

The Binary Black Hole Scenario for the BL Lacertae Object AO 0235+16

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Abstract Recent analysis of the long term radio light curve of the extremely variable BL Lacertae object AO 0235+16 by Raiteri et al. have revealed the presence of recurrent outbursts with a period of $\sim 5.7 \pm 0.5$ yr. Periodicity analysis of the optical light curve also shows evidence for a shorter period. Here we discuss whether such a behavior can be explained by a binary black hole model where the accretion disk of one of the supermassive black holes is precessing due to the tidal effects of the companion. We estimate the mass of the accreting hole and analyze constraints on the secondary mass and the orbital parameters of the system. It is possible to provide a viable interpretation of the available multiwavelength data.

Key words: galaxies: active – BL Lacertae objects: individual: AO 0235+16 – gamma rays: theory – black hole physics

1 INTRODUCTION

The BL Lacertae object AO 0235+16 ($z = 0.94$) is one of the most variable blazars across the entire electromagnetic spectrum. Fan & Lin (2000) have compiled its historical optical light curves which showed large amplitude outbursts. At short timescales, strong radio variability has been found by Quirrenbach et al. (1992), Romero et al. (1997) and Kraus et al. (1999), among others. Very rapid (timescales of hours) optical variations were reported on several occasions (e.g., Rabbette et al. 1996; Heidt & Wagner 1996; Noble & Miller 1996; Romero et al. 2000a). The intranight optical duty cycle of this source seems to be close to 1 (Romero et al. 2002). The X-ray flux also displays significant and rapid outbursts (e.g., Madejski et al. 1996). At gamma-ray energies the source has been detected by EGRET experiment onboard the Compton satellite (Hunter et al. 1993; Hartman et al. 1999). All this activity makes AO 0235+16 an outstanding candidate for probing the most extreme physical conditions in blazars.

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The radio structure of the source has been studied at ground-based (e.g., Jones et al. 1984; Chu et al. 1996; Chen et al. 1999) and space (Frey et al. 2000) VLBI resolutions. The object is very compact at sub-milliarcsecond angular scales. Superluminal components with velocities up to $\sim 30c$ have been detected (e.g., Fan et al. 1996 and references therein). Chen et al. (1999) have argued, based on the variations of the position angle of the superluminal components from 1979 till 1997, that it is possible that the jet is rotating. The evidence, however, is far from conclusive.

Very recently, Raiteri et al. (2001) reported the results of a very extensive multifrequency monitoring of AO 0235+16. On the long term, variations of 5 magnitudes in the R band and up to a factor 18 in the radio emission were found. Periodicity analysis of the radio data based on discrete autocorrelation function, discrete Fourier Transform, and folded light curves, covering a time-span of ~ 25 yr, revealed the likely existence of a period of 5.7 ± 0.54 yr (Raiteri et al. 2001). Additional analysis of the optical light curve with the Jurkevich method by Fan et al. (2002) showed a different periodic signal at 2.95 ± 0.15 yr. The significance of this latter periodicity is confirmed by Monte Carlo simulations of random light curves (see Fan et al. 2002 for details).

Periodic signals in the light curves of different blazars have been interpreted by a number of authors in terms of supermassive binary black holes systems (e.g., Sillanpää et al. 1988; Katz 1997; Villata et al. 1998; Romero et al. 2000b; Rieger & Mannheim 2000; de Paolis et al. 2002). In the present paper we discuss whether the binary black hole hypothesis can be adapted to the interesting case of AO 0235+16. The existence of abundant multiwavelength data on this source will help to constrain the model parameters. We also present the basic features of the precessing jet model for AGNs. Then we will apply the model to AO 0235+16 and discuss the results. We close the paper with some brief conclusions.

2 SUPERMASSIVE BLACK HOLE BINARIES AND DISK PRECESSION

Supermassive black hole binaries (SBHBs) are the natural result of galaxy mergers. Their formation and evolution have been extensively discussed in the literature (e.g., Begelman et al. 1980; Roos 1981; Valtaoja et al. 1989). The fact that many (if not most) galaxies contain massive black holes and that galaxies often merge implies a relatively high formation rate of SBHBs. The current evidence for central engines of active galactic nuclei formed by massive binary systems includes double nuclei (as in the case of NGC4486B), wiggly jets (e.g., Kaastra & Roos 1992), double emission lines observed in several quasars (Gaskell 1996), and periodic optical light curves as in the case of OJ 287 (Sillanpää et al. 1988; Lehto & Valtonen 1996; Villata et al. 1998).

