Giant X-ray cavities lie in some active galactic nuclei (AGNs) located in central galaxies of clusters, which are estimated to have stored $10^{55} - 10^{62}$ erg of energy. Most of these cavities are thought to be inflated by jets of AGNs on a timescale of $\gtrsim 10^7$ years. The jets can be either powered by rotating black holes or the accretion disks surrounding black holes, or both. The observations of giant X-ray cavities can therefore be used to constrain jet formation mechanisms. In this work, we choose the most energetic cavity, MS 0735+7421, with stored energy $\sim 10^{62}$ erg, to constrain the jet formation mechanisms and the evolution of the central massive black hole in this source. The bolometric luminosity of the AGN in this cavity is $\sim 10^{-5} L_{\text{Edd}}$, however, the mean power of the jet required to inflate the cavity is estimated as $\sim 0.02 L_{\text{Edd}}$, which implies that the source has previously experienced strong outbursts. During outbursts, the jet power and the mass accretion rate should be significantly higher than its present values. We construct an accretion disk model in which the angular momentum and energy carried away by jets are properly included to calculate the spin and mass evolution of the massive black hole. In our calculations, different jet formation mechanisms are employed, and we find that the jets generated with the Blandford–Znajek (BZ) mechanism are unable to produce the giant cavity with $\sim 10^{62}$ erg in this source. Only the jets accelerated with a combination of the Blandford–Payne and BZ mechanisms can successfully inflate such a giant cavity if the magnetic pressure is close to equipartition with the total (radiation + gas) pressure of the accretion disk. For a dynamo-generated magnetic field in the disk, such an energetic giant cavity can be inflated by the magnetically driven jets only if the initial black hole spin parameter $a_0 \gtrsim 0.95$. Our calculations show that the final spin parameter $a$ of the black hole is always $\sim 0.9 - 0.998$ for all the computational examples that can provide sufficient energy for the cavity of MS 0735+7421.

**Key words:** accretion, accretion disks – galaxies: active – galaxies: jets – galaxies: magnetic fields

**Online-only material:** color figures

1. INTRODUCTION

Giant X-ray cavities have been discovered in some central galaxies of clusters by *XMM-Newton* and *Chandra* (e.g., Hydra A, McNamara et al. 2000; RBS 797, Schindler et al. 2001; MS 0735+7421, McNamara et al. 2005), which contain large amounts of energy up to $10^{55} - 10^{62}$ erg. They can effectively suppress the cooling of the intracluster medium (ICM) and provide direct evidence for the presence of active galactic nucleus (AGN) feedback in galaxy formation and evolution (e.g., Bırzan et al. 2004; McNamara et al. 2005; Allen et al. 2006; Croton et al. 2006). It is believed that the cavities are inflated by jets launched from the accretion disks in AGNs (for a review, see McNamara & Nulsen 2007 and references therein). Therefore, the X-ray cavities provide a direct measurement of the mechanical energy released by jets through the work done on the hot gas surrounding them. Measurements of this energy, combined with measurements of the timescale required to inflate the cavities, can be used to estimate the mean jet power (e.g., Allen et al. 2006).

The jet formation mechanisms in AGNs have been extensively studied in the last several decades. Currently most favored jet formation mechanisms are divided into two categories, i.e., the Blandford–Znajek (BZ) process (Blandford & Znajek 1977) and the Blandford–Payne (BP) process (Blandford & Payne 1982). In the BZ process, energy and angular momentum are extracted from a rotating black hole and transferred to a remote astrophysical load by open magnetic field lines. In the BP process, the magnetic field threading the disk extracts energy from the rotating gas in the accretion disk to power the jet/outflow. The hybrid model proposed by Meier (1999), as a variant of the BZ model, combines the BZ and BP effects through the large-scale magnetic field threading the accretion disk outside the ergosphere and the rotating plasma within the ergosphere. The ordered large-scale magnetic field threading the disk is a crucial ingredient in jet formation models. In most previous works, the strength of the magnetic field is assumed to scale with the gas/radiation pressure of the accretion disk (e.g., Moderski & Sikora 1996; Ghosh & Abramowicz 1997; Livio et al. 1999; Armitage & Natarajan 1999; Nemmen et al. 2007; Wu & Cao 2008; McNamara et al. 2009; Wu et al. 2011). Livio et al. (1999) pointed out that even the calculations of Ghosh & Abramowicz (1997) have overestimated the power of the BZ process, since they have overestimated the strength of the large-scale field threading the inner region of an accretion disk and then the power of the BZ process. The strength of the large-scale field scales with disk thickness, and it is very weak if the field is created by dynamo processes for thin disk cases (Tout & Pringle 1996; Livio et al. 1999). The maximal jet power extracted from an accretion disk can be estimated on the assumption that the toroidal field component is of the same order of the poloidal field component at the disk surface (see, e.g., Livio & Pringle 1992; Biskamp 1993).

