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Helical Motion and the Origin of QPO in Blazar-type Sources

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Abstract Recent observations and analysis of blazar sources provide strong evidence for (i) the presence of significant periodicities in their lightcurves and (ii) the occurrence of helical trajectories in their radio jets. In scenarios, where the periodicity is caused by differential Doppler boosting effects along a helical jet path, both of these facts may be naturally tied together. Here we discuss four possible driving mechanisms for the occurrence of helical trajectories: orbital motion in a binary system, Newtonian-driven jet precession, internal jet rotation and motion along a global helical magnetic field. We point out that for non-ballistic helical motion the observed period may appear strongly shortened due to classical travel time effects. Finally, the possible relevance of the above mentioned driving mechanisms is discussed for Mkn 501, OJ 287 and AO 0235+16.

Key words: galaxies: active — galaxies: jets — BL Lacertae objects: individual (OJ 287, Mkn 501, AO 0235+16)

1 INTRODUCTION

Collimated, highly relativistic outflows (jets) have been established for many Active Galactic Nuclei (AGN). Among these AGN, the blazar subclass describes those radio-loud objects whose often highly variable continuum is dominated by non-thermal processes and thought to be related to relativistically beamed emission from their inner jets viewed almost face-on. Variability analysis of the lightcurves from these sources has provided strong evidence for significant periodicities on a timescale of days to years: While several of the well-known TeV sources, e.g. Mkn 421, Mkn 501, 3C66A and PKS 2155-30, seem to reveal mid-term periodicity on a timescale of several tens of days in their optical, X-ray or TeV data (e.g., Hayashida et al. 1998; Lainela et al. 1999; Kranich et al. 2001; Osone et al. 2001), the optical lightcurves from classical sources such as BL Lac, ON 231, 3C273, OJ 287, PKS 0735+178, 3C345 and AO 0235+16 typically suggest longterm periodicity on a timescale of several years (e.g., Sillanpää et al. 1988; Webb et al. 1988; Liu et al. 1995; Fan et al. 1997, 1998; Valtaoja et al. 2000; Raiteri et al. 2001; Fan et al. 2001, 2002). Interestingly, high-resolution kinematic studies of parsec-scale radio jets have provided strong observational evidence for the helical motion of components, particularly in many of the above noted objects, e.g. in BL Lac, ON 231, 3C273, 3C345, OJ 287, PKS 0735+178 (e.g., Zensus et al. 1988; Steffen et al. 1995; Vicente et al. 1996; Tateyama et al. 1998;

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Gomez et al. 1999; Kellermann et al. 2004). It appears likely that some of the observed periodic variabilities may be associated with differential Doppler boosting due to the time-dependent change in viewing angle for motion along the helical path.

2 HELICAL MOTION AND THE POSSIBLE ORIGIN OF QPO

2.1 Differential Doppler boosting for helical motion

Consider an emitting component with spectral index α moving relativistically towards the observer. Doppler boosting effects are then known to lead to a modulation of the observed flux given by

$$S(\nu) = \delta^{3+\alpha}\, S'(\nu), \tag{1}$$

with S' the spectral flux density measured in the comoving frame and δ the Doppler factor given by

$$\delta(t) = \frac{1}{\gamma_b\,[1-\beta_b(t)\,\cos\,\theta(t)]}\,, \tag{2}$$

where $\theta(t)$ is the actual angle between the velocity $\boldsymbol{\beta}_b(t) = \dot{\boldsymbol{x}}_b(t)/c$ of the component and the direction of the observer, and $\gamma_b = 1/\sqrt{1-\beta_b(t)^2}$ the bulk Lorentz factor. A periodically changing viewing angle due to regular helical motion for example, may thus naturally lead to a periodicity in the observed lightcurves even for an intrinsically constant flux.

