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A MASSIVE BINARY BLACK HOLE IN 1928+738?

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ABSTRACT

We apply the binary black hole model to explain the wiggles in the milliarcsec radio jet of the superluminal quasar 1928+738 (4C 73.18) observed with VLBI at 1.3 cm wavelength by Hummel et al. The period and amplitude of the wiggles can be explained as due to the orbital motion of a binary black hole with mass of order 10^8 $M_\odot$, mass ratio larger than 0.1, and orbital radius $\sim 10^{16}$ cm. The jet's inclination to the line of sight should be small confirming the standard interpretation of superluminal motion and one-sidedness as due to relativistic motion in a direction close to the line of sight. The small orbital radius suggests that the binary has been losing a significant amount of orbital energy during the last 10^7 yr, possibly by interaction with the matter which is flowing through the active galactic nucleus. The arcsec-scale radio structure provides additional support for a link between activity and binary evolution. If our interpretation of the mass wiggle in this quasar is correct, then many other quasars may contain massive binary black holes as well.

Subject headings: galaxies: interactions — galaxies: jets — quasars: individual (1928+738)

1. INTRODUCTION

Galaxy mergers must have been a common phenomenon especially during the collapse and virialization of rich groups and clusters of galaxies. These mergers lead to the formation of massive binary black holes in galactic nuclei if black holes of 10^{7-9} $M_\odot$ are formed in the nuclei of most bright galaxies at redshifts of about 2.

The orbital evolution of a binary black hole has been discussed by Begelman, Blandford, & Rees (1980, hereafter BBR; see also Roos 1981). In a relaxed stellar system the binary quickly loses energy by interactions with stars and finally settles at a minimum separation $r_{1c} \sim 0.1 r_h = 0.1 GM/\sigma^2$, where M is the mass of the primary black hole, σ is the velocity dispersion of the stars in the galaxy, G is the gravitational constant, and r_h is the cusp radius of the star distribution around the hole. Further evolution of the binary is impeded by the formation of a loss-cone in the velocity distribution of the stars around the binary. Subsequent periods of central activity, perhaps triggered by subsequent mergers, may allow the binary to lose orbital energy again by interacting with the new supplies of stars and/or gas that are fed into the nucleus (Roos 1988). As a result the binary might coalesce while a new wide binary is formed during the final stages of the merger event.

The above considerations leads one to suspect that many (active) galactic nuclei might contain a massive binary black hole (MBBH). This provides a good stimulus to look for observational phenomena which could be attributed to the presence of a MBBH, such as (Lens-Thirring) precession of a jet emitted by one of the binary components (BBR), wiggling of a jet due to the orbital motion (Kaastra & Roos 1992), blue- or redshift of a broad-line region bound to one of the holes (Gaskell 1983), and periodic variations in the luminosity due to perturbation of an accretion disk around one of the holes (Sillanpää et al. 1988). Recently Hummel et al. (1992) have reported the discovery of sinusoidal motion in the milliarcsec jet of the superluminal quasar 1928+738 (4C73.18). VLBI maps of the jet observed at six epochs from 1985.1 to 1989.7 (Fig. 1) could be modeled by an oscillating jet with an oscillation period of 2.9 yr. In the present paper we show that the observations are consistent with a modulation of the jet *direction* due to the orbital motion of a 10^8 $M_\odot$ binary with orbital radius 10^{16} cm. We also discuss some implications of this result for the evolution of MBBHs in AGNs.

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2. MODELING THE WIGGLES IN 1928+73

1928+73 is a quasar at a redshift $z = 0.3$ with bolometric luminosity of order 10^{46} h^{-2} ergs s^{-1}, where h is Hubble's constant in units of 100 km s^{-1} Mpc^{-1} (Hummel et al. 1992). A 20 cm arcsec-scale VLA map shows a two-sided lobe structure (in the NE and SW direction) around a strong core centered on the optical source. The total extent of the resolved extended radio structure is 220 h^{-1} kpc ($\sim 80''$). Observations of the milliarcsec core of 1928+738 using VLBI at different wavelength reveal a one-sided core-jet structure. The jet contains components which appear to move southward with velocities of $\sim 5c$. Hummel et al. (1992) have monitored this source using VLBI at 1.3 cm during 5 yr. They find that the jet exhibits ballistic superluminal motion along a sinusoidally curved jet ridge line. They found a good fit to their observations using a sine wave model with wavelength $\lambda \sim 1.06$ mas, amplitude $A \sim 0.09$ mass, and a phase shift $\mu \sim 0.28$ mas yr^{-1}. The observed phase shift implies an apparent jet velocity of $3.3c$ h^{-1} for a flat universe ($\Omega = 1$). The observed period λ/μ is related to a proper period P in the rest frame of the quasar by $\lambda/\mu = P(1+z)$, yielding $P = 2.9$ yr.

