Mon. Not. R. Astron. Soc. **347,** 1357–1369 (2004)

X-shaped radio galaxies as observational evidence for the interaction of supermassive binary black holes and accretion disc at parsec scale

F. K. Liu★
Astronomy Department, Peking University, 100871 Beijing, China

Accepted 2003 October 21. Received 2003 October 21; in original form 2003 September 28

ABSTRACT

In the hierarchical galaxy formation model, today's galaxies are the product of frequent galaxy merging, triggering the activity of active galactic nuclei and forming a supermassive black hole binary. A binary may become stalling at the parsec scale and is expected to be detected in nearby normal galaxies, which is inconsistent with observations. In this paper, we investigate the interaction of the supermassive binary black holes (SMBBHs) and an accretion disc and show that the stalling can be avoided due to the interaction and a rapid coalescence of SMMBHs can be reached. A binary formed during galaxy merging within Hubble time is most likely inclined with a random inclination angle and twists the accretion disc, aligning the inner part of the disc with the orbital plane on a time-scale $\sim 10^3$ yr. The twisted inner disc subsequently realigns the rotating central supermassive black hole on a time-scale $\lesssim 10^5$ yr due to the Bardeen–Petterson effect. It is shown that the detected X-shaped structure in some FR II radio galaxies may be due to the interaction-realignment of the binary and accretion disc occurring within the parsec scale of the galaxy centre. The configuration is very consistent with the observations of X-shaped radio sources. The X-shaped radio feature forms only in FR II radio sources due to the strong interaction between the binary and a standard disc, while the absence of X-shaped FR I radio galaxies is due to the fact that the interaction between the binary and the radiatively inefficient accretion flow in FR I radio sources is negligible. The detection rate, $\lambda_X \sim 7$ per cent, of the X-shaped structure in a sample of low-luminous FR II radio galaxies implies that the X-shaped feature forms in nearly all FR II radio sources of an average lifetime $t_{\rm life} \sim 10^8$ yr. This is consistent with the estimates of the net lifetime of quasi-stellar objects and radio galaxies and with the picture that the activity of active galactic nuclei is triggered by galaxy merging. As the jet orients vertically to the accretion disc, which is supposed to be aligned with the galactic plane of the host galaxy, the old wings in the X-shaped radio sources are expected to be aligned with the minor axis of the host galaxy while the orientation of the active jet distributes randomly. It is suggested by the model that the binary would remain misaligned with the outer disc for most of the disc viscous time or the lifetime of the FR II radio galaxies and the orientation of the jet in most FR II radio galaxies distributes randomly. As the binary–disc interaction in FR I radio galaxies is negligible or a source evolves from FR II to FR I type after the binary becomes aligned with the outer disc, the jets in most FR I radio galaxies are expected to be vertical to the accretion disc and thus the major axis of the host galaxy. We discuss the relationship of X-shaped and double–double radio galaxies (DDRGs) and suggest that all X-shaped radio sources would evolve into DDRGs after the coalescence of the SMBBHs and that most radio sources evolve from FR II to FR I type after an interruption of jet formation, implying that the average size of FR I radio sources is smaller than that of FR II radio galaxies. The model is applied to two X-shaped radio sources 4C +01.30 and 3C 293 and one DDRG source J0116−473 with a bar-like feature. We show that the SMBBHs in the three objects are minor with mass ratio $q \sim 0.1$–0.3.

Key words: accretion, accretion discs – black hole physics – gravitational waves – galaxies: active – galaxies: interactions – galaxies: jets.

★E-mail: fkliu@bac.pku.edu.cn

© 2004 RAS

Downloaded from https://academic.oup.com/mnras/article/347/4/1357/1000457 by George Mason University user on 24 September 2020

1 INTRODUCTION

Recent observations show that all galaxies with bulges harbour a supermassive black hole (SMBH) of mass tightly correlating with both the mass and the velocity dispersions of the bulge (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Magorrian et al. 1998; McLure & Dunlop 2002; Tremaine et al. 2002). This implies that one event is responsible for the formation of both the bulges and the central SMBH.

In hierarchical galaxy formation models, present-day galaxies are the product of successive minor mergers (Kauffmann & Haehnelt 2000; Haehnelt & Kauffman 2000; Menou, Haiman & Narayanan 2001), triggering the starbursts and the activity of active galactic nuclei (AGNs; Wilson & Colbert 1995). The configuration is supported by the observations of compact steep-spectrum objects (CSSs) and gighertz-peaked sources (GPSs) which are most likely infant AGNs of age $t \lesssim 10^5$ yr and show distortion of the host galaxy, double nuclei, galaxy-interaction or close companion among about 50 per cent of them (O'Dea 1998). In galaxy mergers, the two SMBHs at the galaxy centres become bound due to dynamical friction at a separation a of two SMBHs, $a \sim$ 1–10 pc, and become hard at a separation $a_{\rm h} \sim$ 0.01–1 pc when the loss of the orbital angular momentum is dominated by three-body interactions between SMBBHs and the stars passing by and a loss cone forms (Begelman, Blandford & Rees 1980; Quinlan & Hernquist 1997; Yu 2002; Makino & Funato 2004). The decay time-scale of the binary orbit is then proportional to the relaxation time-scale of the parent galaxy longer than the cosmological time, and the SMBBHs become stalling at $a \sim a_{\rm h}$. Therefore, it is expected to detect SMBBHs in many nearby normal galaxies or AGNs. However, efforts to detect long-lived SMBBHs in normal galaxies have failed (Haehnelt & Kauffman 2002) and SMBBHs may be detected only in a handful AGNs, e.g. OJ287 (Sillanpää et al. 1988; Liu & Wu 2002), ON231 (Liu, Xie & Bai 1995b), PKS1510-089 (Xie et al. 2002), MKN421 (Liu, Liu & Xie 1997), NGC 6260 Komossa et al. 2003 and 3C 66B (Sudou et al. 2003) (for a review of observations of SMMBHs, see Komossa 2003). Liu, Wu & Cao (2003) suggest that SMMBHs in FR II radio galaxies merger during the FR II-active phase, leading to the formation of double–double radio galaxies (DDRGs). Many stellar dynamical mechanisms have been invoked to extract the angular momentum in the literature (for a review, see Milosavljevic & Merritt 2003) and have been found to be inefficient, including black hole wondering (Chatterjee, Hernquist & Loeb 2003), stellar slingshot effects and refilling of the loss cone (Zier & Biermann 2001), and the Kozai mechanism (Blaes, Lee & Socrates 2002). This is the so-called *final parsec problem* (Milosavljevic & Merritt 2003).

Gas in merging galaxies is driven to the centre on a time-scale $t_{\rm g} \approx 10^8$ yr and triggers the starbursts and AGN activity (Gaskell 1985; Hernquist & Mihos 1995; Barnes & Hernquist 1996; Barnes 2002). This forms an accretion disc around a central SMBH with a size as large as $r_{\rm d} \sim 10$ pc (Jones et al. 2000) and, in general, $r_{\rm d} \sim 10^4\ r_{\rm G} \sim$ 0.01–1 pc (Collin & Hure 2001), where $r_{\rm G}$ is the Schwarzschild radius of the central black hole. Therefore, it is expected that the secondary interacts with the accretion disc whenever a binary becomes hard. The interaction of an accretion disc and a binary has been intensively investigated in the literature (e.g. Lin & Papaloizou 1986; Artymowicz & Lubow 1994; Ivanov, Igumenshchev & Novikov 1998; Ivanov, Papaloizou & Polnarev 1999; Gould & Rix 2000; Armitage & Natarajan 2002; Narayan 2000; Liu et al. 2003). If an accretion disc is standard, initially inclined SMBBHs warp, twist and align the accretion disc within some radius $r_{\rm al} > a$ (Ivanov et al. 1999). Then, the orbital plane slowly becomes aligned with the outer disc of $r > r_{\rm al}$ due to the exchange of angular momentum with accreting gas on a time-scale depending on the total disc mass. When the orbital plane completely becomes coplanar with the outer accretion disc, the secondary opens a gap in the disc and loses its angular momentum via viscosity torque and in-spiralling on a viscous time-scale (Lin & Papaloizou 1986; Armitage & Natarajan 2002). When the loss of orbit angular momentum due to gravitational wave radiation becomes dominated at $a \lesssim 10^2\ r_{\rm G}$, the secondary removes the mass of the inner disc and mergers into the primary, leading to the interruption of jet formation (Liu et al. 2003).

Liu et al. (2003) have identified DDRGs with objects in which the coalescence of SMBBHs and the removal of the inner disc occurred. Although the observations of DDRGs are consistent with the scenario, Merritt & Ekers (2002) suggest that binary coalescence leads to a spin-flip of the central SMBH and forms X-shaped radio galaxies. So, the important question is which picture is correct or, if both are correct, what is the relationship between DDRGs and X-shaped radio sources. As there are several difficulties with the configuration of Merritt & Ekers (see the discussion in Section 4.2), we show in this paper that the mechanism to form the X-shaped feature detected in some FR II radio galaxies may be the interaction between the binary and a standard accretion disc at parsec scale and that X-shaped feature and double–double lobes form in different evolution phases of SMBBHs in FR II radio galaxies.

We investigate the interaction of SMBBHs and an accretion disc at parsec scale and the reorientation of the spin axis of the rotating central SMBH. We compare this configuration with the observations of X-shaped radio galaxies, which are consistent with each other. In this scenario, the FR II character of the X-shaped radio galaxies is due to the fact that the accretion disc is a standard α-disc in FR II radio sources, while in FR I radio galaxies the accretion flow is radiatively inefficient advection dominated accretion flow (ADAF) and the interaction of an ADAF and a binary is negligible. Based on this scenario, we predict that the orientations of active radio jets distribute randomly in FR II radio galaxies and are preferentially vertical to the major axis of host galaxies in FR I radio sources. The model also suggests that radio jets are aligned with the minor axis of host galaxies in DDRGs.

In the paper, we discuss the initial conditions of the binary–disc system based on the Bardeen–Petterson effect and we specify the SMBBH system in Section 2. The interaction of the accretion disc and inclined SMBBHs is investigated in detail in Section 3, where we pay special attention to the reorientations of the binary orbit and the rotating central SMBH. In Section 4, we discuss the connection between X-shaped radio galaxies and the objects in which the reorientation of the spin axis of the rotating central SMBH due to disc–binary interaction occurred. All the observations of X-shaped radio sources are discussed based on this scenario. We also discuss the distribution of orientations of wings and active jets in X-shaped and normal radio galaxies in Section 4. The important question about what is the relationship between DDRGs and X-shaped radio sources is addressed in Section 5. Our discussion and conclusions are presented in Section 6.

2 FINAL PARSEC PROBLEM OF THE BINARY EVOLUTION AND THE FORMATION OF DISC–SMBBH SYSTEM

2.1 Bardeen–Petterson effect and alignment of rotating SMBBH and inclined accretion disc

When the part of the cold gas with low angular momentum loses its angular momentum due to viscosity and flows inwards toward

Downloaded from https://academic.oup.com/mnras/article/347/4/1357/1000457 by George Mason University user on 24 September 2020

the central SMBH, an accretion disc and relativistic jets form (Shlosman, Begelman & Frank 1990; Barnes 2002). As the formed accretion disc keeps the angular momentum of gas, it is nearly aligned with the galactic gas disc, if no strong torque is exerted on it. Because all young AGNs with newly born relativistic jets have FR II radio morphologies (O'Dea 1998; Murgia et al. 2002; Perucho & Martí 2002), the accretion disc has an accretion rate $\dot{m} \equiv \dot{M}/\dot{M}_{\rm Edd} = L/L_{\rm Edd} \gtrsim \dot{m}_{\rm FR} = 6 \times 10^{-3}$ (Ghisellini & Celotti 2001; Cavaliere & D'Elia 2002; Maraschi & Travecchio 2003). It is a standard α-disc if $\dot{m} \lesssim 1$ (Shakura & Sunyaev 1973) or a slim disc for $\dot{m} \gtrsim 1$ (Abramowicz et al. 1988). Here, $\dot{M}_{\rm Edd} = L_{\rm Edd}/\epsilon c^2 = 2.30 M_8({\rm M}_\odot\,{\rm yr})$ for $\epsilon = 0.1$ is the Eddington accretion rate (note the different definitions of the Eddington accretion rate), $\epsilon = 0.1\epsilon_{-1} = L/\dot{M}c^2$ is the conversion rate of accretion mass to energy and $M = M_8 \times 10^8\,{\rm M}_\odot$ is the mass of the central SMBH.