The giant cavity in MS 0735+7421, one of the most energetic outbursts in AGNs, stores a total of $\sim 10^{62}$ erg of energy with the timescale of $\sim 10^8$ years required to inflate the cavity.
(McNamara et al. 2005, 2009). This implies that the mean jet power should be \( \sim 10^{46} \text{ erg s}^{-1} \) (McNamara et al. 2005; Gitti et al. 2007), which is about 2\% of the Eddington luminosity \( (L_{\text{Edd}}) \) of a \( 5 \times 10^6 \, M_\odot \) (\( M_\odot \) is the solar mass) black hole in MS 0735+7421 (McNamara et al. 2009). However, the central AGN in this cavity shows very low optical nuclear emission \( (L_1 < 2.5 \times 10^{42} \text{ erg s}^{-1}) \) \( (L_1 \) is the luminosity in the \( I \) band), which implies that its accretion disk is accreting at the current rate being too low to power strong jets with \( \sim 10^{46} \text{ erg s}^{-1} \). McNamara et al. (2009, 2011) argued that the BP process by itself is insufficient to power the giant outbursts in this source. They suggested that the jet is alternatively powered by the rotational energy of an extreme Kerr black hole \( (\sim 10^{62} \text{ erg}) \), which roughly corresponds to the total energy stored in this cavity. However, Livio et al. (1999) pointed out that the magnetic field strength near the horizon of a rotating black hole is dominantly determined by the structure of the inner region of the disk. Thus, it is still quite doubtful if such a faint accretion disk can maintain a strong field near the horizon to power powerful jets with \( \sim 10^{46} \text{ erg s}^{-1} \).

It is well known that quasars are powered by accretion onto massive black holes, and the growth of massive black holes could be dominantly governed by mass accretion in quasars. The massive black holes are therefore the AGN relics (Soltan 1982). The faint AGN in MS 0735+7421 contains a massive black hole with a mass of \( 5 \times 10^9 \, M_\odot \), which may have experienced a quasar phase in the past. During its quasar phase, the black hole was accreting at relatively high rates, and therefore powerful jets can be magnetically accelerated from the region near the black hole either by the BP or BZ processes, or both. In the same period of time, the central massive black hole formed, and the hole was spun up simultaneously. In this work, we choose the most powerful cavity, MS 0735+7421, to constrain the jet formation mechanisms and the mass/spin evolution of the massive black hole in this source.

2. MODEL

2.1. The Accretion Disk Equations

The faint AGN in MS 0735+7421 may have experienced a quasar phase in the past. During its quasar phase, the black hole was accreting at relatively high rates, and therefore its accretion disk can be described by the standard thin disk model (Shakura & Sunyaev 1973). In this work, we consider a relativistic thin accretion disk around a Kerr black hole (Novikov & Thorne 1973; Manmoto 2000), and the metric around the black hole reads (the geometrical unit \( G = c = 1 \) is adopted)

\[
ds^2 = \frac{r^2 \Delta}{A} dt^2 + \frac{A}{r^2} (d\phi - \omega dt)^2 + \frac{r^2}{\Delta} dr^2 + dz^2, \tag{1}
\]

\[\Delta = r^2 - 2Mr + a^2,\]

\[A = r^4 + r^2 a^2 + 2Mar^2,\]

\[\omega = \frac{2Mar}{A},\]

\[a = \frac{J}{M},\]

where \( M \) is the mass of the black hole, \( J \) and \( a \) are the angular momentum and specific angular momentum of the black hole, respectively, and \( \omega \) is the dragging angular velocity of the metric.

The model of the geometrically thin, optically thick, and Keplerian accretion disk surrounding a Kerr black hole was developed by Novikov & Thorne (1973). The structure of the accretion disk may be altered in the presence of the large-scale magnetic field threading the disk, which can drive the outflows/jets from the disk, and a fraction of the angular momentum and energy of the disk is carried away in the outflows/jets (e.g., Ogilvie & Livio 1998; Cao & Spruit 2002). In order to explore the magnetically accelerated jets originating from the accretion disk, we properly consider the effects of the jets on the accretion disk. The basic equations of a relativistic thin disk with magnetically driven outflows/jets are summarized as follows.

The continuity equation is

\[\dot{M} = -2\pi A \Delta^{1/2} \Sigma v_r, \tag{2}\]

where \( v_r \) is the radial velocity of the accretion flow, \( \Sigma = 2\rho H \) is the surface density, and \( \dot{M} \) is the mass accretion rate. As we consider fast moving outflows/jets in this work, the mass-loss rate in the outflow/jet is neglected in the continuity equation of the accretion flow.

