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Double–double radio galaxies: remnants of merged supermassive binary black holes

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ABSTRACT

The activity of active galaxies may be triggered by the merging of galaxies, and present-day galaxies are probably the product of successive minor mergers. The frequent galactic mergers at high redshift imply that active galaxies harbour supermassive unequal-mass binary black holes at their centre at least once during their lifetime. The secondary black hole interacts and becomes coplanar with the accretion disc around the primary, inwardly spiralling toward their mass centre owing to the loss of orbital angular momentum to the disc mass outside the orbit of the secondary and/or to gravitational radiation. The binary black holes finally merge and form a more massive (post-merged) black hole at the centre. In this paper it is shown that the recently-discovered double-lobed FR II radio galaxies are the remnants of such supermassive binary black holes. The inwardly spiraling secondary black hole opens a gap in the accretion disc that increases with time when the loss of the orbital angular momentum via gravitational radiation becomes dominant. When the supermassive black holes merge, the inner accretion disc disappears and the gap becomes a big hole of several hundreds of Schwarzschild radii in the vicinity of the post-merged supermassive black hole, leading to an interruption of jet formation. When the outer accretion disc slowly refills the big hole on a viscous time-scale, jet formation restarts and the interaction of the recurrent jets and the inter-galactic medium forms a secondary pair of lobes. The model is applied to a particular double-lobed radio source – B1834+620 – which has an interruption time-scale ∼1 Myr. It is shown that the orbit of the secondary in B1834+620 is elliptical with a typical eccentricity $e \simeq 0.68$ and that the ratio q of the mass of the secondary to that of the primary is $0.01 \lesssim q \lesssim 0.4$. The accretion disc is a standard α-disc with $0.01 \lesssim \alpha \lesssim 0.04$ and the ratio of disc half height H to radius r is $\delta \simeq 0.01$. The model predicts that double-lobed radio structures form only in FR II or borderline FR I/FR II radio galaxies and that the detection rate of double-lobed radio sources among FR II radio sources is about one per cent.

Key words: accretion, accretion discs – black hole physics – galaxies: active – galaxies: individual: B1834+620 – galaxies: jets – radio continuum: galaxies.

1 INTRODUCTION

Active galactic nuclei (AGNs) consist of a supermassive black hole surrounded by an accretion disc, continuously supplying energy to the extended radio lobes via narrow and relativistic plasma jets. Prominent and continuous large-scale extra-galactic radio jets have been clearly detected in 661 radio sources (Liu & Zhang 2002). Among the extra-galactic radio sources, about ten FR II radio galaxies (Fanaroff & Riley 1974) are very peculiar and consist of a pair of symmetric double-lobed radio structures with one common centre and two extended and edge-brightened inner radio lobes (Schoenmakers et al. 2000a,b; Saripalli, Subrahmanyan & Udaya Shankar 2002). The inner structure has an axis well aligned with the outer lobes and a relatively lower luminosity. These radio sources are called double–double radio galaxies (DDRGs) and their structures are most likely to be due to the interruption and restarting of jet formation in the central engine with an interruption time of the order of Myr (Schoenmakers et al. 2000a). Interruption- and recurrent-jet phenomena are also detected in some non-DDRG radio sources, e.g. 3C 288 (Bridle et al. 1989), 3C 219 (Clarke et al.

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1992), B1144+352 (Schoenmakers et al. 1999), and the compact symmetric object (CSO) B0108+388 (Baum et al. 1990; Owsianik, Conway & Polatidis 1998).

While the evolution of recurrent jets in the intergalactic medium (IGM) has been investigated in some detail (Clarke & Burns 1991; Reynolds & Begelman 1997; Kaiser, Schoenmakers & Röttgering 2000), the mechanism to interrupt and restart the jet formation in the centre of AGNs is unclear. The proposed scenarios in the literature include a passive magnetic field model (Clarke et al. 1992), internal instability in the accretion disc due to radiation-pressure-induced warping (Pringle 1997; Natarajan & Pringle 1998), and a large fraction of gas left by the secondary galaxy in a merging or colliding galaxy system (Schoenmakers et al. 2000a). However, the passive magnetic field model is not consistent with the observations of the DDRG source B1834+620 (Lara et al. 1999). The the internal warping instability is likely to change the direction of the jet considerably (Natarajan & Pringle 1998). The falling or colliding gas model has difficulty in explaining the abrupt interruption and restarting of jet formation and is not consistent with the lack of observational evidence for galaxy interaction in DDRGs.

