An application of the Kerr black hole fly-wheel model to statistical properties of QSOs/AGNs

Shin-ya Nitta\textsuperscript{1,2}\textsuperscript{*}

\textsuperscript{1}Division of Theoretical Astrophysics, National Astronomical Observatory Japan, Osawa 2-21-1, Mitaka 181-8588, Japan
\textsuperscript{2}Department of Astronomical Science, The Graduate University for Advanced Studies, Osawa 2-21-1, Mitaka 181-8588, Japan

Accepted 1999 April 30. Received 1999 April 21; in original form 1998 September 7

ABSTRACT
The aim of this work is to demonstrate the properties of the magnetospheric model around Kerr black holes (BHs), the so-called fly-wheel (rotation driven) model. The fly-wheel engine of the BH–accretion disc system is applied to the statistics of QSOs/AGNs. In the model, the central BH is assumed to be formed at $z \approx 10^2$ and obtains nearly maximum but finite rotation energy (\textit{\textsuperscript{\textdegree} extreme Kerr BH}) at the formation stage. The inherently obtained rotation energy of the Kerr BH is released through a magnetohydrodynamic process. This model naturally leads to a finite lifetime of AGN activity.

Nitta, Takahashi & Tomimatsu clarified the individual evolution of the Kerr BH fly-wheel engine, which is parametrized by BH mass, initial Kerr parameter, magnetic field near the horizon and a dimensionless small parameter. We impose a statistical model for the initial mass function (IMF) of an ensemble of BHs using the Press–Schechter formalism. With the help of additional assumptions, we can discuss the evolution of the luminosity function and the spatial number density of QSOs/AGNs.

By comparing with observations, it is found that a somewhat flat IMF and weak dependence of the magnetic field on the BH mass are preferred. The result explains well the decrease of very bright QSOs and decrease of population after $z \approx 2$.

Key words: black hole physics – MHD – relativity – galaxies: active – quasars: general – galaxies: statistics.

1 INTRODUCTION
We discuss the evolution of quasi-stellar object/active galactic nucleus (QSO/AGN) activities under the fly-wheel (rotation-driven) model, which is one of the plausible models for the powerful engine of AGNs including a rotating central black hole (BH). This fly-wheel engine might not be as familiar as the fuel engine (accretion-driven engine), but it is very attractive because this model can explain the evolution and lifetime of AGN activities very naturally.

It is widely believed that the recent discovery of the red tail of emission lines (Fe K\textalpha) from the central region of AGNs suggests that the central black holes are quickly rotating, i.e. the monster BH should be the Kerr BH (see Tanaka et al. 1995; Iwasawa et al. 1996; Dabrowski et al. 1997). The innermost stable circular orbit around the Kerr BH can intrude closer to the horizon than the Schwarzschild hole (non-rotating BH) of the same mass. Hence, the line emission from the innermost region of the accretion disc should be considerably redshifted by the gravitation, and this causes the red tail.

\* E-mail: snitta@th.nao.ac.jp

© 1999 RAS
hole can have. Hence, it seems reasonable to suppose that the central black hole is similar to the extreme Kerr hole at the formation stage. Such holes have an enormous amount of rotation energy ($\sim 10^{54} J \sim 10^{59} W \times 10^9 $ yr for the hole with mass $\sim 10^8 M_\odot$). This is enough to explain the total energy release of AGNs.

There are two types of engines for energy production in the black hole±accretion disc systems. The first is the well-known ‘fuel engine’, which is accretion-powered. This is the major one which has been frequently adopted to explain the AGN activities. The fuel engine acts by a process of conversion of the gravitational energy released from the infalling matter to radiation. The standard disc model (Shakura & Sunyaev 1973) is representative of this model.

