Periodic variability and binary black hole systems in blazars

Frank M. Rieger

Department of Mathematical Physics, University College Dublin, Belfield, Dublin 4, Ireland

Abstract. We consider the periodic modulation of emission from jets in blazar-type sources. A differential Doppler boosting origin, associated with the helical motion of a radiating component, is analyzed for different periodic driving sources including orbital motion and jet precession in a binary black hole system (BBHS). We emphasize that for non-ballistic helical motion classical travel time effects can lead to strong shortening effects, such that the observed period may be a factor $\gamma^2$ smaller than the underlying driving period, where $\gamma_b$ denotes the bulk Lorentz factor of the jet flow. The relevance of the above noted scenarios is discussed for the BL Lac object AO 0235+16.

INTRODUCTION

Periodic variability has now been detected in the lightcurves of a significant number of blazar sources, albeit often on different timescales: While some of the well-known TeV blazars such as Mkn 421, Mkn 501, 3C66A and PKS 2155-304 apparently reveal evidence for mid-term periodicity with timescales of several tens of days ([18, 22, 23, 26]) in their optical, X-ray and/or TeV lightcurves, the optical lightcurves from the more classical sources, e.g. BL Lac, ON 231, 3C273, 3C345, OJ 287 or AO 0235+16 ([10, 11, 12, 25, 30, 40, 43]), usually suggest periods of the order of several years. It seems quite interesting that in many AGN the high-resolution kinematic studies of their parsec-scale radio jets, particularly in several of the above noted classical objects, provide strong observational evidence for the helical motion of components ([16, 20, 41, 42, 46]). This suggests that some of the observed periodic variabilities may arise as a result of differential Doppler boosting associated with a time-dependent, periodically changing viewing angle due to motion along a helical jet trajectory ([33, 7, 35, 36]).

PERIODIC MODULATION OF EMISSION

For an emitting element moving relativistically towards a distant observer, Doppler boosting effects are known to lead to a modulation of the observed flux given by

$$S_\nu(t) = \delta(t)^n S'_\nu,$$

where $S'_\nu$ is the spectral flux density measured in the comoving frame, $n = 3 + \alpha$ for a resolved blob of plasma with spectral index $\alpha$, and where $\delta(t)$ is the Doppler factor depending on the actual (i.e. time-dependent) angle between the velocity of the element
and the direction of the observer. Obviously, a periodically changing viewing angle due to regular helical motion should naturally lead to a periodicity in the observed lightcurves even for an intrinsically constant flux. It is straightforward to show ([35, 36]) that in the case of non-ballistic (i.e. non-radial) helical motion any underlying physical driving period $P$ will appear shortened when measured by a distant observer as a consequence of classical travel time effects. For a relativistic outflow velocity $v_z$ along the $z$-axis and an inclination angle $i$ between the $z$-axis and the direction of the observer one finds

$$P_{\text{obs}} \simeq (1 + z) \left[1 - \frac{v_z}{c} \cos i\right] P,$$

where $P_{\text{obs}}$ denotes the observed period and $z$ is the redshift of the source. It is obvious that for a sufficiently high $v_z$ and small inclination angles $i$, the observed periods can be much smaller than the physical driving period, cf. Fig. 1. Moreover, for a typical blazar source with inclination angle $i \approx 1/\gamma_b$ and bulk Lorentz factor $\gamma_b \approx (5 - 15)$, Eq. (2) simplifies to

$$P_{\text{obs}} \simeq \frac{(1 + z)}{\gamma_b^2} P.$$

### POSSIBLE PERIODIC DRIVING MECHANISMS

The formation of helical jet trajectories can be related to several periodic driving mechanisms, such as (i) the orbital motion in a binary black hole system (BBHS), (ii) Newtonian jet precession caused by the binary companion, or (iii) an intrinsically rotating jet flow. Models associated with (i) and (ii) are based on the plausibility of close BBHSs in the centres of AGN, an assumption supported by several lines of arguments: Hierarchical
galaxy evolution schemes, for example, suggest that BBHS may be present in the center of elliptical galaxies as a result of mergers between spiral galaxies, each containing its own BH (e.g., [2, 17, 32]). Moreover, a multitude of observational evidence including the misalignment, precession and wiggling of extragalactic radio jets, the helical motion of radio components, and the long- and mid-term periodicities in the optical, X-ray or TeV lightcurves has indeed been successfully interpreted within a binary black hole framework. Finally, the binary concept has recently gained strong observational support by the Chandra discovery of two active nuclei in the merging galaxy NGC 6240 (cf., [21] for a review).

