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PRECESSION OF SUPERMASSIVE BLACK HOLES

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ABSTRACT

In the previous work we made a long term evolution code for the central black hole in an active galactic nucleus under the assumption that the Blandford-Znajek process is the source of the emission. Using our code we get the evolution of the angular velocity of the precession for a supermassive black hole. We consider a hole at the center of an axisymmetric, ellipsoidal galactic nucleus. Our numerical results show that, only for the cases such that the stellar density or the mass of the black hole is large enough, the precession of the black hole — presumably the precession of the galactic jet — is interestingly large.

I. INTRODUCTION

In Park and Vishniac (1988, hereafter PVI) we analyzed the long term evolution of the central black hole in an active galactic nucleus (hereafter, AGN) under the assumption that the mass accretion rate $\dot{M}_+$ is constant. In general these models showed a gradual, long term decrease in luminosity which is inconsistent with the luminosity function of AGNs as a function of redshift. This inconsistency cannot be cured by allowing for some fraction of the luminosity to be due to thermal radiation from the accretion disk, inasmuch as the contribution of the disk is directly proportional to $\dot{M}_+$. We concluded that that $\dot{M}_+$ must be a sharply decreasing function of time and $\dot{m}$, the ratio of $\dot{M}_+$ to the Eddington accretion rate $\dot{M}_E$, also must decrease.

In Park and Vishniac (1990, hereafter PVII) we extended the work, setting

$$\dot{M}_+ = \dot{M}_+(t) \equiv \dot{M}_+(0)e^{-\lambda t}, \tag{1.1}$$

where $\dot{M}_+(0)$ is the initial mass accretion rate, and λ is a positive parameter. Throughout this paper the subscript (0) means the initial value at $t = 0$ and the units are defined such that $c = G \equiv 1$. The central black hole is assumed to be a Kerr black hole which contains a mass M, a total angular momentum J, and an angular momentum density $a(\equiv J/M)$.

We modified the evolution equations to allow for a time-varying accretion rate and estimated the probable value of λ as

$$\lambda \sim 10^{-16} \quad \mathrm{s}^{-1}. \tag{1.2}$$

Using this value of λ, we get the evolution of the power output from the black hole by the Blandford-Znajek process, the total mass of the black hole, the strength of the magnetic field threading the black hole, a/M of the black hole, and the ratio ($\dot{m}$) of $\dot{M}_+$ to the Eddington accretion rate. Our results show that many successive short-lived generations of QSOs could been born and die in the period during which the overall population declines, and that there could be $\sim 10^8$ $M_\odot$ black holes in most bright galaxies.

In this paper, following PVI and PVII, we will investigate the evolution of the precession of the central black holes in galactic nuclei. In §2 we will state evolution equations. In §3 we will show the numerical results and discuss astrophysical implications of the results.

II. EVOLUTION EQUATIONS

Following PVI and PVII, we have

$$\Omega^F \sim \frac{\Omega^H}{2}, \tag{2.1a}$$

$$P \sim 10^{45}\left(\frac{a}{M}\right)^2 M_8^2 B_{\perp 4}^2 \quad \text{ergs s}^{-1}, \tag{2.1b}$$

$$\dot{J} \sim \frac{\dot{M}_-}{\Omega^F} + \dot{M}_+ (r^H)^2 \Omega^F, \tag{2.1c}$$

and

$$B_{\perp 4} \sim \left(\frac{\dot{m}}{M_8}\right)^{1/2}, \tag{2.1d}$$

where Ω^F is the angular velocity of the magnetic field lines, Ω^H is the angular velocity of the black hole, P is the power output due to the mass extraction from the black hole by the Blandford-Znajek process (Blandford and Znajek 1977; Macdonald and Thorne 1982; Thorne et al. 1986), M_8 is M in the unit of $10^8\,M_\odot$, $B_\perp$ is the strength of the magnetic field threading the black hole, $B_{\perp 4}$ is $B_\perp$ in the unit of 10^4 gauss, $\dot{M}_-$ is the rate of the mass loss of the black hole, and r^H is the radius of the black hole.