It was found recently that the central black hole masses in active and inactive galaxies have tight correlations with the central velocity dispersions (e.g. Gebhardt et al. 2000; Merritt & Ferrarese 2001a,b) and the bulge luminosities (e.g. Magorrian et al. 1998; McLure & Dunlop 2002) of the host galaxies. These relations imply that the activity of AGNs may be triggered by galaxy merging, and that present-day galaxies are probably the product of successive minor mergers (Haehnelt & Kauffman 2000; Kauffmann & Haehnelt 2000; Menou, Haiman & Narayanan 2001). The frequent galactic mergers at high red-shift imply that active galaxies harbour supermassive unequal-mass binary black holes at their centre at least once in their lifetime. Supermassive binary black holes may have been observed, e.g. in the BL Lac object OJ287 (Sillanpää et al. 1988; Liu & Wu 2002). Once the supermassive binary black holes form, the secondary interacts with the gas in the circumbinary accretion disc and becomes coplanar, sinking towards the mass centre and merging owing to the loss of orbital angular momentum to the disc mass outside the orbit and/or to gravitational radiation (Goldreich & Tremaine 1980; Lin & Papaloizou 1986; Pringle 1991; Artymowicz 1992; Artymowicz & Lubow 1994; Syer & Clarke 1995; Scheuer & Feiler 1996; Ivanov, Papaloizou & Polnarev 1999; Narayan 2000; Gould & Rix 2000; Armitage & Natarajan 2002; Zhao, Haehnelt & Rees 2002). We show in this paper that DDRGs are the remnants of binary–disc interactions and the coalescence of supermassive binary black holes. As the interaction between the secondary and an advection-dominated accretion flow (ADAF) is negligible (Narayan 2000), we consider only a standard thin α-disc (Shakura & Sunyaev 1973) or a slim disc (Abramowicz et al. 1988) and assume that the rotating primary black hole aligns with the accretion disc due to the Lense–Thirring effect (Scheuer & Feiler 1996; Natarajan & Pringle 1998). We consider an elliptical binary system of initial semimajor axis $a \sim 10^3\ r_{\rm G}$, where shrinking of the binary separation is driven by viscous loss of the angular momentum of the secondary to the outer accretion disc. Here $r_{\rm G}$ is the Schwarzschild radius of the primary black hole. As it takes a very long time for the secondary to pass through the region $a \sim 10^5$ to $10^3\ r_{\rm G}$ (Begelman, Blandford & Rees 1980; Quinlan & Hernquist 1997; Ivanov et al. 1999), the binary system is an old system. As the secondary-disc interaction always tends to align the disc with the orbital plane of the secondary (Scheuer & Feiler 1996; Vokrouhlicky & Karas 1998; Ivanov et al. 1999), we assume that the orbital planes of the binary and of the disc are coplanar at $a \sim 10^3\ r_{\rm G}$. The secondary interacts radially with the accretion disc and opens a gap in it. When gravitational radiation dominates the loss of the orbital angular momentum at a smaller semimajor axis a, the secondary rapidly pushes the gas trapped inside the orbit inwards and the gap gets wider with decreasing binary separation. When two supermassive black holes merge, the gap becomes a big hole in the vicinity of the primary and the inner accretion disc disappears. Jet formation is then interrupted. When the inner edge of the outer accretion disc slowly evolves inwards and reaches the last stable orbit, the big hole is refilled with disc material and jet formation restarts. We show that the observed interruption time of jet formation in DDRGs is the viscous time for the accreted plasma to refill the inner disc. This model can also give explanations for many other observations of DDRGs.

We describe our model in Section 2. The application to DDRGs, in particular B1834+620, is given in Section 3. Our discussions and conclusions are presented in Section 4.

2 CREATION OF A BIG HOLE IN THE ACCRETION DISC

If the orbit of the secondary is coplanar with the accretion disc and the mass ratio $q = m/M$ of the secondary and the primary is

$$1 \gg q > q_{\rm min} = \frac{81\pi}{8}\alpha\delta^2 \simeq 3 \times 10^{-5}\alpha_{-2}\delta_{-2}^2, \qquad (1)$$

the secondary black hole opens a gap in the disc and exchanges angular momentum with disc gas via gravitational torques (Lin & Papaloizou 1986). In equation (1), $\alpha = 0.01\alpha_{-2}$ is the viscous parameter, $\delta = 0.01\delta_{-2} = H/r$ and H is the half thickness of the disc. For a gas-pressure dominated accretion disc, δ is nearly independent of the radius r (Collin-Souffrin & Dumont 1990)