It seems highly unlikely that this rapid periodic motion would be due to geodetic precession of the spin axis of the hole emitting the jet. The precession period for a binary with mass ratio m/M and separation $r_{16} = r/10^{16}$ cm is given by

$$t_{\rm prec} = 600 r_{16}^{5/2} M_8^{-3/2} (M/m) \text{ yr} . \quad (1)$$

where $M_8 = M/10^8$ $M_\odot$. The time scale for loss of orbital energy via emission of gravitational waves is given by

$$t_{\rm grav} = 2.9 \times 10^5 (M/m) M_8^{-3} r_{16}^4 \text{ yr} . \quad (2)$$

A precession period of only 3 yr would imply a gravitational lifetime for the binary which is extremely short.

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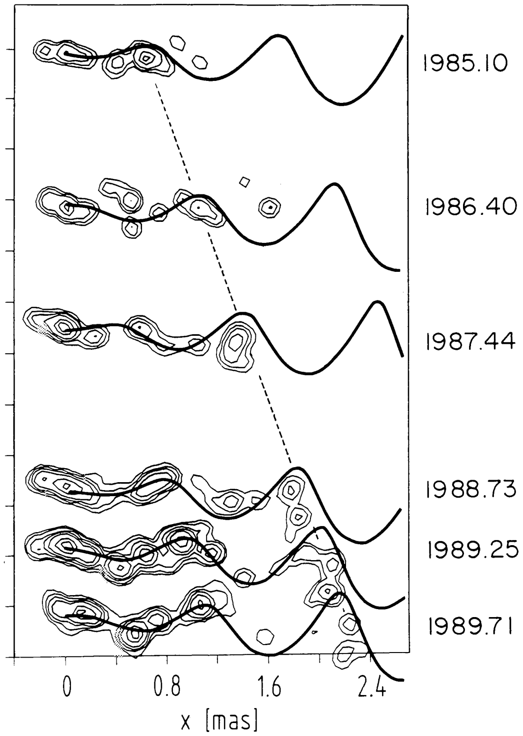

FIG. 1.—Model of a precessing relativistic jet superposed on the "super-resolution" VLBI maps (at 1.3 cm, 0.1 mas Gaussian restoring beam) of the jet in the superluminal quasar 1928+738 (4C73.18), obtained at six different epochs by Hummel et al. (1992, see their Fig. 10). The oscillation is not due to geodetic precession of the spin axis of the hole which emits the jet, but to the orbital motion of the hole. The jet material moves along straight trajectories with velocity $v_{\rm jet} = 0.95c$ and mean inclination to the line of sight $i = 15°$. The opening half-angle of the precession cone is $\psi^{\rm intr} = 2°$. The orbital period is 3.2 yr, and the orbital phase at epoch 1989.71 was 75°.

It is more realistic to assume that the observed period is associated with the orbital motion of a binary with separation

$$r_{16} = 1.4(M_8 + m_8)^{1/3}\left(\frac{P}{3\ \rm yr}\right)^{2/3} . \quad (3)$$

