Periodic Variability and Close Supermassive Binary Black Hole Systems

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We review the origin of periodic variability with observed periods $P_{\rm obs} \gtrsim 10$ days in jet-emitting supermassive binary black hole systems under conditions appropriate for radio-loud blazar sources. Particular attendance is given to a differential Doppler boosting origin along helical jet paths driven by the orbital motion or jet precession. It is shown, for example, that for non-ballistic helical motion travel time effects can lead to strong shortening effects, such that the observable period may be up to a factor γ_b^2 smaller than the real physical driving period. If the optical periodicity on the timescale of several years is related to accretion disk interactions, the observed optical period might be used as an approximate guide to the real orbital period of the binary. We analyze the potential of such a binary framework for the coherent explanation of periodicities on different timescales. Finally, a detailed discussion of models for the origin of the radio and optical periodicity in AO 0235+16 is presented.

1. Introduction

Evidence for mid- and long-term periodicity has now been found in a significant number of blazar sources (cf. **Tab. I**). The analysis of the optical, X-ray and/or TeV lightcurves in well-known γ-ray sources such as Mkn 421, Mkn 501 and PKS 2155-304, for example, indicates periodic variability with periods of several tens of days [25, 33, 34, 43]. On the other hand, the long-term optical lightcurves from the more classical sources such as BL Lac, ON 231, 3C 273, 3C 345, OJ 287 or AO 0235+16 [15, 17, 18, 37, 47, 58, 64] usually suggest periods of the order of several years. It seems very intriguing that in many Active Galactic Nuclei (AGN), particularly in several of the above noted classical objects, the high-resolution kinematic studies of their pc-scale radio jets also provide strong observational evidence for the helical motion of components [20, 30, 59, 62, 68]. This suggests that at least some of the observed periodicities may arise due to differential Doppler boosting effects associated with the time-dependent, periodically changing viewing angle for motion along a helical jet trajectory [11, 49, 51, 52]. Note that in such a case, the evidence for periodicity and the evidence for helical jet paths may provide mutual support for each other.

Regular helical jet paths (whether they are caused, for example, by the orbital motion, jet precession, Kelvin-Helmholtz fluid instabilities or anisotropic radiation drag effects, e.g., [24, 39, 51]), are most likely driven by a central supermassive binary black hole system (SBBHS). Today, there is indeed strong theoretical and observational evidence for the presence of SBBHSs in the centers of AGNs. According to hierarchical galaxy evolution models, for example, the formation of SBBHSs should be a common phenomenon in the Universe as a result of merging events [5, 22, 23, 63]. In particular, giant elliptical galaxies, i.e., the typical hosts of radio-loud AGNs, are thought to be the products of mergers between spiral galaxies (cf. [4]). Since the brightest galaxies generally seem to contain supermassive black holes (BHs) in their nuclei (cf. [19] for a recent review), merging should thus naturally lead to the formation of SBBHSs. This SBBHS concept has recently gained strong observational support by the Chandra discovery of two activity centers (with a separation of ~ 1 kpc !) in the merging galaxy NGC 6240 [32]. If a SBBHS forms during the close encounter of two galaxies, dynamical friction and slingshot interactions with stars will normally ensure that the system quickly evolves to a close binary system [5]. It is still a controversial issue today however, whether a substantial fraction of SBBHSs can really coalesce within a Hubble time, e.g., [5, 8, 21, 26, 41, 46, 56, 67]. The main problem is to overcome the "bottleneck" ('loss cone depletion') of losing sufficient angular momentum after the initial rapid approach due to dynamical friction and before gravitational radiation becomes sufficiently dominant to drive the binary to coalescence very rapidly. If the binary evolution stalls above the separation at which the timescale for angular momentum losses due to emission of gravitational radiation becomes sufficiently small, the binary will spend nearly all of its time at a separation $d \sim (0.05 - 1)$ pc for BH masses of the order of $10^8\,M_\odot$. Hence, while it seems clear that close SBBHSs will form fairly quick, it is unclear whether such systems will eventually coalesce within a Hubble time. Note that the origin of X-shaped radio morphologies in some radio galaxies has been recently interpreted as due to a sudden spin flip when two BHs coalesce, thus possibly providing some circumstantial evidence that at least some of the SBBHSs may indeed have coalesced, e.g., [6, 36, 40]. However, more work is clearly required to test that in more detail.