Geodetic precession of relativistic jets in SBHBs has also been often discussed in relation to large-scale helical jets (e.g., Begelman et al. 1980; Roos 1988). This effect is due to the Lense-Thirring dragging of inertial frames and is much slower than the tidally-induced precession produced by the gravitational torque of one of the black holes on the accretion disk of the other. If we are interested in short timescales we should focus on the second phenomenon (e.g., Katz 1997; Romero et al. 2000b). Newtonian precession of an accretion disk (which can be transmitted to the associated jets) has been extensively studied in the context of galactic binaries and microquasars (e.g., Katz 1973, 1980; Katz et al. 1982; Larwood 1998; Kaufman Bernadó et al. 2002). The general situation in an extragalactic scenario is depicted in Fig. 1. We have two black holes in a close circular orbit of radius r_m . One of the holes has an acce-

tion disk which is non-coplanar with the orbital plane. It is usually expected that the jet is ejected perpendicularly to the disk plane, in the direction of the disk angular velocity ω_d . The gravitational torque of the companion black hole onto the disk will make the innermost part of it to precess, say within a radius r_d where the different parts of the fluid are efficiently coupled at the sound speed c_s . This precession will be transmitted to the jets, which will move with a precession half-opening angle θ and a precession velocity given by (e.g., Katz 1997; Romero et al. 2000b):

$$|\Omega_p| \approx \frac{3}{4} \frac{Gm}{r_m^3} \frac{1}{\omega_d} \cos \theta, \quad (1)$$

where G is the gravitational constant and m is the mass of the black hole that exerts the torque upon the disk. By convention we will call this black hole “secondary” and the accreting hole “primary” (its mass will be denoted by M). This does not necessarily imply that $M > m$. The orbital period T_m is related to the black hole masses and the size of the orbit by Kepler’s law:

$$r_m^3 = \frac{G(m+M)T_m^2}{4\pi^2}. \quad (2)$$

The ratio between the orbital and the precessing periods can be related through the disk angular velocity $\omega_d = (GM/r_d^3)^{1/2}$:

$$\frac{T_m}{T_p} = \frac{3}{4} \frac{m}{M} \kappa^{3/2} \left(\frac{M}{m+M} \right)^{1/2} \cos \theta, \quad (3)$$

where $T_p = 2\pi/\Omega_p$ and $\kappa = r_d/r_m$. Since $\kappa < 1$, normally $T_m/T_p < 1$ too. For X-ray binaries in the Galaxy this ratio is typically ~ 0.1 (e.g., Larwood 1998).

Precession of the jet results in a varying viewing angle $\phi = \phi(t)$, which through the flux modulation due to the Doppler factor $\delta = [\gamma(1 - \beta \cos \phi)]^{-1}$ can produce a periodic signal in the non-thermal jet emission measured in the observer’s frame (e.g., Abraham & Romero 1999):

$$S^{\text{obs}}(\nu) = \delta^{2+\alpha} S(\nu), \quad (4)$$

where α is the synchrotron spectral index.

In the next section we will constrain the value of the different parameters for the application of this scenario to AO 0235+16 and we will then try to evaluate the likelihood of the binary black hole hypothesis as a viable explanation of the radio periodicity observed in AO 0235+16.

3 MODELS FOR AO 0235+16

The non-thermal radio emission of AO 0235+16 is interpreted as incoherent synchrotron radiation produced by a power-law population of relativistic electrons in the jet of the object.

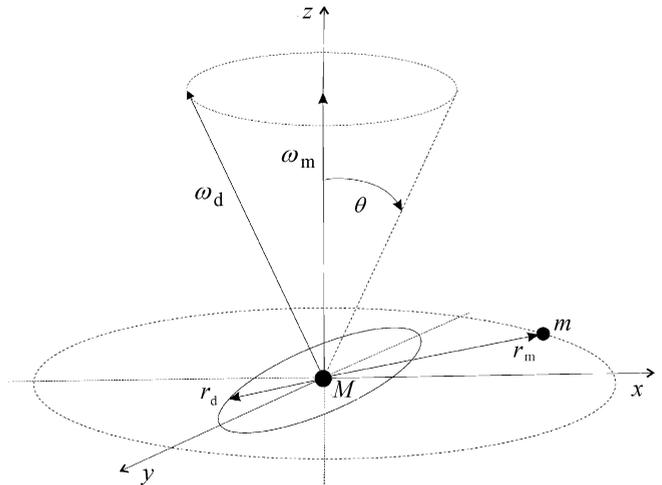


Fig. 1 A sketch of a driven precessing accretion disk in a binary black hole system. Jet direction is indicated by ω_d , adapted from Romero et al. (2000b).