For a gas-pressure dominated standard α-disc, the ratio δ of the half thickness H of accretion disc and radius r is

$$\begin{aligned}\delta &\equiv \tfrac{H}{r} \\ &\simeq 2.8 \times 10^{-3} \alpha_{-2}^{-1/10} \dot{m}_{-1}^{1/5} M_8^{-1/10} x_4^{1/20},\end{aligned} \tag{1}$$

where $\alpha_{-2} = \alpha/0.01$, $\dot{m}_{-1} = \dot{m}/0.1$, $x_4 = r/0^4 r_G$, and $r_{\rm G} = 2\,GM/c^2 = 2.97 \times 10^{13} M_8$ cm is the Schwarzschild radius. Such a gas-pressure dominated disc has a surface mass density

$$\Sigma \simeq 4.0 \times 10^5 \alpha_{-2}^{-4/5} \dot{m}_{-1}^{3/5} M_8^{1/5} x_4^{-3/5}\,{\rm g\,cm^{-2}} \tag{2}$$

and a total mass within the disc radius $r_{\rm d}$

$$M_{\rm d} = \frac{10\pi}{7} \Sigma r_{\rm d}^2 \simeq 7.92 \times 10^7 \alpha_{-2}^{-4/5} \dot{m}_{-1}^{3/5} M_8^{11/5} x_4^{7/5}\,{\rm M}_\odot. \tag{3}$$

The disc radius $r_{\rm d}$ is empirically (Collin & Hure 2001)

$$\begin{aligned}r_{\rm d} &\approx 2 \times 10^4 M_7^{-0.46} r_{\rm G} \\ &\simeq 7 \times 10^3 M_8^{-0.46} r_{\rm G}.\end{aligned} \tag{4}$$

However, the accretion disc is no longer gas-pressure dominated for $r \lesssim 10^2\,r_{\rm G}$ and the disc opening angle is (Collin-Souffrin & Dumont 1990)

$$\delta \simeq 9.9 \times 10^{-3} \alpha_{-2}^{-1/10} \left(\frac{L}{0.1 L_{\rm Edd}}\right)^{1/5} M_8^{-1/10} \epsilon_{-1}^{-1/5} x^{1/20}. \tag{5}$$

For an accretion disc in AGNs of a typical value $\alpha \sim 0.03$, $\delta < \alpha \ll 1$. If the rotating central SMBH is misaligned with the accretion disc, the innermost part of the accretion disc becomes aligned with the SMBH spin direction due to the Bardeen–Petterson effect (Bardeen & Petterson 1975) out to a disc radius $r_{\rm BP} \gg r_{\rm G}$. When the rotating SMBH exerts a torque on the accretion disc and aligns the innermost part of the disc with its spin, the same torque tends to align the spin of the SMBH with the accretion disc (Rees 1978; Scheuer & Feiler 1996), depending on the transfer of warps in the radial direction. For an accretion disc with $\alpha > \delta$ in AGNs, warps transfer in a diffusive way. Papaloizou & Pringle (1983) show that, taking into account the internal hydrodynamics of the disc, the usual azimuthal viscosity ν and the viscosity ν_2 in the vertical direction are different. The inward advection of angular momentum via ν is rather accurately cancelled by the outward viscous transport of angular momentum due to ν, while the radial pressure gradients due to the warp set up radial flows, whose natural period resonates with the period of the applied force and therefore reaches large amplitude. Finally, the effective vertical viscosity is approximately given by $\nu_2 = \nu/2\alpha^2$ (Papaloizou & Pringle 1983; Kumar & Pringle 1985), which is valid even for a significant warp (Ogilvie 1999). Thus, the transfer time-scale of warp in the accretion disc is

$$t_{\rm wp} \simeq \frac{2r^2}{3\nu_2} = 2\alpha^2 t_{\rm v} = 2 \times 10^{-4} \alpha_{-2}^2 t_{\rm v}, \tag{6}$$

where

$$t_{\rm v} = \frac{r}{\upsilon_{\rm r}} = \frac{2r^2}{3\nu} = \frac{2}{3}\delta^{-2}\alpha^{-1}\Omega_{\rm K}^{-1}. \tag{7}$$

Here, $\Omega_{\rm K}$ is the Keplerian angular velocity at radius r and $\upsilon_{\rm r} = 3\nu/2r$ is the flow velocity in radial direction.

Considering the difference of ν_2 and ν and using the accretion disc models for AGNs computed by Collin-Souffrin & Dumont (1990), Natarajan & Pringle (1998) show that the Bardeen–Petterson radius, out to which the inner accretion disc of $L/L_{\rm Edd} = \dot{m} > \dot{m}_{\rm cr}$ is aligned with the rotating SMBH, is

$$r_{\rm BP} = 22 a_*^{5/8} \alpha_{-2}^{3/4} \left(\frac{L}{0.1 L_{\rm Edd}}\right)^{-1/4} M_8^{1/8} \epsilon_{-1}^{1/4}. \tag{8}$$

They also show that the spin axis of a rotating SMBH becomes aligned with the accretion disc due to the Bardeen–Petterson effect on a time-scale

$$t_{\rm al1} = 3.6 \times 10^4\,{\rm yr}\, a_*^{11/16} \alpha_{-2}^{13/8} \left(\frac{L}{0.1 L_{\rm Edd}}\right)^{-7/8} M_8^{-1/16} \epsilon_{-1}^{7/8}, \tag{9}$$

where a_* is the dimensionless spin angular momentum of the primary and L is the luminosity of AGNs. Equation (9) shows that the realignment time-scale $t_{\rm al1}$ is nearly independent of the SMBH mass but sensitive to the parameter α. For an AGN with a moderately rotating central black hole $a_* \simeq 0.7$, and typical parameters $\alpha_{-2} = 3$, $\epsilon_{-1} = 2$ and $L \sim 0.3\,L_{\rm Edd}$, the realignment time-scale is $t_{\rm al1} \simeq 1.1 \times 10^5$ yr. If we take a typical advance speed of radio lobes $\upsilon_{\rm j} \simeq 0.3\,c$ for a young AGN (Owsianik, Conway & Polatidis 1999) (we have assumed an accelerating cosmology with $\Omega_\Lambda = 0.7$, $\Omega_{\rm B} = 0.3$ and $H_0 = 70$ km s^{-1} Mpc^{-1} throughout this paper except where mentioned), the realignment takes place when the source has the largest linear size $l_{\rm m} \lesssim t_{\rm al1}\upsilon_{\rm j} \simeq 10$ kpc. An AGN is detected with a GPS source if $l_{\rm m} < 1$ kpc or a CSS source if $l_{\rm m} \lesssim 20$ kpc (for $H_0 = 100$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$) (O'Dea 1998). Therefore, dramatic distortion may be detected in some radio jets of CSSs and GPSs. When the realignment finishes, lobes randomly orient and jets close to the central nuclei are nearly vertical to the accretion disc.

2.2 Hardening of SMBBHs and the interaction of the secondary and an accretion disc

When the gas in merger galaxies with low angular momentum is driven into the centre and triggers the activity of AGNs, the two SMBHs at the two galaxy centres lose the angular momentum due to dynamic friction and become bound at a separation of the two black holes $\sim$1–10 pc on a time-scale (Merritt 2000)

$$t_{\rm bd} \simeq \frac{r_{\rm e}}{0.30} \frac{\sigma^2}{\sigma_{\rm g}^3}, \tag{10}$$

where σ and $\sigma_{\rm g}$ are, respectively, the one-dimensional velocity dispersions of the larger (primary) and smaller (secondary) galaxies, and $r_{\rm e} \simeq 2.6$ kpc $(\sigma/200$ km s$^{-1})^3$ is the effective radius of the larger galaxy. Relating the one-dimensional velocity dispersions σ to the mass of the central SMBH with the empirical tight relation (Tremaine et al. 2002)

$$\log(M/{\rm M}_\odot) = 8.13 + 4.02 \log(\sigma/200\,{\rm km\,s^{-1}}) \tag{11}$$

and from equation (10), we have

$$t_{\rm bd} \simeq 2.0 \times 10^8\,{\rm yr}\, M_8^{1/2.01} q_{-1}^{-3/4.02}, \tag{12}$$

Downloaded from https://academic.oup.com/mnras/article/347/4/1357/1000457 by George Mason University user on 24 September 2020

where $q \equiv m/M = 0.1\, q_{-1}$. Equation (12) implies that $t_{\rm bd} \sim t_{\rm g}$ and is consistent with the observations of host galaxies of young AGNs that about 50 per cent of the host galaxies contain double nuclei, interaction of galaxies or significant morphological distortions due to galaxy merging (O'Dea 1998).

From equation (12), $t_{\rm bd}$ is larger than the Hubble time $t_{\rm Hubble}$ when $q < 5 \times 10^{-4} M^{2/3}{}_8 (t_{\rm bd}/10^{10}\ {\rm yr})^{-4/3}$, which is consistent with the numerical galaxy dynamical calculations (Yu 2002). As we are interested only in those SMBBHs formed within Hubble time, we have

$$q > q_{\rm cr} \simeq 5 \times 10^{-4} M_8^{2/3} \left(\frac{t_{\rm bd}}{10^{10}\ {\rm yr}}\right)^{-4/3}. \tag{13}$$

Bound SMBBHs become hard at a separation of the two SMBHs (Quinlan 1996; Yu 2002)

$$\begin{aligned} a_{\rm h} &= \frac{GmM}{4\sigma^2(m+M)} \\ &= 6.5 \times 10^3 M_8^{-1/2.01} \left(\frac{q}{0.02}\right) (1+q)^{-1} r_{\rm G} \end{aligned} \tag{14}$$

on a time-scale $\lesssim t_{\rm bd}$ due to dynamic friction. A hard binary loses orbital angular momentum via stellar dynamic interaction on a time-scale perhaps much longer than the Hubble time (Begelman et al. 1980; Quinlan 1996; Yu 2002) (for further discussion, see Section 1). However, equations (4) and (14) show that $a_{\rm h} \lesssim r_{\rm d}$ for a minor merger with $q \lesssim 0.3$ and the binary interacts with the accretion disc soon after it becomes hard. As the interaction between the SMBBHs and a standard accretion disc is very efficient in hardening SMBBHs, the final parsec problem can be avoided. We investigate in detail the interaction between the SMBBHs and an accretion disc in the following sections.

When the orbital radius a is very small, the loss of angular momentum of the SMBBHs due to gravitational radiation becomes important. When a is smaller than a critical radius $a_{\rm cr}$, the loss of angular momentum due to gravitational radiation becomes dominated with respect to binary–disc interaction. Liu et al. (2003) show

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

where f is a function of the binary eccentricity e:

$$f = \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)\left(1-e^2\right)^{-7/2}. \tag{16}$$

From equations (14), (15) and (1), the interaction between the binary and accretion disc is always important only if

$$q > 6.0 \times 10^{-5} M_8^{29/30} \alpha_{-2}^{-8/15} \dot{m}_{-1}^{-4/15} x_2^{-1/15} f^{2/3}, \tag{17}$$

where $x_2 = r/10^2 r_{\rm G}$. Therefore, the interaction of the accretion disc and the SMBH plays a very important role in the evolution of SMBBHs with $q > 5 \times 10^{-4}\ {\rm M}_8^{2/3} (t_{\rm bd}/10^{10}\ {\rm yr})^{-4/3}$.

3 ALIGNMENT OF ACCRETION DISC WITH ORBITAL PLANE AND THE REORIENTATION OF CENTRAL ROTATING SMBH

3.1 Accretion modes in AGNs

Although the accretion disc in young AGNs is most likely a standard thin or slim disc, the accretion rate may have decreased significantly when the binary becomes hard and interacts with the accretion disc. When the secondary SMBH enters the accretion disc with a random inclination angle, it interacts with the disc in two regimes: direct collisions and long-ranged interaction. The interaction between a companion star and the accretion disc around a primary has been investigated intensively in the literature (e.g. Ivanov et al. 1998, 1999; Lin & Papaloizou 1986; Narayan 2000) and the effects of the interaction depend on accretion modes and disc total mass.

