Implications of a possible 23 day periodicity for binary black hole models in Mkn 501

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Abstract. We investigate the implications of a massive binary system in the centre of the gamma-ray blazar Mkn 501 and show that the periodical behaviour recently observed in the TeV and X-ray lightcurves may possibly be related to the orbital motion of the relativistic jet emerging from the less massive black hole. For the special relativistic jet properties inferred from emission models, we derive an intrinsic orbital period of $(6–14)$ yrs and a centre-of-mass distance of $(2.0–3.5) \times 10^{16}$ cm. If the binary is very close with a separation of the order of that for which gravitational radiation becomes dominant, we find a maximum primary mass of $\sim 10^8 M_\odot$ and a corresponding secondary mass in the range of $\sim (4–42) \times 10^6 M_\odot$ depending on the intrinsic jet properties. Such values are in line with the black hole masses expected from merger scenarios.

Key words: galaxies: active – galaxies: BL Lacertae objects: individual: Mkn 501 – galaxies: jets

1. Introduction

Binary black hole systems (BBHSs) are expected to be common in the universe as a result of mergers between galaxies. In the underlying picture for the morphological evolution, galaxies were formed as part of a hierarchical clustering process (e.g. White 1997). Giant elliptical galaxies, such as the host galaxy of Mkn 501, appear to be the products of mergers between spiral galaxies (cf. Fritze v.- Alvensleben 1996). Since the brightest galaxies generally seem to contain massive black holes in their nuclei (e.g. Rees 1984; Kormendy & Richstone 1995; Ho 1998; Magorrian et al. 1998; Richstone et al. 1998), merging would naturally lead to the formation of massive BBHS (Begelman et al. 1980, abbreviated: BBR 80; Rees 1994; Artymowicz 1998; Richstone 1998). The so formed binary black hole is expected to spent most of its time at a separation of ~ 0.1–1 pc for masses of $10^8 M_\odot$ (BBR 80). However if the binary looses further angular momentum e.g. by slingshot interaction with new stars from subsequent merging events (Roos 1988; Roos et al. 1993), infall of gas (BBR 80; cf. also Gould & Rix 2000) or by interactions with an accretion disk (Ivanov et al. 1999), gravitational radia-

tion will eventually become important and the binary evolution could proceed rapidly to coalescence.

Up to now, several phenomena have been attributed to BBHSs: e.g. misalignment (cf. Conway & Wrobel 1995), precession (BBR 80) or wiggling of jets, where the latter is supposed to be induced by the orbital motion (Kaastra & Roos 1992; Roos et al. 1993). Periodic outburst activity in the quasar OJ 287, has commonly been related to a BBHS and is thought to arise due to tidal perturbation (Sillanpää et al. 1988) or due to one black hole crossing the accretion disk of the other (Letho & Valtonen 1996). Other BBHS scenarios assume a pair of bent jets (Villata et al. 1998) or the precession of the disk under the gravitational torque (Katz 1997).

In the particular case of Mkn 501, the complex morphology of its radio jet and the peculiar behaviour of its spectral energy distribution (SED) have prompted elaborate models relating these properties to a BBHS: Conway & Wrobel (1995), for example, have proposed a saturated helix model in order to explain the misalignment of the radio jet on parsec and kiloparsec scales. Villata & Raiteri (1999) have argued that the X-ray variations in the SED of Mkn 501 might be due solely to the changing orientation of a helical synchrotron emitting jet in a close BBHS. The recent discovery of periodicity in the TeV and X-ray fluxes believed to be associated with moving features in the jet of Mkn 501 might add another aspect for assessing the relevance of a BBHS in this galaxy.

Mkn 501 is one of at least four active galactic nuclei which have been detected at TeV energies (for review, see Catanese & Weekes 1999). Being the second closed among these with a redshift of $z = 0.034$, Mkn 501 has been historically classified as an X-ray selected BL Lac object showing virtually no emission lines, and is hosted by the elliptical galaxy UGC 10599 (Stickel at al. 1993). As a BL Lac object, Mkn 501 belongs to the blazar class of AGN which are thought to have relativistic jets oriented at a small viewing angle, thus yielding a strong Doppler enhancement of the observed flux.