We assume that the jet ejecta move on ballistic orbits with velocity $v_{\rm jet} = \beta c$, where c is the light speed. The orbital motion of the hole from which the jet is emitted causes a wiggle which is due to both the motion of the jet origin and the periodic variation of the jet velocity. When we ignore the orbital component of the jet velocity ($v_{\rm orb} \ll v_{\rm jet}$, where $v_{\rm orb}$ is the orbital velocity of the hole emitting the jet), the jet direction is fixed, and the jet material moves on a cylinder surface. As a result the observed wiggle follows a sinusoidal pattern. The wavelength of the wiggle is given by the product of the (observed) binary period and the apparent jet velocity, $v_{\rm app} = \beta c \sin i/(1 - \beta \cos i)$, where i is the angle between the jet and the observer's line of sight, and the amplitude is given by the orbital radius multiplied by a projection factor $1 > f(\theta, i) > (1 - \cos\theta)$, where θ is the angle between the orbital angular momentum and the line of sight ($|\theta| < \pi/2$). In order to quantify the transverse digressions of the jet we may determine the ratio of the amplitude of the wiggle over $\frac{1}{4}\lambda$, which is easily shown to be

$$\frac{4A}{\lambda} = \frac{2}{\pi}\frac{v_{\rm orb}}{v_{\rm jet}}\frac{(1 - \beta\cos i)}{\sin i} f(\theta, i) . \quad (4)$$

The wiggles in 1928+738 cannot be due to such variations in the position of the origin, since a wiggle with $4A/\lambda$ of about 0.4 would imply that the orbital velocity of the binary is comparable to the apparent jet velocity which is larger than the speed of light.

When we add the orbital velocity of the hole to the jet velocity, the cylinder becomes a cone over which the velocity vector of the jet precesses with period equal to the binary period. The (intrinsic) opening half-angle of the cone can be approximated by $\sin \psi^{\rm intr} = v_{\rm orb} \cos\chi/v_{\rm jet}$ for $v_{\rm orb} \ll v_{\rm jet} \sim c$, where χ is the angle between the orbital angular momentum and the jet velocity. For small $\psi^{\rm intr} < i$, the observed opening angle $\psi^{\rm obs}$ is related in a simple way to the intrinsic (deprojected) opening angle by

$$\psi^{\rm obs} \approx \frac{\psi^{\rm intr}}{\sin i} = \frac{v_{\rm orb}}{v_{\rm jet}}\frac{\cos\chi}{\sin i}\ \text{rad} . \quad (5)$$

Comparing the ratios in equations (4) and (5) shows that when the jet is moving with about the speed of light in a direction close to the line of sight, the wiggles due to the variations in jet direction are more important than the sinusoidal wiggles due to variations in the position of the origin. Inserting

$$\frac{v_{{\rm orb},M}}{c} = 0.038 r_{16}^{-1/2} M_8^{1/2}\left(\frac{m}{M}\right)\left(\frac{M+m}{M}\right)^{1/2} \quad (6)$$

for the orbital velocity of the most massive hole in equation (5), where m is the mass of the smaller hole, we find for a circular orbit

$$\psi^{\rm obs} = 2.^{\circ}2 r_{16}^{-1/2} M_8^{1/2}\left(\frac{m}{M}\right)\left(\frac{M+m}{M}\right)^{1/2}\frac{\cos\chi}{\beta\sin i} . \quad (7)$$

Note that the factor m/M drops from the equation in case the jet is emitted by the secondary hole, or, more generally, in case the extra periodic component to the jet velocity is equal to the Kepler velocity at a distance r from the (primary) hole.

In Figure 1 we have drawn the path of a relativistic ballistic jet ($\beta = 0.95$), which precesses over a cone with $\psi^{\rm intr} = 2°$, $i = 15°$, and $P = 3.2$ yr ($h = 1$). These values represent good guesses rather than a best fit to the model.

We may use equations (7) and (3) to obtain an estimate of i, yielding

$$i \approx 15°\beta^{-1}\cos\chi\left(\frac{P}{3\ \rm yr}\right)^{-1/3} \times \left(\frac{\psi^{\rm obs}}{8°}\right)^{-1} M_8^{1/3}\left(\frac{m}{M}\right)\left(\frac{M+m}{M}\right)^{1/3} . \quad (8)$$

The standard interpretation of superluminal velocities involves relativistic motion in directions close to the line of sight. Apparent velocities of $4c$ to $6c$ as are observed in 1928+738 imply inclinations smaller than 30° to 20°, respectively. The small inclination to the line of sight inferred from the wiggle in 1928+738 using equation (8) is consistent with this interpretation of superluminal motion.