From a more phenomenological point of view, several observational findings have been related to the presence of close [$d \lesssim 0(1)$ pc] SBBHSs in the centers of AGNs, including the observed misalignment, precession and wiggling of extragalactic jets [9, 10, 28], the apparent helical trajectories of knots [2, 7, 0] and periodic variability [11, 49, 51, 52]. Note that it is still quite controversial whether 3C66B indeed harbours a very short-living SBBHS, cf. [12, 27, 60]. Modelling of the above noted phenomena can provide important observational constraints on the evolutionary path of close SBBHSs and fundamental insights into the nature of the central engine in AGNs. In the present paper we will consider the implications derived from the analysis of low-frequency ($f < 10^{-6}$ Hz) quasi-periodic variabilities for SBBHSs in blazar sources.

2. POSSIBLE SBBHS ORIGINS OF PERIODICITY

2.1. Disk origin

Interactions of the companion with the accretion disk around the primary BH in a close SBBHS can provide a natural explanation for the longterm (optical) periodicity with timescales of several years as observed in a number of blazar sources. The BL Lac object OJ 287 ($z = 0.306$), famous for its optical longterm periodicity with period $P_{\rm obs} \simeq 11.86$ yr [31, 58, 61], may still be considered as the paradigmatic object for such an explanation [35, 38, 61]. It seems likely that the combined effects of dynamical friction, accretion disk interactions and emission of gravitational radiation usually tend to produce binary orbits that are characterized by rather small eccentricities. Suppose thus for simplicity that the periodicity is caused by the secondary BH crossing the accretion disk around the primary BH on a sligthly non-coplanar, almost circular orbit, cf. [52]. The Keplerian orbital period would then be of order

$$P_k \simeq \frac{2}{(1+z)}\, P_{\rm obs}\,, \qquad (1)$$

i.e., $P_k \simeq 18.16$ yr in the case of OJ 287. While the real situation is expected to be much more complex, Eq. (1) may still be used as an approximate guide (upper limit) for the real orbital periods of SBBHSs in blazars.

2.2. Jet origin

The observations of helical jet paths suggest that quasi-periodic variability may also arise due to differential Doppler boosting effects [11, 49, 51]. For an emitting element moving relativistically towards a distant observer for example, the modulation of the observed flux given by $S_\nu(t) = \delta(t)^n\, S'_\nu$, where S'_ν is the spectral flux density measured in the commoving frame, $\delta(t)$ is the time-dependent Doppler factor depending on the actual angle between the velocity vector of the element and the direction of the observer, and where $n = 3 + \alpha$ for a resolved blob of plasma with spectral index α. It seems obvious that a periodically changing viewing angle due to regular helical motion will thus naturally lead to a periodicity in the observed lightcurves even for an intrinsically constant flux density.

Let P be the real physical period (measured in the frame of the source) for the mechanism driving the helical jet path. It can then be easily shown [51, 52] that for non-ballistic helical motion P appears 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 obtains

$$P_{\rm obs} \simeq (1+z)\, \left[1 - \frac{v_z}{c}\, \cos i\right]\, P\,, \qquad (2)$$

where $P_{\rm obs}$ denotes the observed period and z is the redshift of the source. Clearly, if v_z is sufficiently high and i sufficiently small, the observed periods can be much smaller than the physical driving period, cf. **Fig. 1**. Blazar jets are generally thought to be orientated at small viewing angles, i.e., $i \simeq 1/\gamma_b$ with typical bulk Lorentz factor $\gamma_b \simeq (5 - 15)$, in which case Eq. (2) results in

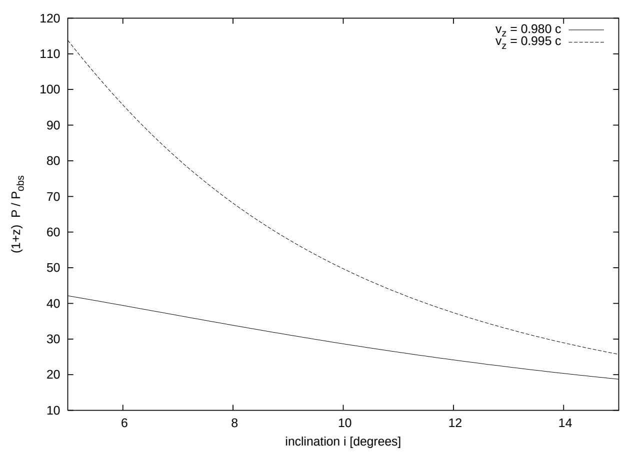

Figure 1: The ratio of real physical driving period P to observed period $P_{\rm obs}$ as a function of the inclination angle i for two different outflow velocities v_z, corresponding to bulk Lorentz factors $\gamma_b \simeq 5$ and 10, respectively.