At the beginning of 1997, Mkn 501 had suddenly undergone a phase of high activity becoming the brightest source in the sky at TeV energies. Subsequent multiwavelength campaigns revealed a variable, two component SED with a low energy part extending up to 100 keV (Pian et al. 1998) and a high energy part which extends at least up to 20 TeV (Samuelson

et al. 1998; Konopelko 1999). During this activity phase, particular types of variability have been observed (e.g. Protheroe et al. 1998), consisting of flaring episodes of several days and additional intraday-variabilities. While the TeV and X-rays variations seem to be well correlated, the evidence for correlations with the optical U-band appears to be rather weak (e.g. Catanese et al 1997; Djannati-Atai et al. 1999; Aharonian et al. 1999). One of the most fascinating features is the observed periodicity in the TeV region with a period in the range of $(23–26)$ days, which has been found in the data taken by several Cherenkov telescopes (see Protheroe et al. 1998; Hayashida et al. 1998). Additionally, a recently performed analysis of RXTE-ASM X-ray data from April to July 1997 also seems to support a periodicity of ~ 23 days (Kranich et al. 1999; Nishikawa et al. 1999).

Here, we speculate on the possibility that this periodicity in the flaring state arises due to the orbital motion of the relativistic jet in a BBHS where the nonthermal radiation is emitted by a relativistic jet which emerges from the less massive black hole, the periodicity thus being due mainly to geometrical origin (i.e. Doppler-shifted modulation).

2. On the influence of a BBHS in Mkn 501

2.1. Doppler-shifted flux modulation

Consider a simple binary model for Mkn 501, where the binary orbit is is assumed to be circular because dynamical friction between two parent galaxies during the merger might ensure that the initial eccentricity of the resulting binary is small (e.g. Polnarev & Rees 1994). Using Kepler's third law, the intrinsic orbital frequency Ω_k of a binary with separation d is given by

$$\Omega_k = \frac{\sqrt{G\,(m+M)}}{d^{3/2}}\,, \tag{1}$$

where m and M denotes the mass of the smaller and the larger hole, respectively, and G is the gravitational constant.

Let us further assume that the observed jet is formed by the less massive black hole and that the nonthermal X-ray and γ-ray radiation in the flaring state is emitted by a relativistic emission region (e.g. knot, blob, shock) which propagates outwards from the core along the jet with gamma factor γ_b. Owing to the (non-relativistic) orbital motion, the true trajectory of the knot is a long stretched helix. The modulation of the emission then occurs as a consequence of the slight variation of the inclination angle i due to the orbital ϕ-component of the velocity field of the knot. This observed flux modulation by Doppler boosting is well-known and can be written in the form

$$S(\nu) = \delta^3\,S'(\nu') = \delta^{3+\alpha}\,S'(\nu), \tag{2}$$

where S' is the spectral flux density measured in the comoving frame, $\delta(t) = 1/(\gamma_b[1 - \beta_b \cos\theta(t)])$ the Doppler factor, $\theta(t)$ is the actual angle between the velocity $\boldsymbol{\beta}_b = \dot{\boldsymbol{x}}_b(t)/c$ of the emission region and the direction of the observer, and where the final equality holds if the source has a spectral index α.

Due to the orbital motion around the center-of-mass, the Doppler factor for the emission region is a periodical function of time. In the simplest case where the angle between the jet axis and the direction of the total angular momentum of the binary is assumed to be zero (e.g. neglecting any kind of precessional motion) the Doppler factor may be written as

$$\delta = \frac{\sqrt{1 - (v_z^2 + \Omega_k^2 R^2)/c^2}}{1 - (v_z \cos i - \Omega_k R \sin i \sin \Omega_k t)/c}\,, \tag{3}$$

with $R = M\,d/(m+M)$ being the centre-of-mass distance, v_z the outflow velocity in the direction of the total angular momentum, i the inclination between the jet axis and the line of sight and c the velocity of light. Obviously, the Doppler factor becomes maximal for $t = 0.75\,P_k$ and minimal for $t = 0.25\,P_k$, where $P_k = 2\,\pi/\Omega_k$ denotes the keplerian period.