Existing binary models aimed at explaining periodicity usually require very close systems with binary separation of the order of $10^{17}$ cm or less. Stability arguments against a rapid loss of orbital angular momentum via gravitational radiation, based on general considerations of the cosmological evolution or longterm periodicity, then typically suggest (Keplerian) orbital periods $P_k$ of the order of several years (or larger), implying observable periods $P_{\text{obs}} > 10$ days (cf. Eq. 3) in the case (i) of orbital-driven (non-ballistic) helical motion ([35]). In the case (ii) of Newtonian jet precession the corresponding periods will be much larger. Newtonian precession may arise due to tidally induced perturbations in the accretion disk of the jet-emitting primary source caused by the binary companion. Under favourable conditions these perturbations can lead to a rigid-body precession of the inner parts of the disk and thus translate into a precession of the jet ([19, 24, 37, 38]). The implied physical precessional driving period $P_p$ is usually a factor ten (or more) larger than the orbital period $P_k$ of the binary (cf. [35]), suggesting that non-ballistic helical motion due to Newtonian jet precession is unlikely to be responsible for periodicity on a observed timescale of less than one hundred days, but may well be associated with observed periods $P_{\text{obs}} \gtrsim 1$ yr.

In general, the helical motion of components does not necessarily require a BBHS. An intrinsically rotating jet (case (iii)) for example, may also mimic some of the observational signatures, provided components are dragged with the underlying rotating flow. The occurrence of such an internal jet rotation (at least initially) appears not unlikely: The strong correlation between the disk luminosity and bulk kinetic power in jets and the phenomenological evidence for a jet-disk symbiosis (e.g., [8, 31]) for example, suggests that a significant amount of accretion energy, and hence rotational energy is channeled into the jet. Moreover, internal jet rotation is a natural consequence if jets are formed as magnetized disk winds (e.g., [4]). Information about the underlying rotation profile may then be used to derive possible observable periods. It can be shown ([35, 36]) for example, that for the lighthouse model of Camenzind & Krockenberger (1992) bounds on the maximum jet radius derived from numerical simulations translate into characteristic periods of $P_{\text{obs}} \lesssim 10$ days (for massive quasars) and $P_{\text{obs}} \sim 1$ day for typical BL Lac objects.

**APPLICATION TO AO 0235+16**

The BL Lac object AO 0235+16 (PKS 0235+164) at redshift $z = 0.94$ is well-known for its extreme variability at almost all wavelengths. Observations of its radio struc-
ture at ground-based (e.g., [5, 6]) and space ([14]) VLBI resolutions have shown that AO 0235+16 is very compact on submilliarcsecond angular scales, and provided evidence for a very high brightness temperature in excess of $5.8 \cdot 10^{15}$ K and high apparent superluminal motion up to $(27 \pm 6) c$, indicating very small viewing angles and large Doppler factors (cf. also [15]). There are some indications that the radio outbursts are associated with the formation of new VLBI components ([1, 6]. Based on the variation in the position angle of the radio jet, Zhang et al. ([47]) have suggested that the jet may be rotating and the central engine precessing (cf. also [5]). A rough order-of-magnitude estimate for the physical parameters in the emitting region may be obtained by fitting the multiwavelength SED with a homogeneous, one-zone synchrotron - inverse Compton model, suggesting viewing angles $\sim 2.9^\circ$, magnetic field strengths $\sim 3.8$ Gauss and bulk Lorentz factors $\sim 16$ for the low state ([28]).

The analysis of the long-term variability in AO 0235+16 over a time range of $\sim 25$ yr has revealed evidence for a $(5.7 \pm 0.5)$ yr periodicity in its radio lightcurves and a possible $(2.95 \pm 0.15)$ yr periodicity in its optical lightcurves, e.g. [12, 30, 35, 44]. Two scenarios have been proposed recently in order to account for these findings, both assuming the presence of a close BBHS:

1. Romero, Fan & Nuza (2003) have argued that AO 0235+16 may harbour a BBHS with the optical periodicity being related to the companion crossing the accretion disk around the jet-emitting black hole on a non-coplanar circular orbit (hence implying an orbital period of $P_k \simeq 2 \times 2.95/[1 + z] \sim 3$ yr) and the radio periodicity being related to Newtonian jet precession.