2.2 Shortening of observed period for non-ballistic helical motion

It can be shown (see Rieger 2004) that for non-ballistic (i.e. non-radial) helical motion the (real) physical period P appears generally shortened when measured by a distant observer. For blazar-type sources with typical inclination angles $i \sim 1/\gamma_b$ and bulk Lorentz factors $\gamma_b \simeq (5-15)$ the observed period is given by

$$P_{\rm obs} \simeq \frac{(1+z)}{\gamma_b^2}\,P\,. \tag{3}$$

This is based on the fact that observationally we measure the arrival times of pulses, e.g. emitted at A and B (see Fig. 1) where the velocity vector points closest towards the observer, whereas due to the relativistic motion of the emitting component at small inclinations the light travel distance for a pulse emitted at B is much smaller than the one for a pulse emitted at A.

2.3 Possible periodic driving processes and associated constraints

In general, a helical trajectory may arise due to several driving processes, including (1) orbital motion in a binary black hole system (BBHS), (2) Newtonian precession, (3) internal jet rotation or (4) global helical magnetic fields. Scenarios associated with (1) and (2) usually rely on the plausibility of close BBHSs in AGN. Today, BBHS are indeed expected to be present in the center of elliptical galaxies as a result of mergers between spiral galaxies, each containing its own BH (e.g., Begelman et al. 1980; Richstone et al. 1998). A multitude of observational evidence including misalignment, precession and wiggling of jets, long- and short-term periodicities and X-shape radio morphologies has been successfully interpreted within a binary framework, whereas more direct observational support has also been recently established for NGC 6240 (cf., Komossa 2003 for a review). Existing binary models aimed at explaining periodicity usually require very close BBHS with separation $\lesssim 10^{17}$ cm. Stability arguments (e.g., cosmological evolution, longterm periodicity) against loss of orbital angular momentum via gravitational radiation typically suggest (Keplerian) orbital periods P_k of the order of several years (or larger) and hence observable periods $P_{\rm obs} \gtrsim 10$ days (cf. Eq. 3) for *orbital-driven*

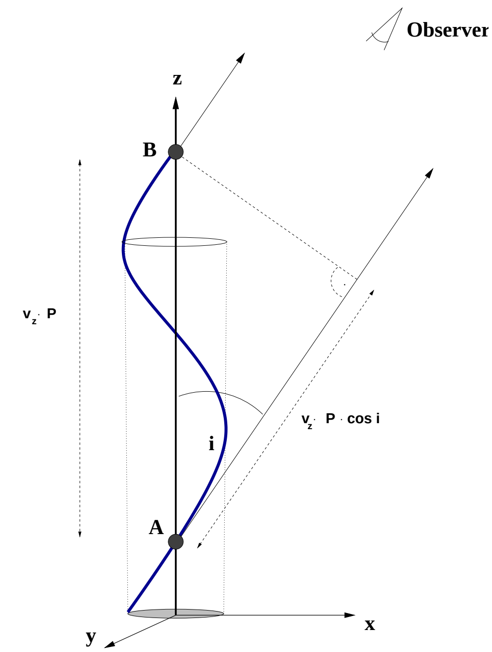

Fig. 1 For non-ballistic helical motion the physical period P appears shortened due to classical travel-time effects, i.e. we have $P_{\rm obs} \simeq (1 - [v_z/c]\,\cos i)\,P$.