$$\delta = \frac{H}{r}$$
$$\simeq 0.01\alpha_{-2}^{-1/10}\left(\frac{L}{0.1L_{\rm E}}\right)^{1/5} M_8^{-1/10}\left(\frac{\epsilon}{0.2}\right)^{-1/5}\left(\frac{r}{10^3 r_{\rm G}}\right)^{1/20}, \qquad (2)$$

where $L_{\rm E} = 6.9 \times 10^{46} M_8$ erg s^{-1} with $M_8 = M/(5 \times 10^8\ {\rm M}_\odot)$ being the Eddington luminosity; $\epsilon = L/\dot{M}c^2$ is the efficiency of the accretion process and can be as high as 0.4 for a Kerr black hole. Equation (2) implies that δ is insensitive to all the variables and we will take 0.01 as its standard value. If the total disc mass $M_{\rm d}$ inside the disc radius $r_{\rm d}$ is $M_{\rm d} \gtrsim m$ and the separation a of the binary is large, the secondary migrates inwards on a viscous time-scale at a speed of (Lin & Papaloizou 1986; Syer & Clarke 1995; Ivanov et al. 1999)

$$\dot{a}_{\rm vis} \simeq -\frac{3}{2}\frac{\nu}{r} \simeq -\frac{3}{2}\delta^2\alpha v_{\rm K}, \qquad (3)$$

where $v_{\rm K}$ is the Keplerian velocity and $H/r \simeq c_{\rm s}/v_{\rm K}$. When a is small, the loss of angular momentum owing to gravitational radiation becomes important. At some critical radius $a_{\rm cr}$, the migration speed $\dot{a}_{\rm vis}$ is comparable with the inwardly spiraling rate due to gravitational radiation (Peters & Mathews 1963):

$$\dot{a}_{\rm gw} = -\frac{64G^3M^3q\,(1+q)}{5c^5a^3}f = -\frac{8}{5}\left(\frac{r_{\rm G}}{a}\right)^3 q\,(1+q)\,fc, \qquad (4)$$

where f is a function of the eccentricity e:

$$f = \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)(1-e^2)^{-7/2}. \qquad (5)$$

The orbit of the secondary is circular owing to the binary–disc interaction for a binary system of $q \lesssim 10^{-2}$ but is elliptical for $q \gtrsim 10^{-2}$

(Artymowicz 1992). As minor galactic mergers are more common than major mergers in the hierarchical models of galaxy formation and $10^{-2} \lesssim q \ll 1$ (Haehnelt & Kauffman 2000), the eccentricity is in the range $0 < e \lesssim 0.75$. Therefore, equation (1) is always satisfied for reasonable values of α and δ and the secondary opens a gap in the accretion disc. From equations (3) and (4), we have

$$a_{\rm cr} = \frac{1}{2}\left(\frac{128}{15}\right)^{2/5} \delta^{-4/5}\alpha^{-2/5}q^{2/5}\,(1+q)^{1/5}\, f^{2/5} r_{\rm G}. \tag{6}$$

When $a = a_{\rm cr}$, the inner edge of the accretion disc outside the orbit of the secondary (outer disc) is at $r_{\rm o} \simeq n^{2/3}a_{\rm cr}$ and the outer edge of the accretion disc inside the orbit (inner disc) is at $r_{\rm i} \simeq n^{-2/3}a_{\rm cr}$ (Artymowicz & Lubow 1994), where n is the resonance number: $n = 2$ for a circular orbit and $n = 5$ for $\alpha \sim 0.01$ and $e \sim 0.5$. For convenience, we define a critical time-scale $t_{\rm cr} \equiv a_{\rm cr}/|\dot{a}_{\rm gw}| = a_{\rm cr}/|\dot{a}_{\rm vis}|$ and

$$t_{\rm cr} = \frac{1}{3}\left(\frac{128}{15}\right)^{3/5} \delta^{-16/5}\alpha^{-8/5}\left(\frac{q^3}{1+q}\right)^{1/5} f^{3/5}\left(\frac{r_{\rm G}}{c}\right). \tag{7}$$

For a typical disc–binary system of $\alpha = 0.01$, $\delta = 0.01$ and $M = 5 \times 10^8\ {\rm M}_\odot$, we have $a_{\rm cr} \simeq 110 r_{\rm G}$ and $t_{\rm cr} = 0.34$ Myr for $e = 0.7$ and $q = 0.01$; and $a_{\rm cr} \simeq 6 r_{\rm G}$ and $t_{\rm cr} = 2000$ yr if $e = 0$ and $q = 5 \times 10^{-5}$.