If the accretion rate $\dot{m}$ of a disc is lower than a critical rate $\dot{m}_{\rm cr} \sim 10^{-2} - 10^{-1}$, the inner disc or the whole accretion disc becomes, probably via disc evaporation (Meyer & Meyer-Hofmeister 1994; Liu, Meyer & Meyer-Hofmeister 1995a; Meyer, Liu & Meyer-Hofmeister 2000), radiatively inefficient ADAF (Narayan & Yi 1994; Abramowicz et al. 1995), advection dominated inflow and outflow (ADIO; Blandford & Begelman 1999) or convection dominated accretion flow (CDAF; Narayan, Igumenshchev & Abramowicz 2000). Narayan & Yi (1995) and Esin, McClintock & Narayan (1997) show that if the fraction of viscously dissipated energy advected is $f \simeq 1$, the transitional accretion rate is $\dot{m}_{\rm cr} \sim 1.3\alpha_{\rm AD}^2$, where $\alpha_{\rm AD}$ is the viscous parameter of the radiatively inefficient accretion flow. Both dynamical investigations (Liu & Wu 2002) and spectrum fits (Esin et al. 1997; Quataert & Narayan 1999) show that $\alpha_{\rm AD}$ is typically between 0.3 and 0.1. As the critical accretion rate corresponds to the transition from a radiation dominated regime of $f \simeq 0$ to advection dominated accretion of $f \simeq 1$, it is expected that $0 < f < 1$ and $\dot{m}_{\rm cr}$ critically depends on the physical process in the disc. Mahadevan (1997) shows

$$\begin{aligned} \dot{m}_{\rm cr} &= 7.8 \frac{(1-f)}{f} \frac{(1-\beta)}{\beta} \alpha_{\rm AD}^2 c_1^2 \frac{1}{g(\theta_{\rm e})} \\ &\simeq 0.28\alpha_{\rm AD}^2, \end{aligned} \tag{18}$$

where β is the ratio of gas pressure to total pressure, $c_1 \simeq 0.5$, and $g(\theta_{\rm e})$ is a function of electron temperature with $g(\theta_{\rm e}) \sim 7$. In computing equation (18), Mahadevan (1997) takes $f \sim 0.5$ and $\beta \sim 0.5$, which is consistent with the recent suggestion that the transition most likely occurs at the region where radiation pressure becomes important. If the FR transition of radio galaxies corresponds to the transition of accretion mode, $\dot{m}_{\rm FR} \simeq 6 \times 10^{-3}$ implies that the typical viscous parameter in FR I radio galaxies is $\alpha_{\rm AD} \simeq 0.15$. The accretion disc is believed to be thin (Shakura & Sunyaev 1973) for $1 \gtrsim \dot{m} \gtrsim \dot{m}_{\rm cr}$ and slim (Abramowicz et al. 1988) when $\dot{m} \gtrsim 1$.

3.2 Interaction between SMBBHs and standard thin discs

As the outer part of an accretion disc with $r \gtrsim 10^2\ r_{\rm G}$ is most possibly a gas-pressure dominated standard disc, we first explore its interaction with SMBBHs. From equations (3) and (4), we obtain the ratio η of the disc total mass and the mass of the secondary

$$\begin{aligned} \eta &\equiv \frac{M_{\rm d}}{m} \\ &\approx 5 q_{-1}^{-1} \alpha_{-2}^{-4/5} \dot{m}_{-1}^{3/5} M_8^{0.556}. \end{aligned} \tag{19}$$

For those AGNs or quasi-stellar objects (QSOs) with super Eddington accretion $\dot{m} \gtrsim 1$, η is always greater than unity for any central BH masses in the range from 10^6 to $10^{10}\ {\rm M}_\odot$ (Wu, Liu & Zhang 2002). For a minor merger with mass ratio $q < 0.3$ and of a standard thin disc of accretion rate $\dot{m} > \dot{m}_{\rm cr} \sim 10^{-2} - 10^{-1}$, $M_{\rm d} \gtrsim m$.

When the secondary enters the accretion disc with a radius $a \simeq r_{\rm d}$, the disc mass $M_{\rm b}$ contained inside its orbit is $\sim M_{\rm d}$ and $M_{\rm b} \sim \eta m \gtrsim m$ and the interaction between the secondary and accretion disc is dominated by BH–disc direct collisions, and the distortion of the accretion disc due to the long-range interaction of the secondary is small (Ivanov et al. 1998, 1999). Ivanov et al. (1998) and Vokrouhlicky & Karas (1998) show that during each direct collision an amount of gas of mass $\sim \pi \Sigma r^2{}_{\rm a}$ is accreted by the secondary.

Downloaded from https://academic.oup.com/mnras/article/347/4/1357/1000457 by George Mason University user on 24 September 2020

Another amount of approximately the same mass obtains velocities larger than the escape velocity in the SMBBH potential and leaves the system, where the accretion radius $r_{\rm a}$ of the secondary is

$$r_{\rm a} = \frac{2Gm}{v_{\rm rel}^2} \sim \frac{2Gm}{v_{\rm K}^2} = 2qr. \tag{20}$$

$v_{\rm rel} \sim v_{\rm K}$ is the velocity of the secondary relative to the disc gas. The outflow rate of the mass due to the direct collision is

$$\dot{M}_{\rm out} \sim 2 \times \frac{2\pi\Sigma r_{\rm a}^2}{t_{\rm orb}} = 2\Sigma r_{\rm a}^2 \Omega_{\rm K}. \tag{21}$$

The disc drag to the secondary is important only when the outflow is compensated by the radial inflow of mass, i.e. $\dot{M}_{\rm out} < \dot{M} = 3\pi\nu\Sigma = 3\pi\alpha\delta^2 r^2 \Omega_{\rm K}\Sigma$, which implies

$$\begin{aligned} q < q_0 &= \sqrt{\frac{3\pi}{8}}\alpha^{1/2}\delta \\ &\simeq 3 \times 10^{-4} \alpha_{-2}^{2/5} \dot{m}_{-1}^{1/5} M_8^{-1/10} x_4^{1/20}. \end{aligned} \tag{22}$$

Equations (13) and (22) suggest that, for SMMBHs with $q > q_{\rm cr}$ formed during galaxy merging within Hubble time, the depleted region by the secondary cannot be sufficiently refilled with gas and its surface density is thus much less than the unperturbed value. The secondary would lose its angular momentum and migrate inwards on accretion time-scale $\sim t_{\rm acc}$ (Ivanov et al. 1999)

$$t_{\rm acc} \equiv \frac{m}{\dot{M}} = \frac{q}{\dot{m}} t_{\rm s} = 4.5 \times 10^7 \,{\rm yr}\, q_{-1} \dot{m}_{-1}^{-1}, \tag{23}$$

where $t_{\rm s} \equiv M/\dot{M}_{\rm Edd} = 4.5 \times 10^7$ yr.

When the secondary migrates toward the mass centre of binary and has an orbital radius a less than a critical radius $a_{\rm m}$ within which the disc mass $M_{\rm b}$ is equal to its mass m, the long-ranged averaged quadrupole component of the binary gravitational field becomes important and warps the disc first in the vicinity of the orbit (Lin & Papaloizou 1986; Ivanov et al. 1999; Kumar 1990). From equation (3), we have

$$a_{\rm m} = 2.3 \times 10^3 q_{-1}^{5/7} \alpha_{-2}^{4/7} \dot{m}_{-1}^{-3/7} M_8^{-6/7} r_{\rm G} \tag{24}$$

and $a_{\rm m} \gg r_{\rm BP}$. The twist and warp transfers both inwards and outwards. Numerical simulation given by Ivanov et al. (1999) shows that the inner accretion disc evolves into a quasi-stationary twisted configuration and becomes coplanar with the binary orbital plane for any value of α (Ivanov et al. 1999). The alignment time-scale $t_{\rm al2}$ is the warp transfer time-scale $t_{\rm tw}$. For an accretion disc with $\alpha > \delta$ the transfer is radiative with

$$t_{\rm al2} \simeq 3.0 \times 10^3 \,{\rm yr}\, \alpha_{-2}^{6/5} \dot{m}_{-1}^{-2/5} M_8^{6/5} x_3^{7/5}, \tag{25}$$

where $x_3 = a/10^3\ r_{\rm G}$. To obtain equation (25), we have used equations (6), (7) and (1). For an accretion disc with $\alpha < \delta$, the transfer is wave-like (Ivanov et al. 1999) and the time-scale $t_{\rm al2}$ is $\sim a/c_{\rm s} \simeq \delta^{-1}\Omega^{-1}{}_{\rm K} \sim 1.4$ yr $\delta^{-1}x^{3/2}{}_3 M_8$. However, the innermost region of the aligned disc in the vicinity of the primary SMBH with $r \lesssim r_{\rm bp}$ is twisted and aligned with the rotating central SMBH due to the Bardeen–Petterson effect. The rotating SMBH becomes nearly coplanar with the binary orbital plane on another time-scale $t_{\rm al1} \sim 10^4$ yr $\gtrsim t_{\rm al2}$ only if the binary orbital angular momentum $J_{\rm b} = amv_{\rm b} \simeq m\,(GMa)^{1/2}$ is larger than the rotation angular momentum $J_{\rm BH} = a_*\, GM^2/c$ of the central black hole. Taking $a \sim a_{\rm m}$, we have

$$\frac{J_{\rm b}}{J_{\rm BH}} \simeq 6.8 \times 10^2 \left(\frac{a_*}{0.1}\right)^{-1} q_{-1}^{19/14} \alpha_{-2}^{2/7} \dot{m}_{-1}^{-3/14} M_8^{-3/7}, \tag{26}$$

which gives $J_{\rm b} > J_{\rm BH}$ for

$$q \gtrsim 8 \times 10^{-4} \left(\frac{a_*}{0.1}\right)^{14/19} \alpha_{-2}^{-4/19} \dot{m}_{-1}^{3/19} M_8^{6/19} \sim q_{\rm cr}. \tag{27}$$

Equation (27) implies that the spin axis of the central SMBH formed during galaxy merging within Hubble time changes its orientation from vertical to the outer accretion disc to well aligned with the rotation axis of the binary on a time-scale $t \lesssim 10^5$ yr. As the inclination angle of binary plane is random, the angle of the spin axis of the central SMBH relative to the galactic plane distributes randomly.

When the secondary interacts with the accretion disc and distorts the inner disc, it also twists and warps the accretion disc outside its orbit to some radius $r_{\rm al}$, as the quadrupole contribution to the potential causes the precession of the major axis of an elliptical orbit with frequency (Ivanov et al. 1999)

$$\Omega_{\rm ap} = \frac{3}{4} q \left(\frac{a}{r}\right)^2 \Omega_{\rm K}, \tag{28}$$

where $\Omega_{\rm K}$ is the Keplerian angular velocity at r. The radius $r_{\rm al}$, out to which the disc is aligned with the orbital plane, depends on the quadrupole component of the binary gravitational field and the transfer of warp and angular momentum in the disc. It can be estimated simply, assuming that at the radius $r_{\rm al}$ the time-scale for radial transfer of the warp, $t_{\rm warp}$, is of the order of the local quadrupole precession time-scale $\Omega_{\rm ap}^{-1}$. From $t_{\rm wp} = \Omega^{-1}{}_{\rm ap}$ and equation (6), we have

$$r_{\rm al} \sim (q\alpha)^{1/2} \delta^{-1} a \tag{29}$$

for an accretion disc with $\alpha > \delta$ and diffusive-like transfer of disc warp, or

$$r_{\rm al} \sim \frac{3^{1/2}}{2} q^{1/2} \delta^{-1/2} a \tag{30}$$

for a disc with $\alpha < \delta$ and wave-like transfer of disc warp of $t_{\rm wp} \sim r/c_{\rm s}$. The realignment radius $r_{\rm al}$ given by equations (29) or (30) is exactly the same as that given by Ivanov et al. (1999) and Kumar (1990). To have the alignment scale larger than the binary orbit radius, we need

$$q > 5 \times 10^{-4} \alpha_{-2}^{-6/5} \dot{m}_{-1}^{2/5} M_8^{-1/5} x_3^{1/10}. \tag{31}$$

Here we have used equation (1) to obtain equation (31). Equations (13) and (31) suggest that for any SMBBHs–disc system formed during galaxy merging within Hubble time the secondary always aligns the accretion disc from the vicinity of the primary SMBH out to a radius $r_{\rm al} > a$. If the accretion disc is a slim disc with $\dot{m} \gtrsim 1$ and $\delta \sim 1 > \alpha$, equation (30) implies $q \gtrsim \frac{4}{3}\delta \sim 1$ for $r_{\rm al} > a$. Therefore, only major merger can twist and align a slim disc.

3.3 Interaction between SMBBHs and ADAFs

As for an ADAF, the accretion gas has a quasi-spherical morphology with $\delta \sim 1$ and the orbital velocity v_ϕ of the gas is significantly subKeplerian. The interaction between the secondary and the accretion flow is insensitive to the inclination of the orbit relative to the angular momentum vector of the accreting gas.