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

While different mechanisms are conceivable, the orbital motion of the jet-emitting BH and the (Newtonian) precession of the jet represent the most obvious driving sources for helical jet paths, cf. [29, 49, 51, 54].

In the first case we may use $P = P_k$ as derived in Eq. (1) to estimate the expected periodicity from Eq. (3). Newtonian precession, on the other hand, is usually much slower, being characterized by a driving period P_p which is at least an order of magnitude higher than the orbital period P_k [51].

3. IMPLICATIONS

3.1. General

In **Tab. I** we have collected mid- and long-term periodicities in blazar sources as reported in the literature. It goes without saying that not all of these periods are equally significant and that some may even be spurious and an artefact of unevenly or limited sampled data sets afflicted by a poor number of measurement points, the short time coverage of the observing campaigns or perhaps inaccurate analysis methods. Nevertheless, there seems to be an overall trend for an observed optical long-term periodicity of order $(5 - 10)$ yrs and for a radio long-term periodicity on a timescale usually different from and smaller than the optical one. Moreover, it appears that during brighter states some sources reveal mid-term periodicity on timescales of the order of several tens of days in the higher energy (optical, X-ray, γ-ray) bands. It is suggested here that these phenomena may generally be linked with each other and may be successfully interpretable in a SBBHS framework. Such a binary explanation for periodic variability is, of course, not necessarily unique as other origins are conceivable as well. However, at present the binary interpretation seems explanatory much more powerful than many competing hypotheses by offering, for example, an explanation for the origin of helical jet paths and a crucial link between different periodicities:

Suppose, for example, that the optical long-term periodicity is related to accretion disk interactions such that Eq. (1), i.e., $P_k \simeq 2P_{\rm obs}^{\rm opt}/(1+z)$ applies. Mass estimates derived from host galaxy observations of BL Lacs usually indicate central masses in the range $6 \cdot 10^7\, M_\odot \stackrel{<}{\sim} (M+m) \stackrel{<}{\sim} 10^9\, M_\odot$ [13, 66]. This suggests that BL Lacs may harbour very close SBBHSs with typical separations $d \stackrel{<}{\sim} 0.03$ pc and gravitational lifetimes

$$\tau_{\rm grav} \stackrel{>}{\sim} 10^6\, \frac{d_{16}^4}{(m_8+M_8)^3}\ {\rm yr}\ \stackrel{>}{\sim} 10^7\ {\rm yr}\,, \tag{4}$$

where d_{16} and m_8, M_8 have been expressed in units of 10^{16} cm and $10^8\, M_\odot$, respectively.

One usually expects that the main part of radio jet emission originates from larger scales, i.e., from scales where the jet motion in a SBBHS may perhaps already be dominated by Newtonian precession. The precessional period due to Newtonian perturbation effects is likely to be (at least) an order of magnitude higher than the orbital period, i.e., $P_p \stackrel{>}{\sim} 10\, P_k$ [51]. Hence, if the radio periodicity is indeed dominated by differential Doppler boosting effects at larger scales, the observable radio period would be given by (cf. Eq. 3)

$$P_{\rm obs}^{\rm radio} \stackrel{>}{\sim} 20\, \frac{P_{\rm obs}^{\rm opt}}{\gamma_b^2}\,, \tag{5}$$

suggesting that moderate bulk Lorentz factors may be sufficient to account for observable radio periods smaller than those measured in the optical.

It appears very likely, on the other hand, that during a bright source state the observed high energy flux is dominated by a single component moving outwards along the jet [49, 51]. In that case the high energy flux variations may very well be related to differential Doppler boosting effects along a helical jet trajectory initially dominated by the orbital motion of the binary. Eq. (3) then suggests observable periods

$$P_{\rm obs} \sim 30\, \left(\frac{P_{\rm obs}^{\rm opt}}{10\,{\rm yr}}\right) \left(\frac{15}{\gamma_b}\right)^2\ {\rm d}\,, \tag{6}$$

i.e., we may easily obtain mid-term periodicities on timescales of several tens of days.