When $a < a_{\rm cr}$, the inwardly spiraling secondary black hole begins to push the inner disc inwards on a gravitational radiation time-scale (see also Armitage & Natarajan 2002 for a circular system). When the semimajor axis a is $\simeq n^{2/3} 2\, r_{\rm G} \simeq 5.8 r_{\rm G}$, the outer edge of the inner disc is at about $r_{\rm i} \simeq 2r_{\rm G}$ and the inner disc disappears. When $r_{\rm i} = 2r_{\rm G}$, the radial flow speed v of the inner disc is the inwardly spiraling speed of the secondary and $v = \dot{a}_{\rm gw} = -1.6 \times 10^{-2} q(1+q)^{1/2} f v_{\rm K2}$ where $v_{\rm K2}$ is the Newtonian Kepplerian velocity at $2r_{\rm G}$. For $q = 0.01$ and $e = 0.7$, $v \simeq -4.4 \times 10^{-3} v_{\rm K2}$. From equation (3), $|\dot{a}_{\rm vis}| \sim 10^{-6}\delta^2_{-2}\alpha_{-2} v_{\rm K}$ and $|v| \sim 10^3 |\dot{a}_{\rm vis}|$. Thus, the dissipated energy will go into thermal energy instead of being radiated away and the inner disc becomes hotter and thicker (Begelman & Meier 1982). If α does not change and $|v| \sim |\dot{a}_{\rm vis}|$, $\delta \simeq 0.3$ and a thin-disc assumption might be still valid. As $|v| \ll v_{\rm K2}$ and the gap in the disc is determined by the dynamical orbital resonance, it might be reasonable to assume that the size of the inner disc steadily reduces all the way from $r_{\rm i} \simeq n^{-2/3}a_{\rm cr}$ to $r_{\rm i} \simeq 2r_{\rm G}$ owing to the continuous push of the secondary. The situation might be different from that in a binary system having a circular orbit, in which a strong wind is suggested by Armitage & Natarajan (2002). In either case, it can be expected that the inner disc disappears around the time when the supermassive binary black holes merge.

From equation (4), the inwardly spiraling secondary black hole evolves from $a_{\rm cr}$ to about $\sim r_{\rm G}$ on a time-scale $t_{\rm gw} \simeq t_{\rm cr}/4$ if e is constant. From equations (3) and (6), the inner edge of the outer disc moves inwards during $t_{\rm gw}$ from $r_{\rm o} \simeq n^{2/3}a_{\rm cr}$ to a radius

$$r_{\rm m} \simeq \frac{a_{\rm cr}}{4}\,(8n-3)^{2/3}\,. \tag{8}$$

For the typical parameters $\alpha = 0.01$, $\delta = 0.01$ and $M = 5 \times 10^8\ {\rm M}_\odot$, we have $r_{\rm m} \simeq 310 r_{\rm G}$ for $q = 0.01$ and $e = 0.7$ ($n = 5$) and $r_{\rm m} \simeq 60 r_{\rm G}$ for $q = 5 \times 10^{-5}$ and $e = 0$ ($n = 2$). Thus, when the two supermassive black holes merge, a big hole ranging from $r_{\rm G}$ to $r_{\rm m}$ ($\gg r_{\rm G}$) forms in the inner disc around the post-merged black hole.

When the big hole forms, the accretion disc has no plasma to fuel jets and jet formation stops. Jet formation revives only when the inner edge of the outer disc evolves from $r_{\rm m}$ to about $2r_{\rm G}$, which corresponds to $a < n^{-2/3} 2r_{\rm G} \simeq 0.7 r_{\rm G}$. Therefore, the binary black holes must have merged before the jet formation restarts and the revival of jet formation ensures the coalescence of the supermassive binary black holes. From equation (3), the interruption time interval is

$$t_{\rm m} \simeq \frac{8n-3}{12} t_{\rm cr}. \tag{9}$$

For the typical supermassive binary system, $t_{\rm m} \simeq 1.0$ Myr for $q = 10^{-2}$, $e = 0.7$ and $n = 5$; and $t_{\rm m} \simeq 820$ yr for $q = 10^{-3}$, $e = 0$ and $n = 2$.