The radial momentum equation is

\[\frac{\gamma v \dot{A} M}{r^2 \Delta} (\Omega - \Omega_k^+(\Omega - \Omega_k^-)) + g_m = 0, \tag{3}\]

where \( \Omega \) is the angular velocity, and the Lorentz factor \( \gamma_v \) of the rotational velocity \( v_r \) is given by

\[\gamma_v = (1 - v_r^2)^{-1/2},\]

\[v_r = A\dot{\Omega}/r^2 \Delta^{1/2},\]

and \( \dot{\Omega} = \Omega - \omega \). In this work, we consider the geometrically thin disks, and the gas pressure gradient in the radial direction can be omitted in the radial momentum equation of the disk (Shakura & Sunyaev 1973). The first term in Equation (3) represents the net force exerted on the gas moving with a circular angular velocity \( \Omega \) in the Kerr metric. It should be balanced with the radial magnetic force \( g_m \), induced by the large-scale magnetic field threading the accretion disk without considering the radial pressure gradient in the thin disk case. The Keplerian angular velocities of the prograde (+) and retrograde (−) motions are

\[\Omega_k^{\pm} = \pm M^{1/2} r^{3/2} \pm a M^{1/2},\]

and the radial magnetic force is

\[g_m = B_r B_z/2\pi \Sigma, \tag{4}\]

where \( B_r \) and \( B_z \) are the radial and vertical components of the magnetic fields at the disk surface, respectively. The inclination of the field line at the disk surface \( \kappa_0 \) is defined as \( \kappa_0 = B_z/B_r \).

The angular momentum equation is

\[-\frac{M}{2\pi} \frac{dL}{dr} + \frac{d}{dr} (r W_\phi^2) + T_m r = 0, \tag{5}\]

where the angular momentum of the accretion flow \( L \) is

\[L = \frac{A^{1/2} (\gamma_v^2 - 1)^{1/2}}{r}.\]
and the height-integrated viscous tensor is

\[ W_\psi = \alpha \frac{A^{3/2} \Lambda^{1/2} \gamma^3}{r^6} W, \]

where \( \alpha \) is the Shakura–Sunyaev viscosity parameter. The height-integrated pressure \( W = 2H P_{\text{tot}} \), where the total pressure \( P_{\text{tot}} = P_{\text{gas}} + P_{\text{rad}} + P_{\text{m}} \), \( P_{\text{gas}} \), \( P_{\text{rad}} \), \( P_{\text{m}} \), and \( P_{\text{m}} = (1 - \beta) P_{\text{tot}} \) are the gas pressure, radiation pressure, and magnetic pressure, respectively \((1 - \beta) \) is the ratio of the magnetic pressure to the total pressure). The scale height \( H \) of the accretion disk is given by

\[ H^2 = c_s^2 r^4 / (L^2 - a^2), \]

where \( c_s = \sqrt{\gamma P_{\text{gas}} / \rho} \) is the sound speed of the gas in the disk.

The first two terms in Equation (5) represent the change rate of angular momentum and the transfer rate of angular momentum caused by the viscous torque in the gas, and the third term is the rate of angular momentum carried away by the magnetically driven outflows/jets. The magnetic torque exerted on the accretion flow due to the outflows/jets is

\[ T_m = -B_r B_\psi R / 2\pi, \]

(7)

where \( B_\psi \) is the toroidal component of the field strength at the disk surface. Equation (7) is the vertical integration of magnetic torque in the ideal MHD angular momentum equation (Cao & Spruit 2002).

The energy equation is

\[ \nu \Sigma \frac{dA^2}{dr} \frac{d\Omega}{dr} = \frac{16\alpha c T^4}{3\kappa}, \]

where \( \nu \Sigma d\Omega / dr = -\alpha W / r \) in \( \alpha \)-viscosity, and \( T \) is the temperature of the gas in the disk (Abramowicz et al. 1996). The left term in this equation is the surface heat generation rate caused by turbulence of the gas in the disk, which is balanced with the cooling rate of the disk. The radial advection of energy is neglected in the thin disk case. The opacity \( \kappa \) of the gas is given by

\[ \kappa = \kappa_e + \kappa_{\text{ff}} = 0.4 + 0.64 \times 10^3 \rho T^{-7/2} \text{ cm}^{-2} \text{ g}^{-1}, \]

where \( \kappa_e \) and \( \kappa_{\text{ff}} \) are the electron scattering opacity and free–free opacity, respectively.