The second is the ‘fly-wheel engine’. This is the rotation-powered engine. While the fly-wheel engine is not so familiar in the field of AGNs, this engine is as powerful as the fuel engine, and has very interesting features as discussed in the following sections. In contrast with the fuel engines, the energy source is the rotation of the Kerr BH itself. Of course, the rotation of the accretion disc can be another energy source. However, we focus on the case in which the rotation of the BH is the energy source, because the rotation energy of the disc is supplied by accretion, so we are apprehensive about possible confusion between the two engines. The author strongly hopes to introduce this fascinating engine to researchers working in the field of AGNs. The comparison of the fly-wheel engine and the fuel engine is discussed in Section 2.

Let us summarize the properties of the fly-wheel engine. The idea of extracting the rotation energy of the Kerr holes was first proposed by Penrose (1969). When an incident particle on to the Kerr hole splits into two parts inside the ergosphere with very large relative velocity, one particle is thrown into the negative-energy orbit falling towards the hole and the other particle escapes outwards with larger energy than the initial energy of the incident particle. In this case, the rotation energy of the hole is reduced by the infall of the negative-energy particle, and the reduced energy is carried away by the escaping particle. This is the well-known ‘Penrose process’. Unfortunately, it is pointed out that the Penrose process is not effective for astrophysical problems (see Bardeen, Press & Teukolsky 1972) because the critical value of the relative velocity required in order to realize the negative-energy orbit is close to one half of light velocity. Such a large relative velocity can be realized only by nuclear reactions of particles and cannot be achieved by usual dynamical processes, e.g., the tidal disruption of accreting matter.

The electromagnetic mechanism of extracting the rotation energy of the Kerr BHs was first proposed by Blandford & Znajek (1977). This is well known as the ‘magnetic braking process’ or the ‘BZ process’. In their study, the magnetosphere is supposed to be ‘force-free’ (strictly speaking, this is ‘magnetically dominated’), and they clearly showed the energy extraction in the form of the Poynting flux when the rotation speed of BH is greater than that of the magnetosphere. An extension of the magnetic braking process to the full magnetohydrodynamic (MHD) system was performed by Takahashi et al. (1990) as an elementary process of the BH engines. By precise analysis of the MHD accretion flow on to the Kerr BH, they succeeded in clarifying the condition to realize the ‘negative-energy MHD inflow’. This process is named the ‘MHD Penrose process’ by the authors. Nitta et al. (1991) studied the magnetospheric structure filled with transmagnetosonic MHD inflow on to the Kerr hole, and applied the MHD Penrose process to the problem of the individual evolution of AGNs. The result of this work is briefly reviewed in Section 3.

Recently, the BZ process was speculatively proposed again as the elementary process of the $\gamma$-ray burst (GRB, see Paczynski 1998). In this case, the rotation energy ($\sim 10^{57} J$) of the nearly maximum rotating Kerr BH of mass $\sim 10 M_\odot$ is considered to be extracted by a very strong magnetic field ($\sim 10^{11} T$) in a few seconds. The extracted Poynting energy is expected to produce the ultrarelativistic wind with the Lorentz factor $\Gamma \approx 10^2$. Of course, the ‘magnetically dominated’ assumption of the original BZ process is too simple to treat the wind acceleration, and it needs to be extended to the full MHD fly-wheel model. The fly-wheel model is still unclear, but it should be a fascinating process to unify physics of quasars and microquasars.

In this paper, the result of Nitta et al. (1991) for the individual evolution of the fly-wheel engine is applied to the statistics of an ensemble of QSOs/AGNs and compared with the observations. Fig. 1 shows the observation of the luminosity function (LF) of QSOs. Fig. 2 shows the observation of the evolution of the spatial number density of QSOs. Our attention will be focused on explaining the evolution of QSOs/AGNs in the range $0 \leq z \leq 5$ by a mechanical process.

In order to discuss the physical process of the plasma inflows and the magnetospheric structure of the Kerr BH, we assume general relativistic, stationary and axisymmetric ideal cold MHD flows. In this case, MHD equations reduce to well-known basic equations: the Bernoulli equation and the Grad±Shafranov equation (see Takahashi et al. 1990 and Nitta et al. 1991) with constants of the motion. By using these basic equations, we discuss the properties of the fly-wheel engine and apply it to the evolution of an ensemble of QSOs/AGNs in Section 4. We should note again that our primary purpose is to demonstrate the fascinating properties of the fly-wheel model and not to produce a serious model for the evolution and statistics of QSOs/AGNs.