3 INTERRUPTION AND RESTARTING OF JET FORMATION IN DDRGS

3.1 Interruption time-scale

From the apparent magnitude $m_{\rm R} = 19.7$ of the host galaxy of the DDRG source B1834+620 at red-shift $z = 0.5194$ (Schoenmakers et al. 2000b) and the correlation of central black hole mass and galaxy bulge luminosity for active and inactive galaxies (McLure & Dunlop 2002), the central black hole mass is estimated to be $M \simeq 6 \times 10^8\ {\rm M}_\odot$. The observed interruption time of B1834+620 is $t_{\rm obs} = 1$ Myr (Schoenmakers et al. 2000b) and from equations (9) and (7) we have the interruption time of jet formation:

$$t_{\rm m} \simeq 1.1 \delta_{-2}^{-16/5}\alpha_{-2}^{-8/5} f_{(0.68)}^{3/5}\left(\frac{q}{0.01}\right)^{3/5}(1+q)^{-1/5} \times\left(\frac{M}{6\times 10^8\ {\rm M}_\odot}\right) {\rm Myr}, \tag{10}$$

where $n = 5$ and $f_{(0.68)} = f/21.8$ for $e = 0.68$. For typical disc parameters $\alpha = 0.01$ and $\delta = 0.01$, Fig. 1 shows the relation of the eccentricity e and the mass ratio q for B1834+620. For a circular orbit $e = 0$, $q > 1$ is required. Therefore, the orbit of the binary system in B1834+620 is not circular but elliptical. On the other hand, Fig. 1 shows that if $q \ll 10^{-2}$, $e > 0.7$. Artymowicz (1992) shows that when $e \gtrsim 0.7$ a binary system suffers a slow eccentricity damping for any q and it is difficult to keep an extremely high eccentricity $e \gtrsim 0.8$ for a long time. In fact, the orbit of the secondary black hole would be circularized by binary–disc interaction for $q < 10^{-2}$ (Artymowicz 1992). Therefore, we conclude that the binary harboured in B1834+620 is elliptical with $10^{-2} \lesssim q \ll 1$ and $0.3 \lesssim e \lesssim 0.7$.

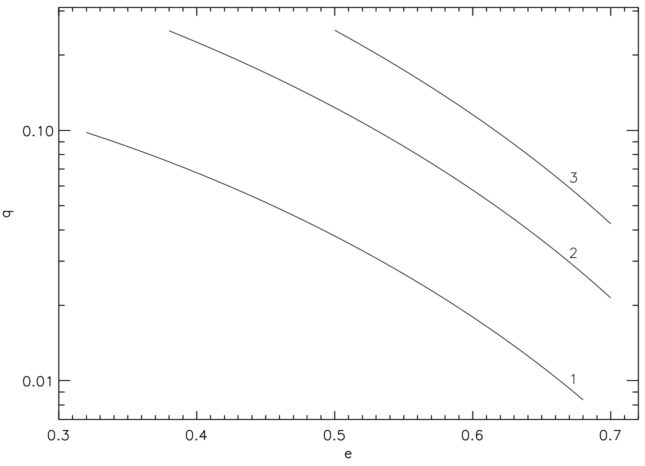

Figure 1. Relation between mass ratio q and eccentricity e for $\alpha = 0.01$ and $\delta = H/r = 0.01$. *Curve 1:* for central black hole mass $M = 6 \times 10^8\ {\rm M}_\odot$ and interruption time $t_{\rm m} = 1 \times 10^6$ yr (the DDRG source B1834+620). *Curve 2:* for $M = 6 \times 10^7\ {\rm M}_\odot$ and $t_{\rm m} = 2 \times 10^5$ yr. *Curve 3:* for $M = 6 \times 10^6\ {\rm M}_\odot$ and $t_{\rm m} = 3 \times 10^4$ yr.

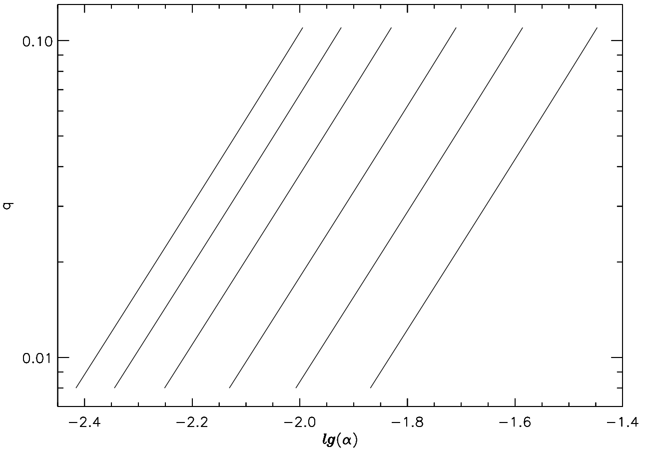

Figure 2. Mass ratio q as a function of α for the DDRG source B1834+620 with $M = 6 \times 10^8\ \mathrm{M}_\odot$, $t_\mathrm{m} = 1$ Myr and $\delta = 0.01$. The curves correspond, from left to right, to $e = 0.3$, 0.4, 0.5, 0.6, 0.68 and 0.75, respectively.