Hence, the radio periodicity identified by Raiteri et al. (2001) should be related to processes occurring in the jet. We assume that the observed period is the consequence of precession of the jet. In the observer's frame, this period is $T_p^{\text{obs}} \approx 5.7$ yr. Due to relativistic effects, the intrinsic period in the blazar will be (e.g., Roland et al. 1994; Rieger & Mannheim 2000; Britzen et al. 2001):

$$T_p^{\text{obs}} = (1+z) \int_0^{T_p} (1 - \beta \cos \phi(t)) dt. \quad (5)$$

For small viewing angles, as it is the case with AO 0235+16, this yields:

$$T_p \approx \frac{2\gamma^2 T_p^{\text{obs}}}{1+z}. \quad (6)$$

As mentioned by Romero et al. (2000b) for the case of 3C273, a secondary black hole in a non-coplanar circular orbit around an accreting black hole must penetrate the outer parts of the disk, producing optical flares. A similar scenario has been discussed in connection with OJ 287 by Letho & Valtonen (1996). Since two black-hole/disk collisions are expected in every orbit, the periodicity of the optical flares should be $\sim T_m/2$.

We shall assume that the optical periodicity found by Fan et al. (2002) in AO 0235+16 corresponds to disk penetration by the secondary. Allowing for the redshift, we obtain $T_m \approx 3$ yr. Since this emission is originated in the accretion disk, which can be considered as stationary in the observer's frame, no relativistic corrections should be applied to this period. Just as an example, we mention that in the case of a jet with a Lorentz factor $\gamma = 2.5$ we have a ratio $T_m/T_p \sim 0.08$, which is quite reasonable from a dynamical point of view (Katz 1973; Larwood 1998). Several specific models will be calculated below.

Estimates of the central black hole mass of AO 0235+16 can be obtained using high-energy data. The object has been observed by *ROSAT* and *ASCA* at soft X-ray energies (Madejski et al. 1996). The *ROSAT* data show rapid (~ 3 days) and significant variability whereas the *ASCA* data present a steady source with a hard power-law energy index $\alpha_x = 0.96 \pm 0.09$ and a flux of $0.3 \mu\text{Jy}$ at 1 keV. A small part of the X-ray emission is expected to be an isotropic field produced by the innermost part of the accretion disk, while the remaining X-rays are probably beamed radiation from the jet, as suggested by the rapid variability observed by *ROSAT*. Gamma-rays produced close to the black hole will be absorbed in the isotropic X-ray fields by pair production (Becker & Kafatos 1995; Blandford & Levinson 1995). The region at which the opacity to pair creation drops to one for a given energy E defines the concept of a γ -sphere: no photons with energy greater than E will escape from the interior of the corresponding γ -sphere. Hence, if we have an adequate model for the accretion disk generating the absorbing field and an independent estimate (e.g., through high-energy variability observations) of the size of a given γ -sphere, we can calculate the mass of the black hole (see details in Section 3.3 below). This procedure has been adopted by a number of authors in studies of the central objects of gamma-ray blazars (e.g., Becker & Kafatos 1995; Fan et al. 1999, 2000; Cheng et al. 1999; Romero et al. 2000c). In particular, Fan et al. (2000) have estimated the mass of the accreting black hole in AO 0235+16 to be in the range $(3.5 - 5.4) \times 10^8 M_\odot$. In their calculation they assumed a Schwarzschild black hole, with a specific two-temperature disk model which is responsible for the bulk of the X-ray emission. In the present work we will relax these assumptions and calculate a variety of models for both the black hole and the accretion disk. In addition, we will separate the X-ray emission in a jet-beamed component and an isotropic component following the technique introduced by Kembhavi (1993) and Kembhavi & Narlikar (1999).

3.1 Separation of the X-ray Components

In 1987, Browne and Murphy assumed that the X-ray luminosity of active radio sources, L_x , can be separated into two parts, namely, a beamed part, L_{xb} and an unbeamed part, L_{xu} : $L_x = L_{xb} + L_{xu}$.