As an ADAF has $\delta(\sim 1) > \alpha$, transfer of any of its distortion (warp and twist) is wave-like (Papaloizou & Lin 1995; Musil & Karas 2002). As the accretion flow has a very low accretion rate and is quasi-spherical, its warp and twist due to interaction with the secondary is negligible. The drag of the accretion flow to the secondary SMBH can be approximated with the interaction of a uniform gas of density (Narayan 2000)

$$\rho = \frac{\dot{M}}{4\pi r^2 v_{\rm r}} \simeq \frac{\dot{m}\dot{M}_{\rm Edd}}{4\pi r^2 \alpha_{\rm AD} V_{\rm K}}. \tag{32}$$

As the moving SMBH has a relative velocity $|\boldsymbol{v}_{\rm rel}| \sim v_{\rm K}$ to the gas, the drag force is (Ostriker 1999)

© 2004 RAS, MNRAS **347,** 1357–1369

Downloaded from https://academic.oup.com/mnras/article/347/4/1357/1000457 by George Mason University user on 24 September 2020

$$F_{\mathrm{df}} = -4\pi I \left(\frac{Gm}{v_{\mathrm{rel}}}\right)^2 \rho, \tag{33}$$

where the coefficient I depends on the Mach number $M \equiv v_{\mathrm{rel}}/c_{\mathrm{s}}$ and c_{s} is the sound velocity. As in our problem, $v_{\mathrm{rel}} \sim V_{\mathrm{K}} \gtrsim c_{\mathrm{s}}$ with $M \gtrsim 1$ and I is approximately (Ostriker 1999; Narayan 2000)

$$I \sim \ln(R_{\max}/R_{\min}). \tag{34}$$

$R_{\max} \sim H \sim r$ is the size of the system and $R_{\min}$ is the effective size of the secondary, which is approximately the accretion radius $R_{\min} \sim r_{\mathrm{a}} = 2\,Gm/v_{\mathrm{rel}}^2$. Therefore, we have

$$I \sim \ln\left(\frac{r v_{\mathrm{rel}}^2}{2Gm}\right) = \ln\left(\frac{M}{2m}\right) \simeq 2 - \ln q_{-1}. \tag{35}$$

Thus, the hydrodynamic drag time-scale is

$$\begin{aligned} t_{\mathrm{hd}} &\equiv \frac{m v_{\mathrm{K}}}{|F_{\mathrm{df}}|} \simeq \frac{\alpha_{\mathrm{AD}}}{I\dot{m}} q^{-1} t_{\mathrm{s}} \\ &\simeq 3 \times 10^9\,\mathrm{yr}\, q_{-1}^{-1} \left(\frac{\alpha_{\mathrm{AD}}}{0.15}\right) \dot{m}_{-2}^{-1}, \end{aligned} \tag{36}$$

where $\dot{m}_{-2} = \dot{m}/10^{-2}$. Therefore, the hydrodynamic drag of an ADAF on an orbiting SMBH is negligible.

When the secondary moves in an ADAF, some amount of gas is accreted and approximately the same amount of mass obtains velocities greater than the escape velocity, as that in a standard thin disc (see Section 3.2). Although it is different in ADAFs as the flow is significantly subKeplerian and $\alpha_{\mathrm{AD}} \sim 0.3$ and $\delta \sim 1$, equation (22) can give a reasonable lower estimate to the upper limit q_0. When $q < q_0$, the accretion flow can compensate the outflow due to the collision of the secondary and the accretion flow. Equation (22) gives $q_0 \sim \sqrt{3\pi/8}\alpha^{1/2}\delta \simeq 0.6$. Therefore, the accretion flow can compensate the mass outflow due to the SMBBHs–disc collision even for a major merger.

3.4 Realignment time-scale of the orbital plane and the outer disc and the lifetime of AGNs

When the twisted inner disc and the binary orbital plane become coplanar, the system remains quasi-stationary. As it is determined by the specific angular momentum of the gas entering the disc, the orientation of outer accretion disc with $r > r_{\mathrm{al}}$ is determined by the outer gas system and is supposed to be nearly aligned with that of the galactic disc. The gas in the accretion disc at $r > r_{\mathrm{al}}$ is accreting through the twisted disc and exchanges angular momentum with the binary, leading to the rotation axis of the aligned inner system slowly processing and realigning with that of the outer disc plane (Rees 1978; Ivanov et al. 1999), similar to the realignment of a rotating black hole with an inclined accretion disc due to the Bardeen–Petterson effect (Scheuer & Feiler 1996; Natarajan & Pringle 1998). The realignment time-scale for a disc with $\alpha \sim 1$ is (Ivanov et al. 1999)

$$t_{\mathrm{al3}} \sim \frac{J_{\mathrm{b}}}{\dot{J}_{\mathrm{d}}} \simeq \frac{a m v_{\mathrm{b}}}{\dot{M} r_{\mathrm{al}} v_{\mathrm{d}}(r_{\mathrm{al}})} \simeq \left(\frac{a}{r_{\mathrm{al}}}\right)^{1/2} t_{\mathrm{acc}} < t_{\mathrm{acc}} \tag{37}$$

where $\dot{J}_{\mathrm{d}}$ is the angular momentum flux of the disc at r_{al} and $v_{\mathrm{d}}(r_{\mathrm{al}}) \simeq v_{\mathrm{K}}(r_{\mathrm{al}})$ is the disc angular velocity at r_{al}. Defining a disc viscous time-scale

$$t_{\mathrm{d}} \equiv \frac{M_{\mathrm{d}}}{\dot{M}} = \eta t_{\mathrm{acc}}, \tag{38}$$

and from equations (29), (1), and (19), we have

$$\begin{aligned} t_{\mathrm{al3}} &\sim \left(\frac{a}{r_{\mathrm{al}}}\right)^{1/2} \eta^{-1} t_{\mathrm{d}} \\ &\simeq 0.60 q_{-1}^{3/4} \alpha^{1/2} \dot{m}_{-1}^{-1/2} M_8^{-0.61} x_4^{1/40} t_{\mathrm{d}}, \end{aligned} \tag{39}$$

where $x_4 = r_{\mathrm{al}}/10^4\ r_{\mathrm{G}}$.

However, for an accretion disc in AGNs, the viscous parameter α is $\ll 1$ and the case is more complex (Scheuer & Feiler 1996; Natarajan & Pringle 1998). The effect of the binary on the accretion disc is to force the rotation axis of the disc to process and to align with the binary orbital plane and, by Newtonian third law, the binary orbit realigns with the accretion disc due to the feedback effect. Both precession and alignment take place on the same time-scale similar to the realignment of the rotating SMBH due to the Bardeen–Petterson effect, i.e.

$$t_{\mathrm{al3}} \sim \Omega_{\mathrm{ap}}^{-1}, \tag{40}$$

where Ω_{ap} is the precessing angular velocity at r_{al}. From equations (28), (29), (1) and (42), this gives

$$t_{\mathrm{al3}} \sim 0.49 \alpha_{-1}^{29/10} q_{-1}^{3/4} \dot{m}_{-1}^{-3/10} M_8^{0.79} x_3^{53/40} t_{\mathrm{d}}, \tag{41}$$

where $x_3 = a/10^3\ r_{\mathrm{G}}$. Equations (41) and (39) give a similar result that it takes about half of the disc viscous time to realign the binary orbit with the outer accretion disc and that $t_{\mathrm{al3}} \sim 10^7$–$10^8$ yr. As the binary–disc interaction takes place at $a > a_{\mathrm{cr}}$, equation (37) suggests that the binary orbital plane should become coplanar with the accretion disc before the separation a becomes $\ll a_{\mathrm{cr}}$. Therefore, the spin axis of the rotating central SMBH should be vertical to the accretion disc when the secondary merges into the primary due to gravitation wave radiation.

From equations (38), (3) and (4), we have

$$t_{\mathrm{d}} = 2.2 \times 10^8\,\mathrm{yr}\, \alpha_{-2}^{-4/5} \dot{m}_{-1}^{-2/5} M_8^{0.556}. \tag{42}$$

The lifetime of AGNs is a very important parameter in determining the fuelling mechanism of AGNs and the SMBH growth. Most estimates of the net lifetime are in the range $t_{\mathrm{Q}} = 10^7$–10^8 yr for luminous quasars with central SMBHs of mass $M \sim 10^8$–$10^9\ \mathrm{M}_{\odot}$ (Haehnelt, Natarajan & Rees 1998; Martini & Weinberg 2001; Steidel et al. 2002; Yu & Tremaine 2002) and most probably $t_{\mathrm{Q}} \simeq 5 \times 10^7$ yr (Jakobsen et al. 2003) and $t_{\mathrm{Q}} \sim 6.6 \times 10^5$ yr for mini-quasars with central SMBHs of mass $M \sim 10^5\ \mathrm{M}_{\odot}$ (Haiman & Loeb 1998, 1999; for a recent review, see Martini 2003). It is generally believed that the accretions in luminous QSOs and in mini-quasars are approximately at the Eddington rate. Taking the fiducial value of the parameters, $\alpha = 0.03$, $\dot{m} = 1$ and $M_8 = 1$ for luminous QSOs and $M_8 \sim 10^{-3}$ for mini-quasars, we have $t_{\mathrm{d}} = 3.6 \times 10^7$ yr for luminous QSOs and $t_{\mathrm{d}} = 7.8 \times 10^5$ yr for mini-quasars, which are consistent with the estimates in the literature. Therefore, we take the disc viscous time-scale t_{d} as an indicator of the lifetimes of an accretion disc and of AGNs. Equation (38) implies that SMBBHs in AGNs should merge within the viscous time-scale of an accretion disc. However, equation (41) suggests that the binary orbital plane and the rotating central SMBH remain misaligned with the outer accretion disc with a random inclination angle with respect to the outer accretion disc for a greater fraction of the viscous time of an accretion disc and of the lifetime of AGNs.

When the binary orbital orbit becomes coplanar with the accretion disc, the secondary black hole opens a gap in the accretion disc and exchanges angular momentum with the outer disc gas via gravitational torques, leading to shrinking of the binary separation on a viscous time-scale t_{acc} (Lin & Papaloizou 1986; Ivanov et al. 1999; Armitage & Natarajan 2002). The interaction of SMBBHs and a coplanar accretion disc and the final coalescence of SMBBHs has been discussed in detail by Liu et al. (2003).

Downloaded from https://academic.oup.com/mnras/article/347/4/1357/1000457 by George Mason University user on 24 September 2020

4 JET ORIENTATION AND THE FORMATION OF X-SHAPED FEATURE IN RADIO GALAXIES

In Sections 2 and 3, we discussed the possible SMBBHs–disc system and their interaction on a subparsec scale. As relativistic jets in radio sources most likely initiate forming before the two SMBHs become bound, the relativistic jets may have developed to a large-scale size when the binary becomes hard and interacts with accretion disc. It is believed that relativistic plasma jets form along the spin axis of the central SMBH and are perpendicular to the accretion disc due to the Bardeen–Petterson effect (Rees 1984; Marscher et al. 2002),

When the orbital radius of a binary is less than the radius $a_{\rm m}$ and the accretion disc is still a standard α-disc with accretion rate $\dot{m} > \dot{m}_{\rm cr} \sim 10^{-2} - 10^{-1}$, the secondary realigns the central rotating SMBH via binary–disc interaction, leading to reorientations of its spin axis and of the relativistic jets with a reorientation time-scale $t_{\rm al1} \lesssim 10^5$ yr. As a relic radio lobe can be detected within about $t_{\rm relic} \sim 10^6$–10^8 yr depending on the environment (Komissarov & Gubanov 1994; Slee et al. 2001; Kaiser & Cotter 2002), the reorientation of radio jets may be observed in some radio sources. Actually, the observed X-shaped (or winged) radio sources (Leahy & Parma 1992; Dennett-Thorpe et al. 2002) might be such objects.

4.1 Summary of observations of X-shaped radio sources

X-shaped, or winged, radio galaxies (Högbom & Carlsson 1974) are a subclass of extragalactic radio sources of very peculiar morphology: a second axis of symmetry of two large-scale old diffuse wings or tails, orienting at an angle to the currently active lobes (Dennett-Thorpe et al. 2002; Capetti et al. 2002). Many observations have been made of these sources, showing the following.

(1) The winged sources are about 7 per cent of the sample radio galaxies investigated by Leahy & Parma (1992).

(2) They are low-luminous FR II or borderline FR I/FR II radio galaxies and none of them belongs to FR I type (Dennett-Thorpe et al. 2002).

(3) There is no evidence for a merger with a large galaxy in the last $\sim 10^8$ yr (Dennett-Thorpe et al. 2002) in the sources except B2 0828+32 (Ulrich & Roennback 1996) and 3C 293 (Evans et al. 1999; Martel et al. 1999).

(4) All are narrow-line galaxies except 4C +01.30 which show weak broad emission lines (Wang, Zhou & Dong 2003).

(5) The old wings as long as, or even longer than, the directly powered active lobes have no pronounced spectral gradients and form due to a jet reorientation within a few Myr (Dennett-Thorpe et al. 2002).

(6) The wings are aligned with the minor axis and vertical to the major axis of the host galaxy (Capetti et al. 2002; Wang et al. 2003).

(7) The active radio lobes have a random inclination angle relative to the major axis of host galaxy.

