CONSTRAINTS ON JET FORMATION MECHANISMS WITH THE MOST ENERGETIC GIANT OUTBURSTS IN MS 0735+7421

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Outline

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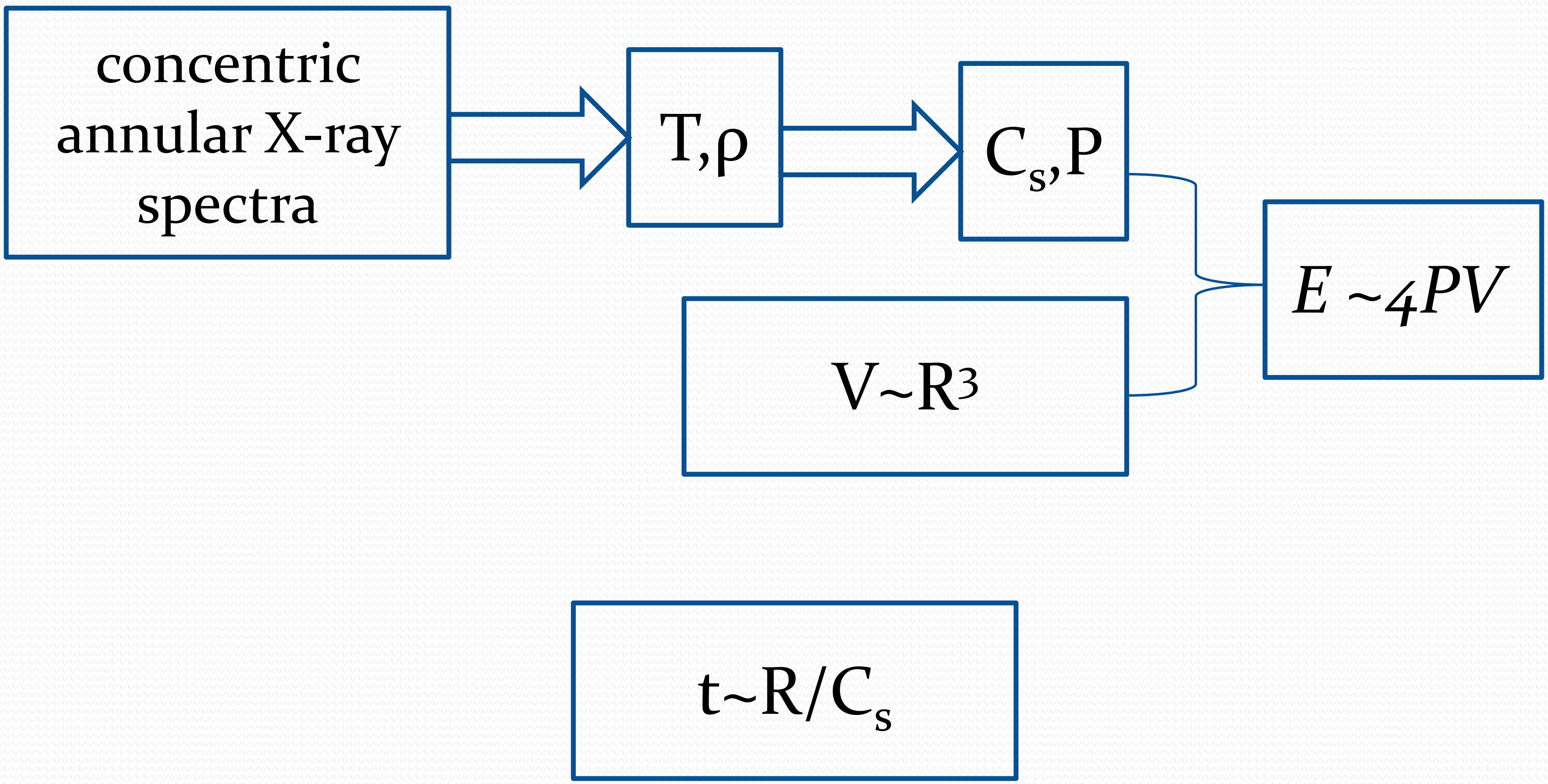
- 2, MODELS
- 3, RESULTS
- 4, DISCUSSION AND CONCLUSIONS

1 Introduction

- There are many giant X-ray cavities in many central galaxies of clusters: e.g., Hydra A (McNamara et al. 2000); RBS 797 (Schindler et al. 2001) and MS 0735+7421 (McNamara et al. 2005)

- Black hole mass: ~10^9 $M_\odot$
- Mechanical energy: 10^{55}–10^{62} erg
- Mean jet power: 10^{41}–10^{46} erg s^{-1}


concentric annular X-ray spectra
T,ρ
Cs,P
E ~4PV
V~R3
t~R/Cs

MS 0735+7421

- Black hole mass: 5×10^{9} $M_{\odot}$
- E_{tot}: 1.21×10^{62} erg
- L_{kin}: 3.5×10^{46} erg s^{-1}
- $L_{I} < 2.5 \times 10^{42}$ erg
- Age: 1.1×10^{8} yr