In standard radio beaming models it is usually assumed that the ratio of the beamed radio emission, at transverse orientation to the line of sight, to the extended radio emission is a constant. Browne & Murphy (1987) extended this to the X-ray luminosity and assumed that the beamed X-ray luminosity at transverse orientation is also proportional to the extended radio emission, i.e., $L_{xb}(90 \text{ deg}) = A L_{r, \text{ext}}$, with $A = \text{constant}$. The beamed luminosity for an inclination angle ϕ between the beam direction and the line of sight is $L_{xb}(\phi) = g_x(\beta, \phi)L_{xb}(90 \text{ deg})$, where $g_x(\beta, \phi)$ is the X-ray beaming factor, given by

$$g_x(\beta, \phi) = \frac{1}{2}[(1 - \beta \cos \phi)^{-(2+\alpha_x)} + (1 + \beta \cos \phi)^{-(2+\alpha_x)}]. \quad (7)$$

Here, β is the bulk velocity of the beamed flow in units of c , and α_x is the spectral index of the beamed X-ray emission. The expression $\beta \cos \phi$ can be obtained for each source from the following relation derived by Orr & Browne (1982) for radio quasars

$$R_{\text{radio}} = R_{90} \frac{1}{2}[(1 - \beta \cos \phi)^{-2} + (1 + \beta \cos \phi)^{-2}], \quad (8)$$

where $R_{\text{radio}} = L_{rc}/L_{r, \text{ext}}$ is the core-dominance ratio with L_{rc} and $L_{r, \text{ext}}$ being the core and extended luminosities, and $R_{90} = 0.024$ according to a statistical analysis by Orr & Browne (1982) for a sample of 38 flat-spectrum ($S_\nu \propto \nu^{-\alpha}$, $\alpha = 0$) quasars taken from Jenkins et al. (1977) sample. Then the ratio of the beamed to unbeamed X-ray luminosity can be written as:

$$R_x = \frac{L_{xb}}{L_{xu}} = R_{\text{tx}} g_x(\beta, \phi), \quad R_{\text{tx}} = \frac{L_{xb}(90 \text{ deg})}{L_{xb}}. \quad (9)$$

In the latter expression R_{tx} is assumed to be a constant.

There are two problems with the Browne-Murphy model, i.e., a) it is not suitable for radio quiet quasars, and b) the correlation $L_{xu} \propto L_{r, \text{ext}}$ depends on the redshift (see Kembhavi & Narlikar 1999). In order to overcome these problems Kembhavi (1993) proposed a beaming model that uses the formalism suggested by Browne and Murphy but with a different scheme for separating the X-ray luminosity into beamed and isotropic parts. He considered a subset of 34 quasars with $L_{rc}/L_{r, \text{ext}} > 10$ (selected from Browne & Murphy 1987) for which a significant correlation was found between $\log L_x$ and $\log L_{rc}$. Because the fit is dominated by beamed emission, the $\log L_x - \log L_{rc}$ relation suggests that there is a relation between the beamed X-ray and radio components. Following this method, we considered a sample of 19 gamma-ray loud blazars with $L_{rc}/L_{r, \text{ext}} > 10$ and found a correlation

$$\log \left(\frac{L_x}{\text{W Hz}^{-1}} \right) = (0.64 \pm 0.14) \log \left(\frac{L_{rc}}{\text{W Hz}^{-1}} \right) + 3.49. \quad (10)$$

Then we assumed that a relation

$$\log \left(\frac{L_x}{\text{W Hz}^{-1}} \right) = 0.64 \log \left(\frac{L_{rc}}{\text{W Hz}^{-1}} \right) + \log k \quad (11)$$

holds for all gamma-ray loud blazars, where k is a constant. In this sense, the total X-ray luminosity is given by

$$L_x = L_{xb} + L_{xu} = L_{xb} \left(1 + \frac{1}{R_{tx} g_x(\beta, \phi)} \right) \quad (12)$$

$$= k L_{rc}^{0.64} \left(1 + \frac{1}{R_{tx} g_x(\beta, \phi)} \right). \quad (13)$$

The two constants, $\log k = 3.48$ and $R_{tx} = L_{xb}(90 \text{ deg})/L_{xu} = 5.9 \times 10^{-3}$, were determined by minimizing $\Sigma [\log(L_x/L_x^{\text{obs}})]^2$ as in Browne & Murphy (1987) and Kembhavi (1993). For the specific case of AO 0235+16 we obtain (all specific luminosities expressed in units of W Hz^{-1}): $\log L_{rc} = 27.6$, $\log L_{r, \text{ext}} = 26.41$, $\log L_x = 21.97$, and $L_{xb}/L_{xu} = 1030$. This means that only a fraction $\sim 10^{-3}$ of the total X-ray flux can be attributed to the accretion disk. A detail discussion will be presented in a separating paper by Fan et al. (2003, in preparation).