(8) The host galaxy has a high eccentricity (Capetti et al. 2002).

(9) The wings are Z-symmetric (Gopal-Krishna, Biermann & Wiita 2003).

4.2 Models in the literature and their difficulties

Several scenarios have been suggested for the formation of the X-shaped structure in some FR II radio sources in the literature: (1) back-flow of radio plasma from the active lobes into wings via buoyancy (Leahy & Williams 1984) or diversion through the galactic disc (Capetti et al. 2002); (2) slow conical precession of jet axis (Parma, Ekers & Fanti 1985); (3) quick reorientation of jet axis with or without turn-off of jet formation for some time (Dennett-Thorpe et al. 2002; Merritt & Ekers 2002). Dennett-Thorpe et al. (2002) review all the models and find that the first two are inconsistent with the observations and the third scenario together with minor galaxy mergers is favoured.

A rapid reorientation of the jet axis may result from the realignment of a rotating SMBH due to the Bardeen–Petterson effect with a misaligned accretion disc which forms due to the disc instabilities (Dennett-Thorpe et al. 2002), or from the spin-flip of the active SMBH due to the coalescence of an inclined binary black hole (Dennett-Thorpe et al. 2002; Merritt & Ekers 2002; Zier & Biermann 2001). However, disc instabilities would be suppressed even by a mild rotation of the SMBH and cannot explain the straightness of the jet from Very Long Base Interferometry (VLBI) to Very Large Array (VLA) scale (Pringle 1996). Another difficulty with the disc instability model is in explaining why such instability does not exist in other radio galaxies which have stable jet direction and why it occurred only once in X-shaped sources (Dennett-Thorpe et al. 2002).

Merritt & Ekers (2002) suggest that the rapid change of jet orientation may be due to a spin-flip of the central active black hole due to a coalescence of misaligned SMBBHs. To explain the detection rate of X-shaped radio sources, they show that the merger has to be minor. Although the observations of X-shaped radio sources favour the minor merger scenario (Dennett-Thorpe et al. 2002; Gopal-Krishna et al. 2003), the spin-flip picture has several defects. First of all, an inclined rotating SMBH formed via binary coalescence should realign with the accretion disc due to the Bardeen–Petterson effect on a short time-scale $t_{\rm al1} \lesssim 10^5$ yr. This implies that the relativistic jets reorient in the direction of the old wings on the time-scale and we should detect a distorted jet of a length $l_{\rm j} \sim t_{\rm al1} v_{\rm j} \lesssim 10$ kpc for a typical jet velocity $v_{\rm j} \sim 0.3c$ instead of straight wings of hundreds of kpc. Secondly, Merritt & Ekers perform the calculation ignoring gravitational radiation, while calculations based on general relativity show that the change in inclination of a rotating central SMBH is negligible in a minor merger and a significant reorientation of the active SMBH requires a comparatively rare major merger (Hughes & Blandford 2003). Thirdly, as we show in Section 3, binary–disc interactions would align a central SMBH with an inclined binary orbital plane before the binary coalesces and no change in the orientation of the spin axis of the central SMBH occurs even in a major merger. The last is from observations. The model does not reasonably explain the sharp transition that the X-shaped feature is detected only in FR II radio galaxies but not in FR I radio galaxies with similar luminosity.

4.3 Reorientation of radio jets in FR II radio galaxies

Here we suggest that the formation of the X-shaped feature in some radio sources is due to the realignment of the rotating central SMBHs with the binary orbital plane via binary–disc interaction and the Bardeen–Petterson effect. In this scenario, the accretion disc and the gas in a galactic disc have already settled down and large-scale relativistic jets in radio galaxies have formed, before the secondary SMBH distorts the accretion disc. It is expected that the accretion disc is nearly coplanar with the dust lane or galactic disc due to the conservation of angular momentum of gas. Thus, the large-scale relativistic radio jets and lobes are nearly vertical to the galactic plane.

If the accretion rate is greater than the critical rate $\dot{m}_{\rm cr} \sim 10^{-2} - 10^{-1}$ and the accretion disc is a standard thin disc, the twisted disc

Downloaded from https://academic.oup.com/mnras/article/347/4/1357/1000457 by George Mason University user on 24 September 2020

reorients the spin axis of the rotating SMBH, leading to the rapid change of jet direction on a time-scale $t_{\rm reor} \sim t_{\rm al1} \lesssim 10^5$ yr. The relic of the old radio lobes forms the detected old wings in the X-shaped radio sources. As the jet before the reorientation is vertical to the accretion disc, the wings are expected to be nearly perpendicular to the galactic plane, as is observed.

The winged radio source 4C +01.30 shows weak broad emission lines and contains a partially obscured quasar nucleus. The mass of its central SMBH is $M \sim 4 \times 10^8$ M$_\odot$ and the accretion disc is a standard α-disc with $\dot{m} = L/L_{\rm Edd} \simeq 0.2$ (Wang et al. 2003). From equation (9), the reorientation takes place on a time-scale $t_{\rm reor} \simeq 2 \times 10^5$ yr for typical parameters $a_* = 0.7$, $\alpha = 0.03$ and $\epsilon = 0.3$. From equation (25), the disc becomes twisted and warped due to the interaction with the secondary and coplanar with the binary orbital plane on a time-scale $t_{\rm al2} \simeq 4 \times 10^4$ yr. From equation (42), the viscous time of the sources is $t_{\rm life} \simeq 1.5 \times 10^8$ yr. The mass ratio of the accretion disc and the secondary SMBH is $\eta \approx 7q^{-1}{}_{-1}$ and $\eta > 1$ even for a major merger with $q \sim 0.7$.

As the other X-shaped radio galaxies show only narrow emission lines, the central quasar nuclei may have been completely obscured by the dust torus and the X-shaped sources are edge-on. This is easy to understand as, with observations, it is preferable to detect the X-shaped feature in radio sources with large-scale projected jets. Therefore, the high eccentricity of the host galaxy of X-shaped radio sources is most likely due to selection effects and does not relate to the origin of the X-shaped structure. This might be the reason why in the control sample of radio galaxies used by Capetti et al. (2002) the radio galaxies with a host galaxy of a similar or even higher eccentricity do not show winged features.

4.4 The missing of winged FR I radio galaxies

It is possible that the accretion rate has become less than the critical rate $\dot{m}_{\rm cr}$ and that the accretion disc is no longer a standard α-disc but a radiatively inefficient accretion flow, e.g. an ADAF, when the interaction between the secondary and an accretion disc starts. As the interaction between an ADAF and a binary is negligible, reorientation of the spin axis of the central SMBH takes place on a very long time-scale $t_{\rm hd} \sim 10^9$ yr, which is longer than the observable time-scale of a radio relic $t_{\rm relic} \sim 10^7$–10^8 yr (see the discussion below). As the transition of FR I and FR II radio galaxies is related to an accretion rate $\dot{m}_{\rm FR} \sim \dot{m}_{\rm cr}$ (Ghisellini & Celotti 2001; Cavaliere & D'Elia 2002; Maraschi & Tavecchio 2003), the FR division may reflect the transition of the accretion mode from a standard disc to a radiatively inefficient accretion flow and the accretion disc in FR I radio galaxies is radiatively inefficient. This implies that the binary–disc interaction cannot form a winged structure in FR I radio sources and the missing of X-shaped FR I radio sources is due to the radiatively inefficient accretion mode, i.e. ADAF, ADIO or CADF. However, it is possible that the outer part of the accretion disc is standard and the inner accretion flow is an ADAF. In this case, the interaction between the binary and the outer accretion disc can twist part of the standard disc on a time-scale $t_{\rm al2} \sim 10^3$ yr but the inner ADAF realigns the central rotating black hole on a time-scale $t_{\rm al1} \sim 10^7$ yr for $\alpha_{\rm AD} \sim 0.15$ and $\dot{m} \sim 10^{-2}$, which is of the same order of the relic time $t_{\rm relic}$. Here, we use equation (9) to estimate the realignment time-scale for a transition system $\dot{m} \sim \dot{m}_{\rm cr}$. Therefore, it is expected that the S-shaped structure would be observed in high-luminous FR I radio sources.

One possibility to detect the X-shaped feature in FR I radio sources is that radio sources evolves from FR II type into FR I type after the wings forms with $t_{\rm al3} > t_{\rm d}$. From equation (41), this implies

$$q > 1.5 \left(\frac{\alpha}{0.05}\right)^{-58/15} \dot{m}_{-2}^{2/5} M_8^{-1.05} x_3^{-53/30}. \qquad (43)$$

As the mass ratio q should be smaller than unity, equation (43) implies that it is not possible for an X-shaped FR I radio galaxy to form.

4.5 Evidence against recent mergers

The undisturbed properties of host galaxies of winged radio sources except 3C 293 imply that mergers are minor or, if major, longer than a few 10^8 yr ago. Equation (12) shows that two SMBHs become bound on a time-scale $\sim 10^8$ yr. A bound binary becomes hard and interacts with an accretion disc at a parsec scale on a similar time-scale (cf. Yu 2002). Therefore, the galaxy merging in X-shaped radio sources may occur $\sim 10^9$ yr ago in our scenario, which is consistent with the observations of 3C 293 (Evans et al. 1999).

3C 293 is the only winged source showing obvious signs of interaction of a tidal tail and a close companion galaxy (Evans et al. 1999; Martel et al. 1999). The relative masses of its host galaxy and the companion suggest that the tidal feature is most likely a remnant from a merger event occurring more than $t_{\rm td} \sim 10^9$ yr ago (Evans et al. 1999). The spectroscopic observations of the central bulge region show a strong CO emission line with a velocity width ~400 km s^{-1}. From equation (11), the mass of the central SMBH is $M \simeq 2.2 \times 10^9$ M$_\odot$. If we take $t_{\rm td} \sim 10^9$ yr $\sim 2\, t_{\rm bd}$, equation (12) gives a mass ratio $q \sim 0.3$, implying that the merger in 3C 293 is minor, but with a moderate mass ratio, and is rare. This is consistent the observations that the merger occurred quite a long time ago but still can be detected and that 3C 293 is the only X-shaped radio source showing signs of interaction. The mass ratios of the disc and the secondary are $\eta \sim 9\alpha_{-2}^{-4/5}\dot{m}_{-1}^{3/5}$ and $\eta > 1$ for $\dot{m} > \dot{m}_{\rm cr}$. Therefore, the binary black hole will become realigned with the outer accretion disc and merger into one more massive SMBH, leading to the formation of a double–double FR II radio galaxy. From equation (24), the interaction occurs likely at $\lesssim 3.6 \times 10^2 r_{\rm G}\alpha_{-2}^{4/7}\dot{m}_{-1}^{-3/7} \sim 0.08$ pc, which is much less than the disc size $r_{\rm d} \simeq 0.4$ pc.

4.6 Detection rate of winged radio sources and the lifetime of low-luminosity FR II radio galaxies

Leahy & Parma (1992) show that the probability $\lambda_{\rm X}$ of detecting a FR II radio source with an X-shaped radio feature is ≈7 per cent in a sample of radio galaxies with luminosity between 3×10^{24} and 3×10^{26} W Hz^{-1} at 1.4 GHz. The detection rate depends on both the mean observable time-scale, $t_{\rm relic}$, of relic radio lobes and the minimum $t_{\rm min}$ between the lifetime $t_{\rm life}$ of FR II radio galaxies and the mean merge time $t_{\rm merger}$ between mergers, $t_{\rm min} = \min(t_{\rm life}, t_{\rm merge})$. It is difficult to accurately estimate the mean time-scale $t_{\rm relic}$ in a survey sample. The estimated time-scale $t_{\rm relic}$ is in the range of $\sim 10^6$–10^8 yr, depending on both the environment and the survey frequency (Komissarov & Gubanov 1994; Slee et al. 2001; Kaiser & Cotter 2002). This is consistent with the spectrally estimated age limit of radio wings in some X-shaped sources: <34 Myr for 3C 223.1 and <17 Myr for 3C 403 (Dennett-Thorpe et al. 2002), and <75 Myr for B2 0828+32 (Klein et al. 1995).