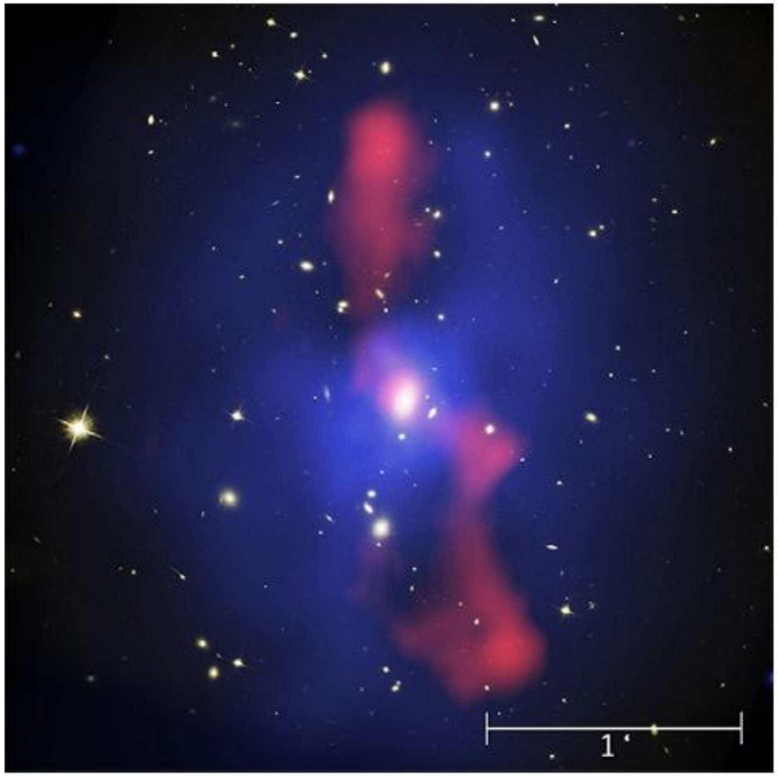


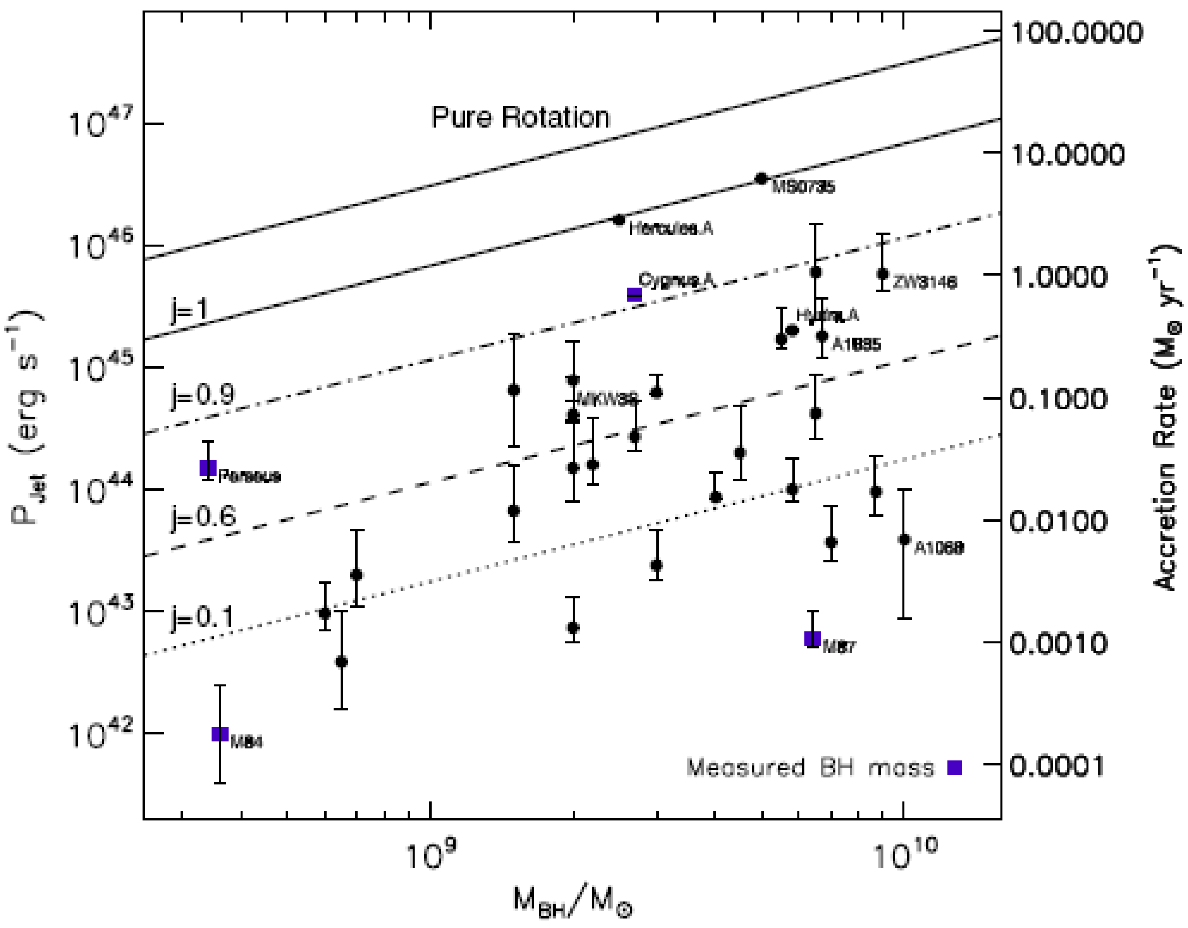
Figure 1. Image of the inner 200″ (700 kpc) of the MS0735.6+7421 cluster combining the X-ray (blue), *I*-band (white), and radio wavelengths (red).

McNamara et al. (2009)

Jet formation mechanisms

- Jet launching is very sensitive to both the strength and the poloidal component of magnetic field. (Beckwith 2008)

- Blandford-Znajek (BZ) (Blandford & Znajek 1977)
- Blandford-Payne (BP) (Blandford & Payne 1982)



McNamara et al. (2011)

1, $L_I < 2.5 \times 10^{42}$ erg

2, A maximally spinning 10^9 $M_\odot$ black hole contains ~ 10^{62} erg

3, Hybrid model (Meier 1999, 2001), ADAF

Why we do this work

- 1, Episodic activity of jets? Smaller j? Inadequate jet power?
- 2, For MS 0735, L_{kin}/L_{Edd}~0.02
- 3, To constrain the jet formation mechanisms

2 Model 2.1. *The equations of accretion disk*

The metric around the black hole reads (the geometrical unit $G = c = 1$ is adopted):

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

where

$$\Delta = r^2 - 2Mr + a^2,$$

$$A = r^4 + r^2a^2 + 2Mra^2,$$

$$\omega = \frac{2Mar}{A},$$

$$a = \frac{J}{M},$$

The continuity equation is

$$\dot{M} = -2\pi\Delta^{1/2}\Sigma v_{\rm r}, \qquad (2)$$

where v_r is the radial velocity of the accretion flow, $\Sigma = 2\rho H$ is the surface density , $\dot{M}$ is the accretion rate.