2. Ostorero, Villata & Raiteri (2004) on the other hand, have argued that both, the radio and optical periodicity (assuming the optical period to be the same as the radio!) may be associated with a helically bent, steadily emitting inhomogeneous jet, driven by the orbital motion in a close BBHS.

If scenario (1) is indeed realized, the fluid motion must be non-ballistic as otherwise the precessional period would be too short to be generated via tidally induced perturbations. As pointed out above, the ratio of precessional to orbital period is usually of the order of ten or larger, i.e. one has $P_p \gtrsim 30$ yr. Provided the jet is not strongly inhomogeneous and the cone opening angle sufficiently small, this period will appear shortened when measured by a distant observer following Eq. (3), thus indicating that one requires bulk flow Lorentz factors $\gamma_b \gtrsim 3.2$. On the other hand, for bulk Lorentz factors of the order $\sim 10$, as suggested from the studies above, the precessional driving period would be $P_p \sim 300$ yr. The projected wavelength of the associated helical trajectory $\lambda \simeq P_p c / \gamma_b$ should then be of order 3 parsec (for $P_p \simeq 30$ yr) and 9 parsec (for $P_p \simeq 300$ yr), or 0.36 mas and 1.1 mas, respectively (assuming $q_0 = 0$ and $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$), and thus likely to be accessible for high-resolution VLBI observations. On the basis of scenario (1) it may also be useful to search for signs of quasi-periodic variability on the timescale of several months or less in the high energy range. For apart from a periodic modulation due to precession, one may also expect the orbital motion of the binary to lead to some quasi-periodic modulation, at least from the initial parts of the jet where its width is still smaller than the separation of the binary. For a Keplerian period $P_k \simeq 3$ yr, possible observable variability timescales range from $\sim 7$ months (for $\gamma_b \sim 3$) to $\sim 20$
days (for $\gamma_b \sim 10$) or perhaps even less.

Note that central BH masses for BL Lac objects, estimated from observations of their host galaxies, usually fall within a mass range $6 \cdot 10^7 M_\odot \lesssim (M + m) \lesssim 10^9 M_\odot$ (e.g., [45]), a range consistent with constraints derived for AO 0235+16, thus suggesting a binary separation of $d \lesssim 3 \cdot 10^{16}$ cm.

The situation may however be quite different if a scenario following (2) is correct. At first glance such a scenario seems to be associated with the requirement that the observed timescale for the optical periodicity coincides with the one for the radio periodicity, and may thus appear less plausible if the difference suggested above is indeed confirmed by further observation and analysis. It is likely however, that the real case is much more complex: For a helically bent, steadily emitting inhomogeneous jet driven by the orbital motion, high energy observations probing the smallest scales are expected to provide the most useful tracers of the underlying Keplerian period. At radio energies, the corresponding jet flow will repeatedly approach the line-of-sight along its helical path, leading to a maximization of beaming effects (and thus offering a possible interpretation for the detected radio knots). Unless the radio jet is very inhomogeneous, the physical orbital period in the radio band will thus appear strongly shortened when measured by a distant observer as shown above, i.e. the real Keplerian period of the binary may be much larger than the observed radio period, an effect not considered by Ostorero et al. (2004).

For an observed radio period of 5.7 yr, for example, the real Keplerian period may be in the range between $P_k \simeq 26$ yr (for $\gamma_b = 3$) and $P \sim 300$ yr (for $\gamma_b = 10$), implying a binary separation of $d \gtrsim 2 \cdot 10^{17}$ cm assuming the mass range given above. The observed radio lightcurves may then be characterized by pronounced peaks separated by $(1 + z) P_k$, with intermediate peaks occurring on a timescale of 5.7 yr.

**CONCLUSION**

There is mounting evidence that the mid- and long-term periodicity observed in blazar-type sources is related to the presence of close BBHSs in their centres. Here we have shown that the observed timescales of periodicity may carry valuable information about their physical nature. Continuous observations in different energy ranges, a thorough periodicity analysis of their lightcurves and detailed theoretical modelling will allow to shed more light on their histories and properties.

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