From the measured rate and the time-scale $t_{\rm relic}$, we have

$$t_{\rm min} = \frac{t_{\rm relic}}{\lambda_{\rm X}} \lesssim 10^9 \text{ yr} \left(\frac{t_{\rm relic}}{10^8 \text{ yr}}\right). \qquad (44)$$

Downloaded from https://academic.oup.com/mnras/article/347/4/1357/1000457 by George Mason University user on 24 September 2020

Merritt & Ekers (2002) take the upper limit $t_{\rm relic} \sim 10^8$ yr and obtain $t_{\rm min} \simeq 10^9$ yr, which is too large to be the age of radio sources. They interpret $t_{\rm min}$ as the mean merge time-scale of galaxy, $t_{\rm merge}$, which is higher than the estimate of the galaxy merge rate given in the literature (Haehnelt 1998; Carlberg et al. 2000), although it is not implausible. However, a relic with an age $t_{\rm relic} \sim 10^8$ yr is most likely invisible even at a very low survey frequency due to expansion and radiation. To use the detection rate given by Leahy & Parma (1992) for a sample of low-luminous FR II radio galaxies with a high survey frequency of 1.4 GHz, it is most plausible to adopt $t_{\rm relic} \approx 10^7$ yr, which gives $t_{\rm min} \simeq 10^8$ yr. As the lifetime $t_{\rm life}$ of low-luminosity FR II radio galaxies is much less than the mean merge time-scale $t_{\rm merge}$ of the galaxy which is $\gtrsim 10^9$ yr, we take $t_{\rm min}$ as the mean lifetime of low-luminous FR II radio sources and have $t_{\rm life} \sim 10^8$ yr, which is consistent with the estimated lifetime $t_{\rm life} \sim 10^8$ yr for low-luminous AGNs in the literature. As in low-luminous FR II radio galaxies the accretion rate is $\dot{m} \gtrsim \dot{m}_{\rm FR}$, we take a mean accretion rate $\dot{m} \sim 0.1$ for the Leahy & Parma sample and from equation (42) obtain a disc viscous time $t_{\rm d} \simeq 10^8$ yr for $\alpha = 0.03$. The estimates of the lifetime of low-luminous FR II radio sources in different ways are very consistent with each other.

4.7 Orientations of wings and active radio lobes in FR II radio sources

As an accretion disc forms with gas of low angular momentum in a merging system of galaxies and the gas is settled down into the galactic plane with low gravitational potential, it is expected that large-scale relativistic plasma jets are perpendicular to the accretion disc due to the Bardeen–Petterson effect and to the galactic plane. Because the radio wings in X-shaped radio sources are the relics of radio jets and lobes, they should be vertical to the major axis of the host galaxy. However, the orientations of active jets are aligned with the rotation axis of the binary and distribute randomly. This is consistent with the observations of X-shaped radio galaxies (Capetti et al. 2002) that the wings in all the winged radio galaxies are nearly aligned with the minor axis of the host galaxy and the active lobes have no preferential orientation.

To reorient the rotating central SMBH, the accretion disc has to be standard with $\dot{m} > \dot{m}_{\rm cr}$ and thus the radio galaxies morphologically belong to FR II type. However, if the binary hardening time-scale ($\sim t_{\rm bd}$) is much larger than the disc viscous time $t_{\rm d}$, the accretion disc becomes a radiatively inefficient disc, e.g. an ADAF, with $\dot{m} < \dot{m}_{\rm cr} \sim \dot{m}_{\rm FR}$ before binary–disc interaction. Thus, a radio source evolves from FR II into FR I class without the formation of an X-shaped radio structure. Equations (12) and (42) suggest that an X-shaped radio structure cannot form in a galaxy merging with a mass ratio

$$q \ll q_{\rm X} \equiv 3 \times 10^{-2} M_8^{-0.08} \alpha_{-2}^{1.07} \dot{m}_{-2}^{0.54}. \tag{45}$$

Therefore, the mass ratio in any X-shaped FR II radio galaxies should be $q \gtrsim 10^{-2}$, which is consistent with the estimates of the X-shaped sources 3C 293 and 4C +01.30. From equations (26) and (45), we have $J_{\rm b} \gg J_{\rm BH}$ even for a central SMBH with $a_* \sim 1$. Equations (13) and (45) imply that nearly all the hard binary systems formed during galaxy merging within Hubble time would produce X-shaped features.

When a binary twists the inner accretion disc and aligns the central SMBH, the orbital plane remains inclined for a time-scale $t_{\rm al3}$ which is a great fraction of the disc viscous time $t_{\rm d}$. It is expected that large-scale jets in most FR II radio sources would randomly orient with respect to the major axis of the host galaxy. The inclined radio jets in radio galaxies are nearly aligned from the VLBI to the VLA as $t_{\rm al3} \sim 10^7$–10^8 yr $> t_{\rm relic} \gtrsim 10^7$ yr. When the binary orbital plane becomes coplanar with the outer accretion disc, radio jet becomes vertical to the galactic plane and aligns with the minor axis of host galaxy. After the binary becomes coplanar with the outer accretion disc, they merge on a short time-scale and the radio source becomes a DDRG (Liu et al. 2003). Therefore, the fraction of FR II radio galaxies with vertical large-scale radio jets is small. When a radio source becomes a DDRG, the mass in the inner accretion disc has been removed, accelerating the evolution of the disc. It is expected that the accretion disc becomes radiatively inefficient in a relatively short time $< t_{\rm d}$. Therefore, the fraction of FR II radio galaxies with random orientation of jets is determined by the ratio $t_{\rm al3}/t_{\rm d} \sim 0.6$.

The random orientations of jets in FR II radio galaxies may have been observed. It is found that the jet orientations in radio sources randomly distribute relative to the dust lane or the major axis of the host galaxy (Birkinshaw & Davies 1985; Schmitt et al. 2002). There is no significant correlation between the misalignment angle and any of the intrinsic kinematic parameters of the host galaxy, in particular rotation velocity and central velocity dispersion which is related to the mass of the central SMBH. Schmitt et al. (2002) show that the dust discs are closely aligned with the major axis of the host galaxy and the jets are well aligned from the VLBI to the VLA scales. None of the possible mechanisms for the origin of the observed misalignment between jet and the rotation axis of host galaxy could consistently explain the observations (Schmitt et al. 2002). In our scenario, jet orientation is determined by the impact angle of the merging galaxy and the misaligned angle between the radio jet and the minor axis in FR II radio galaxies should be independent of any intrinsic kinematic parameter of the parent galaxy. However, the model suggests that the misalignment occurs in an accretion disc at parsec scale inside the broad-line region (BLR). The emission-line flux depends on the ionization radiation which is a function of the inclination angle between the inner radiation region and the BLR and the BLR cover factor. A positive correlation between the misalignment angle and the relative line flux may be expected.

Two more important implications of the model are that the distribution of jet orientation depends on the FR type and that the jets in DDRGs are nearly vertical to the major axis of the host galaxy. We will discuss the two predictions in more detail in Sections 4.8 and 5.

4.8 Relationship of FR I and FR II radio sources and jet orientations in FR I radio sources

As all young AGNs have been detected as FR II radio galaxies, it is most likely that FR I radio sources are evolved from FR II type (O'Dea 1998). There are three possible ways for a radio source to evolve from FR II to FR I type in our scenario. If the activity of a FR I radio source is triggered by minor mergers with mass ratio $q \ll q_{\rm X}$, the evolution finishes before the binary–disc interaction. In those sources (Class I FR I radio sources), the change of jet orientation due to the interaction may occur on a time-scale $t_{\rm al1} \sim 10^7$–10^8 yr, leading to the formation of an S-shaped structure in FR I radio sources. As the realignment time-scale $t_{\rm al1}$ inversely correlates with the accretion rate $\dot{m}$, S-shaped radio structures are most likely to form in luminous FR I radio sources with an accretion rate close to $\dot{m}_{\rm FR} \sim \dot{m}_{\rm cr}$. The jet orientations in most Class I FR I radio sources are random relative to the galactic plane of the host galaxy. Because Class I FR I radio sources should contain a binary of mass ratio $q_{\rm cr} \sim 5 \times 10^{-4} \ll q \ll q_{\rm X} \sim 10^{-2}$, they should make up $\lesssim$1/5 of FR I

Downloaded from https://academic.oup.com/mnras/article/347/4/1357/1000457 by George Mason University user on 24 September 2020

radio sources. Class FR I radio galaxies have linear size larger than their progenitor FR II radio galaxies.

Most radio sources with larger mass ratio $q \gtrsim q_X$ spend much more time on FR II phase, which have more energetic radio jets with larger size. The second possible case is that the alignment time-scale t_{al3} in a FR II radio source is much larger than the disc viscous time-scale t_d and the accretion disc becomes radiatively inefficient before the outer disc–binary realignment. The jets in these subclass FR I radio sources (Class II) randomly orient. Class II FR I radio sources have an average linear size larger than that of Class I FR I radio galaxies. From equation (41), the activity of Class II FR I radio sources must be triggered by major mergers with $q \gg 0.1$. Therefore, the Class II FR I radio galaxies with random jet orientation and largest size make up a very small fraction of FR I radio sources, as major mergers in galaxy merging are very rare.

Most radio sources evolve from FR II into FR I type after the binary plane becomes coplanar with the outer accretion disc and the galactic plane. Liu et al. (2003) and the discussion in Sections 4.7 and 5 show that SMBBHs become merged on a time-scale $\lesssim t_{acc}$ and FR II radio galaxies become DDRGs, before evolving from FR II to FR I type. Radio jets in this subclass of FR I radio sources (Class III) should be vertical to the galactic plane and aligned with the minor axis of the host galaxy. After the galaxies become DDRGs and the radio jets restart, the accretion rate becomes $1 \gg \dot{m} \gtrsim \dot{m}_{cr} \sim \dot{m}_{FR}$. The reborn radio sources have FR II morphology with jets less powerful than in normal FR II radio galaxies. Because the formation of jets is interrupted for quite a long time before the radio sources evolves from FR II to FR I type, the size of active radio lobes in Class III FR I radio sources is the size of the reborn sources and is as large as that of the Class I FR I radio sources, which is much smaller than the size of most FR II radio galaxies. Therefore, our conclusion is that the average linear size of FR I radio galaxies is smaller than that of FR II radio galaxies. However, the relics of up to four giant radio lobes could be detected in some Class III FR I radio galaxies as the sources become giant when they become DDRGs (Liu et al. 2003).

The two predictions about jet orientations and the source size of radio sources can be tested. We note that de Koff et al. (2000) suggest that the jet orientations in FR II radio galaxies randomly distribute while the jets in most FR I radio sources are vertical to the major axis of the host galaxy. However, the conclusion is based on a small sample of radio galaxies and should be checked with a much larger sample of radio sources.

5 RELATIONSHIP BETWEEN X-SHAPED AND DOUBLE–DOUBLE RADIO GALAXIES

In a minor merger of mass ratio $q \gtrsim q_X$, the binary orbital plane and the accretion disc become coplanar on a time-scale $t_{al3} \sim 10^7$–10^8 yr after an X-shaped radio structure forms in a FR II radio galaxy. The secondary SMBH opens a gap in the accretion disc and exchanges angular momentum with disc gas via gravitational torques for a minor merger with $> q_{min} = (81\,\pi/8)\,\alpha\,\delta^2 \simeq 3 \times 10^{-5}\alpha_{-2}\delta^2{}_{-2}$ (Lin & Papaloizou 1986). The secondary migrates inwards on a viscous time-scale $\sim t_{acc}$ and merges into the primary, leading to the removal of the inner accretion disc and to an interruption of jet formation (Liu et al. 2003). Liu et al. (2003) identify DDRGs (Schoenmakers et al. 2000) with the objects in which coalescence of SMBBHs, removal of inner accretion disc and interruption of jet formation occurred. DDRGs are a subclass of giant FR II radio galaxies, consisting of a pair of symmetric double-lobed structures with one common centre. The new-born inner structure with relative low luminosity is well aligned with the outer old lobes. The generation of inner lobes in DDRGs is due to the interaction of warm clouds and recurrent jets of interruption time ∼Myr (Kaiser, Schoenmakers & Röttgering 2000; Schoenmakers et al. 2000). When the interruption time is $\ll 10^6$ yr, the interaction of the recurrent jet and intergalactic medium (IGM) could not produce new lobes (Kaiser et al. 2000), as may be the case in the non-DDRG recurrent sources 3C 288 (Bridle et al. 1989), 3C 219 (Clarke et al. 1992) and B1144+352 (Schoenmakers et al. 1999).

The scenario of the binary coalescence and disc removal (Liu et al. 2003) implies that nearly all the SMBBHs in FR II radio galaxies merge into one more massive black hole and that all the winged radio sources would evolve into DDRGs on a time-scale $t_{X-DD} \sim t_{acc}$. This picture is consistent with the fact that double–double lobes are detected only in FR II radio galaxies. As the outer accretion disc is nearly aligned with the outer galactic plane, it is expected that the restarting jets in DDRGs are vertical to the major axis of the host galaxy and aligned with the old radio wings in its X-shaped progenitor. We are statistically testing this prediction and our preliminary results confirm the prediction that the jets in DDRGs are well aligned with the minor axis of the host galaxy (Liu et al., in preparation).