The dimensionless evolution equations are

$$\frac{\dot{\zeta}}{\zeta} = -(\zeta + \eta) - \lambda \tag{2.2a}$$

and

$$\frac{\dot{\xi}}{\xi} = \left(\frac{4}{\xi^2}\eta + \frac{\zeta}{4}\right)\{1 + (1-\xi^2)^{1/2}\} - 2(\zeta + \eta) \tag{2.2b}$$

with

$$P = \frac{\xi^2 \dot{M}_+}{13} \tag{2.2c}$$

and

$$\eta = -\frac{\xi^2 \zeta}{13}, \tag{2.2d}$$

where

$$\zeta \equiv \frac{\dot{M}_+}{M} \quad (\zeta \geq 0), \tag{2.2e}$$

$$\eta \equiv \frac{\dot{M}_-}{M} \quad (\eta \leq 0), \tag{2.2f}$$

and

$$\xi \equiv \frac{a}{M} \quad (0 \leq \xi \leq 1). \tag{2.2g}$$

Now consider a Kerr black hole with angular momentum

$$J_i = M a \hat{J}_i \tag{2.3}$$

where $\hat{J}$ is a unit vector pointing in the spin direction. Then the tidal torque vector $\mathbf{N}$ is given by

$$\mathbf{N} = \boldsymbol{\Omega} \times \mathbf{J}, \tag{2.4a}$$

where

$$\Omega_i = -\mathcal{E}_{ij} a \hat{J}^j \tag{2.4b}$$

is the angular velocity of tidally-torqued precession. In equation (2.4b) $\mathcal{E}_{ij}$ is the tidal field tensor defined as

$$\mathcal{E}_{ij} = \frac{\partial^2 \Phi}{\partial x^i \partial x^j}, \tag{2.5}$$

where Φ is the gravitational potential for the external field.

Now let us consider a supermassive black hole at the center of an axisymmetric, ellipsoidal galactic nucleus. We assume that the nucleus is not so compact that its gravity is Newtonian. Let ρ be the mean stellar density of the nucleus. If the direction of the hole's angular momentum is oriented at a small angle to the nucleus' axis, then Ω in equation (2.4b) is given by (eq. [5.78] in Thorne et al. 1986)

$$\Omega \sim 10^{-8} \quad \rho_9 \xi M_8 \quad \mathrm{yr}^{-1}, \tag{2.6}$$

where ρ_9 is ρ in the unit of 10^9 $\mathrm{M}_\odot$ $(\mathrm{ly})^{-3}$ and the shape of the nucleus is assumed to be like a pancake. Therefore, Ω is directly proportional to a, the angular momentum density in this case. It is, however, not simple at all to estimate the evolution of a. a may even increase if there is a significant angular momentum input from the surrounding accretion disk or torus.

III. NUMERICAL RESULTS AND CONCLUSIONS

If $\rho_9 \sim 1$ is assumed throughout the evolution and λ is given as in equation (1.2), we have three independent initial conditions in this analysis, i.e., $\xi(0)$, $\dot{M}_+(0)$, and $M(0)$. Obviously $\dot{m}(0)$ can be substituted for either $\dot{M}_+(0)$ or $M(0)$. As the initial conditions of our model we choose as in equation (3.1) in PVII,

$$\xi(0) \sim 1, \tag{3.1a}$$

$$\dot{m}(0) \sim 1, \tag{3.1b}$$

and

$$M_8(0) \sim 1, \tag{3.1c}$$

so that

$$P(0) \sim 10^{45} \quad \mathrm{ergs\ s}^{-1} \tag{3.1d}$$

and

$$B_{\perp 4}(0) \sim 1, \tag{3.1e}$$

which corresponds to a fairly luminous QSO with $\dot{M}_+(0) \sim 0.23$ $\mathrm{M}_\odot$ yr^{-1}.

As in PVII, we stop numerical calculation if $\dot{m}$ reaches 0.001. Using the above initial conditions in equation (3.1), we get (eq. [3.12] in PVII)

$$\tau \sim 2.02 \times 10^9 \quad \mathrm{yr}, \tag{3.2a}$$

$$P(\tau) \sim 1.81 \times 10^{41} \quad \mathrm{ergs\ s}^{-1}, \tag{3.2b}$$

$$M_8(\tau) \sim 1.70, \tag{3.2c}$$

$$B_{\perp 4}(\tau) \sim 2.42 \times 10^{-2}, \tag{3.2d}$$

and

$$\xi(\tau) \sim 0.33, \tag{3.2e}$$

for our model AGN. In our code M always tends to increase due to mass accretion (i.e., $\zeta > -\eta$), while ξ tends to decrease due to energy extraction.

The evolution of P, M, and $B_\perp$ in our code are plotted in PVII Fig. 2, Fig. 3, and Fig. 4, respectively. We find that P and $B_\perp$ decrease more rapidly than in the case of a constant mass influx, and M stops increasing when $t \gg 1/\lambda$ because of the exponentially-decreasing $\dot{M}_+$.