The momentum equation is

$$\frac{\gamma_\phi AM}{r^4\Delta}\frac{(\Omega-\Omega_{\rm k}^+)(\Omega-\Omega_{\rm k}^-)}{\Omega_{\rm k}^+\Omega_{\rm k}^-} + g_{\rm m} = 0, \qquad (3)$$

where Ω is the angular velocity, the Lorentz factor γ_ϕ of the rotational velocity v_ϕ is given by

$$\gamma_\phi = (1 - v_\phi^2)^{-1/2},$$

where $v_\phi = A\tilde{\Omega}/r^2\Delta^{1/2}$, $\tilde{\Omega} = \Omega - \omega$.

$$\Omega_{\rm k}^\pm = \pm\frac{M^{1/2}}{r^{3/2} \pm aM^{1/2}},$$

is the Keplerian angular velocity of the prograde (+) and retrograde (-) motions. $g_{\rm m} = B_{\rm r}B_{\rm z}/2\pi\Sigma$ is the radial magnetic force ($B_{\rm r}$ and $B_{\rm z}$ are the radial and vertical components of the magnetic fields respectively, the angle between magnetic filed lines and disk midplane is set to 60° for simplicity).

The angular momentum equation is

$$-\frac{\dot{M}}{2\pi}\frac{dL}{dr}+\frac{d}{dr}(rW_{\phi}^{r})+T_{\rm m}r=0, \tag{4}$$

where L is the angular momentum of the accretion flow, which can be written as:

$$L=\frac{A^{1/2}(\gamma_{\phi}^{2}-1)^{1/2}}{r},$$

and

$$W_{\phi}^{r}=\alpha\frac{A^{3/2}\Delta^{1/2}\gamma_{\phi}^{3}}{r^{6}}W$$

is the height-integrated α-viscosity tensor, where $W=2HP_{\rm tot}$, $P_{\rm tot}=P_{\rm gas}+P_{\rm rad}+P_{\rm m}$ is the total pressure, $P_{\rm gas}, P_{\rm rad}$ and $P_{\rm m}=(1-\beta)P_{\rm tot}$ are the gas pressure, radiation pressure and magnetic pressure respectively (β is the ratio of the gas pressure plus radiation pressure to the total pressure), the scale height H is given by $H^{2}=c_{s}^{2}r^{4}/(L^{2}-a^{2})$ ($c_{\rm s}=\sqrt{P_{\rm tot}/\rho}$ is the sound speed), $T_{\rm m}=-B_{\rm z}B_{\varphi}R/2\pi$ is the magnetic torque exerted on the accretion flow due to the outflows/jets, B_{φ} is the toroidal field strength (see, e.g., Cao 2002, for details).

The energy equation is

$$\nu\Sigma\frac{\gamma_{\phi}^{4}A^{2}}{r^{6}}\left(\frac{d\Omega}{dr}\right)^{2}=\frac{16acT^{4}}{3\bar{\kappa}\Sigma}, \tag{5}$$

where ν is the viscosity coefficient, $\nu\Sigma d\Omega/dr=-\alpha W/r$ is simply adopted from the α-viscosity description, and T is the temperature, the opacity $\bar{\kappa}$ is given by

$$\bar{\kappa}=\kappa_{\rm es}+\kappa_{\rm ff}=0.4+0.64\times10^{23}\rho T^{-7/2}{\rm cm}^{2}{\rm g}^{-1},$$

where $\kappa_{\rm es}$ and $\kappa_{\rm ff}$ are the electron scattering opacity and free-free opacity respectively.

2.2 *The evolution of black holes*

- The basic black hole evolution equations can be written as (Moderski & Sikora 1996):

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \frac{\dot{M}}{M}(\tilde{j}_{\mathrm{ms}} - 2a\tilde{e}_{\mathrm{ms}}) - \frac{L_{\mathrm{BZ}}}{M c^2}\left(\frac{1}{k\tilde{\Omega}_{\mathrm{h}}} - 2a\right), \qquad (5)$$

$$\frac{\mathrm{d}\ln M}{\mathrm{d}t} = \frac{\dot{M}}{M}\tilde{e}_{\mathrm{ms}} - \frac{L_{\mathrm{BZ}}}{M c^2}, \qquad (6)$$

2.3. *The mechanisms of jet formation*

- Model A: BZ process

$$L_{\rm BZ} = \frac{1}{32}\omega_{\rm F}^2 B_{\perp}^2 r_{\rm H}^2 (J/J_{\rm max})^2 c, \qquad (8)$$

BP process

$$L_{\rm BP} = \int_{R_{\rm in}}^{R_{\rm out}} \frac{B_{\rm p}^2}{4\pi} R\Omega 2\pi R {\rm d}R, \qquad (9)$$

- Model B: Livio' model, $B_p' \sim (H/R) B_p$

The total energy E_{tot}

- The total energy released through *BZ + BP mechanism* during the outbursts is:

$$E_{\rm tot} = E_{\rm BZ} + E_{\rm BP} = \int_0^t (L_{\rm BZ} + L_{\rm BP}) {\rm d}t = \int_0^t L_{\rm jet} {\rm d}t,$$

where, t is the time of AGN outbursts

3. Results

- We solve the sets of nonlinear equations (2) - (5) numerically with the initial parameters (M_o, a_o, m_dot$_o$, α and β) firstly and then calculate the jet power with various models.

- m_dot=0.25
- The evolution of mass accretion rate m_dot *can be calculated from Eq. (15) with the initial accretion* rate m_dot$_o$ *as suggested by Hopkins & Hernquist (2009)*:

$$\frac{dt}{d\log \dot{m}} = -\tau_Q \left(\frac{\dot{m}}{\dot{m}_0}\right)^{-\beta_L} \exp\left(-\frac{\dot{m}}{\dot{m}_0}\right), \qquad (16)$$

- In our calculations, the conventional values of disk parameters α=0.1 and the initial Eddington ratio m_dot$_0$ =1 are always adopted. In order to fit the giant bubbles in MS 0735+7421, the initial black hole mass $M_{\odot}$ is chosen in such a way to let the final black hole mass be $5 \times 10^9 M_{\odot}$ as that in the AGN of MS 0735+7421 when the outbursts finish (m_dot~0.01) in all our calculations.