As the active jets in DDRGs are aligned with the old wings and $t_{X-DD} \sim 10^7$–10^8 yr $\gtrsim t_{relic}$, it is impossible to detect the coexistence of the wings and the double–double lobes in one DDRG. However, it is possible to detect the coexistence of double–double radio lobes and the cavities in the IGM, excavated by the past plasma jet with random orientation and filled with back-flow radio plasma from the outer double lobes. The cavities formed in such a way should have straight and sharp edges toward the core on the opposite side and diffusive edges on the same side of the active radio jets. The observations of the FR II radio galaxy J0116–473 may fit the description. Saripalli, Subrahmanyan & Udaya Shankar (2002) show that J0116–473 is a low-luminosity FR II radio galaxy and contains both double–double radio lobes and a bar-like feature with sharply bounded northern edge. The observations show that the bar-like feature may have an age of $\sim 10^8$ yr and the present activity restarts about $\sim$(3–4) $\times\, 10^6$ yr ago. The elapsed time since the last energy supply to the outer giant lobes is smaller than $< 7 \times 10^7$ yr (Saripalli et al. 2002). If J0116–473 contained SMBBHs once before, the bar-like structure is the cavity produced by the past misaligned jet and filled with the back-flow plasma due to the alignment of the binary orbital plane with outer accretion disc on a time-scale $t_{al3} \sim t_{acc}$. The estimated age $t_{acc} \sim 10^8$ yr of the bar-like feature together with equation (23) implies that the mass ratio $q \simeq 0.2\dot{m}_{-1}$ and the merger is minor with $q > q_X$.

Because DDRGs evolve from X-shaped radio galaxies, it is expected that double–double radio lobes like the X-shaped feature should be detected only in FR II radio sources. The probability λ_{DD} to detect recurrent jets in FR II radio sources is $\lambda_{DD} \sim t_{DD}/t_{life}$, where $t_{DD} = t_{int} + t_{tr}$, t_{int} is the interruption time-scale of jet formation and $t_{tr} = l_j/v_{lobe}$ is the time-scale for relativistic plasma lobes to travel along the jet from the central engine to the outer relic radio lobes. For a typical value of advancing velocity $v_{lobe} \sim 0.2c$ and a typical length-scale of giant radio sources $l_j \sim 1$ Mpc, we have $t_{tr} \sim 10^7$ yr. As the interruption time-scale $t_{int} \sim$ Myr, we adopt $t_{DD} \simeq 10^7$ yr and obtain $\lambda_{DD} \lesssim 5$ per cent. From equation (44), we have

$$\lambda_{DD} = \left(\frac{t_{DD}}{t_{relic}}\right)\lambda_X < \lambda_X \tag{46}$$

with $t_{DD} < t_{relic}$. Equation (46) suggests that the detection rate of DDRGs in a sample of FR II radio sources is between 1 and 10

Downloaded from https://academic.oup.com/mnras/article/347/4/1357/1000457 by George Mason University user on 24 September 2020

per cent. In estimating the time-scale $t_{\rm tr}$, we used the length-scale of giant radio sources as Liu et al. (2003) suggest that the radio galaxies would become giant when they become DDRGs. As the accretion rate to produce the restarting relativistic jets is much smaller than that producing the relic outer lobes, the active jets in DDRGs are much less luminous and may not be able to reach the outer lobes on the time-scale $\sim t_{\rm relic}$. If so, $t_{\rm tr} \sim t_{\rm relic}$ and $\lambda_{\rm DD} \simeq \lambda_{\rm X}$. If the giant radio galaxies form mainly due to the explosive increase of accretion rate via the interaction of SMBBHs and accretion disc, the detection rate of recurrent jets in a sample of giant radio galaxies may be as high as $\sim$100 per cent.

6 DISCUSSION AND CONCLUSIONS

Galactic dynamical simulations show that SMBBHs may stall, when becoming hard at $a_{\rm h} \sim 0.01$–1 pc, and merge on a time-scale longer than Hubble time. We show that the interaction of the accretion disc and SMBBHs may dominate the evolution of a binary formed during galaxy merging within Hubble time, after it becomes hard. We investigate the interaction of inclined SMBBHs and an accretion disc at subparsec scale and its feasibility to significantly change the orientation of the spin axis of the central SMBH, which is believed to be aligned with the orientation of relativistic jets in AGNs. We identify the interaction and the reorientations of the spin axis of the central black hole with jet orientations in some radio sources.

It is shown that the inclined secondary twists the accretion disc and aligns the inner accretion disc. We analytically calculate the alignment time-scale and show that the alignment finishes on a time-scale $\sim 10^3$ yr, which is the same result as that obtained with numerical computations by Ivanov et al. (1999) who also numerically calculate the alignment. We show that the quick alignment of the inner accretion disc is slowed down at the Bardeen–Petterson radius $r_{\rm BP} \sim 20 r_{\rm G}$ and completed on another time-scale $t_{\rm al1} \sim 10^4$ yr due to the Bardeen–Petterson effect, which is associated with the reorientation time-scale of relativistic plasma jets. We suggest that the reorientation of the spin axis of the central rotating SMBH causes the formation of X-shaped features observed in some FR II radio galaxies. In our scenario, the wing of X-shaped radio sources is the relic of past jets and lobes and its alignment with the minor axis of host galaxy is due to the conservation of angular momentum of accreting gas and the alignment of the accretion disc and the galactic plane. The random distribution of the orientation of the active jet is due to the random impact of two merging galaxies. The back-flow-diversion model (Capetti et al. 2002) suggests that a back-flow is driven out along the minor axis of the host galaxy due to the largest pressure gradient in the direction. However, this picture cannot explain why many radio galaxies with similar luminosity and eccentricity of host galaxy have no X-shaped feature and why the sizes of wings in some X-shaped radio sources are much larger than the directly powered lobes. Although the spin-flip model has a theoretical problem if a merger is minor, it is possible to have old wings along the minor of the host galaxy if the merger is major and the coalescence of two black holes finishes on a time-scale $\ll t_{\rm al1} \sim 10^4$ yr. The difficulty with the scenario is that the new-born jet is distorted due to the Bardeen–Petterson effect and becomes realigned with the old wings on a time-scale $\lesssim 10^5$ yr, which implies a distorted jet of size $\lesssim$10 kpc instead of straight large-scale radio jets.

To be more specific, we consistently explain the observations of X-shaped radio galaxies with our scenario and in particularly apply it to the two winged sources 4C +01.30 and 3C 293. We show that the mass ratio of the secondary and the primary in 4C +01.30 and 3C 293 are indeed minor with $q \sim 0.2$ and the reorientation occurs on a time-scale $\sim 2 \times 10^5$ yr, which is consistent with the observation of $\lesssim$Myr.

Based on the model and the detection rate $\sim$7 per cent of X-shaped structures in low-luminous FR II radio galaxies (Leahy & Parma 1992), we estimate the average lifetime of low-luminous FR II radio sources to be $t_{\rm life} \sim 10^8$ yr if taking a mean observable time-scale, $t_{\rm relic} \sim 10^7$ yr, of the relic of radio lobes in the sample of Leahy & Parma. The estimate of the lifetime of low-luminous FR II radio sources is consistent with the estimates of low-luminous AGNs and the disc viscous time-scale but much larger than the estimate for QSOs which may accrete at the Eddington accretion rate. This is reasonable if the activity of AGNs is triggered by a minor merger. The theoretical calculation also shows that the interaction of an accretion disc and a binary formed by a minor merger can lead to the formation of X-shaped structures in radio galaxies. In the back-flow model, wings form by the back-flow plasma in each radio galaxy with high eccentricity (Capetti et al. 2002), which suggests the formation of X-shaped structure in each radio galaxy with similar eccentricity of host galaxy and is inconsistent with the observations. Merritt & Ekers (2002) take $t_{\rm relic} \simeq 10^8$ yr in the spin-flip model and obtain $t_{\rm life} \sim 10^9$ yr. They suggest that the time-scale $t_{\rm life}$ is the mean merger time-scale of the galaxy and obtain a coalescence rate of SMBHs ~ 1 Gyr^{-1} which is consistent with those inferred for galaxies in dense regions or groups but higher than most estimates of the overall galaxy merger rate (Haehnelt 1998; Carlberg et al. 2000). However, the explanation has two difficulties. The first is that the relic of radio lobes cannot be detectable, especially at a survey frequency as high as 1.4 GHz, on a time-scale $t_{\rm relic} \sim 10^8$ yr due to radiation loss and plasma expansion. The other is that the mean lifetime of radio sources is much shorter than the mean merger time-scale and the estimate $t_{\rm life}$ should be the average lifetime of radio sources with low luminosity between 3×10^{24} and 3×10^{26} W Hz^{-1} at 1.4 GHz.

In our model, the lack of X-shaped FR I radio galaxies may be due to the fact that the accretion flow in FR I radio galaxies is geometrically thick and optically thin and weakly interacts with SMBBHs. Or it may also be due to the fact that FR I radio galaxies are evolved from FR II radio galaxies on a time-scale much longer than the detectable time-scale of relic lobes $t_{\rm relic}$. As the accretion disc in FR II is standard with high accretion rate $\dot{m} > \dot{m}_{\rm cr}$ while radiatively inefficient accretion flow with accretion rate $\dot{m} < \dot{m}_{\rm cr}$, it is most likely that radio galaxies evolves from FR II to FR I type. We have discussed the three types of possible evolution and suggest that the orientation of the jet in most but not all FR II radio galaxies distributes randomly while it is nearly vertical to the galactic plane in most but not all FR I radio galaxies. The different distribution of jet orientation in different FR-type radio galaxies may be observed (de Koff et al. 2000). Schmitt et al. (2002) discussed all the possible explanations in the literature to the detected distribution of jet orientation and concluded that none of them is plausible. Here we give a reasonable model. However, the sample is too small to be very meaningful and the result needs to be confirmed with larger samples of radio galaxies.

Our model also suggests that all SMBBHs in FR II radio galaxies become coplanar with the galactic plane and merge into a more massive black hole within the lifetime of the FR II radio galaxies. Liu et al. (2003) suggest that the coalescence of SMBBHs in FR II radio galaxies leads to the formation of DDRGs. This implies that X-shaped FR II radio galaxies form ahead of DDRGs on a viscous time-scale $t_{\rm acc} \sim 10^8$ yr. We applied the configuration to the DDRG J0116–473 which also shows a bar-like feature much older than the

Downloaded from https://academic.oup.com/mnras/article/347/4/1357/1000457 by George Mason University user on 24 September 2020

relic outer lobes. If we suggest that the bar-like feature in J0116–473 forms due to the refill with back-flow radio plasma of the cavities in the IGM excavated by the past plasma jet, the observations imply that the merger is minor with a mass ratio $q \sim 0.2$.

We divided FR I radio sources into three subclasses according to the different relation to FR II radio galaxies. Class I FR I radio sources are evolved from FR II radio sources before the interaction of accretion disc and SMMBHs. As in this subclass the stage of FR II phase is shorter than the average lifetime of most FR II radio galaxies, it may be expected that the average size is shorter than that of FR II radio sources. While Class III FR I radio sources form after SMBBHs become merged and relativistic jets restart with lower power, the average size of the subclass is determined by the recurrent jets and is also expected to be smaller than that of FR II radio sources. One expectation is that it is possible to detect relics of outer giant radio lobes in some FR I radio sources, which should be aligned with the inner active radio lobes. If $t_{\rm acc} \ll t_{\rm relic}$, we may even detect a third pair of outer lobes with oldest age and S-shaped structure. From equation (23), this implies that $q \ll 10^{-2}\dot{m}_{-2}(t_{\rm relic}/10^7\ {\rm yr})$. Such triple pairs of radio lobes may have been detected in the nearest AGN Cen A (NGC 5128) (Israel 1998). However, to compare the observation of Cen A and the model in more detail, we need the estimates of ages of the lobes.

Our model implies that Class I and Class II FR I radio galaxies and FR II radio galaxies with random jet orientation with respect to the galactic plane harbour SMBBHs with separation of $10^2\ r_{\rm G} \lesssim a \lesssim 10^3\ r_{\rm G}$. A close binary of $a < a_{\rm cr} \sim 10^2\ r_{\rm G}$ is a source of gravitational radiation. The coalescence of SMBBHs can produce an enormous burst of gravitational radiation. As the orbital plane of the binary of $< a_{\rm cr} \sim 10^2\ r_{\rm G}$ is coplanar with the accretion disc and the system is old, it may be expected to detect in low-luminous FR II radio sources with jets nearly vertical to the galactic disc with a close binary, which give rise to strong gravitational wave radiation and would be good targets for the monitoring of gravitational wave interferometers, e.g. the Laser Interferometer Space Antenna (LISA). Although FR II radio galaxies in which a binary merged also show vertical radio jets, it is easy to distinguish them from the former subclass of FR II radio galaxies as they may have passed through the DDRG phase and contain giant relics of outer radio lobes.