The scenario considered above clearly amounts to the simplest physical situation. In reality it appears likely that we have contributions from different components and/or superposition effects of different periodic (e.g., orbital as well as classical and relativistic precessional) driving mechanisms, that may sometimes mask the above noted generic features. The observable significance in the radio regime, for example, will sensitively depend on the degree of intrinsic jet inhomogeneities, the contributions from re-acceleration (such as shock or shear) processes and the commoving spectral index evolution (e.g., whether the frequency of observation falls within the optically-thin or -thick regime). In the optical regime, on the other hand, we may have a strong accretion disk contribution dominating over part of the optical jet emission or accretion disk hot spots and instabilities leading to additional periodic variabilities. This may suggest that the observations of mid-term periodicities in X- and γ-rays during bright sources states can be of particular relevance for disclosing the intrinsic nature of the system.

3.2. A0 0235+16

The above noted general considerations may be of particular importance for understanding the intrinsic nature of the very compact, highly variable and superluminal BL Lac source AO 0235+16 at redshift $z = 0.94$ (see [53] for more details). The periodicity analysis of the long-term variability in this source has provided strong evidence for a (5.7 ± 0.5)

yr periodicity in its radio lightcurves and a possible (2.95 ± 0.15) yr periodicity in its optical lightcurves, cf. [18, 47, 57, 65]. Two different models have been proposed recently in order to account for these findings, both assuming the presence of a close SBBHS:
(1) Romero, Fan & Nuza (2003) have suggested that AO 0235+16 may harbour a close SBBHS where the observed optical periodicity with $P_{\rm obs} \simeq 2.95$ yr is caused by the companion crossing the accretion disk around the jet-emitting black hole on a non-coplanar circular orbit (thus implying an orbital period of $P_k \simeq 2 \times 2.95/[1+z] \sim 3$ yr), while the radio periodicity is related to Newtonian jet precession.
(2) Ostorero, Villata & Raiteri (2004), on the other hand, have argued that both, the radio and optical periodicity (assuming both periods to be the same!) may be associated with a helically bent, steadily emitting inhomogeneous jet, driven by the orbital motion in a close SBBHS.

Now, if scenario (1) is indeed realized, the jet fluid motion has to be non-ballistic as classical perturbation effects are not able to produce such short precessional periods [51]. As noted 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). Hence moderate bulk flow Lorentz factors $\gamma_b \gtrsim 3.2$ may well be sufficient to account for the observed radio periodicity. On the other hand, if the typical bulk Lorentz factor is much higher, say of the order of ~ 10, as suggested from the observations of high superluminal motion in AO 0235+16, the precessional driving period would be $P_p \sim 300$ yr. The projected wavelength of the associated helical trajectory $\lambda \simeq P_p\, c\,/\gamma_b$ [51] would then be of the order of ~ 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 possibly accessible for coming high-resolution VLBI observations. Moreover, if a scenario such as (1) is indeed realized, periodic variability with a timescale of several months or less might be expected in the high energy bands. For similarly to the periodic modulation driven by Newtonian precession, the orbital motion of the binary is also likely to lead to some quasi-periodic modulation, at least from the initial parts of the jet. For a Keplerian period of $P_k \simeq 3$ yr, possible observable variability timescales would range from ~ 7 months (for $\gamma_b \sim 3$) to ~ 20 days (for $\gamma_b \sim 10$) or perhaps even less.

The situation may, however, be quite different if a scenario following (2) is correct. At first glance such a scenario seems to require that the observed timescale for the optical periodicity coincides with the one for the radio periodicity, and thus appears less plausible if the difference suggested above is indeed confirmed by further observation and analysis. It is likely, however, that the real situation is much more complex: For a helically bent, steadily emitting inhomogeneous jet, which is 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 again 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 accounted for by Ostorero et al. (2004). For an observed radio period of 5.7 yr, for example, the real Keplerian period may range from $P_k \simeq 26$ yr (for $\gamma_b = 3$) to $P \sim 300$ 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.