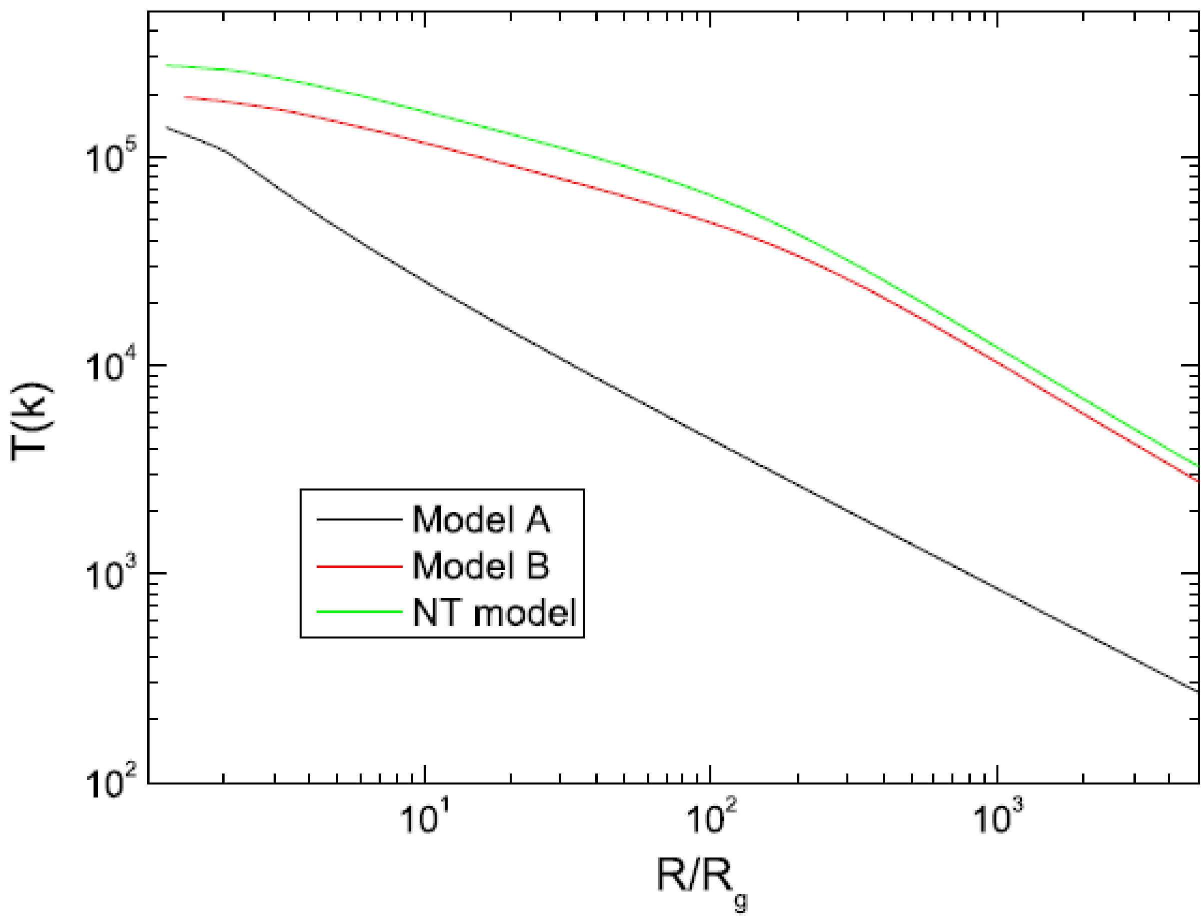


Figure 1. Disk temperature of a relativistic thin accretion disk with magnetically driven outflows, where $a_0 = 0.95$, $\beta = 0.5$, and $\dot{m} = 0.25$ are adopted. The black and red lines are for the results calculated with model A and model B, respectively. We also plot the results of a relativistic thin accretion disk without outflows for comparison (green lines).