3.2 Characterization of the Models

In order to make quantitative estimates for the possible binary systems we shall follow the analytical treatment of Becker & Kafatos (1995) to fix the mass of the accreting black hole¹. In particular we shall assume that the inner disk emission can be represented by models where the intensity has a dependency $I(E, R) \propto E^{-\alpha_x} R^{-\xi}$, where E is the photon energy and R is the radial distance on the disk ($R_{\text{min}} \leq R \leq R_0$). The parameter ξ characterizes the kind of the disk emission structure. A value $\xi = 3$ corresponds to two-temperature disks where electrons mainly cool through Compton losses and protons through Coulomb interactions (e.g., Shapiro et al. 1976). These disks have a flux with a nearly power-law dependence on the radius $F(R) \propto R^{-3}$ (as the Shakura-Sunyaev disks) and an X-ray power-law spectrum with an index

$$\alpha_x = -\frac{3}{2} + \sqrt{\frac{9}{4} + \frac{4}{y}} \quad (14)$$

in the source frame, where $y \sim 1$ is the Compton y parameter (e.g., Eliek & Kafatos 1983). A value $\xi = 0$ corresponds to models of uniform bright at X-rays (no dependence on R) with a single-temperature hot corona that cools by interactions with soft photons from an underlying cool disk (e.g., Liang 1979). We shall consider models with Schwarzschild or Kerr black holes, with disks of single or two temperatures, and different outer radii R_0 (the inner radii R_{min} corresponds to the last stable orbit in each kind of black hole). We label these models, following Romero et al. (2000b), from A to H. They are defined in Table 1. The radii are expressed in units of the gravitational radius $R_g = GM/c^2$. The extent of the X-ray emitting region is not well known. Typical values for R_0 are $\sim 30 R_g$ (e.g., Shapiro et al. 1976), but higher values are possible. We consider cases with $R_0 = 30 R_g$ and $R_0 = 100 R_g$.

3.3 Mass of the Accreting Black Hole

For each model in Table 1 we can now estimate the optical depth to pair creation for photons of energy E propagating through the accretion disk field

$$\tau_{x\gamma}(E_\gamma, z) = \int_z^\infty \alpha_{x\gamma}(E_\gamma, z_*) dz_*, \quad (15)$$

¹ Throughout this paper we assume a Hubble constant $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$, with $h = 0.75$, and a deceleration parameter $q_0 = 0.5$.

where $\alpha_{x\gamma}$ is the photon-photon absorption coefficient along the rotation axis of the disk (coincident with the jet that is nearly pointing to the observer). This coefficient can be calculated as in Becker & Kafatos (1995)—see also Cheng et al. (1999)—using the photon–photon cross section given by (e.g., Lang 1999)

$$\sigma(E_x, E_\gamma) = \frac{\pi r_0^2}{2}(1 - \zeta^2) \left[2\zeta(\zeta^2 - 2) + (3 - \zeta^4) \ln \left(\frac{1 + \zeta}{1 - \zeta} \right) \right], \quad (16)$$

where

$$\zeta = \left[1 - \frac{(m_e c^2)^2}{E_x E_\gamma} \right]^{1/2}, \quad (17)$$

$r_0 = 2.818 \times 10^{-13}$ cm is the classical electron radius, m_e its mass, and E_i the energy of the interacting photons.

For calculation purposes, we can write the disk X-ray intensity as

$$I(E_x, R) = I_0 \left(\frac{E_x}{m_e c^2} \right)^{-\alpha_x} \left(\frac{R}{R_g} \right)^{-\xi}. \quad (18)$$

Then, the differential absorption coefficient will be

$$d\alpha_{x\gamma} = \frac{I}{cE_x} \sigma(E_x, E_\gamma) (1 - \cos \Theta) dE_x d\Omega, \quad (19)$$

where Θ is the angle between $d\Omega$ and the direction of propagation of the γ -ray. When these rays propagate mainly along the rotation axis z , as is expected for jet beamed emission, we use Eq. (15) and introduce geometrical simplifications due to the axial symmetry. After some algebra, this yields

$$\tau_{x\gamma}(E_\gamma, z) \cong \frac{AR_g}{2\alpha_x + 3} \left(\frac{z}{R_g} \right)^{-2\alpha_x - 3} \left(\frac{E_\gamma}{4m_e c^2} \right)^{\alpha_x}. \quad (20)$$

Here,

$$A \equiv \frac{\pi I_0 \sigma_T \Psi(\alpha_x)}{(2\alpha_x + 4 - \xi)c} \left[\left(\frac{R_0}{R_g} \right)^{2\alpha_x + 4 - \xi} - \left(\frac{R_{\min}}{R_g} \right)^{2\alpha_x + 4 - \xi} \right], \quad (21)$$

with σ_T the Thomson cross section, and $\Psi(\alpha_x)$ a function plotted in fig. 1 of Becker & Kafatos (1995) ($\Psi(\alpha_x) \approx 0.18$ for AO 0235+16). The intensity I_0 can be estimated from the observed X-ray flux, F_{keV} , by equation (5.1) of the same paper along with the condition imposed by our Eq. (13).