4. CONCLUSION

There is mounting evidence that helical jet trajectories as well as mid- and long-term periodicities observed in blazar sources may be related to the presence of close SBBHSs in their centres. Here we have suggested that several trends in these periodicities might be coherently and successfully explained with reference to a disk, orbital and precessional origin indicating that the observed timescales of periodicity may carry valuable information about the nature and the physics of SBBHSs. Continuous observations in different energy ranges, a thorough periodicity analysis of their lightcurves and detailed theoretical modelling will be important to shed further light on their histories and properties.

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Table I Identified mid-term and long-term quasi-periodic variability for a sample of blazar sources. The question mark in the fifth column (observed periods) indicates periods which are somewhat more speculative due to being analyzed using limited data sets (wrt. time coverage, measurements points) and/or limited methods. For references and more details, see Rieger, in preparation.

object/name	**typ**	**redshift**	**energy range/frequency**	**identified observed periods**
Mkn 421	BL Lac	0.031	X-ray/RXTE (1996-2000)	62.1 d
			optical B (over 90 yr)	23.1±1.1 yr
				(15.3±0.7 yr)
Mkn 501	BL Lac	0.033	X-ray/RXTE (8/96-3/98)	23.6 d
			TeV/HEGRA,TA (1997)	$\sim$ 23 d
PKS 1514-241	BL Lac	0.049	optical B (1972-1987)	2 ± 0.2 yr
3C 371	BL Lac	0.051	optical B (over 22 yr)	2.70±0.15 yr (?)
BL Lac	BL Lac	0.069	optical B (over 100 yr)	13.97±0.75 yr
			radio (over $\sim$ 20 yr)	$\sim$ 4 yr
			radio (over $\sim$ 20 yr)	7.53±0.79 yr
ON 231	BL Lac	0.102	optical B (over 100 yr)	13.6±1.3 yr
			optical B (1971-1997)	3.8 yr
PKS 2155-304	BL Lac	0.117	X-ray/RXTE (1996-2000)	143 d
			optical V (over 16 yr)	[4.16±0.2 yr] (?)
			optical V (over 16 yr)	7.0±0.16 yr (?)
ON 325	BL Lac	0.130	optical B (over 35 yr)	6.89±1.0 yr
3C 273	LPQ	0.158	optical B (over 110 yr)	13.65±0.2 yr
			radio (over $\sim$ 20 yr)	8.55±0.28 yr
PKS 0754+100	BL Lac	0.266	optical B (over 70 yr)	3.0±0.35 yr
			optical B (over 82 yr)	17.85±1.3 yr
OJ 287	BL Lac	0.306	optical V (over 100 yr)	11.86 yr
			optical B (over 100 yr)	11.86 yr
			infrared (JHK) (over $\sim$ 25 yr)	$\sim$ 12 yr
			radio (over 20 yr)	$\sim$1.66 yr
PKS 0735+178	BL Lac	0.424	optical B (over 90 yr)	14.2 yr
3C 66A	BL Lac	0.444	optical V (R) (1993-1998)	65 d
			optical B (over 20 yr)	4.52±0.28 yr
3C 279	HPQ	0.536	infrared K (over 27 yr)	7.1±0.44 yr
3C 345	HPQ/OVV	0.593	optical B (over 100 yr)	10.1±0.8 yr
			optical B (91/92 flaring)	$\sim$ 6 months(?)
1803+784	BL Lac	0.680	radio (over 20 yr)	$\sim$ 3.6 yr
PKS 0202+149	HPQ	0.833(?)	radio (over 24 yr)	$\sim$ 4.2± 0.8 yr
			radio (over 24 yr)	$\sim$ 14 (?)
3C 454.3	HPQ	0.859	radio (over $\sim$ 20 yr)	6.32±0.22 yr
PKS 0402-014	HPQ	0.914	optical R (1991f flaring)	$\lesssim$ 1 yr (?)
AO 0235+16	BL Lac	0.940	radio+optical (1975-2000)	5.7 yr
			optical B (over 16 yr)	2.95±0.15 yr
1308+326	BL Lac	0.996	optical B (over 15 yr)	1.4±0.3 yr (?)
3C 446	HPQ	1.404	optical B (1971-1985)	4.7 yr
S5 0716+714	BL Lac	$\gtrsim$0.3	optical R (1994-2001)	3.3 yr
			radio ($\sim$ 20 yr)	(5.5 - 6) yr
			optical (over 5.3 yr)	$\sim$ 10 d
			optical polarimetry (in 1991/93/94)	12.5 d