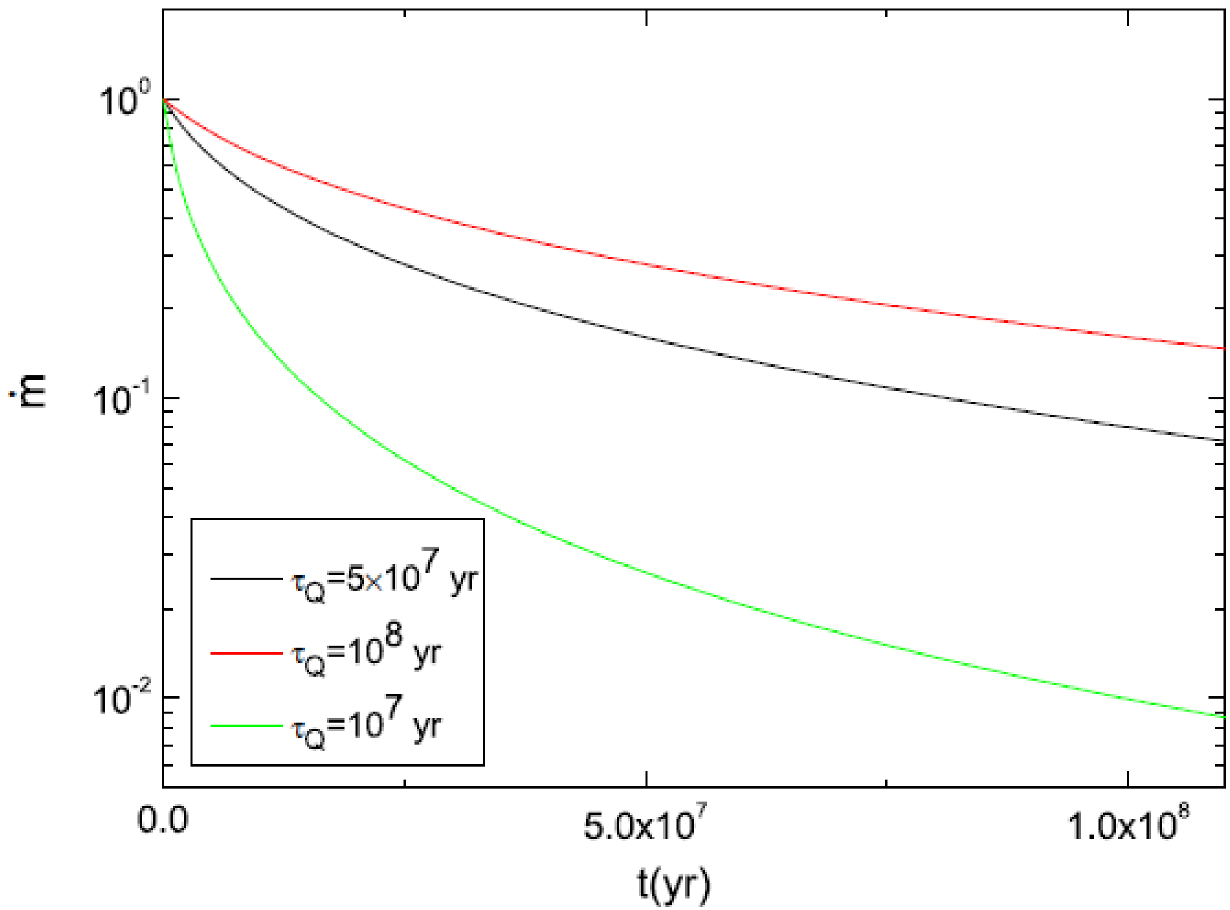


Figure 2. Evolution of accretion rate as functions of outburst time. The colored lines correspond to different values of τ_Q, $\tau_Q = 5 \times 10^7$ (black), 10^8 (red), and 10^7 years (green), respectively. In all our calculations, the initial black hole mass M_0 is chosen in such a way to let the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

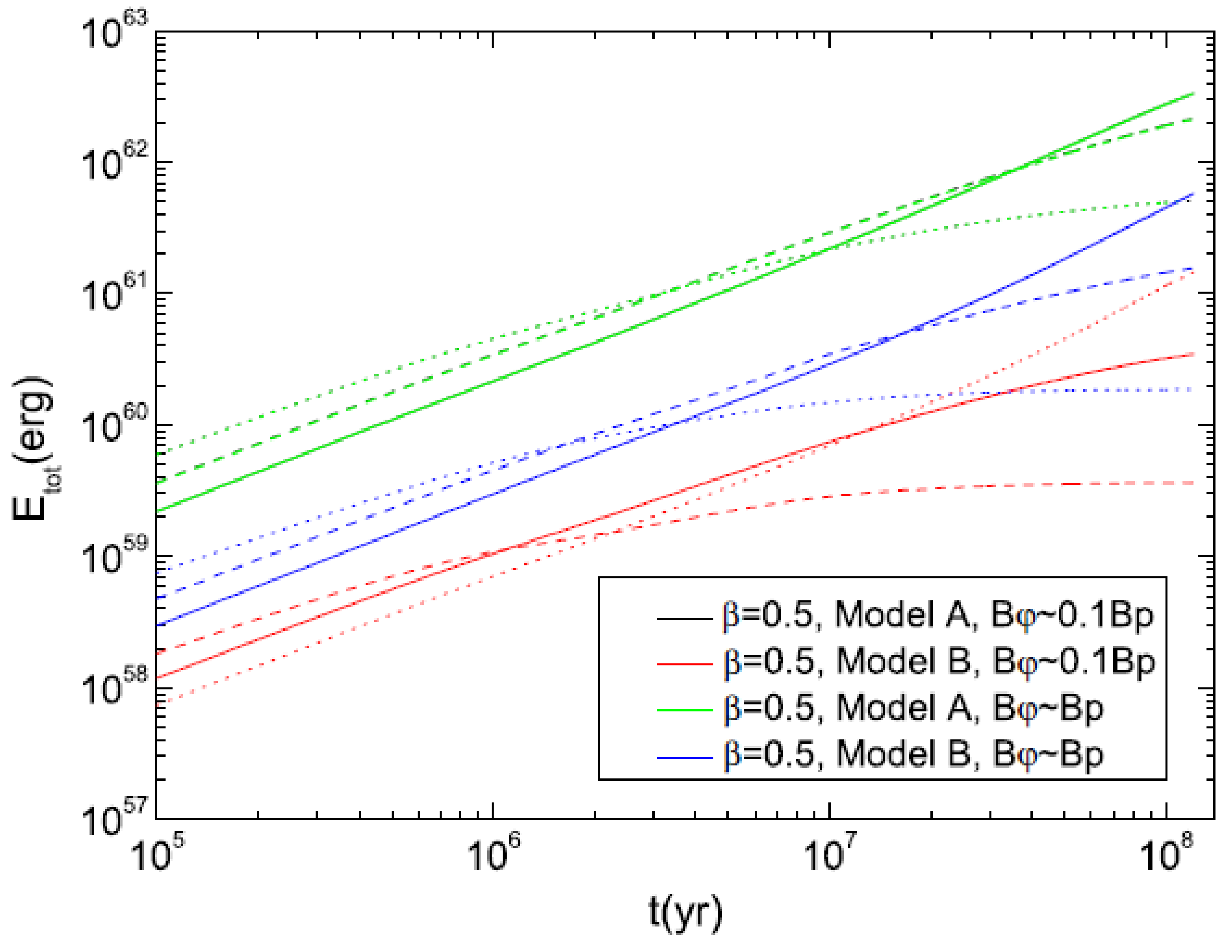


Figure 3. Energy released during the outbursts as functions of the outburst time with $a_0 = 0.1$ and $\beta = 0.5$. The different color lines represent the results calculated for different jet formation models and different values of azimuthal component of the field at the disk surface (see the figure). The solid, dashed, and dotted lines are for the results with $\tau_Q = 10^8$, 5×10^7, and 10^7 years, respectively.