Since it is an observational fact that AO 0235+16 emits photons with energies $E = 1$ GeV (Hartman et al. 1999) we can impose the condition $\tau_{x\gamma} \sim 1$ for photons of such energy. This condition along with an independent estimate of the size of the gamma-ray emitting region obtained from high-energy variability observations allows us to estimate the mass of the accreting black hole through Eq. (20). Note that the mass of the central black hole determines the gravitational radius R_g . The constraint on the size of the γ -spheres is

$$z_\gamma \leq ct_v \frac{\delta}{1 + z} \quad \text{cm}. \quad (22)$$

For AO 0235+16, $t_v \sim 3$ days (Fan et al. 2000). The Doppler factor δ of the underlying jet flow is unknown. It should be significantly smaller than the extreme Doppler factor inferred

for the superluminal component, which are usually interpreted as relativistic perturbations or shocks propagating downstream. Fan et al. (2000) estimated a value $\delta \sim 2$. Madejski et al. (1996) gave a higher value $\delta \geq 3.1$. Zhang et al. (2002) suggested $\delta = 8.9$. We perform our calculations for three different values: $\delta = 2$, $\delta = 5$, and $\delta = 10$.

Table 1 Models for the Accreting Black Hole in AO 0235+16

Model	BH Type	Disk Type	R_0/R_g
A	Schwarzschild	$\xi = 3$	100
B	Schwarzschild	$\xi = 0$	100
C	Schwarzschild	$\xi = 3$	30
D	Schwarzschild	$\xi = 0$	30
E	Kerr	$\xi = 3$	100
F	Kerr	$\xi = 0$	100
G	Kerr	$\xi = 3$	30
H	Kerr	$\xi = 0$	30

The results of our estimates of the mass of the accreting black hole are shown in Tables 2–4. The obtained values for the different models range from $3 \times 10^8 M_\odot$ (e.g., models B and F for $\delta = 2$) up to $\sim 17 \times 10^9 M_\odot$ (model G for $\delta = 10$). The mass we obtain here for the case considered by Fan et al. (2000) –model C in Table 2– is higher because of the refinement introduced in this paper with the separation of the isotropic and beamed X-ray components.

We turn now to the secondary black hole mass and the orbital parameters in order to establish at least an upper bound on them.

3.4 Mass of the Secondary

A close supermassive black hole system will lose energy by gravitational radiation and these losses will affect the orbital parameters. Hence, the errors in the determination of any periodic signal related to the orbital motion should impose an upper bound on these losses. From the work by Fan et al. (2002) we find that in the case of AO 0235+16, $\Delta T_m/T_m \sim 0.05$. The orbit of the binary will decay on a timescale of (e.g., Shapiro & Teukolsky 1983)

$$\tau_0 = |r/\dot{r}| \sim \frac{5}{256} \frac{c^5}{G^3} \frac{r_m^4}{(m+M)^2 \mu}, \quad (23)$$

where $\mu = mM/(m+M)$. We rewrite the orbital radius given by Eq. (2) as

$$r_m \approx 1.4 \times 10^{16} (m_8 + M_8)^{1/3} \text{ cm}. \quad (24)$$

Here we have used $T_m = 3 \text{ yr}$ and the masses are expressed in units of $10^8 M_\odot$. With this, Eq. (23) becomes

$$\tau_0 \approx 2.8 \times 10^5 \frac{(m_8 + M_8)^{1/3}}{m_8 M_8} \text{ yr}. \quad (25)$$

The relative constancy of the period found by Fan et al. (2002) implies that $\tau_0 > 10^3 \text{ yr}$, which translates into a maximum possible value of the secondary black hole mass. Equation (24) then imposes a maximum value to r_m . For calculation purposes we adopt $\tau_0 = 10^3 \text{ yr}$ (in the source frame) in order to obtain upper limits for parameters. Shorter timescales are unlikely since the system would be in the final steps before the merger and other observational consequences should then be manifest (like a tidal disruption of the disk, which is contradicted by

the observation of a persistent jet). The resulting values for both m and r_m are shown in the third and fourth columns of Tables 2–4.