helical motion (Rieger 2004). Periodicity may however also arise due to *Newtonian-driven jet precession:* Tidally induced perturbations in the accretion disk due to the influence of the binary companion for example, can lead to a rigid-body precession of the inner parts of the disk and thus translate into a precession of the jet (e.g., Katz 1997; Larwood, 1998; Romero et al. 2000, 2003). In general, the implied (physical) precessional periods P_p are usually a factor of order ten times larger than the orbital period P_k of the binary (Rieger 2004). Hence non-ballistic helical motion due to Newtonian jet precession is unlikely to be responsible for periodicity on a timescale $P_{\rm obs} \lesssim 100$ days (cf. Eq. 3), but may well be associated with periods $P_{\rm obs} \gtrsim 1$ yr. *Internal jet rotation* represents yet another possibility, provided components are dragged with the underlying rotating flow. The occurrence of such rotation (at least initially) appears well-supported: The strong correlation between the disk luminosity and bulk kinetic power in jets and the observational evidence for a jet-disk symbiosis (e.g., Rawlings & Saunders 1991; Falcke & Biermann 1995) for example, indicate that a significant amount of accretion energy, and hence rotational energy (cf. virial theorem), is channeled into the jet. Moreover, internal jet rotation is also implied in theoretical MHD models of jets as magnetized disk winds (e.g., Camenzind & Krockenberger 1992; Sauty et al. 2002) and supported by recent observations of stellar jets (e.g., Coffey et al. 2004). Knowledge of the underlying rotation law may then be used to estimate possible observable periods. It can be shown (Rieger 2004) for example, that for the elaborate lighthouse model of Camenzind & Krockenberger (1992) bounds on the maximum jet radius derived from numerical simulations translate into characteristic periods of $P_{\rm obs} \lesssim 10$ days (for massive quasars) and $P_{\rm obs} \sim 1$ day for typical BL Lac objects. Finally, periodicity may perhaps also be related to a component moving along a putative *global helical magnetic field*. Such a configuration may possibly be associated with certain types of MHD models (cf., Königl & Choudhuri 1985; Koide et al. 2002) and may observationally be suggested by rotation measure asymmetries across the jet in several sources (e.g., Asada et al. 2002; Gabuzda et al. 2004). However, to allow for significant Doppler boosting and modulation one then usually requires $B_z \gg B_\Phi$, i.e. small helix pitch angles ψ with $\psi \lesssim i$.

3 POSSIBLE APPLICATIONS AND RELEVANCE

3.1 Mkn 501

The nearby TeV blazar Mkn 501 ($z = 0.033$) attracted attention in 1997, when the source underwent a phase of high activity becoming the brightest source in the sky at TeV energies. Among the most interesting features during this high state are the (apparent) evidence for a periodicity on an observed timescale $P_{\rm obs} \simeq 23$ days, reported by several independent groups in both the TeV and X-ray range (e.g., Hayashida et al. 1998; Kranich et al. 2001). We have shown recently (cf., Rieger & Mannheim 2000, hereafter RM00; cf. also De Paolis et al. 2002) that such a periodicity may be caused by orbital-driven helical motion, i.e. the orbital motion of the relativistic jet emerging from the less massive BH (with mass m) in a close binary system with an orbital period of the order of several years, i.e. $P_k \simeq (6-14)$ yrs for $\gamma_b \simeq (10-15)$ (see Eq. 3). Information about the ratio f between the maximum and minimum amplitude (here $f \simeq 8$) and the relevant spectral index (here $\alpha \simeq 1.2$) may be used to derive an estimate for the center-of-mass distance R and the mass ratio of the binary (cf. Eq. 7 and 8 in RM00). One thus obtains $R \sim 10^{16}$ cm and

$$\left(\frac{M}{10^8\,{\rm M}_\odot}\right) \simeq 0.89\,\left(\frac{10}{\gamma_b}\right)\,\left(1+\frac{m}{M}\right)^2\,, \tag{4}$$

suggesting a possible total mass for the binary in the range $8.9\cdot 10^7\,M_\odot\,(\gamma_b/10) < (m+M) < 7.1\cdot 10^8\,M_\odot\,(\gamma_b/10)$, which seems well consistent with estimates derived from host galaxy observations (Rieger & Mannheim 2003a). As $P_{\rm obs}$ seems still relatively small, it may be interesting to investigate whether the observed periodicity may also be explainable in the lighthouse scenario proposed by Camenzind & Krockenberger (1992). Using f and α as given above, it can be shown (cf., Rieger & Mannheim 2003b) that one requires $r_0/r_{\rm L} \simeq 100$, with $r_L \simeq 10^{14}$ cm the light cylinder radius and r_0 the presumed radial scale where the component is injected. Consistency in the lighthouse approach generally suggests however that $r_0 \lesssim 10\,r_{\rm L}$ (cf., Camenzind 1996; Fendt 1997). It seems thus unlikely, that the observed periodicity in Mkn 501 is due to such a scenario.