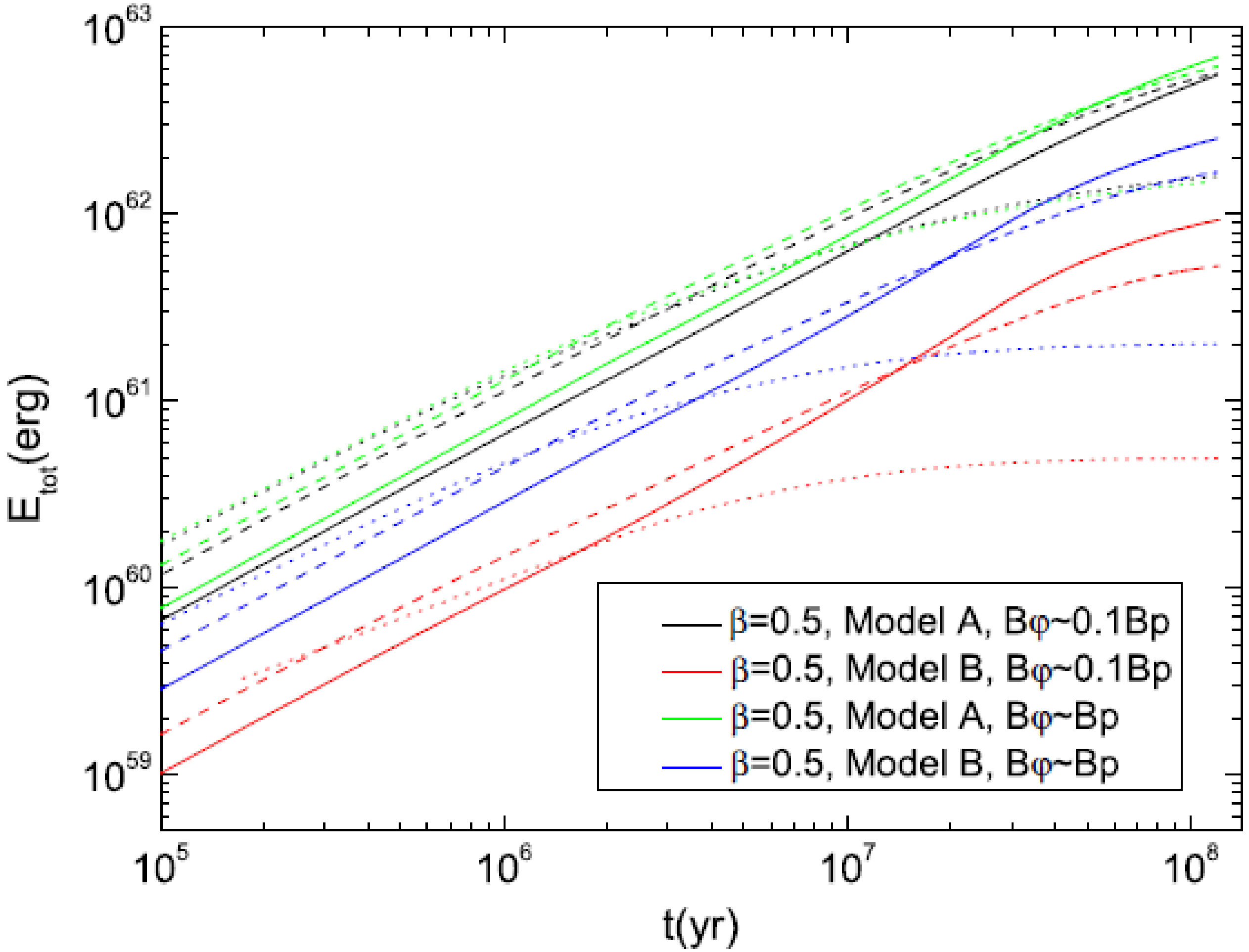


Figure 4. Same as Figure 3, except that the initial spin $a_0 = 0.95$ is adopted.

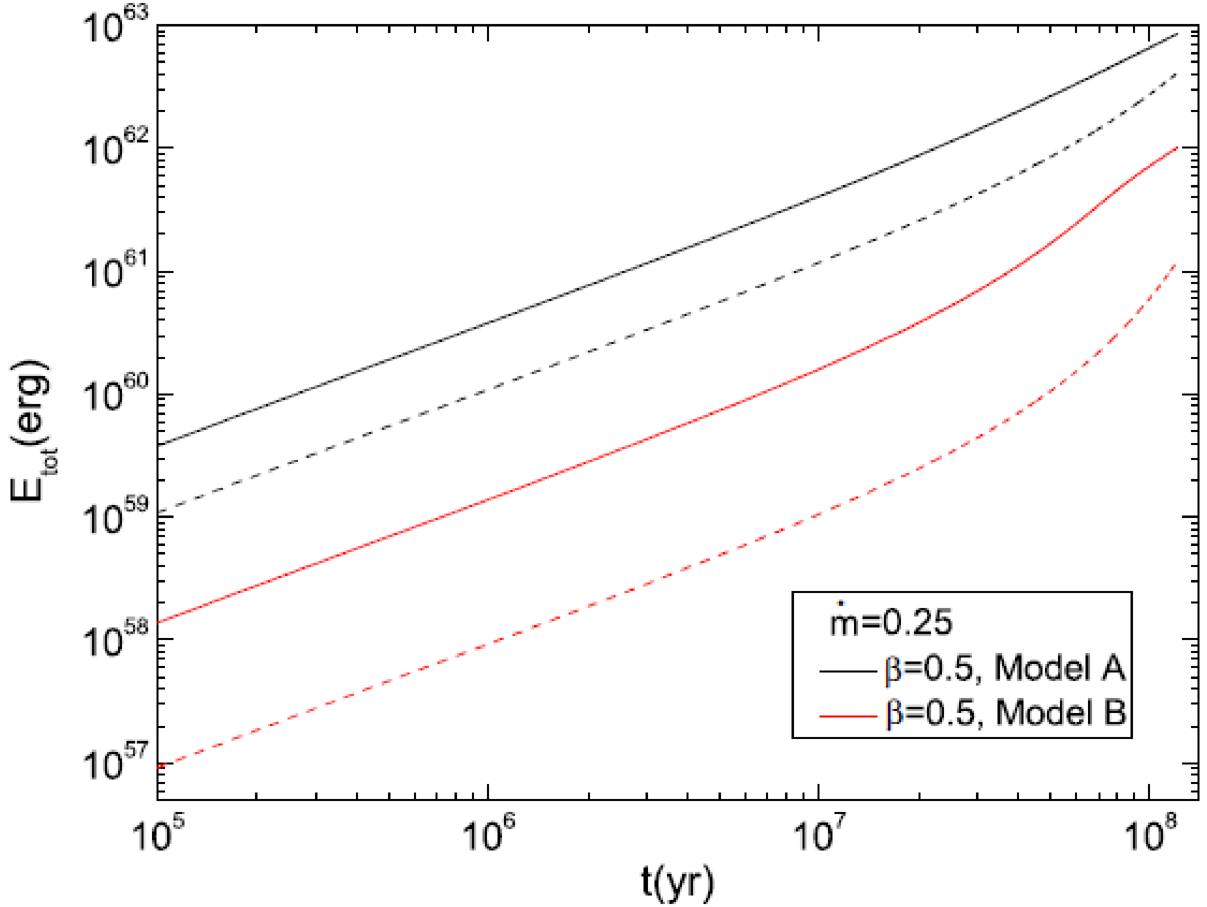


Figure 5. Energy released during the outbursts as functions of outburst time with the initial spin parameter, $a_0 = 0.1$ (dashed) and 0.95 (solid), respectively. The model parameter $\beta = 0.5$, $\xi_\varphi = 0.1$, and a constant accretion rate $\dot{m} = 0.25$ are adopted. The colored lines are for the results calculated with different jet formation models, models A (black) and B (red).