Table 2 Results for Different Models with $\delta = 2$

Model ($\delta = 2$)	M ($10^8 M_\odot$)	m^{\max} ($10^8 M_\odot$)	r_m^{\max} (10^{16} cm)	r_d/r_m^{\max}
A	6.0	320.7	10.0	0.20
B	3.0	898.1	14.0	0.11
D	9.9	153.7	7.9	0.32
E	9.4	163.8	8.1	0.30
F	3.0	893.6	14.0	0.11
G	23.1	50.2	6.0	0.67
H	10.0	151.5	7.9	0.32

Table 3 Results for Different Models with $\delta = 5$

Model ($\delta = 5$)	M ($10^8 M_\odot$)	m^{\max} ($10^8 M_\odot$)	r_m^{\max} (10^{16} cm)	r_d/r_m^{\max}
A	18.7	64.7	6.3	0.16
B	9.4	164.8	8.1	0.09
C	44.4	25.7	6.0	0.38
D	31.0	36.4	5.9	0.26
E	30.0	38.2	5.9	0.25
F	9.4	164.8	8.1	0.09
G	72.7	17.1	6.5	0.65
H	31.3	36.0	5.9	0.27

Table 4 Results for Different Models with $\delta = 10$

Model ($\delta = 10$)	M ($10^8 M_\odot$)	m^{\max} ($10^8 M_\odot$)	r_m^{\max} (10^{16} cm)	r_d/r_m^{\max}
A	44.4	25.7	6.0	0.15
B	22.3	35.8	5.6	0.09
C	106.0	12.8	7.1	0.38
D	73.7	16.9	6.5	0.26
E	70.5	17.5	6.4	0.25
F	22.3	35.8	5.6	0.09
G	173.0	9.1	8.2	0.66
H	74.5	16.7	6.5	0.28

4 ANALYSIS OF THE RESULTS

Uniform disk precession will occur in the scenario here discussed only if the sound crossing time through the disk is considerably shorter than the characteristic precession period induced by the secondary. This allows the bending waves (which propagates at a velocity $v \sim c_s$ through the disk) to efficiently couple the different parts of the fluid in order to adjust the precession rate to a constant value (Papaloizou et al. 1998). This was confirmed by the numerical simulations performed by Larwood et al. (1996).

The radius r_d of the precessing part of the disk is related to the disk angular velocity ω_d by $\omega_d = (GM/r_d^3)^{1/2}$. Then, using Eq. (1) with the observational fact that $\cos\theta \sim 1$ (Fujisawa et al. 1999), we can establish the ratio $\kappa = r_d/r_m$ for each model. Only models for which κ is significantly smaller than 1 can display uniform, nearly rigid precession in their inner accretion disks (e.g., Katz 1973; Larwood 1998). Since we have only an upper bound to the mass of the secondary black hole, we plot the curves $\kappa = \kappa(m)$ for all models whose primary masses are listed in Tables 2–4. These curves are presented as Figs. 2–4. The value of κ corresponding to the largest possible value of r_m is given in the last column of Tables 2–4.

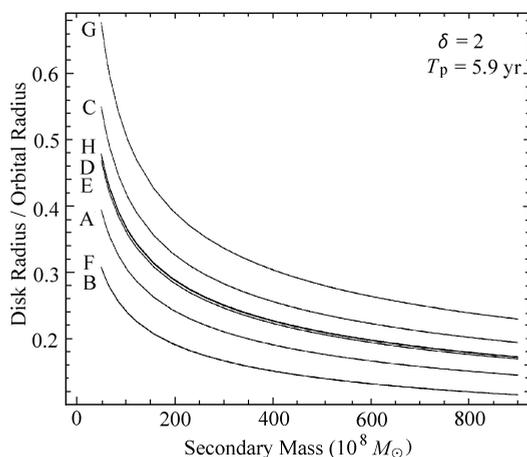


Fig. 2 Ratio of the precessing disk to orbital radius as a function of the secondary black hole mass for the different primary models defined in Table 1. The jet Doppler factor is 2 and the precessing period in the source frame is 5.9 yr.

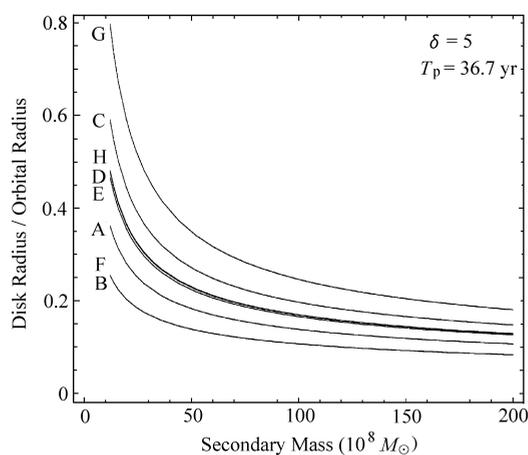


Fig. 3 Same as Fig. 2 but for a jet Doppler factor of 5. The corresponding precessing period in the source frame is 36.7 yr.