![Figure 1. Observed luminosity function of QSOs, taken from fig. 1 of Boyle et al. (1991). QSO LF for $z < 2.9$ in a $q_0 = 0.5$ universe. The error bars are based on Poisson statistics. The dotted lines indicate the derived model fit to the data. Courtesy of the Astronomical Society of the Pacific Conference Series and one of the authors, Dr Boyle.](https://academic.oup.com/mnras/article-abstract/308/4/995/1030870/13849651030870?arrivée=13December2018)
2 COMPARISON OF FLY-WHEEL ENGINE WITH FUEL ENGINE

Here we compare the fly-wheel model with the fuel model, and clarify the differences between them. Our attention is focused on the energy source, the power output and the form of energy transfer.

The most fundamental difference is the energy source. The energy source of the fuel engine is the gravitational energy of infalling matter released through some dissipation process like α-viscosity (Shakura & Sunyaev 1973). Hence, this engine can act while accretion continues. The energy source of the fly-wheel engine is the rotation energy of the central spinning BH itself, which can be extracted through an electromagnetic process (the magnetic braking). We should note that the rotation energy of the BH is obtained at the formation stage, and is finite. Thus the lifetime of the fly-wheel engine, contrary to the fuel engine, must be finite.

![Figure 2. Observed evolution of QSO population (Shaver et al. 1996). Space densities, comoving, normalized to \( z \) for each decade of distance Simple & unified scheme](https://academic.oup.com/mnras/article-abstract/308/4/995/1030870)

The output power of the fuel engine essentially depends upon the mass accretion rate of the infalling matter, and is widely variable. The upper boundary of the power approximately corresponds to the Eddington luminosity. On the contrary, the output power of the fly-wheel engine is determined by the magnetospheric equilibrium; in a typical case, the power (\( \sim 10^{39} \text{ W} \)) for the BH mass (\( \sim 10^9 \text{ M}_\odot \)) (see the next section), and is sufficient to explain actual QSOs/AGNs.

In the fuel engine, the generated power is in a thermal form (e.g. the standard disc model) and is immediately converted to radiation from the central region. The mechanical process of the fuelling is very complicated. We need several models of the angular-momentum extraction for each decade of distance from the BH. These mechanisms must be matched consistently; however, this is very difficult.

In the fly-wheel engine, the extracted rotation energy from the BH is stored in the form of Maxwell stress of the magnetosphere. This stress causes a global electric current circuit in the magnetosphere, and a magnetocentrifugal force drives the plasma outflow, for example, the highly collimated bipolar jets in radio-loud AGNs or the equatorial wind in BAL QSOs. The kinetic energy of the plasma outflow is finally converted to radiation at some distant region through an emission process (e.g. the synchrotron radiation produced by the 1st Fermi acceleration on the shock). The mechanical process of the fly-wheel engine is simple. We can clarify it by closed discussion in the vicinity of the BH. In addition, we should note that the fly-wheel model can be a simple and unified mechanism throughout the entire magnetosphere in a range from au to kpc or Mpc.

These properties of the fuel engine and the fly-wheel engine are summarized in Table 1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Fuel</th>
<th>Fly-wheel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy source</td>
<td>Gravitational energy of accreting matter</td>
<td>Rotation energy of Kerr BH</td>
</tr>
<tr>
<td>Lifetime</td>
<td></td>
<td>Finite lifetime</td>
</tr>
<tr>
<td>Energy transfer</td>
<td>Thermarized at central region ( \Rightarrow ) radiation</td>
<td>Induces the magnetospheric stress</td>
</tr>
<tr>
<td>Applicable region</td>
<td></td>
<td>( \Rightarrow ) plasma outflow propagating toward distant region</td>
</tr>
<tr>
<td>Properties</td>
<td>Central activity</td>
<td>Central(( \sim ) au) to Distant(( \sim ) Mpc) Region</td>
</tr>
<tr>
<td></td>
<td>Needs different fuelling mechanisms for each decade of distance</td>
<td>Closed discussion around BH is possible</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simple &amp; unified scheme</td>
</tr>
</tbody>
</table>