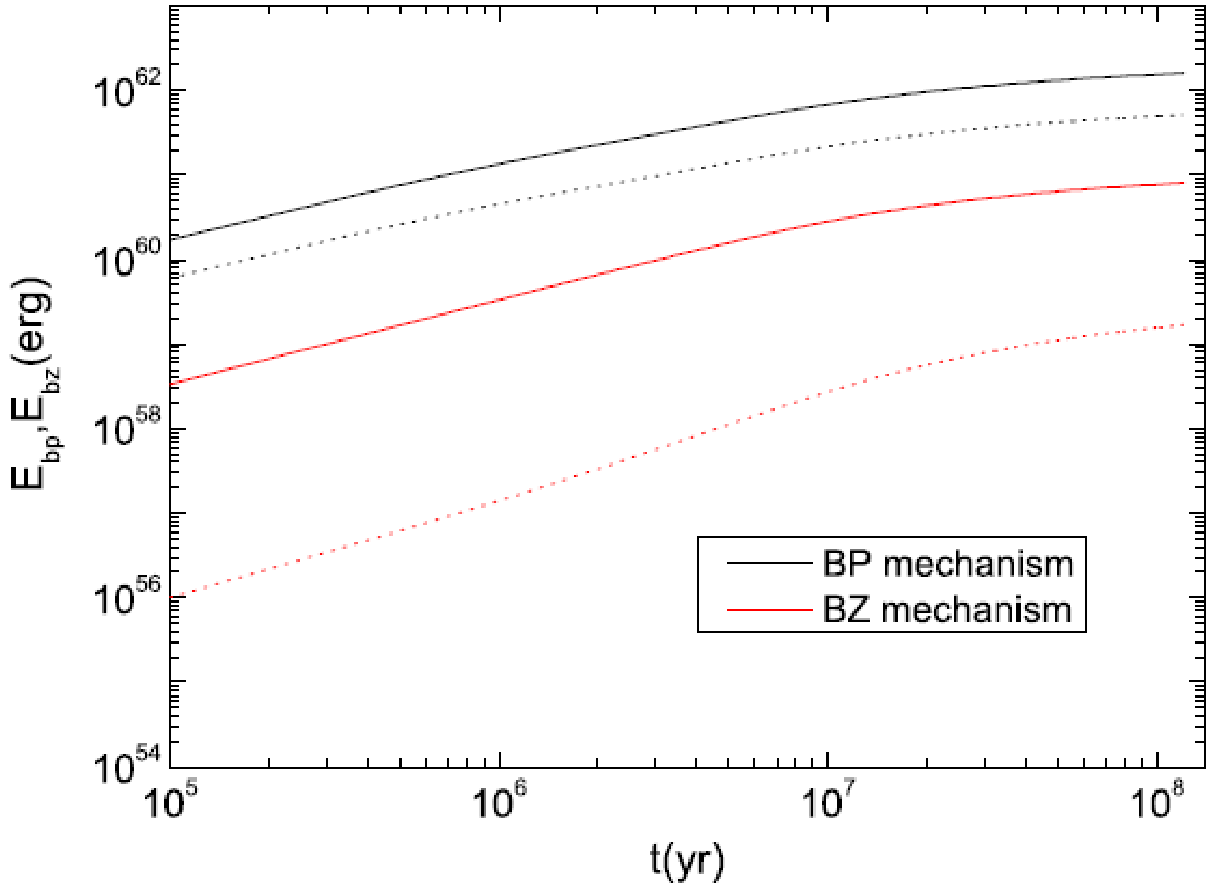


Figure 6. Energy released by BZ + BP mechanisms (model A) as functions of outburst time, where $\beta = 0.5$, $\xi_\varphi = 0.1$, and $\tau_Q = 1 \times 10^7$ years are adopted. The black and red lines are the results calculated for the BP and BZ mechanisms, respectively. The solid and dotted lines correspond to different initial conditions, $a_0 = 0.95$ and $a_0 = 0.1$, respectively.