From the TeV flux ratio of $f \sim 8$ between the maximum and the minimum state during the observation (cf. Protheroe et al. 1998; Hayashida et al. 1998, Aharonian et al. 1999) and the assumption that the periodicity arise in the main due to geometrical origin, we now obtain the condition $\delta_{\max}/\delta_{\min} \simeq f^{1/(3+\alpha)}$ (see Eq. (2)). Consequently, by using Eq. (3) one finds

$$\Omega_k\,R = \frac{f^{1/(3+\alpha)} - 1}{f^{1/(3+\alpha)} + 1}\left(\frac{1}{\sin i} - \frac{v_z}{c}\cot i\right)c\,. \tag{4}$$

For a source region which moves in the time interval dt from point A to point B with relativistic velocity v_z and at an angle ψ to the line of sight, the observed difference in arrival times for radiation emitted at A and B is generally given by $dt_{\mathrm{obs}} = dt - dt\,(v_z/c)\cos\psi$, thus leading to a shortening of the observed time interval. Along this line of argument, one may easily derive that the observer in the model presented here will only perceive a strongly shortened period, i.e. the observed period P_{obs} is related to the intrinsic period P_k by (cf. also Camenzind & Krockenberger 1992, Roland et al. 1994)

$$P_{\mathrm{obs}} = (1 + z)\int_0^{P_k}(1 - \beta_b\,\cos\theta(t))\,\mathrm{d}t\,. \tag{5}$$

Performing the integration, one immediately arrives at

$$P_{\mathrm{obs}} = (1 + z)\left(1 - \frac{v_z}{c}\cos i\right)P_k\,. \tag{6}$$

From the theoretical point of view, relativistic blazar jets are thought to be oriented at a small viewing angle. Current emission models favour an inclination angle $i \simeq 1/\gamma_b$ (Spada 1999; cf. also Chiaberge et al. 2000) with typical bulk Lorentz factors in the range 10–15 (e.g. Mannheim et al. 1996; Hillas 1999; Spada et al. 1999). For such values and by using an observed period of 23 days and a characteristic outflow velocity of $v_z/c \simeq (1 - 1/\gamma_b^2)^{0.5}$, Eq. (6) results in an intrinsic period of $P_k = (6 - 14)$ yrs.

Combining Eq. (6) and Eq. (4) we may also derive an expression for the the centre-of-mass distance

$$R = \frac{P_{\mathrm{obs}}}{2\,\pi\,(1 + z)}\frac{f^{1/(3+\alpha)} - 1}{f^{1/(3+\alpha)} + 1}\frac{c}{\sin i}\,. \tag{7}$$

Given the observed period and the spectral index, Eq. (7) only depends on the inclination angle. Accordingly, for an observed

period of 23 days, a ratio $f = 8$ and a TeV spectral index of $\alpha \simeq (1.2–1.7)$ (cf. Aharonian et al. 1999), one gets $R \simeq (2.0–3.5) \times 10^{16}$ cm using the inclination values above.

By inserting Eq. (1) in Eq. (7), the appropriate binary mass ratio is given by

$$\frac{M}{(m + M)^{2/3}} = \frac{P_{\mathrm{obs}}^{1/3}}{(2\pi\,[1 + z]\,G)^{1/3}}\,\frac{c}{\sin i}$$
$$\times \frac{f^{1/(3+\alpha)} - 1}{f^{1/(3+\alpha)} + 1}\,\left(1 - \frac{v_z}{c}\,\cos i\right)^{2/3}. \quad (8)$$

For a secondary mass in the range of $(10^6–10^8)\,M_\odot$ the required primary masses are calculated in Fig. 1 (see the curves $K(10), K(15)$) for two different inclination angles and $f = 8$ yielding primary masses of the order of $10^8\,M_\odot$.