3 EVOLUTION OF THE POWER OUTPUT FROM THE KERR BLACK HOLE MAGNETOSPHERE

In the MHD scheme, the magnetosphere near the horizon of a BH must be filled with supermagnetosonic accretion flow to keep the causality. The transmagnetosonic condition crucially restricts the magnetospheric structure.

Nitta et al. (1991) studied the magnetospheric structure of a Kerr BH filled with transmagnetosonic accretion flow. The BH magnetosphere is characterized by the coexistence of the outgoing flow and the accreting flow. In order to realize the outgoing flow and the accreting flow simultaneously, they assume a stagnation region (source region), which is sustained by the magnetocentrifugal force against the gravity. This is the source of ingoing/outgoing flows. The stagnation region may correspond to the pair-creation region near the outer gap (near the surface \( \omega = \Omega_F \), where \( \Omega_F \) is the angular velocity of the magnetosphere and \( \omega \) is...
the Lense–Thirring rotation of the inertial frame: see Hirotani & Okamoto (1998) or the disc halo. The accretion flow starts with very low poloidal velocity and accelerates towards the horizon, passing through the Alfvén point and the fast point before reaching the horizon.

In their results, it is clarified that the strong gravity of the BH causes the accretion flow and amplifies the magnetic flux, but the total magnetic flux \( \Phi_H \) and the particle number flux \( N_H \) crossing the horizon are suppressed by the rotation of the hole,

\[
\Psi_H \sim \frac{\Omega_r}{\omega_H} \Psi_0, \tag{1}
\]

where \( \Psi_0 \) denotes the total magnetic flux of the magnetosphere and \( \omega_H \) is the angular velocity of the Kerr black hole (the Lense–Thirring angular velocity at the horizon),

\[
N_H \sim \frac{B_0^2}{\mu \Omega_f \omega_H}, \tag{2}
\]

where \( B_0 \) is the magnetic field at the source region of the accretion flow and \( \mu \) is the averaged rest mass of the particles of the flow. We also find that one infalling particle can release rotation energy of the BH by the order of its rest-mass energy.

According to these results we can estimate the total power output \( L_{BH} \) from the rotating BH as

\[
L_{BH}(m, \epsilon, B_0; t) = P_0(m, B_0, \epsilon) \times \left[ \frac{t - t_{max}(m, B_0, \epsilon)}{\sqrt{1 - t/t_{evo}(m, B_0, \epsilon)}} \right] \tag{3}
\]

where \( t \) is the time after the birth of the BH, \( P_0 = m^2 B_0^2 / \epsilon \), \( \tau_{evo} = \epsilon^2 / (m B_0^2) \), \( \epsilon = m \Omega_f \) (always less than unity, see Nitta et al. 1991), and \( \theta \) is the Heaviside function \( \theta(x) = 0 \) for \( x < 0 \) and \( \theta(x) = 1 \) for \( x \geq 0 \). We should note that this formula is somewhat simplified from the original form (see equation 5.9 of Nitta et al. 1991). As this formula is derived by estimation of the order of magnitude, the formula contains unspecified factors of the order of unity. Here we assume these factors to be unity for simplicity. For the typical case, the values of \( P_0 \) and \( \epsilon \) are given as

\[
P_0 \sim 10^{39} \text{[W]} \left( \frac{\epsilon}{0.1} \right)^{-1} \left( \frac{m}{10^8 M_\odot} \right)^2 \left( \frac{B_0}{1 \text{[T]}} \right)^2, \tag{4}
\]

\[
\tau_{evo} \sim 10^8 \text{[yr]} \left( \frac{\epsilon}{0.1} \right)^2 \left( \frac{m}{10^8 M_\odot} \right)^{-1} \left( \frac{B_0}{1 \text{[T]}} \right)^{-2}. \tag{5}
\]

In this model, the initially quickly rotating BH (\( \omega_H \cong \Omega_f \)) spins down by the magnetic braking process and releases its rotation energy. When \( t = t_{max} (\omega_H = \Omega_f) \), the output power is maximum, and the engine suddenly ceases to act.