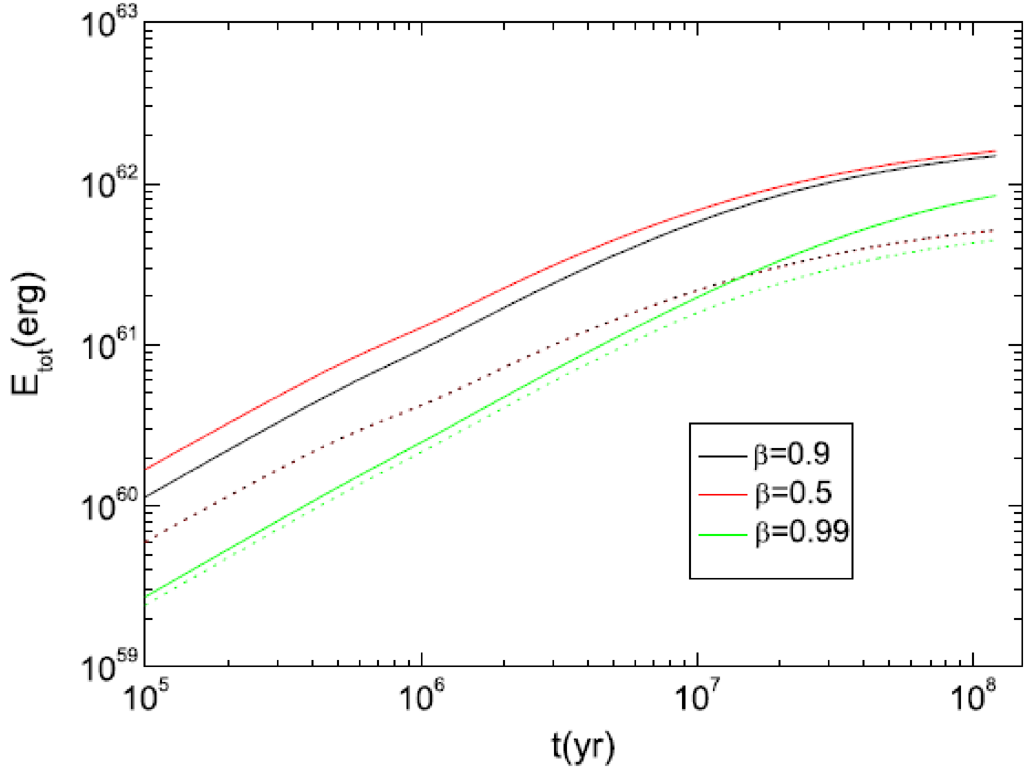


Figure 7. Energy released during the outbursts as functions of outburst time with different values of β for model A, where $\xi_\varphi = 0.1, \tau_Q = 10^7$ years are adopted in the calculations. The colored lines are for the results calculated with $\beta = 0.99$ (green), 0.9 (black), and 0.5 (red), respectively. The solid and dotted lines correspond to different initial conditions, $a_0 = 0.95$ and $a_0 = 0.1$, respectively.

$L_{bp} \sim B_p^2 R\Omega_k R \sim (1-\beta)PRv_k$, $L_d \sim \alpha PH\Omega_k R$

$L_{bp}/L_d \sim (1-\beta)R/(\alpha H)$

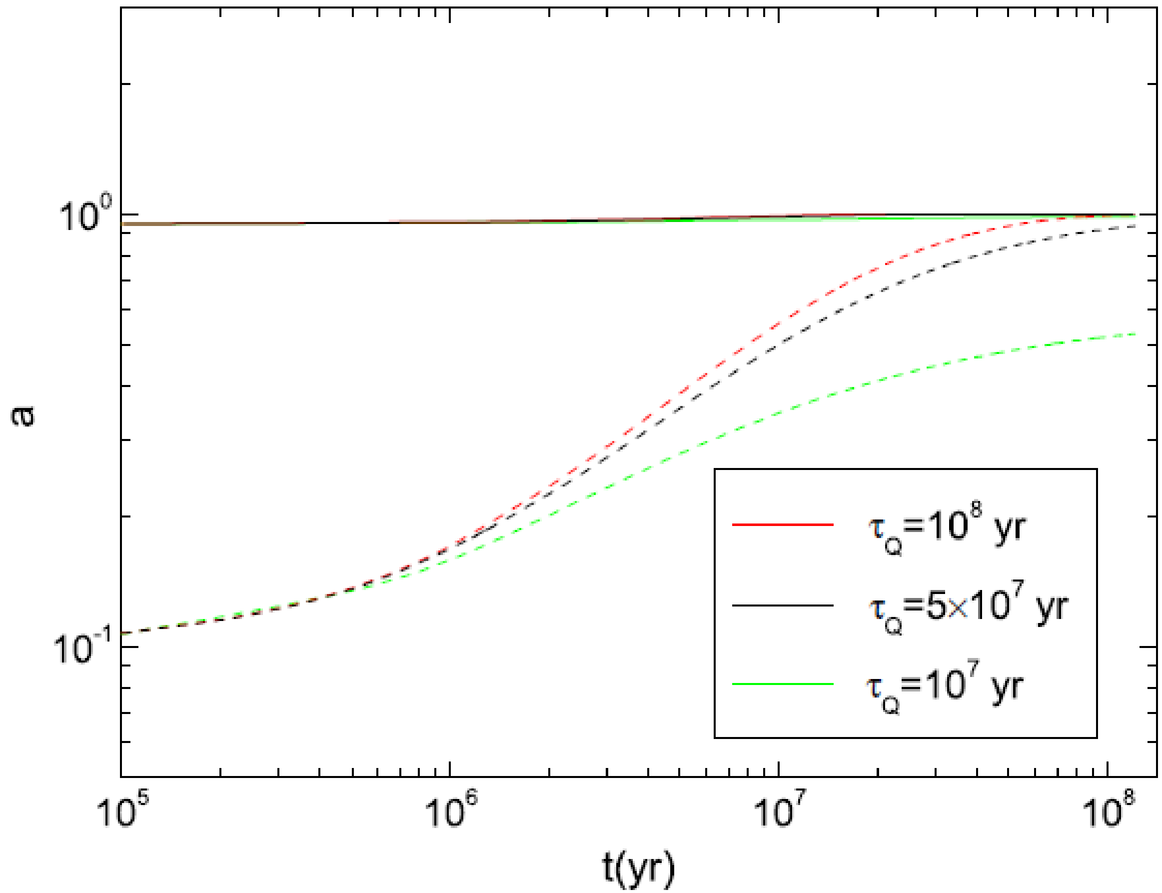


Figure 8. Evolution of black hole spin as functions of outburst time for model A, where $\beta = 0.5$ and $\xi_\varphi = 0.1$ are adopted. The colored lines correspond to different values of $\tau_{\rm Q}$, $\tau_{\rm Q} = 5 \times 10^7$ (black), 10^8 (red), and 10^7 years (green), respectively. The dashed and solid lines correspond to different initial conditions, $a_0 = 0.1$ and $a_0 = 0.95$, respectively.

4 DISCUSSION AND CONCLUSIONS

- 1. 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.

- It is found that the total energy released in the jets can easily reach 10^{62} erg for model A; For dynamo generated magnetic field in the disk (model B), such an energetic giant cavity can be inflated by the magnetically driven jets only if the initial black hole spin parameter $a_0 \geq 0.95$.

- 2. E_{BP} is over one order of magnitude more than E_{BZ} for both a_0 = 0.1 and a_0 = 0.95, which is the direct evidence of the domination of BP mechanism.
- Our calculational results support the conclusions of Livio et al. (1999), the jet power accelerated from accretion disk absolutely dominates that from black holes.

- 3. Our calculations show that the final spin parameter a of the black hole is always ~0.9–0.998 for all the computational examples which can provide sufficient energe for the cavity of MS 0735+7421.

Thank You!