2.2. The Jet Formation Mechanisms

In the general form of the BZ mechanism, the jet power \( L_{\text{BZ}} \) can be estimated with (Ghosh & Abramowicz 1997)

\[ L_{\text{BZ}} = \frac{1}{32} \kappa_e^2 B_r^2 r_h^2 (J / J_{\text{max}})^2 c, \]

where \( r_h \) is the horizon radius, \( B_r \) is the component of the magnetic field normal to the black hole horizon, \( J \) and \( J_{\text{max}} = GM^2 / c \) are the angular momentum and maximum angular momentum of a black hole, and \( \kappa_e \equiv \Omega_H (\Omega_H - \Omega_p) / \Omega_H^2 \) is a factor at the black hole horizon determined by the angular velocity of the black hole and that of the magnetic field lines. In this work, we simply adopt \( B_r \sim B (B^2 = B_r^2 + B_\psi^2) \), which is the maximal magnetic field strength in the disk (see Ghosh & Abramowicz 1997 for the details). It is easy to conclude that the maximal jet power \( L_{\text{BZ}}^{\text{max}} \) corresponds to \( \Omega_p = 1/2 \Omega_H \). The power of the jets accelerated from an accretion disk can be calculated with (e.g., Livio et al. 1999; Cao 2002)

\[ L_{\text{BP}} = \int_{r_m}^{r_{\text{out}}} \frac{B_p B_\psi}{4\pi} r \Omega_{\text{max}} \Omega_{\text{max}} r dr, \]

where \( B_p (B_p^2 = B_r^2 + B_\psi^2) \) is the poloidal field strength, and \( r_m \) and \( r_{\text{out}} \) are the inner and outer radius of the accretion disk, respectively.

Tout & Pringle (1996) suggested that the typical size of the magnetic fields produced by dynamo processes is roughly around the disk thickness \( H \). The large-scale field can be produced from the small-scale field created by dynamo processes as \( B(\lambda) \propto \lambda^{-1} \) for the idealized case, where \( \lambda \) is the length scale of the field. For the magnetically launching problem for jets, the size of magnetic field lines \( \geq R \) is required in order to accelerate the jets/outflows efficiently. Thus, Livio et al. (1999) proposed that the poloidal magnetic fields \( B \) should be \( \sim (H / r)B \) if they are generated through dynamo processes in the accretion disk. The jet power of the BZ and BP mechanisms is given by

\[ L_{\text{BZ}} = \frac{1}{32} \kappa_e^2 \left( \frac{B_r}{H} \right)^2 \frac{r_h^2 (J / J_{\text{max}})^2 c}{}, \]

(11)

and

\[ L_{\text{BP}} = \int_{r_m}^{r_{\text{out}}} \frac{B_p B_\psi}{4\pi} r \Omega_{\text{max}} \Omega_{\text{max}} r dr, \]

(12)

on the assumption of a magnetic field generated through dynamo processes, where \( \left( B_r H / r \right)_{\text{max}} \) is the maximal \( (B_r H / r) \) in the inner region of the accretion disk.

The difficulties in estimating the jet power, either for the BP or the BZ processes, are the magnetic field strength and the field geometry, which are still highly uncertain. The conventional estimates of the field strength are more or less based on the assumption of equipartition between magnetic pressure and gas pressure/radiation pressure (e.g., Moderski & Sikora 1996; Ghosh & Abramowicz 1997; Livio et al. 1999; Armitage & Natarajan 1999; Nemmen et al. 2007; Wu & Cao 2008; McNamara et al. 2009; Wu et al. 2011). In this work, we adopt a parameter \( \beta \) to describe the field strength in the disk. The magnetic pressure \( P_m = (1 - \beta) P_{\text{tot}} \) \( P_{\text{tot}} = P_{\text{gas}} + P_{\text{rad}} \), and therefore the field strength \( B = \sqrt{(1 - \beta) P_{\text{tot}}} \). In principle, the magnetic field strength and the structure of the accretion disk are available by solving a set of dynamical equations of the disk described in Section 2.1 simultaneously, if the value of \( \beta \) and the field geometry are known. However, the geometry of the magnetic field of the disk is in principle a global problem (see, e.g., Spruit 2011 for a detailed discussion, and the references therein). It depends not only on the initial strength and geometry of the magnetic field as indicated by some MHD simulations (e.g., Igumenshchev et al. 2003; Beckwith et al. 2008; McKinney et al. 2012), but also on the processes of diffusion and advection in accretion disks (Lubow et al. 1994; Cao 2011; McKinney et al. 2012), which is beyond the scope of this paper. The inclination of the field line at the disk surface plays a key role in launching jets. More specifically, the angle of field lines inclined to the mid-plane of the disk is required to be less than 60° for launching jets from a Keplerian cold disk (Blandford & Payne 1982). This critical angle can be slightly larger than 60° if the internal energy of the gas in the disk is considered (Cao & Spruit 1994). This critical angle could be larger than 60° even for the cold gas magnetically launched.
from the inner edge of the accretion disk very close to a rapidly spinning black hole (Cao 1997), which indicates that the spin of the black hole may help to launch jets centrifugally by cold magnetized disks (Cao 1997; Sadowski & Sikora 2010). This is because the frame drag effect of the spinning black hole may help to accelerate the outflows. For realistic cases, the internal energy of the gas is included in the Bernoulli equation of the outflow, and an additional force due to the pressure gradient helps to accelerate the gas in the outflow (e.g., see Equation (14) in Cao & Spruit 1994). In this case, the outflow can be launched if the inclination angle is slightly larger than the critical value. As the final derived accretion disk structure is insensitive to the precise value of the field inclination at the disk surface, we simply adopt an inclination of 60° in all our calculations. The strength of the azimuthal component of the field at the disk surface is mainly determined by the properties of the jets. The model properly including both the accretion disk solution and jet solution is very complicated and beyond the scope of this work. It was pointed out that the fast moving jets/outflows always correspond to the case $B_p \ll B_B$, in which $B_p \sim B_B$ is satisfied for slowly moving outflows with a relatively high mass-loss rate (Cao & Spruit 1994; Ogilvie & Livio 1998; Cao & Spruit 2002; Cao 2002). In the case of the problem considered in this work, we focus on the fast moving jets from the disk, and $B_p \ll B_B$ should be satisfied. In this work, we adopt $\xi_p = 0.1$ ($B_p = \xi_p B_B$) in most of our calculations.