A typical sample is shown in Fig. 3 where \( L_{BH} \) is denoted as a function of the time after the BH formation. In this scheme, the extracted energy is in the form of the Poynting flux, and it will be converted to the thermal energy of the magnetospheric plasma through some dissipative process or the kinetic energy of outflows by magnetocentrifugal drive which will act outside the source region. Let us assume here that all the extracted energy converted to the radiation through some unspecified mechanism, hence the total output power should be interpreted as the bolometric luminosity. We should note that during the evolution, the BH mass \( m \) is nearly constant, because the time-scale of the mass variation is much longer than that of the angular momentum variation which determines the time-scale of evolution (see Nitta et al. 1991).

Here, the evolution of the power output of the individual Kerr BH magnetosphere has been clarified. We now try to apply this result to the statistical discussion for an ensemble of QSOs/AGNs.

It should be noted that the strength of the BZ process depends crucially on that of the magnetic field crossing the horizon. Blandford & Znajek (1977) were the first to discuss the BH fly-wheel engine, but the total magnetic flux on the horizon was a free parameter in their discussion based on the magnetically dominated limit. On the contrary, Nitta et al. (1991) used a full MHD discussion, which enabled them to obtain the magnetic flux on the horizon as a result of the inner magnetospheric equilibrium based on full MHD. The total magnetic flux of the entire magnetosphere is treated as a free parameter. This point will be discussed in Section 6.

4 APPLICATION TO STATISTICS OF QSOs/AGNs

General relativistic theory of QSO core formation is still an open question. Hence we do not have statistical properties of the parameters of QSOs/AGNs. If we assume the statistical distributions of the BH mass \( m \) (the initial mass function), the Kerr parameter \( a \) (the initial Kerr parameter function) of seed BH and the magnetic field strength \( B_0 \) at the source region (this should depend on the BH mass, the accretion rate and the dynamo theory), we can sum up the contribution of each BH over the ensemble, and can suggest the statistical properties of QSOs/AGNs by the Kerr BH fly-wheel model.

Here we will demonstrate a preliminary application of the Kerr BH fly-wheel model to QSO statistics. The discussion is based on the Press–Shechter formalism as a probable seed BH formation scenario. Sasaki & Umemura (1996) discussed an additional process, the Compton-drag scenario, for further angular momentum extraction to form the seed BH from the protogalactic cloud, and suggest the initial mass function in fig. 1 of their paper. Unfortunately, the distribution of the Kerr parameter and the magnetic field strength at the source region are not mentioned. Hence we will assume the magnetic field strength \( B_0 \) at the source region and the initial Kerr parameter \( a_{\text{BH}} \) as follows.
The magnetic field at the source region is usually estimated as $B_0 \sim 1$ (T) for $m = 10^8 M_\odot$ in order to explain typical QSO luminosity. This value probably depends on the BH mass, so we assume

$$B_0 = 1(T) \times (m/10^8 M_\odot)^{1/2}. \quad (6)$$

We also assume the initial Kerr parameter $a/m \sim 1$ (nearly the extreme Kerr BH at the initial stage) and the small parameter $\epsilon = mL_\nu \sim 0.1$. Then the power output $L_{\text{BH}}$ is the function of $m$ and $t$ (see equation 3). Thus the only one we need is the initial mass function of BHs.