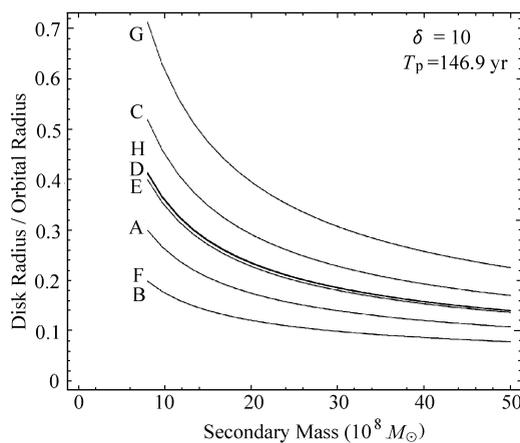


Fig. 4 Same as Fig. 2 but for a jet Doppler factor 10. The corresponding precessing period in the source frame is 146.9 yr.

From Fig. 2 to Fig. 4 we see that models with single temperature disks and large outer radii (models F and B) are more prone to display uniform precession. Models with $\delta = 10$ in general imply $M > m$. Nonetheless, some models with $\delta = 2$ and 5 are possible with $m > M$. We cannot exclude these models based only on a priori considerations. It is possible to imagine, for instance, that the original merger that resulted in the formation of the binary system occurred between an active blazar and a “dormant” quasar with a very massive central object that already swallowed up all available gas. Deep observations of the host galaxy can shed some light on this particular point. The detection of peculiar Fe K α line profiles can be used to test whether the secondary has or not associated an accretion disk (Yu & Lu 2001).

The sound speed in the disk of the primary can be approximated by $c_s \sim H\omega_d$, with H the disk half-thickness. In the inner disk, the constraint of efficient physical communication in the fluid imposes $c_s > \Omega_p r_d$. Then, we have that in this region

$$H > \frac{\Omega_p}{\sqrt{GM}} r_d^{5/2}. \quad (26)$$

In our models for AO 0235+16 we found $H \geq 5 \times 10^{12}$ cm.

5 ADDITIONAL COMMENTS

Precessing jet models are not the only kind of models based on binary black hole systems that can explain periodic behavior in AGNs. Other alternatives are orbital motion of a secondary black hole with an associated jet (e.g., Rieger & Mannheim 2000; De Paolis et al. 2002), accretion disk instabilities (Fan et al. 2001 and reference therein), and pair jets (Villata et al. 1998). The main difference between these models and the precessing jet model is that the latter implies the precession of the innermost part of the accretion disk.

Compton reflection of hard X-ray emission in the cold, outer material can be expected in these kind of systems. The iron K α line should change in the observer frame, oscillating around an average value with a period $\sim \Omega_p$. Periodic changes in the intensity of the line with amplitudes up to $\sim 30\%$ should also be observable (Torres et al. 2003). Although the detection of the iron K α line in AO 0235+16 is beyond the current sensitivity of X-ray observatories, future space missions like Constellation-X, with its superb spectral resolution and sensitivity might detect the line and its oscillation, then providing a tool to probe the nature of the periodic phenomena in this blazar, and the particular kind of models discussed here.

6 CONCLUSIONS

We have analyzed the feasibility of precessing disk models for a binary black hole system in the extremely variable BL Lacertae object AO 0235+16. We presented an improved determination of the black hole mass of the accreting object in the system. We have also determined values and bounds to all other relevant parameters in the system. We found that, if the periodic activity recently reported for this object is based on jet precession induced by the gravitational torque of the companion black hole on the disk, then a large variety of models are possible, including models where either the mass of the primary is larger than the mass of the secondary or vice versa. If the Doppler factor of the relativistic flow is ~ 10 , as suggested by some authors, then $M > m$ for almost all possible models. We emphasize, however, that the ultimate nature of the central engine in this violent blazar remains an open problem. The models here

proposed can be tested through some simple predictions for the periodic behavior of the Fe K α line. Hopefully, future observational constraints from long-term multifrequency monitoring and space X-ray observations will help to unveil the source of the periodic events reported for AO 0235+16.

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