Equation (8) can also be used to argue that $m/M \gtrsim 0.1$ when the jet wiggle is due to the orbital motion of the primary hole, because otherwise i would have to be very small and we would be dealing with a very exceptional object. For instance, only about 2% of all superluminal sources with $\beta_{\rm app} = 5$ (implying $\sin i \sim \frac{1}{5}$) are expected to have inclination $i \lesssim 1°$. A similar statistical constraint can be obtained by considering the life-

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time of a binary black hole determined by the energy loss via gravitational radiation given in equation (2). Using equations (3) and (8) we find

$$t_{\rm grav} \approx 10^6 M_8 (m/M)^7 (i/15°)^{-8} (\psi/8°)^8 \beta^{-8} \cos^8 \chi \text{ yr} . \quad (9)$$

This also shows that (m/M) cannot be too small or else the binary lifetime (or the inclination) becomes so small that the chance to observe such a system would become unacceptably low.

If the wiggles in the mas jet of 1928+738 are due to the orbital motion of a massive binary, the mean direction of the jet should perform Lense-Thirring (or geodetic) precession around the orbital angular momentum of the binary with period of order 10^3 yr (eq. [1]). This is an important prediction of the model which might be checked in the next decennia. The precession pattern should be discernible on a scale $\sim 0.1\, h\beta_{\rm app}(t_{\rm prec}/10^3 \text{ yr})$ arcsec. Careful monitoring of the mas jet should show a change in the mean position angle of the jet by a few degrees in about $10(M/m)$ yr. Unfortunately the data collected so far do not yet allow a determination of such a small change in mean position angle.

3. BINARY EVOLUTION AND ACTIVITY

The putative binary black hole in 1928+738 is a relatively short-lived phenomenon. Its orbital period implies a gravitational radiation time scale of only $10^6 (M/m) M_8^{-5/3}$ yr. We are observing the binary hole in a rather special moment in its lifetime. The fact that this short phase of rapid orbital evolution occurs simultaneously with an active period of the galactic nucleus strongly suggests a causal relation between central activity and binary evolution. It seems plausible that both are driven by the flow of large amounts of matter into the nucleus of the host galaxy as suggested by Roos 1988).

What process could have been responsible for the evolution of the binary from a separation of $r_{\rm lc} \sim 10^{17}$–10^{18} cm to its present radius? Note that if the characteristic time scale for the process we are looking for would exceed the present gravitational radiation time scale by a large factor, it would make the binary in 1928+738 a very exceptional object. Emission of gravitational radiation seems ruled out since its evolution time scale increases with r^4. Adiabatic contraction of the binary orbit due to growth of the primary hole (Mr constant) also seems too slow. The evolution time is given by $t_{\rm ev}^{\rm ad} = M/\dot{M}$. The accretion rate $\dot{M}$ is related to the bolometric luminosity of the quasar L by

$$\dot{M} = 1\ M_\odot \text{ yr}^{-1} \left(\frac{L}{6 \times 10^{45} \text{ ergs s}^{-1}} \right) \eta_{0.1}^{-1} , \quad (10)$$

where $\eta_{0.1} = \eta/0.1$ is the mass to energy conversion efficiency. Note that it takes already $10^9 M_8$ yr for the orbital radius to shrink by a factor 10 when the primary grows by $1\ M_\odot \text{ yr}^{-1}$.

A third possibility is slingshot interaction of the binary with stars passing through the binary orbit. When the nucleus is perturbed, for instance, during the late stages of a merger with another galaxy, loss-cone orbits can be repopulated. The large amounts of stars (and gas) that are flowing through the nucleus may then cause a rapid evolution of the binary, while a small fraction of the inflowing mass may be accreted by the hole causing the observed quasar activity (Roos 1988). The mean fraction of orbital energy of the binary that is carried off by a (low-velocity) star of mass m^* passing through the binary orbit is $C2m^*/(M + m)$, where the constant C depends on the orbital parameters of the stars and the binary and has a value between 1 and 10. The evolution time of the binary is now $t_{\rm ev} = (M + m)/2C\dot{M}_{\rm bin}$, where $\dot{M}_{\rm bin}$ is the amount of mass that is flowing through the binary orbit. Assuming an isotropic velocity distribution for the stellar system around the binary, we find for the stellar mass flow through the binary orbit with size r