### 4.1 Evolution of the luminosity function

From Sasaki & Umemura (1996) we obtain the initial mass function $f_{\text{BH}}$ of BHs based on the standard cold dark matter (CDM) model as

$$f_{\text{BH}}(m) = n + 3 \rho_0 \left[ \frac{M(m)}{M_m} \right]^{1/2}, \quad (7)$$

where

$$\nu = \left[ \frac{M(m)}{M_m} \right]^{(n+3)/6} \left( 1 + z_{\text{vir}} \right). \quad (8)$$

where $M$ is the total (dark matter + baryon) mass of the protogalactic cloud, $\rho_0$ is the present total mass density, $M_m = \rho_0 4\pi (16 \text{Mpc})^3/3$. $M$ is related with the BH mass $m$ by

$$m = r_{\text{BH}} \Omega_0 \frac{M}{M_m}, \quad (9)$$

where $\Omega_0$ is the fraction of the baryonic mass to the total mass and $r_{\text{BH}}$ is the ratio of the BH mass to the baryonic mass. We assume $\rho_0 = 6.9 \times 10^{10} [M_\odot/\text{Mpc}^3]$, $\Omega_0 = 0.05$ and $r_{\text{BH}} = 0.1$ in this paper (we adopt a cosmological model with total density $\Omega_0 = 1$ and the present Hubble constant $H_0 = 50 \text{km s}^{-1} \text{Mpc}^{-1}$).

In their paper, the BH formation epoch $z_{\text{vir}}$ is obtained via a somewhat complicated procedure. However, in a BH mass range of $10^6 M_\odot \leq m \leq 10^{10} M_\odot$, $z_{\text{vir}}$ varies in a very narrow range around $z_{\text{vir}} \sim 200$, so we neglect the mass dependence for simplicity and put $z_{\text{vir}} = 200$ throughout this paper. The resultant mass functions of BHs are shown in Fig. 4.

We can obtain the luminosity function $\Phi$ at the cosmic time $t$,

$$\Phi(m; t) = \frac{dn_{\text{BH}}(m)}{dL_{\text{BH}}(m; t)} = \left[ \frac{dn_{\text{BH}}(m)}{dm} \right] \left[ \frac{dL_{\text{BH}}(m; t)}{dL_{\text{BH}}(m; t)/dm} \right] = \left[ \frac{f_{\text{BH}}(m)}{dL_{\text{BH}}(m; t)/dm} \right], \quad (10)$$

where $n_{\text{BH}}(m)$ is the total number of BHs having a mass smaller than $m$. Usually, evolution of the luminosity function is parametrized by $z$ instead of $t$. We adopt here the Einstein–de Sitter universe as the cosmological model to relate $t$ to $z$,

$$t = t_0/(z + 1)^{3/2}, \quad (11)$$

where $t_0 \sim 10^10$ (yr) is the present time.

Here we discuss a number of examples of the dependence of the magnetic field $B_0$ at the source region on the BH mass $m$. The locus of the plasma source is supposed to be several times the horizon radius ($\sim me^{-2/3} \sim 4.5m$ for $m = 1$) where pair creation seems to be effective owing to the outer gap model (Hirotani & Okamoto 1998). The case $B_0 \propto m^{-1/2}$ ($\xi = -1/2$) is so-called the Eddington value. This formula is derived as follows. Based on spherical accretion with the Eddington accretion rate, we assume the equipartition condition of energy density between the gravitational one and the magnetic one. However, in this case, the lifetime of the fly-wheel engine is determined independently of $m$ from equation (3). We can easily imagine the evolution of the luminosity function of this case. The curve moves rightward holding its shape corresponding to the increase of output power, arrives at the explosive stage, and then all the BH engines simultaneously cease their activity. This is trivially inconsistent with observation (see Fig. 1), hence we reject this case.

