffe et al.[9] have performed

3D hydrodynamical simulations of dense strongly precessing jets. Cox, Gull and Scheuer [10] have applied similar simulations with small precession angles to explain secondary hot spots in radio galaxies. Extensive kinematic modeling of extragalactic large-scale radio sources with precessing relativistic jets has been done by Gower et al.[15]. The possibly disruptive influence of dynamically important magnetic fields on ballistic precessing jets has been considered by Berry and Kahn [2].

If the precession angle is similar to the jet opening angle, coupling between the precession and another important process causing helical jet structures may occur, namely Kelvin-Helmholtz instabilities which can cause helical twisting of the jet with different characteristics of growth of amplitude and wavelength [16].

Physical reasons for jet precession may be the wobble of an accretion disk from which the jet is emerging due to its gravitational interaction with a secondary mass centre. The coupling between unaligned spin axes of the central and the accretion disk can also result in a precession of the jet. The Lense-Thirring effect, the interaction between unaligned axis of the orbit and the spin axis of the body with a jet, can be a reason for precession. If two jets are present this will result in a point symmetric structure of the twin-jets.

Orbital motion of the object with associated jets around a companion with orbit sizes considerably larger than the jet diameter will cause the position of the jet ejection in space to change in a circle or ellipse. The observed ridge line will then be similar to the case with precession: a wiggling line of emission along a cylinder without an appreciable opening angle, as opposed to the precessing jet, which will have a noticeable opening angle. The observed proper motion will be parallel to the axis of this cylinder and back-extrapolation will generally *not* line up with the source of the jet at its current position. In the case that two jets are present they will show mirror symmetry with respect to the orbital plane.

4 Helical bending

In the case discussed above the jet fluid does not flow along the observed jet structure but rather independently on straight trajectories into the environment. However, if the jet as a whole is helically bent, for whatever reason, and the fluid flows along the helix, then we encounter different phenomena. If traveling inhomogeneities are present, both direction and magnitude of their proper motion vary as they move along the bent trajectory (Fig.1c). Similarly, the radial velocity changes since the direction of the velocity vector varies. Note that the variations will be most pronounced on the side where the local jet axis points closest to the observer, where traveling and possible stationary components may merge [14]. An important observational signature of helical bending of the jet as a whole is that all internal structures move along the same path. This is

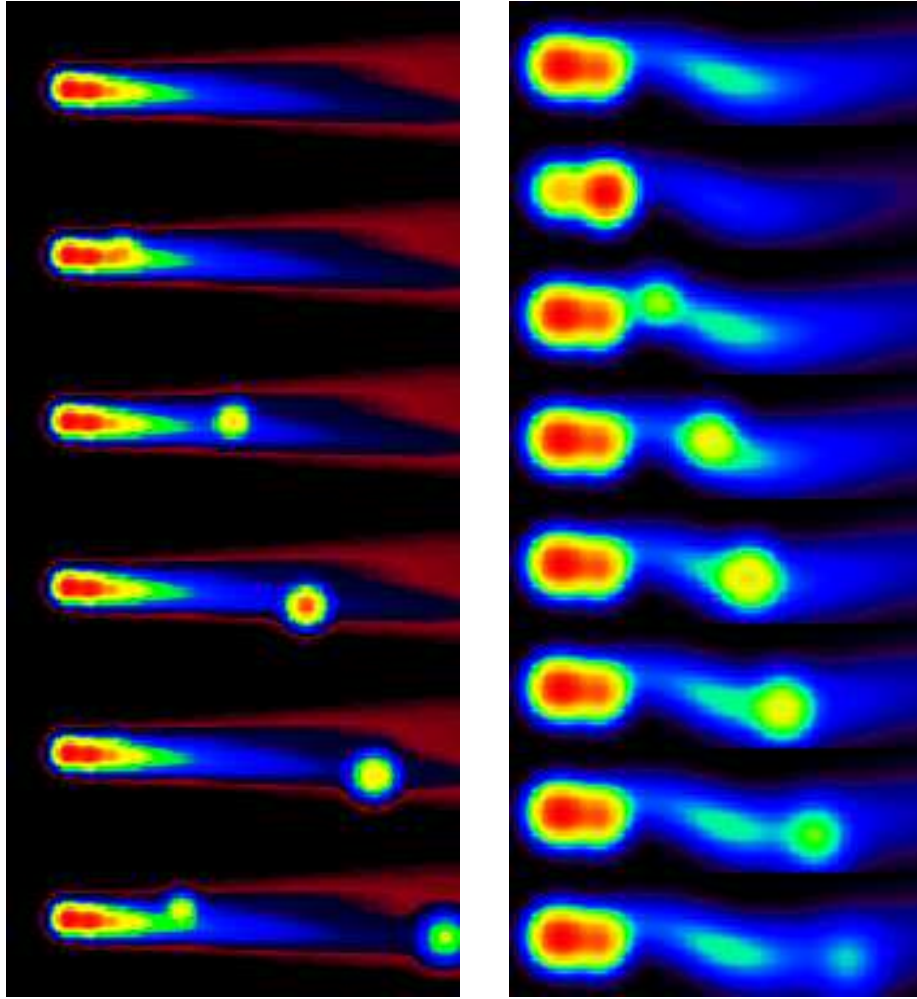


Figure 2: Time sequences of kinematic simulations of relativistic helical jets with constant opening angles are shown. The right side is a straight jet with a helical internal flow field. Note that the emission is Doppler-boosted on one side of the jet axis. On the right side a helically bent jet is shown with stationary components at the positions where the helix points are closest to the observer. In both simulations a plasma inhomogeneity propagates along a helical path through the jet, changing brightness due to expansion and differential Doppler effect. Both components move with varying apparent superluminal motion.