2.2. A gravitational constraint on the binary separation

Observationally, BL Lacs are in general less luminous radio sources, showing a lack of strong optical emission lines and little signs of cosmological evolution (cf. Bade et al. 1998; Cavaliere & Malquori 1999). Celotti et al. (1998) have suggested that BL Lac objects correspond to the final evolutionary stage of sources accreting at low radiative efficiencies (i.e. a dormant black hole system), which seems to be supported by HST observation indicating that the less luminous AGN stages occur after the original quasar has dimmed (Bahcall et al. 1994). Recently, Villata & Raiteri (1999) have argued that BL Lacs represent advanced and close BBHS with a decreased mass accretion rate, the binary separation in the case of Mkn 501 being of the order of that for which gravitational radiation becomes dominant. Thus, we might set an upper limit on the allowed binary masses in Mkn 501 by assuming that the current separation equals the gravitational separation d_g, i.e. the position where the gas dynamical time scale is balanced by the time scale for gravitational energy losses (BBR 80). Gas, which may be constantly supplied for example by tidal interaction between galaxies (cf. Heidt 1999) and accreted onto the more massive black hole, will cause the binary separation to shrink on a time scale $t_{\mathrm{gas}} \simeq M\,(1M_\odot\,\mathrm{yr}^{-1}/\dot{M})$, with $\dot{M}$ the accretion rate (BBR 80). For a simple estimate let us assume that during the optical bright QSO phase mass accretion occurs at about the Eddington limit. The phase of nuclear activity seems to be rather short with a typical duration of a few times 10^7 yrs (Haehnelt et al. 1998; Richstone et al. 1998). In particular, for a duration of nuclear activity of the order of the salpeter lifetime $t_s = \epsilon\sigma_T c/4\pi G m_p = 4.5\,\epsilon_{0.1} \times 10^7$ yrs and for a primary black hole mass of $\sim 10^8\,M_\odot$, gas infall rates of $\sim 2\,M_\odot\mathrm{yr}^{-1}$ are required to sustain the Eddington luminosity, using a canonical 10% efficiency. On the other hand, assuming a circular orbit, the time scale for gravitational radiation is given by $\tau_{\mathrm{grav}} = 6.3\times10^4\,d_{16}^4/(M_8\,m_8\,[m_8 + M_8])$ yrs, where the distance and the masses are expressed in units of 10^{16} cm and $10^8\,M_\odot$, respectively. Thus, by equating the gas dynamical time scale t_{gas} with τ_{grav}, the separation at which gravitational radiation becomes dominant may be written as
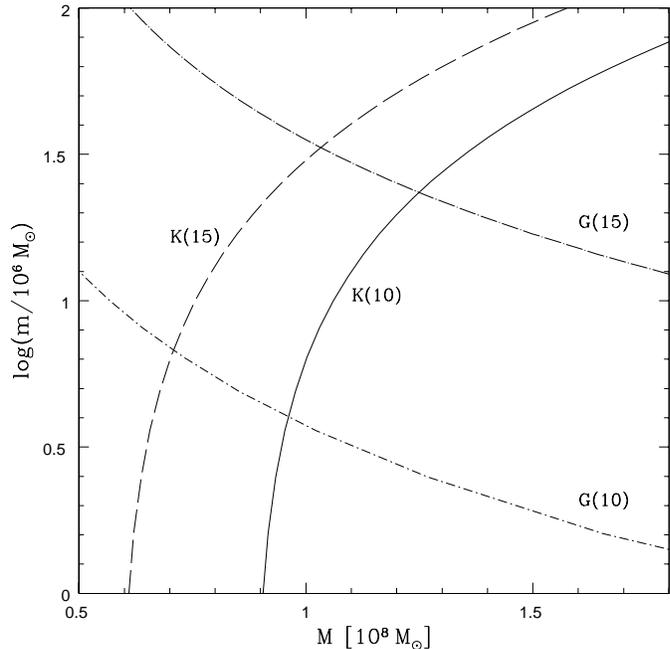

Fig. 1. Required mass dependence for a BBHS in Mkn 501. The solid [$K(10)$] and long dashed [$K(15)$] curve are given by the Doppler condition Eq. (8) for inclination angles $i = 1/\gamma_b$ with $\gamma_b = 10$ and 15, respectively. The curves $G(1/i)$ are given by the condition that the current binary separation equals the gravitational distance d_g, see Eq. (10), thus yielding upper limits on the allowed binary masses. A TeV spectral index of 1.2 has been applied for the calculation.