Equation (10) indicates that the interruption time t_m is sensitive to disc parameters α and δ. Fig. 2 gives q as a function of α and e for B1834+620. For $0.01 \lesssim q \lesssim 0.1$ and $0.3 \lesssim e \lesssim 0.75$, α is in the range $3.5 \times 10^{-3} \lesssim \alpha \lesssim 4.0 \times 10^{-2}$. If $\delta = 0.01$ and $e = 0.68$, the mass of the secondary black hole in B1834+620 is $m \simeq 5 \times 10^6\ \mathrm{M}_\odot$ for $\alpha = 0.01$; $m \simeq 3 \times 10^7\ \mathrm{M}_\odot$ for $\alpha = 0.02$; and $m \simeq 1 \times 10^8\ \mathrm{M}_\odot$ for $\alpha = 0.03$, respectively.

As the central black hole masses in AGNs are in the ranges $10^{7.5}\ \mathrm{M}_\odot \lesssim M \lesssim 10^{9.5}\ \mathrm{M}_\odot$ (see, for example, Wu, Liu & Zhang 2002), the possible interruption time of jet formation is 50 Kyr $\lesssim t_\mathrm{m} \lesssim 5$ Myr, if the disc–binary system is typical with $\alpha = 0.02$, $\delta = 0.01$, $q = 0.05$ and $e = 0.68$. When the interruption time-scale t_m is of order 10^6 yr, warm clouds of gas embedded in the hot intergalactic medium can fill the old outer cocoon and the new jets may give rise to two new radio lobes in FR II radio galaxies (Kaiser et al. 2000), while if $t_\mathrm{m} \ll 10^6$ yr no new inner radio lobe can form by the restarting jets, as in 3C 288 (Bridle et al. 1989), 3C 219 (Clarke et al. 1992) and B0108+388 (Baum et al. 1990; Owsianik et al. 1998).

3.2 FR II radio morphology and detection rate of DDRGs

One requirement for the massive secondary to open a gap in the accretion disc and to migrate inwards on a viscous time-scale at large separation of the binary is $M_\mathrm{d} \gtrsim m$ (Syer & Clarke 1995; Ivanov et al. 1999). The size of a thin standard accretion disc $r_\mathrm{d} \sim 10^4 r_\mathrm{G}$ may be determined by star formation in the outermost regions of the disc or by the specific angular momentum of the gas that enters the disc. For a simple α-disc (Shakura & Sunyaev 1973), the steady-state disc surface density is given by

$$\Sigma \simeq 3.5 \times 10^4 \alpha_{-2}^{-4/5} M_8^{1/5} \dot{m}_{-2}^{3/5} r_4^{-3/5}\ \mathrm{g\ cm^{-2}}, \tag{11}$$

where $r_4 = r_\mathrm{d}/10^4 r_\mathrm{G}$ and $\dot{m} = \dot{M}/\dot{M}_\mathrm{Edd} = 10^{-2}\dot{m}_{-2}$ with the Eddington accretion rate $\dot{M}_\mathrm{Edd} = 1.2 M_8$ ($\mathrm{M}_\odot$ yr^{-1}). From equation (11), we have

$$M_\mathrm{d}/m = \frac{10\pi\Sigma r_\mathrm{d}^2}{7m} \simeq 7\alpha_{-2}^{-4/5} M_8^{6/5} \dot{m}_{-2}^{3/5} r_4^{7/5} \left(\frac{q}{0.05}\right)^{-1}. \tag{12}$$

FR I and FR II radio galaxies can be separated clearly according to their radio power (Fanaroff & Riley 1974) and/or to the optical luminosity of the host galaxy in the sense of increasing division radio luminosity with increasing optical luminosity of the host galaxy (Ledlow & Owen 1996). The dividing line in the radio power–host galaxy optical luminosity plane corresponds to a critical accretion rate (Ghisellini & Celotti 2001):

$$\dot{m}_\mathrm{cr} = \frac{\dot{M}}{\dot{M}_\mathrm{Edd}} \sim 3 \times 10^{-2} \left(\frac{\epsilon}{0.2}\right)^{-1}. \tag{13}$$