In summary, we calculate the jet power $L_{\text{jet}}$ with two models in this work, i.e., Model A (general BZ + BP processes), $L_{\text{jet}} = L_{\text{BZ} + \text{BP}}$, where $L_{\text{BZ}}$ and $L_{\text{BP}}$ are calculated with Equations (9) and (10), respectively, and Model B (Livio’s model), $L_{\text{jet}} = L_{\text{BZ} + \text{BP}}$, where $L_{\text{BZ}}$ and $L_{\text{BP}}$ are calculated with Equations (11) and (12), respectively.

The main difference between models A and B is the estimate of the field strength in the accretion disk. Finally, the energy released through the BZ + BP process during the outbursts is available with

$$E_{\text{tot}} = E_{\text{BZ}} + E_{\text{BP}} = \int_0^t L_{\text{jet}} dt,$$

where $t$ is the duration of the AGN outbursts.

2.3. The Evolution of the Black Hole

For a massive black hole surrounded by an accretion disk, the black hole mass and spin evolution is described by (e.g., Moderski & Sikora 1996; Lu et al. 1996)

$$\frac{dM}{dt} = \frac{M}{M_{\odot}} \tilde{j}_{\text{ms}} (1 - 2a \tilde{e}_{\text{ms}}) - \frac{L_{\text{BZ}}}{M c^2} \left( \frac{1}{k \Omega_p} - 2a \right),$$

$$\frac{d \ln M}{dt} = \frac{M}{M_{\odot}} \tilde{j}_{\text{ms}} - \frac{L_{\text{BZ}}}{M c^2},$$

where $a (0 \leq a < 1)$ is the dimensionless angular momentum of a black hole, $M \equiv dM/dt$ is the accretion rate, $M$ is the mass of the black hole, $\tilde{j}_{\text{ms}}$ and $\tilde{e}_{\text{ms}}$ are the dimensionless specific angular momentum and energy of the gas in the accretion disk at the marginally stable orbit, respectively, $\Omega_p$ is the dimensionless angular velocity at the horizon of the black hole, $L_{\text{BZ}}$ is the jet power due to the BZ process, and $k \equiv \Omega_p/\Omega_{BZ} < 1$ is a constant, where $\Omega_{BZ}$ is the angular velocity of magnetic field lines at the horizon.

The time evolution of the mass accretion rate is still quite unclear, which may be dependent on the circumnuclear gas near the black hole and/or feedback of the quasar at the center of the galaxy (e.g., Di Matteo et al. 2005). The observed Eddington ratio distribution for AGNs can be roughly described by a power-law distribution, which is consistent with the self-regulated black hole growth model. In this model, the feedback of AGNs produces a self-regulating decay or blowout phase after the AGN reaches a peak luminosity and begins to expel gas and shut down accretion (Hopkins et al. 2005a, 2005b; Hopkins & Hernquist 2009). Hopkins & Hernquist (2009) suggested that the quasar luminosity (then the accretion rate) evolving with time can be described by

$$\frac{dt}{d \log m} = -\tau_{Q} \left( \frac{\dot{m}}{m_0} \right)^{-\beta_L} \exp \left( - \frac{\dot{m}}{m_0} \right),$$

where $\dot{m} \equiv M/M_{\text{Edd}}$ is the accretion rate in units of Eddington accretion rate ($M_{\text{Edd}} = 1.5 \times 10^{16} M_{\odot} \text{ g s}^{-1}$ is the Eddington accretion rate), $\tau_Q$ is a constant, and $m_0$ is the peak accretion rate of a quasar. The index $\beta_L \sim 0.6$ is adopted as suggested by Hopkins & Hernquist (2009). We define the lifetime $t_Q$ of a quasar as

$$t_Q = \int_0^{m_Q} dt = - \int_{m_0}^{m_Q} \tau_Q \left( \frac{\dot{m}}{m_0} \right)^{-\beta_L} \exp \left( - \frac{\dot{m}}{m_0} \right) d \log m,$$

where the integral upper limit $\dot{m} = 0.01$ is adopted as the typical lower limit on broadline AGNs (e.g., Kollmeier et al. 2006; Trump et al. 2011). We assume $m_0 = 1$ in all our calculations. The quasar lifetime $t_Q \sim 10 \tau_Q$ for $\beta_L = 0.6$.