$$d_{g_{16}} = 6.3\,M_8^{1/2}\,m_8^{1/4}\,(m_8 + M_8)^{1/4}\,\left(\frac{M_\odot\,\mathrm{yr}^{-1}}{\dot{M}}\right)^{1/4}. \quad (9)$$

From Eq. (9) and Eq. (1) we immediately get the relation

$$\frac{M^{1/2}m^{1/4}}{(m + M)^{1/12}} = 1.29 \times 10^{22}\,\left(\frac{\dot{M}}{M_\odot\,\mathrm{yr}^{-1}}\right)^{1/4}$$
$$\times \frac{P_{\mathrm{obs}}^{2/3}}{(2\pi\,[1 + z])^{2/3}\,(1 - \frac{v_z}{c}\,\cos i)^{2/3}}. \quad (10)$$

This mass dependence is illustrated in Fig. 1 (curves G). The respective upper limit is given by the point of intersection with the relevant curve K. For example, applying $\alpha = 1.2$ and using $i = 1/10$, we have a maximum secondary mass $m \simeq 4 \times 10^6\,M_\odot$ and a corresponding primary mass of $M \simeq 10^8\,M_\odot$ (cf. also Table 1). The masses shown in Fig. 1 are in a reasonable range for ellipticals. Masses of the order of one million solar masses for the companion black hole appear to be in agreement with the concept that the galaxy swallowed in the merger process was a minor spiral galaxy. On the other hand, the host galaxy of Mkn 501 seems to belong to these classes of ellipticals which have black holes in the centers of at least a few hundred million solar masses. Therefore, the binary scenario for Mkn 501 seems not unlikely.

Table 1. Maximum binary masses, separation d, intrinsic orbital period P_k, gravitational lifetime τ_{grav} and precessional period P_p for inclination angles i, accretion rate $\dot{M} = 2\,M_\odot/\mathrm{yr}$ and spectral index $\alpha = 1.2\,(1.7)$.

$i = 1/\gamma_b$	1/10		1/15	
$m\,[10^8\,M_\odot]$	0.040	(0.061)	0.33	(0.42)
$M\,[10^8\,M_\odot]$	0.96	(0.75)	1.03	(0.91)
$d\,[10^{16}\,\mathrm{cm}]$	2.40	(2.24)	4.57	(4.54)
$P_k\,[\mathrm{yrs}]$	6.10		13.7	
$\tau_{\mathrm{grav}}\,[10^7\,\mathrm{yrs}]$	5.46	(4.25)	5.86	(5.18)
$P_p\,[10^4\,\mathrm{yrs}]$	0.52	(0.39)	3.03	(2.93)

3. Discussion

In this paper we have suggested that the periodicity in the flaring state observed in Mkn 501 might be caused by the orbital motion of the jet in a close BBHS. Applying a simple toy-model we have shown that the BBHS may have a period of $\sim (6\text{–}14)$ yrs and a centre-of-mass distance of $\sim (2.0\text{–}3.5) \times 10^{16}$ cm. If one assumes that this separation corresponds to the distance at which gravitational radiation becomes important, several upper limits for the binary masses may be derived. These mass ranges, which are shown in Table 1 using an observed period $P_{\mathrm{obs}} = 23\,\mathrm{days}$ seem to be in line with the expectations from merger scenarios and the suggestions made by Villata & Raiteri (1999).

The TeV observations indicate that we may have $N \leq 6$ for the number N of periodic oscillations (cf. Aharonian et al. 1999; Catanese & Weekes 1999; Quinn et al. 1999), which results in a required propagation length for the emitting component of $l_z = N\,P_k\,v_z \simeq 11\text{–}26$ pc. Thus, for the projected length at the position of Mkn 501 one finds $l_p \simeq 1.4\text{–}2.1$ mas for $i = (1/15) - (1/10)$ rad. Remarkably, the jet of Mkn 501 bends dramatically at about 3 mas from the core (Marscher 1999). Hence, a change in the jet parameters might be the reason for the termination of the observed periodicity.