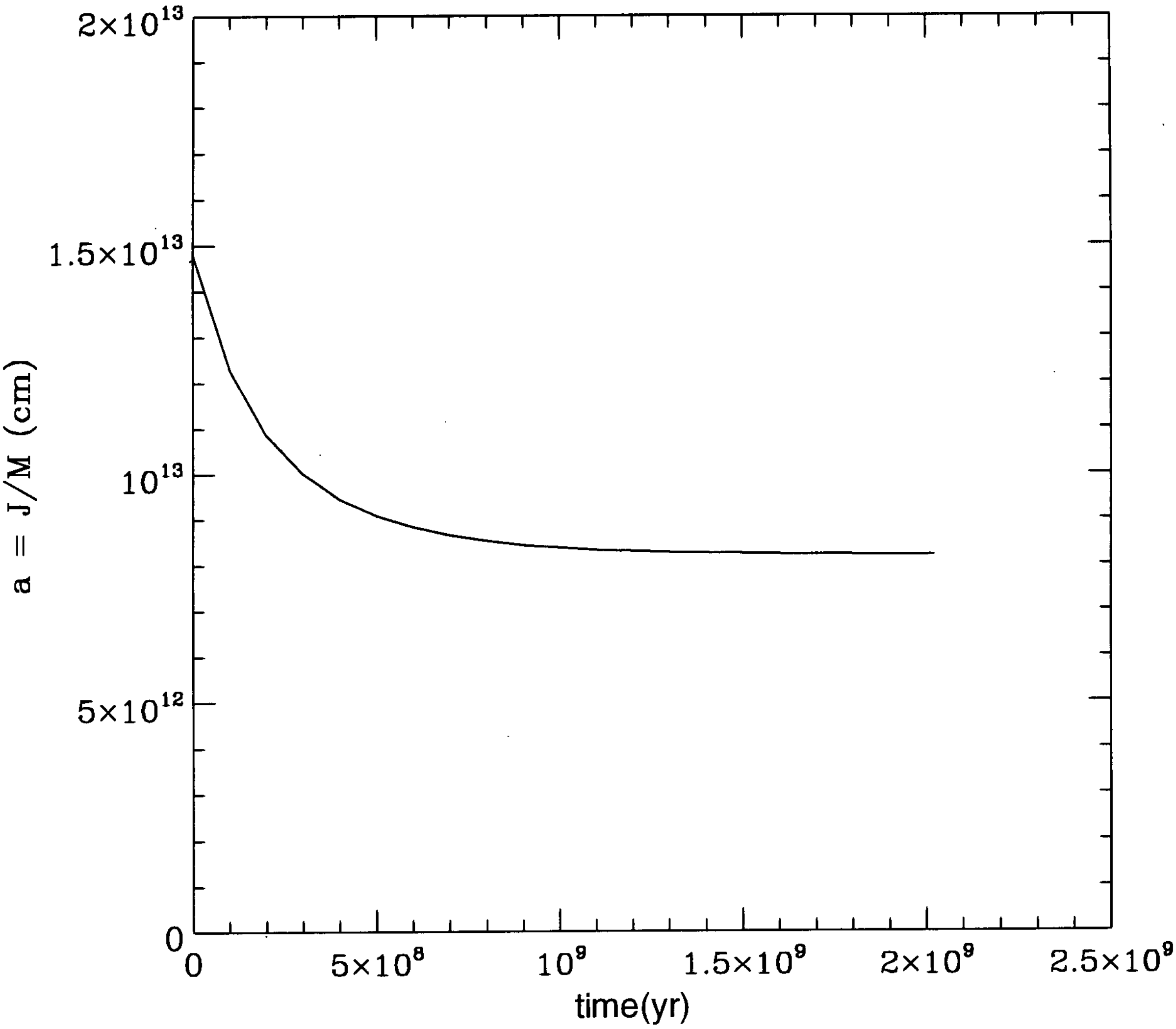

Fig. 1. The probable evolution of the angular momentum density of the central supermassive black hole in our model AGN

In the beginning $a \sim M \sim 1.47 \times 10^{13}$cm since condition (3.1$a$). Our code gives the final value of a as $\sim 8.20 \times 10^{12}$cm. The evolution during the lifetime is plotted in Fig. 1. It clearly shows that we cannot expect an interestingly large value of Ω in this case. In equation (2.6) Ω may be large if $\rho > 10^9$ $M_\odot$ (ly)$^{-3}$ and $M > 10^8$ $M_\odot$.

Our conclusion, therefore, must be that only for the cases such that the stellar density or the mass of the black hole is large enough, the precession is interestingly large. Galactic jets which are believed to be formed under the strong action of the central black hole may not show interestingly large precessions, either.

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