3. RESULTS

As described in Sections 2.1 and 2.2, the structure of an accretion disk surrounding a rotating black hole with mass $M$ and spin parameter $a$ can be calculated by solving Equations (2)–(8) for different jet formation mechanisms, provided the values of the disk parameters, $\alpha$, $\beta$, and $M$, are supplied. Based on the derived disk structure and jet power, the mass and spin evolution of the black hole can be calculated with Equations (14) and (15), if suitable initial conditions and the mass accretion rate as a function of time are specified. The conventional value of the viscosity parameter $\alpha = 0.1$ is adopted in all our calculations. In Figure 1, we find that the disk structure has been significantly altered by the magnetically accelerated jets. The temperature of the accretion disk with outflows/jets is obviously lower than that of the standard thin accretion disk, because a fraction of the gravitational energy released in the disk is carried away in the outflows/jets. The temperature of the accretion disk decreases significantly more for model A than for model B because the jet power is higher for model A if all other model parameters are fixed (see Figure 1).

The central AGN in the cavity of MS 0735+7421 contains a $5 \times 10^9 M_{\odot}$ black hole, which shows very low optical nuclear emission ($L_1 < 2.5 \times 10^{42} \text{ erg s}^{-1}$ in $I$ band). The model calculations for this source should satisfy three observational quantities: total energy stored in the cavity $\sim 10^{52} \text{ erg}$, present mass of the central black hole $5 \times 10^9 M_{\odot}$, and the timescale of the jet activity in this AGN $\sim 10^8$ years (McNamara et al. 2005, 2009). This implies that the giant cavity in this source was inflated by the jets when the black hole was accreting at relatively high rates in the past. In all our calculations, the initial black hole mass $M_{0}$ is chosen in such a way as to let the final black hole mass be $5 \times 10^9 M_{\odot}$ like that in the AGN of MS
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Figure 1. Disk temperature of a relativistic thin accretion disk with magnetically driven outflows, where $a_0 = 0.95$, $\beta = 0.5$, and $\dot{m} = 0.25$ are adopted. The black and red lines are for the results calculated with model A and model B, respectively. We also plot the results of a relativistic thin accretion disk without outflows for comparison (green lines).

(A color version of this figure is available in the online journal.)

Figure 2. Evolution of accretion rate as a function of outburst time. The colored lines correspond to different values of $\tau_Q$, $\tau_Q = 5 \times 10^7$ (black), $10^8$ (red), and $10^7$ years (green), respectively. In all our calculations, the initial black hole mass $M_0$ is chosen in such a way as to let the final black hole mass be $5 \times 10^9 M_\odot$.

(A color version of this figure is available in the online journal.)

0735+7421. Thus, the time-dependent mass accretion rate $\dot{m}(t)$ is a crucial ingredient in our model calculations. In this work, we adopt a power-law time-dependent $\dot{m}(t)$ with an exponential cutoff at the high-end $\dot{m}_0$ suggested by Hopkins & Hernquist (2009). It is found that the mass accretion rate declines very rapidly for this time-dependent $\dot{m}(t)$ when $\tau_Q$ is small, i.e., a short quasar lifetime (see Figure 2).

The total energy released during the outbursts as functions of time with different values of the model parameters for different jet formation models is plotted in Figures 3–7. In Figures 3 and 4, we plot the energy released during the outbursts as functions of the outburst time with different sets of the model parameters for different initial black hole spin parameters $a_0 = 0.1$ and 0.95, respectively. It is found that the total energy released in the cavity is higher for model A than for model B. The total energy increases with $\tau_Q$, and much energy is carried away in the jets provided the initial black hole spin parameter is high, if all other parameters are fixed.