For the proposed model to be valid, the jet has to be perfectly collimated with an intrinsic opening angle of less then $\arctan(d/l_z) \sim 0.05°$. Such values are indeed expected in scenarios for the formation and collimation of magnetized BL Lac jets (cf. Camenzind & Krockenberger 1992; Appl & Camenzind 1993; Schramm et al. 1993). At first sight, such a cylindrical jet structure seems to be at least ~ 20 times more collimated than the jet seen on VLBA maps (cf. Marscher 1999). However, there is evidence for an at least two-component jet structure in Mkn 501 suggesting an inner spine with transverse magnetic field and an envelope with longitudinal magnetic field (Aaron 1999; Marscher 1999), the polarization properties of the inner spine strongly supporting shocked-jet models (cf. Attridge et al. 1999). In fact, our model requires that the high energy emission originates in a channel along the jet axis as in two-fluid models (e.g. Sol et al. 1989, Roland et al. 1994), the inner emission probably being self-absorbed on the VLBA scale. Recent observations of radio jets indeed indicate a confinement of the higher energy emission to a well-defined channel within a much more extended radio emission (Bahcall et al. 1995; Perl-

man et al. 1999; Swain et al. 1999). The unification of BL Lacs and FR I objects may add another piece of evidence to such a jet configuration: in order to account for the observed spectral properties an at least two-fold jet velocity structure seems to be required in which a fast spine is surrounded by a slow (but still relativistic) layer (Chiaberge et al. 2000). Support for such a possibility is positively provided by numerical simulations (cf. Aloy et al. 2000; Frank et al. 2000).

For a TeV flux ratio between minimum and maximum of ~ 8, the corresponding shift in the break frequency would be given by a factor of $\sim (1.5\text{–}1.6)$ while the X-ray flux ratio becomes $\sim (5\text{–}7)$ applying an hard X-ray spectral index $\alpha \simeq 0.6\text{–}0.9$ (cf. Lamer & Wagner 1998; Pian et al. 1998). Such values seem to be consistent with BeppoSAX observations (Pian et al. 1998) and may also be recovered, using a broken power law fit, in RXTE observations of Mkn 501 (cf. Krawczynski et al. 2000, their Figs. 1 and 2a). Gamma-ray observations carried out by the CAT Telescope also reveal a shift of the maximum peak energy apparently in accordance with the expectation above (Djannati-Atai et al. 1999). Small changes in the maximum electron Lorentz factor or the magnetic field along the trajectory of the emission region may further add to flux variations. If there is indeed an additional flux contribution, e.g. low energy emission from the layer, a stationary component comparable to the observed infared-optical flux (e.g. Pian et al. 1998; cf. also Kataoka et al. 1999) or an additional component responsible for the soft X-ray emission (e.g. Lamer & Wagner 1998; Wagner et al. 1999), the amplitude of the Doppler modulation may decrease to lower frequencies.

In the simple model presented above, we have not yet considered the influence of jet precession due to gravitomagnetic and geodetic origin with a period $P_p \simeq 580 \times d_{16}^{5/2} (M_8 + m_8)^{1/2}\,m_8^{-1}\,M_8^{-1}(1 + 3M/4m)^{-1}\mathrm{yrs}$ (cf. Thorne et al. 1986). Since this driving period is much larger than the orbital period (cf. Table 1), a precessional modulation should be negligible during a few revolutions. Interestingly, a precessional period of $\sim 10^4$ yrs agrees with the driving frequency found by Conway & Wrobel (1995) in order to explain the misalignment of the radio jet in Mkn 501 on parsec and kiloparsec scale (see also Villata & Raiteri 1999). If the binary hypothesis is correct, the observable period should remain similar during different outburst phases unless there is a change in the general jet properties. For example, an increase in the observed period should then be accompanied by a decrease in the bulk Lorentz factor or, on larger time scales, by an increase of the inclination angle due to the jet precession (cf. also Eq. (6)).

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