true as long as the helical pattern can be assumed stationary on the timescale in consideration. If the propagation of the overall helical pattern is noticeable, the path of consecutive internal features has to be consistent with the motion of the pattern.

The motion of the helical pattern should be radially outwards at roughly constant speed, similar to what is found in the precession case, the main difference being that the wavelength and amplitude may vary in a different manner. For dynamical reasons, the propagation speed of the helical pattern as a whole should be considerably smaller than the internal jet speed. If this is not the case, we are confronted with a transition case between the helically bent tube and the ballistic helical jet. This may occur for jets with densities similar to the external medium, whereas ballistic jets have higher effective densities and strongly helically bent jets are likely to be considerably “lighter” than the environment, except if magnetic confinement is very strong.

Jets can be bent by several mechanisms, like e.g. transverse winds, collisions with clouds, or density gradients. However, none of these processes provides a helical three-dimensional winding of the jet, but the bending takes place in a plane. Exceptions can occur in the case of multiple cloud collisions, which, however, will most likely show a random zick-zack course with probable jet destruction after a few interactions [18]. Random processes can produce quasi-regular patterns which can be confused with some characteristics of helical structures [31]. The precession of a “light” jet can also produce a helical jet with the plasma flowing along the curved jet. In this case it has to be taken into account that the densities which is relevant for the propagation of the jet upstream from the head of the jet are those of the and the cocoon cavity which is likely to be formed.

Instabilities of hydrodynamical or magneto-hydrodynamical nature are able to impose a helical deformation on the surface or the whole body of the jet. A large number of workers have modelled this behaviour in two and, more recently, in three dimensions using analytic calculations or numerical computer simulations [1, 8, 13, 16, 17].

In Fig.2 (right) a kinematic simulation shows a plasma inhomogeneity traveling at relativistic speed along a helically bent jet which itself is also relativistic. It is based on a kinematic model of the jet in the BL Lac object 1803+78 [34, 35, 36].

5 Internal helix

If the fluid inside the jet flows along twisted lines the observed phenomena may be considerably more complicated compared to the previous cases. A stationary uniform non-relativistic jet will look very much like a normal straight jet without internal structure. If the internal magnetic field in a radio jet is at least to some degree ordered and follows the helical structure, then using high dynamic

range radio polarization measurements a difference in the polarization properties might be found on both sides of the jet axis [14]. As a result of differential Doppler-boosting the side approaching the observer more than the other in a relativistic jet will appear slightly brighter than the other. The amount of asymmetry produced by this effect depends strongly on the Lorentz factor and the twist of the helix. In Fig. 2 (left) a kinematic simulation of this effect on the parsec scale of quasar jets is shown. The change in flux density along the jet axis is the result of adiabatic expansion of the jet [36, 35].

The paths of off-axis internal features propagating along different helical field lines will be different for consecutive features [35, 38]. Differential Doppler-boosting in a relativistic jet will cause the emission to vary in addition to intrinsic changes (Fig.2, left) [14, 27]. Very near the core of an active galactic nucleus this “lighthouse effect” may even cause quasi-periodic variations of the optical continuum emission [33]. Similarly, the proper motions of individual internal features vary along their path, since each field line is similar to a helically bent jet as discussed in Section 4.

Most theoretical scenarios for the formation of galactic and extragalactic jets focus on the symbiosis of a massive and compact object surrounded by an accretion disk and associated magnetic fields [4]. This seems to be the only viable mechanism known which can produce highly relativistic and well collimated jets. Internal helical features described above can be directly associated with this magnetic field line structure at the base of the jet in this model for the formation of jets [5, 35]. This mechanism, also known as the ‘sling-shot’ model, accelerates accretion disk gas along magnetic field lines which are anchored in the black hole and the disk. In this process a helical magnetic field and flow configuration is set up. In a perfectly cylindrical tube the helical motion of the jet gas could be maintained for a long time, but only a rather small opening angle of a few degrees, causes the helical trajectories to open fairly quickly due to angular momentum conservation [6, 35].

A different scenario is a force-free configuration of the plasma flow and the magnetic field as discussed by Königl and Choudhuri [23] where a helical mode can dominate the structure of the jet. Königl and Choudhuri make predictions of synchrotron emission and its polarization which can be compared with observations [21].

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