No X-shaped structure is observed in high-luminosity FR II radio galaxies and QSOs, which may be due to the selection effect (Dennett-Thorpe et al. 2002). The accretion may be at the Eddington accretion rate $\dot{m} \sim 1$ and the accretion disc is slim but not standard in QSOs. From equations (12) and (42), we have $t_{\rm bd} \simeq 14 t_{\rm d} \alpha_{-1}^{4/5} \dot{m}^{2/5} M_8^{0.06} q_{-1}^{-3/4.02} \gg 1$, which implies that the missing of high-luminous FR II radio galaxies and QSOs may be due to no binary–disc interaction during the phase of high accretion rate. In the QSO, it is expected that the jets are nearly aligned with the minor axis of host galaxy. If the binary interacts with the accretion disc during the phase of QSO and luminous radio galaxies, the transfer of warp is in a wave-like way and the time-scales $t_{\rm al1}$ and $t_{\rm al2}$ are smaller than with those given by equation (9) and (25), leading to a rapid reorientation of jet in QSO. Because the time-scale $t_{\rm al3} \sim 4 \times 10^6$ yr is too short for the jet to form a large-scale X-shaped structure, we could detect distorted radio jets in QSOs and luminous radio galaxies.

ACKNOWLEDGMENTS

We thank Dr Z. H. Fan for helpful comments and Professor D. N. C. Lin and Professor X.-B. Wu for pleasant discussions. This work is supported by the National Natural Science Foundation of China (NSFC 10203001) and the National Key Project on Fundamental Researches (NKBRSF G19990754).

REFERENCES

Abramowicz M. A., Czerny B., Lasota J. P., Szuszkiewicz E., 1988, ApJ, 332, 646
Abramowicz M. A., Chen X., Kato S., Lasota J.-P., Regev O., 1995, ApJ, 438, L37
Armitage P. J., Natarajan P., 2002, ApJ, 567, L9
Artymowicz P., Lubow S. H., 1994, ApJ, 421 651
Bardeen J. M., Petterson J. A., 1975, ApJ, 195, L65
Barnes J. E., 2002, MNRAS, 333, 481
Barnes J. E., Hernquist L., 1996, ApJ, 471, 115
Begelman M. C., Blandford R. D., Rees M. J., 1980, Nat, 287, 307
Birkinshaw M., Davies R. L., 1985, ApJ, 291, 32
Blaes O., Lee M. H., Socrates A., 2002, ApJ, 578, 775
Blandford R. D., Begelman M. C., 1999, MNRAS, 303, L1
Bridle A. H., Fomalont E. B., Byrd G. G., Valtonen M. J., 1989, AJ, 97, 674
Capetti A., Zamfir S., Rossi P., Bodo G., Zanni C., Massaglia S., 2002, A&A, 394, 39
Carlberg R. G. et al., 2000, ApJ, 532, L1
Cavaliere A., D'Elia V., 2002, ApJ, 571, 226
Chatterjee P., Hernquist L., Loeb A., 2003, ApJ, 592, 32
Clarke D. A., Bridle A. H., Burns J. O., Perley R. A., Norman M. L., 1992, ApJ, 385, 173
Collin S., Hure J.-M., 2001, A&A, 372, 50
Collin-Souffrin S., Dumont A. M., 1990, A&A, 229, 292
de Koff S. et al., 2000, ApJS, 129, 33
Dennett-Thorpe J., Scheuer P. A. G., Laing R. A., Bridle A. H., Pooley G. G., Reich W., 2002, MNRAS, 330, 609
Esin A. A., McClintock J. E., Narayan R., 1997, ApJ, 489, 865
Evans A. S., Sanders D. B., Surace J. A., Mazzarella J. M., 1999, ApJ, 511, 730
Ferrarese L., Merritt D., 2000, ApJ, 539, L9
Gaskell C. M., 1985, Nat, 315, 386
Gebhardt K. et al., 2000, ApJ, 539, L13
Ghisellini G., Celotti A., 2001, A&A, 379, L1
Gopal-Krishna, Biermann P. L., Wiita P. J., 2003, ApJ, 594, L103
Gould A., Rix H.-W., 2000, ApJ, 532, L29
Haehnelt M. G., 1998, in Folkner W. M., ed., AIP Conf. Proc., Vol. 456, Laser Interferometer Space Antenna. American Institute of Physics, Woodbury, NY, p. 45
Haehnelt M. G., Kauffman G., 2000, MNRAS, 318, L35
Haehnelt M. G., Kauffman G., 2002, MNRAS, 336, L61
Haehnelt M. G., Natarajan P., Rees M. J., 1998, MNRAS, 300, 817
Haiman Z., Loeb A., 1998, ApJ, 503, 505
Haiman Z., Loeb A., 1999, ApJ, 519, 479
Hernquist L., Mihos J. C., 1995, ApJ, 448, 41
Högbom J. A., Carlsson I., 1974, A&A, 34, 341
Hughes S. A., Blandford R. D., 2003, ApJ, 585, L101
Israel F. P., 1998, A&AR, 8, 237
Ivanov P. B., Igumenshchev I. V., Novikov I. D., 1998, ApJ, 507, 131
Ivanov P. B., Papaloizou J. C. B., Polnarev A. G., 1999, MNRAS, 307, 79
Jakobsen P., Jansen R. A., Wagner S., Reimers D., 2003, A&A, 397, 891
Jones D. L., Wehrle A. E., Meier D. L., Piner B. G., 2000, ApJ, 534, 165
Kaiser C. R., Cotter G., 2002, MNRAS, 336, 649
Kaiser C. R., Schoenmakers A. P., Röttgering H. J. A., 2000, MNRAS, 315, 381
Kauffmann G., Haehnelt M., 2000, MNRAS, 311, 576
Klein U., Mack K.-H., Gregorini L., Parma P., 1995, A&A, 303, 427
Komissarov S. S., Gubanov A. G., 1994, A&A, 285, 247
Komossa S., 2003, in Centrella J., ed., AIP Conf. Proc. 686, The Astrophysics of Gravitational Wave Sources. AIP, New York, p. 161
Komossa S., Burwitz V., Hasinger G., Predehl P., Kaastra J. S., Ikebe Y., 2003, ApJ, 582, L15
Kumar S., 1990, MNRAS, 245, 670

Downloaded from https://academic.oup.com/mnras/article/347/4/1357/1000457 by George Mason University user on 24 September 2020

Kumar S., Pringle J. E., 1985, MNRAS, 213, 435
Leahy J. P., Parma P., 1992, in Roland J., Sol H., Pelletier G., eds, Extragalactic Radio Sources: From Beams to Jets. Cambridge Univ. Press, Cambridge, p. 307
Leahy J. P., Williams A. G., 1984, MNRAS, 210, 929
Lin D. N. C., Papaloizou J., 1986, ApJ, 309, 846
Liu F. K., Wu X.-B., 2002, A&A, 388, L48
Liu F. K., Meyer F., Meyer-Hofmeister E., 1995a, A&A, 300, 823
Liu F. K., Xie G. Z., Bai J. M., 1995b, A&A, 295, 1
Liu F. K., Liu B. F., Xie G. Z., 1997, A&AS, 123, 569
Liu F. K., Wu X.-B., Cao S. L., 2003, MNRAS, 340, 411
McLure R. J., Dunlop J. S., 2002, MNRAS, 331, 795
Magorrian J. et al., 1998, AJ, 115, 2285
Mahadevan R., 1997, ApJ, 477, 585
Makino J., Funato Y., 2004, ApJ, in press (astro-ph/0307327)
Maraschi L., Tavecchio F., 2003, ApJ, 593, 667
Marscher A. P., Jorstad S. G., Gómez J.-L., Aller M. F., Teräsranta H., Lister M. L., Stirling A. M., 2002, Nat, 417, 625
Martel A. R. et al., 1999, ApJS, 122, 81
Martini P., 2003, in Ho L. C., ed., Carnegie Observatories Astrophysics Series, Vol. 1: Coevolution of Black Holes and Galaxies. Cambridge Univ. Press, Cambridge, in press (astro-ph/0304009)
Martini P., Weinberg D. H., 2001, ApJ, 547, 12
Menou K., Haiman Z., Narayanan V. K., 2001, ApJ, 558, 535
Merritt D., 2000, in Combes F. Mamon G. A., Charmandaris V., eds, ASP Conf. Ser. Vol. 197, XVth IAP Meeting Dynamics of Galaxies: From the Early Universe to the Present. Astron. Soc. Pac., San Francisco, p. 221
Merritt D., Ekers R. D., 2002, Sci, 297, 1310
Meyer F., Meyer-Hofmeister E., 1994, A&A, 288, 175
Meyer F., Liu B. F., Meyer-Hofmeister E., 2000, A&A, 361, 175
Milosavljevic M., Merritt D., 2003, in Centrella J., ed., The Astrophysics of Gravitational Wave Sources. AIP, New York, in press (astro-ph/0212270)
Murgia M., Fanti C., Fanti R., Gregorini L., Klein U., Mack K.-H., Vigotti M., 2002, New Astron. Rev., 46, 307
Musil T., Karas V., 2002, PASJ, 54, 641
Narayan R., 2000, ApJ, 536, 663
Natarajan P., Pringle J. E., 1998, ApJ, 506, L97
Narayan R., Yi I., 1994, ApJ, 428, L13
Narayan R., Yi I., 1995, ApJ, 452, 710
Narayan R., Igumenshchev I. V., Abramowicz M. A., 2000, MNRAS, 539, 798
O'Dea C. P., 1998, PASP, 110, 493
Ogilvie G. I., 1999, MNRAS, 304, 557
Ostriker E. C., 1999, ApJ, 513, 252
Owsianik I., Conway J. E., Polatidis A. G., 1999, New Astron. Rev., 43, 669
Papaloizou J. C. B., Lin D. N. C., 1985, ApJ, 438, 841
Papaloizou J. C. B., Pringle J. E., 1983, MNRAS, 202, 1181
Parma P., Ekers R. D., Fanti R., 1985, A&AS, 59, 511
Perucho M., Martí J. M., 2002, ApJ, 568, 639
Pringle J. E., 1996, MNRAS, 281, 357
Quataert E., Narayan R., 1999, ApJ, 520, 298
Quinlan G. D., 1996, New Astron., 1, 35
Quinlan G. D., Hernquist L., 1997, New Astron., 2, 533
Rees M. J., 1978, Nat, 275, 516
Rees M. J., 1984, ARA&A, 22, 471
Saripalli L., Subrahmanyan R., Udaya Shankar N., 2002, ApJ, 565, 256
Scheuer P. A. G., Feiler R., 1996, MNRAS, 282, 291
Schmitt H. R., Pringle J. E., Clarke C. J., Kinney A. L., 2002, ApJ, 575, 150
Schoenmakers A. P., de Bruyn A. G., Röttgering H. J. A., van der Laan H., 1999, A&A, 341, 44
Schoenmakers A. P., de Bruyn A. G., Röttgering H. J. A., van der Laan H., Kaiser C. R., 2000, MNRAS, 315, 371
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Shlosman I., Begelman M. C., Frank J., 1990, Nat, 345, 679
Sillanpää A., Haarala S., Valtonen M. J., Sundelius B., Byrd G. G., 1988, ApJ, 325, 628
Slee O. B., Roy A. L., Murgia M., Andernach H., Ehle M., 2001, AJ, 122, 1172
Steidel C. C., Hunt M. P., Shapley A. E., Adelberger K. L., Pettini M., Dickinson M., Giavalisco M., 2002, ApJ, 576, 653
Sudou H., Iguchi S., Murata Y., Taniguchi Y., 2003, Sci, 300, 1263
Tremaine S. et al., 2002, ApJ, 574, 740
Ulrich M.-H., Roennback J., 1996, A&A, 313, 750
Vokrouhlicky D., Karas V., 1998, MNRAS, 293, L1
Wang T.-G., Zhou H.-Y., Dong X.-B., 2003, AJ, 126, 113
Wilson A. S., Colbert E. J. M., 1995, ApJ, 438, 62
Wu X. B., Liu F. K., Zhang T. Z., 2002, A&A, 389, 742
Xie G. Z., Liang E. W., Zhou S. B., Li K. H., Dai B. Z., Ma L., 2002, MNRAS, 334, 459
Yu Q. J., 2002, MNRAS, 331, 935
Yu Q. J., Tremaine S., 2002, MNRAS, 335, 965
Zier C., Biermann P. L., 2001, A&A, 377, 23

This paper has been typeset from a TEX/LATEX file prepared by the author.

Downloaded from https://academic.oup.com/mnras/article/347/4/1357/1000457 by George Mason University user on 24 September 2020