In FR I radio galaxies, the accretion rate $\dot{m} < \dot{m}_\mathrm{cr}$, while in FR II radio galaxies $\dot{m} > \dot{m}_\mathrm{cr}$. A low accretion rate $\dot{m} \lesssim 10^{-2}$ in FR I radio galaxies and a high accretion rate $\dot{m} \gg 10^{-2}$ in FR II radio galaxies are also suggested by Böttcher & Dermer (2002) and Cavaliere & D'Elia (2002). From equations (12) and (13), $M_\mathrm{d}/m \gtrsim 1$ in FR II radio galaxies, while $M_\mathrm{d}/m \lesssim 1$ in FR I radio galaxies. For an accretion disc with $\dot{m} \lesssim 10^{-2}$, the accretion does not appear in a thin or slim disc but possibly in ADAF (Narayan & Yi 1994; Abramowicz et al. 1995), while the accretion disc is geometrically thin (Shakura & Sunyaev 1973) for $10^{-2} \ll \dot{m} \lesssim 1$ or slim (Abramowicz et al. 1988) when $\dot{m} \gtrsim 1$. Therefore, only binary black holes in FR II or possibly borderline FR I/FR II radio galaxies can lead to the interruption and restarting of jet formation, and DDRGs should have FR II or borderline FR I/FR II radio morphology. Since in our model the primary, the secondary and the accretion disc are roughly coplanar with one another, the rotating post-merged supermassive black hole is thus roughly aligned with the rotating primary and the new-born jets in DDRGs should restart symmetrically and roughly in the same direction as former jets.

When the secondary migrates from a_cr to r_G and pushes the gas in the inner accretion disc inwards with a velocity $|\dot{a}_\mathrm{gw}| > |\dot{a}_\mathrm{vis}|$ (Armitage & Natarajan 2002), the mass accreting into the primary black hole and down to the jets increases dramatically. The jets become extremely strong and the extremely large (giant) outer lobes of DDRGs thus formed have relatively high luminosity as compared with the inner radio structure formed by the recurrent jets. As the lifetime of a binary system in AGNs is very long (Begelman et al. 1980; Quinlan & Hernquist 1997) and our model concerns the last stage of supermassive binary black holes, a DDRG source is a post-merged galaxy and should form the largest (giant) possible structure of a few hundred kpc with no possibility of finding clear evidence for galaxy merging in its host galaxy.

The time for jet material to travel from the central nuclei to the extended radio lobes in DDRGs is ∼Myr (Kaiser et al. 2000) and the possible time t_DD to detect a radio galaxy with a DDRG is the total time of the interruption (∼Myr) and the travelling time (∼Myr) of jet plasma from the central core to radio lobe. If every FR II radio galaxy harbours a supermassive binary once in its lifetime of $\sim 10^9$ yr and we take $t_\mathrm{DD} \sim 10^7$ yr, the possibility of detecting an FR II radio source with a DDRG is ∼1 per cent. This is consistent with the observations of a low detection rate of DDRGs.

4 DISCUSSIONS AND CONCLUSIONS

We present a supermassive binary black hole scenario to explain the interruption and restarting of jet formation in DDRGs. The orbit of the secondary with a mass ratio $10^{-2} \lesssim q \ll 1$ is elliptical with a typical eccentricity $e \sim 0.68$ coplanar with the accretion disc. The secondary opens a gap in the accretion disc at large binary separation, while when the binary merges the gap extends and becomes a big hole in the vicinity of the post-merged black hole, leading to the interruption of jet formation. When the big hole is refilled with accreting plasma, jet formation restarts. Before the hole is filled, the two black holes must have already merged. We show that the viscous time for accreting matter to refill the big hole is the observed interruption time of jet formation in DDRGs. Prior to the merging of the binary, the accretion rate becomes extremely high and the jet produced is very strong. Thus, the outer radio structures formed are very large (giant), with relatively high luminosity as compared with the inner structure formed by the recurrent jets. As the merging of binary black holes does not change the direction of the spinning axis of the central supermassive black hole, the inner radio structure should align with the outer lobes. We also show that only in FR II or borderline FR I/FR II radio galaxies could the accretion disc strongly interact with the supermassive binary black holes, and DDRGs should have FR II radio morphology.