3.2 OJ 287

The BL Lac object OJ 287 ($z = 0.306$) is famous for its optical long-term periodicity on a timescale $P_{\rm obs} \simeq 11.86$ yr (Sillanpää et al. 1988; Valtaoja et al. 2000). Several models have been proposed to explain the periodicity, with accretion disk interactions in a BBHS among the most prominent ones (e.g., Lehto & Valtonen 1996; Valtaoja et al. 2000; Liu & Wu 2002). Suppose for simplicity that the periodicity is caused by the secondary BH crossing the accretion disk around the primary BH on a non-coplanar, almost circular orbit. The physical orbital period is then of order $P_k = 2 \times 11.65/(1+z) \simeq 18.16$ yr. According to Vicente et al. (1996), the VLBI jet in OJ 287 reveals evidence for non-ballistic helical motion of components. For a typical bulk Lorentz factor for OJ 287 of $\gamma_b \sim 4.4$ in the radio regime (cf., Vicente et al. 1996; Hughes et al. 1998), orbital-driven helical motion results in an observable period (cf. Eq. 3) $P_{\rm obs,radio} \sim 1.25$ yr. Interestingly, a wavelet transform analysis of the UMRAO radio data for OJ 287 has revealed a period of 1.12 yr (in the observer frame) in the 1980s (Hughes et al. 1998). It seems thus very tempting to relate this periodicity to the orbital-driven, non-ballistic helical motion of a component dominating the emission. Further research appears important to assess the plausibility of such a scenario.

3.3 AO 0235+16

The low energy peaked BL Lac object AO 0235+16 ($z = 0.94$) is well known for its extreme variability at almost all wavelengths. Recently, the analysis of its long-term variability has provided evidence for a possible ~ 5.7 yr periodicity in its radio light curves and ~ 2.95 yr periodicity in its optical light curves (e.g., Raiteri et al. 2001; Fan et al. 2002). Romero, Fan & Nuza (2003) have shown that the optical periodicity (corresponding to $P_k \simeq 2 \times 2.95/[1+z] \simeq 3$ yr) might be related to the secondary crossing the accretion disk around the primary on a non-coplanar circular orbit, while the radio periodicity might be associated with Newtonian jet precession. As argued above, the ratio of the precessional to orbital period is usually expected to be of the order of ten or larger, i.e. $P_p \gtrsim 30$ yr. Eq. (3) then suggests that we require bulk Lorentz factors $\gamma_b \gtrsim 3$. Estimates derived from host galaxy observations of BL Lacs usually indicates central masses in the range $6 \cdot 10^7\, M_\odot \lesssim (M+m) \lesssim 10^9\, M_\odot$ (e.g., Wu et al. 2002; Falomo et al. 2003), thus suggesting a binary separation for AO 0235+16 likely to be in the range $10^{16}\,\mathrm{cm} \lesssim d \lesssim 3 \cdot 10^{16}\,\mathrm{cm}$.

4 CONCLUSIONS

In this contribution we have shown that periodicity in blazar-type sources may arise simply due to differential Doppler boosting effects along a helical path inclined at small viewing angle. Accordingly, the observation of non-ballistic helical motions in radio jets and the detection of periodicities on timescales of several years or less (in the frequency-domain where the observed emission is dominated by the jet) may mutually support each other. As different driving mechanisms are usually associated with different driving periods, the observed timescale of periodicity may be used to single out the most likely underlying driving mechanism, thus allowing to draw valuable conclusions on the nature of the central engine.

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