$$\dot{M}_{\rm bin}(r) = \frac{M^*_{\rm cusp}}{2t_h} \frac{r}{r_h}$$

$$= 0.33 r_{16} M_8^{-1} \sigma_{200}^5 \left(\frac{M^*_{\rm cusp}}{M} \right) M_\odot \text{ yr}^{-1} , \quad (11)$$

where $M^*_{\rm cusp}$ is the mass of stars within the cusp radius r_h, $t_h = r_h/\sigma$ is the dynamical time in the cusp, and σ_{200} is the velocity dispersion of stars around the cusp in units of 200 km s^{-1}. It is clear that this mass flow can be much larger than $\dot{M}$, and the evolution time shorter than $t_{\rm ev}^{\rm ad}$ when the binary is surrounded by a high-density cusp of stars ($M^*_{\rm cusp} \sim M$) with isotropic velocity distribution. The evolution time is now

$$t_{\rm ev} \sim 1.5 \times 10^8 C^{-1} r_{16}^{-1} M_8^2 \sigma_{200}^{-5} \left(\frac{M}{M^*_{\rm cusp}} \right) \text{ yr} . \quad (12)$$

Hills (1983) has done a numerical study of the evolution of a massive binary in a background of low-velocity stars. Comparing equation (12) with the expression given by Hills (his eq. [37]) yields $C \approx 6$. The binary evolution slows down as the binary orbit shrinks until $t_{\rm ev}$ reaches a maximum at a radius $r_{\rm grav}$ given by $t_{\rm grav} = t_{\rm ev}$, where loss of orbital energy by emission of gravitational waves becomes dominant. This radius is given by

$$r_{\rm grav,16} = 2.4 M_8 \sigma_{200}^{-1} \left(\frac{m}{M^*_{\rm cusp}} \right)^{1/5} . \quad (13)$$

The conclusion from these considerations is that during the final stage of a merger event a preexisting wide binary with orbital radius $\sim r_{\rm lc} \sim 0.1 r_h$ suddenly starts losing orbital energy by slingshot interactions with stars that are scattered into the binary orbit. The binary quickly becomes a close binary with radius $\sim r_{\rm grav}$. This suggests that most MBBHs have orbital radii equal to either $r_{\rm lc}$ or $r_{\rm grav}$ where the binary evolution time is maximal. The lifetime of close binaries could be similar to the duration of the active period of the quasar. Close binaries with radii of order $r_{\rm grav}$ are expected in AGNs with large accretion rates. It is intriguing that the radius given by equation (13) agrees very well with the radius inferred from the wiggle period in 1928+738 and also with the periods claimed in OJ 287 (Sillanpää et al. 1988) and in 3C 120 (Webb 1990).

The evolution of the binary may have left its traces in the arcsec-scale radio structures of 1928+738. When the binary was still wide, having separation $r_{\rm lc} \sim 0.1 r_h \sim 3 \times 10^{18} M_8$ cm, the (geodetic) precession period was too long to produce an observable change in the orientation of the arcsec jet. Supposing that $t_0 \sim 10^7$ yr ago the binary suddenly started to lose orbital energy (on a time scale given by eq. [13]), we would expect a transition from a straight large-scale jet to a precessing jet at a distance smaller than 1100 $h\beta_{\rm app}(t_0/10^7 \text{ yr})$ arcsec from the core. A precession pattern, however, can only form when the precession period becomes smaller than the binary evolution time, yielding a characteristic precession period $t_{\rm prec} \sim 4 \times 10^6 M_8 (M/m)^{2/7} (C^{-1} \sigma_{200}^{-5} M/M^*_{\rm cusp})^{5/7}$ yr. A similar

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precession period of order 10^6 yr was indeed inferred from the arcsec radio structure of 1928+738 by Hummel et al. (1992).

The presence of a secondary black hole in an AGN is likely to affect the flow of matter in AGNs. It might help the accretion of matter onto the primary hole by perturbing the accretion disk around the hole, but it could also perturb and perhaps cut off or reverse the flow of matter into the nucleus (outside the binary orbit). Such effects certainly deserve further study. The optical spectrum of 1928+738 looks quite normal (e.g., Lawrence et al. 1987). We feel that this cannot be used as an argument against the presence of a MBBH in this quasar because a MBBH may be a normal phenomenon in an active galactic nucleus.

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