The magnetic field of the inner region of the Shakura–Sunyaev’s accretion disc is evaluated as follows. They assumed the equipartition between the magnetic energy and the thermal energy. For the radiation-pressure supported case, $\xi = -1/20$ (similar to the Eddington value). This case is also unsuitable as discussed above. For the gas-pressure supported case, $\xi = -1/20$ assuming that the mass accretion rate is proportional to $m$ (like the Eddington limit). In our discussion, because the dynamic range of the BH mass $m$ is $10^6 M_\odot \leq m \leq 10^{10} M_\odot$, merely in the dynamic range of the fourth order of magnitude, the dependence $\xi = -1/20$ implies $B_0 \sim \text{const}$. Hence we can assume that the mass dependence of the magnetic field $B_0$ at the source region is presumably very weak, $-1/2 < \xi$. In the following discussion, we assume $\xi = 0$ and set $B_0 = 1$ (T) independent of $m$.

Evolution of the luminosity function is shown in Figs 5 and 6 for the typical case $\xi = 0$, $n = -0.8$. In the case $\xi = 0$, the initial luminosity is proportional to $m^2$, hence the luminosity function at the formation stage $z \sim z_{\text{vir}}$ remarkably reflects the initial mass function (see Fig. 4). The curve of the luminosity function consists of a monotonically decreasing power-law slope and an exponential cut-off.

For $\xi = 0$, the lifetime of the fly-wheel engine is a decreasing function of $m$ (see equation 3). When the BHs of mass, say,
 Evolution of luminosity function of the BH mass for $\xi = 0$ and $n = -0.8$. The brighter end of the curve lifts up for $5 > z > 2$, then it drops and shrinks for $2 > z > 0$. This tendency is consistent with observations.

4.2 Evolution of the QSO population

Similarly we can discuss the evolution of the QSO spatial number density (or more usually called the ‘population’) as a function of $z$. At time $t$, the BHs of mass $m$ with $t \leq t_{\text{vir}} + t_{\max}(m)$ are still alive. This condition gives the upper boundary $m_\text{u}(t)$ of the mass of the active BHs, because $t_{\max}(m)$ is an increasing function of $m$ in case $B_0 \propto m^0$. From the condition

$$ t_{\text{vir}} + (1 - e^2)\tau_{\text{evo}}(m) \geq t, $$

we obtain

$$ m_\text{u}(t) = \frac{e^2(1 - e^2)}{B_0^2} \frac{1}{t - t_{\text{vir}}} $$

$$ = 10^8 [M_\odot] \left(\frac{e}{0.1}\right)^2 \left(\frac{B_0}{1 \text{T}}\right)^{-2} \left(1 - e^2\right) \left(\frac{10^9 \text{yr}}{t - t_{\text{vir}}} \right). $$

Hereafter we treat only the active BHs ($m \equiv m_\text{u}(t)$).

Next we assume the detection limit $L_\text{lim}(t)$ of observation on the bolometric luminosity, and let us count the number of BHs satisfying

$$ L_{\text{BH}} \geq L_\text{lim} $$

as QSOs. Note that because we cannot discuss the spectrum of released energy, so we can treat only the total output power of the fly-wheel engine. The released energy from the fly-wheel engine produces, at first, plasma outflows, and finally, it will be converted to radiation through some physical processes like Fermi acceleration on the shock surface. Hence our attention should be focused on the bolometric luminosity under an assumption that released energy is completely converted to the radiation. Of course, actual observational segregation of QSOs from other objects is based on multicolour spectroscopy, but, unfortunately, we can only discuss the bolometric luminosity here.

Models of the functional form of $L_{\text{BH}}(t)$ will be given later. The condition (15) gives the lower boundary $m_\text{l}(t)$ of the BH mass, which can be detected as QSOs at time $t$. The relation $L_{\text{BH}}(m; t) = L_\text{lim}(t)$ reduces to an equation for $m$.

$$ B_0(m)^2 m^4 / e^2 + L_{\text{lim}}(t)^2 L_{\text{BH}}(m)^2 m / e^2 - L_{\text{BH}}(t)^2 = 0. $$

This equation can be easily solved numerically. For the case $\xi = 0$ (see equation 6), this equation can be reduced to a fourth order algebraic equation,

$$ k_1 m^4 + k_2(t) m + k_3(t) = 0, $$

increasing function of $m$. Hence, the brighter end corresponds to massive and short lifetime BHs. Massive BHs quickly evolve to the explosive stage (raising the curve at the exponential cut-off part or increasing the slope of the power-law part), and then they cease to release energy (shortening the curve).