The binary orbit in the model is elliptical. Gravitational wave emission is very effective for eccentric binaries. A high eccentricity significantly shortens the evolutionary time-scale of the binary and enlarges the big hole as compared to that dug by a circular binary. The interruption time of a circular orbit system is too short to explain the observations of DDRGs. In the course of binary evolution, dynamical friction with stars in the cluster around the central black hole is unlikely to lead to a substantial increase of the eccentricity (Polnarev & Rees 1994), but the eccentricity of a binary system changes with time due to the interaction of the disc to the secondary (Artymowicz 1992). For a secondary with $q \lesssim 10^{-2}$, the orbit is circularized at the initial stage when the binary–disc system forms. For a massive secondary of $10^{-2} \lesssim q \lesssim 10^{-1}$, the eccentricity is excited if $e \lesssim 0.7$ and gets slowly damped if $e > 0.7$ (Artymowicz 1992). Therefore, the required binary parameters of $10^{-2} \lesssim q \ll 1$ and $0.3 \lesssim e \lesssim 0.7$ at $a \simeq a_{\rm cr}$ are quite reasonable and the typical values $q = 0.05$ and $e \simeq 0.68$ are favourite and close to the balance value $e \simeq 0.70$. When we estimated the gravitational radiation dynamic time $t_{\rm gw}$, we assumed the eccentricity e to be constant. When the loss of the angular momentum due to the gravitational radiation becomes dominant, the eccentricity slowly decreases with time. However, equations (8) and (9) show that the size of the big hole in the disc and the interruption time of jet formation are mainly determined by the binary parameters at $a \simeq a_{\rm cr}$ and the assumption of constant e does not significantly change the result.

In general, the binary orbital plane of the secondary initially inclines with respect to the disc plane when the secondary passes through the star cluster in the galactic disc and reaches a separation $a < r_{\rm d}$. Ivanov et al. (1999) show that the inner part of the disc with radius smaller than some alignment radius $r_{\rm al}$ ($\gtrsim a$) becomes twisted on a short time-scale $t_{\rm al1}$ and lies in the orbital plane if $\alpha > \delta$. When the inner disc becomes coplanar with the orbital plane of the secondary, the rotating primary black hole is realigned with the twisted inner accretion disc owing to Lense–Thirring drag (Scheuer & Feiler 1996) on a relatively short time-scale $t_{\rm al2}$ when $10^3 r_{\rm G} \ll a < r_{\rm d}$ (Natarajan & Pringle 1998). At the same time, the orientation of the binary orbital plane slowly changes with time and has a tendency to become vertical with respect to the outer accretion disc on a much longer time-scale $t_{\rm al3}$ (Ivanov et al. 1999). The time-scale $t_{\rm al3}$ depends on α and accretion rate $\dot{M}$ for $q > 10^{-3}$. For an accretion disc with $\alpha \simeq 1$, the time-scale $t_{\rm al3}$ with $t_{\rm al3} \gg t_{\rm al1} \sim t_{\rm al2}$ (Liu 2003) is much smaller than the lifetime $\sim 10^9$ yr of an active galaxy, while for binary systems like those in DDRGs with $10^{-2} \lesssim q \ll 1$ and $\alpha \ll 1$, the situation is more complicated (Scheuer & Feiler 1996; Ivanov et al. 1999). But it is still possible for the orbital plane of the secondary to be coplanar with the accretion disc within a reasonable time-scale, as the vertical shear of the twisted disc may be much stronger than its azimuthal counterpart (Papaloizou & Pringle 1983; Kumar & Pringle 1985; Natarajan & Pringle 1998).

When the primary, the secondary and the accretion disc become coplanar with one another, the orientation of the spinning axis of the primary dramatically changes twice, and so does the orientation of the jets. The first change happens on a short time-scale $\sim t_{\rm al2}$, while the second does so on a much longer time-scale $t_{\rm al3}$. When jets change their orientations, X-shaped radio structure forms (Liu 2003). As the rapid realignment happens only when the accretion disc is a thin α-disc with $M_{\rm d}/m \gtrsim 1$, X-shaped radio structures, like the double–double radio lobes in DDRGs, can be detected only in FR II or extremely-luminous FR I radio galaxies. Detailed discussion of how our model works for X-shaped radio galaxies (Dennett-Thorpe et al. 2002), and of the relation between X-shaped radio galaxies and DDRGs, is beyond the scope of the present paper and will be presented in a further work (Liu 2003).

When the semimajor axis of the orbit is smaller than the critical radius, the gap rapidly increases with decreasing separation. When the binary is close and almost ready to merge, the inner accretion disc becomes extremely hot and strong outflow might form. The sources may become extremely bright in X-rays. The gravitational wave radiation of the binary system is very strong and the system becomes a very good target for monitoring by gravitational wave detectors. However, such strong X-ray and gravitational radiation sources may be difficult to discover, because their lifetime is less than a few thousand years. When two supermassive black holes become merged, the inner region of the accretion disc becomes empty and no X-ray or radio radiation comes from the accretion disc or jets. It is possible in a large sky survey to detect some sources with luminous radio lobes and bright jet-fragments, but with a weak central nucleus in radio and X-ray wavebands.

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