The black hole mass and bolometric luminosity of broad-line AGNs can be well estimated with the observations of the SEDs and broad-line width, and therefore the Eddington ratio distribution of broad-line AGNs is available. The peaks of the Eddington ratio distributions derived with different broad-line AGN samples are around 0.1–0.4 (e.g., McLure & Dunlop 2004; Warner et al. 2004; Kollmeier et al. 2006; Kauffmann & Heckman 2009; Shen & Kelly 2012). The time evolution of the accretion rate is still quite uncertain. A constant accretion rate is usually assumed for AGNs in most of the previous studies of the cosmological evolution of massive black holes (e.g., Yu & Tremaine 2002; Marconi et al. 2004; Shankar et al. 2004). The jet power is dependent on the mass accretion rate $\dot{m}$, and for comparison, we alternatively adopt a constant mass accretion rate, $\dot{m} = 0.25$, which is around the peak value of the distribution.
Figure 5. Energy released during the outbursts as a function of outburst time with an initial spin parameter, $a_0 = 0.1$ (dashed) and 0.95 (solid), respectively. The model parameter $\beta = 0.5$, $\xi_{\phi} = 0.1$, and a constant accretion rate $\dot{m} = 0.25$ are adopted. The colored lines are for the results calculated with different jet formation models, models A (black) and B (red).
(A color version of this figure is available in the online journal.)

Figure 6. Energy released by BZ + BP mechanisms (model A) as a function of outburst time, where $\beta = 0.5$, $\xi_{\phi} = 0.1$, and $\tau_Q = 1 \times 10^7$ years are adopted. The black and red lines are the results calculated for the BP and BZ mechanisms, respectively. The solid and dotted lines correspond to different initial conditions, $a_0 = 0.95$ and $a_0 = 0.1$, respectively.
(A color version of this figure is available in the online journal.)

in the sample of Kollmeier et al. (2006), to calculate the total energy released in the cavity as functions of time (see Figure 5).

We compare the relative importance of the BP and BZ mechanisms in Figure 6. Similar to that suggested by Livio et al. (1999), we find that the BP power always dominates over the BZ power even if the black hole is rotating rapidly. The results calculated with different values of $\beta$ are plotted in Figure 7. The jet power decreases significantly with increasing $\beta$. In most of our calculations, $\beta = 0.5$ is adopted, which is almost the upper limit on the magnetic field strength, and then corresponds with the upper limit of the jet power.

The evolution of black hole spin for different jet formation models is given in Figure 8.

4. DISCUSSION

The physics of jet formation is still quite unclear. As described in the previous sections, the total energy released by the jets of the AGN and the mass/spin evolution of the central massive black hole can be calculated with suitable initial conditions for a given jet formation model. The most powerful outbursts observed in MS 0735+7421 provide constraints on different jet formation models.

The basic physics of the jet formation models adopted in this work is the same as the previous works of Ghosh & Abramowicz (1997) and Livio et al. (1999), however, their estimates of the magnetic field strength of the disk are based on the conventional accretion disk models without a magnetic field. This is a good approximation in the weak magnetic field case, as the disk structure has not been altered significantly by the field, while the assumption becomes invalid for strong field cases. In this work, we calculate the structure of the accretion disk including
the magnetic torque exerted on the disk and the energy carried away by the jets (see Section 2.1).

The giant cavity in MS 0735+7421 stores a total of $10^{62}$ erg of energy, which is the most energetic outbursts of an AGN discovered thus far, if the cavity is inflated by the jets of the AGN. The observations of MS 0735+7421 provide very useful information that can constrain the detailed jet formation models. A power-law time-dependent $m(t)$ with an exponential cutoff at the high end is adopted in most of our calculations, which is derived based on the scenario of the feedback of AGNs producing a self-regulating decay or blowout phase after the AGN reaches a peak luminosity (Hopkins et al. 2005a, 2005b; Hopkins & Hernquist 2009). It is found that the total energy released in the jets can be as high as $10^{62}$ erg only in the calculations with model A, i.e., the strength of a large-scale magnetic field scales directly with the total pressure of the accretion disk, if an initial black hole spin parameter $a_0 = 0.1$ is adopted (see Figure 3). The other jet formation model does not seem to be able to produce such a giant cavity containing $10^{62}$ erg even if equipartition between magnetic and total (radiation + gas) pressure in the disk is assumed (i.e., $B = 0.5$). As discussed in Section 2.2, $B_p \ll B_p$ is required for the fast moving jets from the disk, and we adopt $\xi_p = 0.1$ ($B_p = \xi_p B_p$) in most of our calculations. For comparison, we also plot the results calculated with $B_p = B_p$ in Figures 3 and 4. We find that the maximal jet power that can be extracted with model A is insensitive to the value of $\xi_p$ adopted, because most of the gravitational energy released in the accretion disk is transported into the jets by the magnetic field. The results of the calculations with $\xi_p = 0.1$ are given in all other plots.

The initial black hole spin parameter $a_0$ can be higher than 0.1, for example, a rapidly rotating black hole can be formed after a merger of the black hole binary with mass ratio approaching unity (Hughes & Blandford 2003). Thus, we also calculate the problem with a relatively high initial black hole spin parameter $a_0 = 0.95$ in Figure 4. It is not surprising that the observed feature of the cavity can be reproduced by the calculations with model A, as much energy can be extracted for a faster rotating black hole. One can find that the total energy released in the jets can be as high as $10^{62}$ erg if $a_0 = 0.95$ and $t_0 = 10^8$ years, even for model B, i.e., the energy density of the large-scale magnetic field is scaled with $p_{\text{rad}}(H/r)^{-2}$ (see Equations (11) and (12) in Section 2.2), based on the scenario that the strength of the magnetic field generated by dynamo processes with typical size $\lambda$ decays with $\lambda^{-1}$ (Tout & Pringle 1999). If this is the case, the life timescale of this AGN $t_0 \approx 10 t_0 = 10^9$ years, which is roughly consistent with the estimates in previous works (e.g., Di Matteo et al. 2005; Hopkins & Hernquist 2009; Kelly et al. 2010; Cao 2010). This implies that the duty cycle of radio activity is around 0.1 if model B is responsible for the jet formation in this source. Besides the time-dependent mass accretion rate $m(t)$, we alternatively adopt a constant accretion rate in our calculations, $\dot{m} = 0.25$, which is the typical value of broadband AGNs (e.g., Kollmeier et al. 2006). We find that the results change little if a different value of mass accretion rate in the range of $0.1$–$0.5$ is adopted. The results obtained with a constant accretion rate are similar to those carried out with the time-dependent mass accretion rate, i.e., the jets can provide sufficient energy to inflate the cavity of MS 0735+7421 within the timescale of $10^9$ years with model A or model B if an initial black hole is spinning at $a_0 = 0.95$ (see Figure 5).

We compare the relative importance of the BP and BZ methods in Figure 6. Similar to that suggested by Livio et al. (1999), we find that the BP power always dominates over the BZ power even if the black hole is rotating rapidly. The reason for this is that the area of the disk launching the jets is significantly larger than the surface area of the black hole, and the strength of the field threading the horizon of the hole is comparable to that in the inner region of the disk (see Livio et al. 1999 for a detailed discussion). The initial black hole spin $a_0$ can change the power output of both the BZ and BP method: as shown in Figure 6. The jet power produced by the BZ process can vary over one order of magnitude, which is consistent with the results of MHD simulation for a thin disk in Tchekhovskoy et al. (2010). Black hole spin can play a more important role in the jet formation of thicker accretion disks (Tchekhovskoy et al. 2010). The large-scale magnetic field is dragged in by the advection-dominated accretion flow (ADAF), and Cao (2011) found that the magnetic field strength of the flow near the black hole horizon can be more than one order of magnitude higher than that in the ADAF at $\sim 66M/c^2$, due to the large radial velocity of the accretion near the black hole horizon. It is still unclear if such an effect is important in the thin accretion disk, which is beyond the scope of this work. We compare the results with different values of $\beta$ adopted in Figure 7. The jet power decreases significantly with increasing $\beta$. In most of our calculations, $\beta = 0.5$ is adopted, which is almost the upper limit on the magnetic field strength, and then corresponds with the upper limit of the jet power. Our main conclusions will not be altered even if a lower $\beta$ is adopted, while the total energy derived with model B may be insufficient for the energy stored in the cavity of MS 0735+7421 provided a lower $\beta$ is adopted. Our results show that a strong magnetic field nearly equipartition with the total pressure (radiation + gas pressure) in the accretion disk is indeed required at least for the most energetic cavity of MS 0735+7421, which provides a useful clue about the formation of the large-scale magnetic field in the accretion disk. For other less energetic cavities, the magnetic field strength can be significantly lower than the equipartition value, and less strict constraints are set on the jet formation mechanisms.

It is found that the final spin parameter $a_f$ is always very high ($a_f > 0.9$) for all the jets that can provide sufficient energy for the cavity of MS 0735+7421 (also see Figure 3), either for a low or high initial spin parameter $a_0$ ($a_f = 0.923$ and 0.998 for $a_0 = 0.1$ and $a_0 = 0.9$, respectively). This means that the central black hole of the AGN in MS 0735+7421 should be rotating very rapidly now.

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REFERENCES

Abramowicz, M. A., Chen, X.-M., Granath, M., & Lasota, J.-P. 1996, ApJ, 471, 762
Allen, S. W., Dunn, R. J. H., Fabian, A. C., Taylor, G. B., & Reynolds, C. S. 2006, MNRAS, 372, 21
Armitage, P. J., & Natarajan, P. 1999, ApJ, 523, L7
Beckwith, K., Hawley, J. F., & Krolik, J. H. 2008, ApJ, 678, 1180
Birzan, L., Rafferty, D. A., McNamara, B. R., Wise, M. W., & Nulsen, P. E. J. 2004, ApJ, 607, 800
Biskamp, D. 1993, Cambridge Monographs on Plasma Physics (Cambridge: Cambridge Univ. Press)