From the observational studies of the QSOs number counting, the bending of the luminosity-function curve has been pointed out (see e.g. Boyle 1993, Pei 1995). The functional form of the curve is guessed to be double power law or power law with exponential cut-off. Boyle (1993) argued the evolutionary motion of the bending point (see fig. 2 of Boyle 1993). The result of the fly-wheel model suggests that the bending point is determined by the initial mass function and does not move during evolution.
where
\[
k_1 = B_0^4/e^2 = 10^{36} [\text{erg}^2/s^2/M_\odot^2] \left( \frac{\epsilon}{0.1} \right)^{-2} \left( \frac{B_0}{1 \text{T}} \right)^4,
\]
and
\[
k_2(t) = L_{\text{lim}}(t)^2 t B_0^2/e^2 \]
\[= L_{\text{lim}}(t)^2 \left( \frac{t}{1 \text{yr}} \right) 10^{-17} [1/\text{yr}/M_\odot] \left( \frac{\epsilon}{0.1} \right)^{-2} \left( \frac{B_0}{1 \text{T}} \right)^2,
\]
and
\[
k_3(t) = -L_{\text{lim}}(t)^2.
\]
We can obtain the unique real-positive root of this equation as \(m^*_0(t)\). Let us sum up the number of BHs in the range \(m(t) = m = m^*_0(t)\),
\[
n_{\text{QSO}}(t) = \int_{m^*_0(t)}^{m_0(t)} f_{\text{BH}}(m) \, dm.
\]
This is the spatial number density of QSOs.

The results of simple cases of \(L_{\text{lim}}(t)\) as
\[
L_{\text{lim}}(t) = 10^{38.9} \text{ [W]} \quad \text{(solid line)}
\]
and
\[
L_{\text{lim}}(t) = 10^{37.7} \text{ [W]} \quad \text{(dashed line)}
\]
are shown in Fig. 7. These values correspond to the luminosity at absolute magnitude \(M = -26\) (typical value for QSOs) and \(-23\) (typical value for AGNs), respectively.

Fig. 7 for \(n = -0.8\) shows very plausible evolution that is consistent with observations, in a qualitative sense, but the plot for \(n = -1\) (not plotted in figure) shows a rather sudden decrease after the peak (\(\zeta \approx 3\)). This is owing to the difference between these cases of evolution of the luminosity function in this range of \(\zeta\).

In the actual observation, the detection limit \(L_{\text{lim}}\) should be an increasing function of the look-back time \(t_0 - t\) or the red shift \(\zeta\), because the detection limit corresponds to the limit on the energy flux \(F\) like \(F \geq F_{\text{lim}}\). We have also tried a more realistic function of the detection limit,
\[
L_{\text{lim}}(\zeta) = F_{\text{lim}} 4\pi [\sqrt{1 + \zeta - 1}]^2 (1 + \zeta)/(H_0/c)^2,
\]
where \(F_{\text{lim}} = 6.6 \times 10^{-16} \text{ [W m}^{-2}\text{]}\) (typical magnitude \(m_{\text{lim}} = 18.9\) is the detection limit on the energy flux, \(H_0 = 50 \text{ [km s}^{-1}\text{ Mpc}^{-1}\text{]}\) is the Hubble constant at the present epoch and \(c\) is the speed of light. This is the formula of the translation of the energy flux \(F_{\text{lim}}\) to the luminosity \(L_{\text{lim}}\) based on the Einstein–de Sitter universe. The result is plotted as the dot–dashed line in Fig. 7. This value of \(F_{\text{lim}}\) is a tentative and artificial one, chosen to intersect the solid line and the dot–dashed line at \(\zeta = 2.5\).

The conversion of the detection limit on the flux \(L_{\text{lim}}\) to the limit on the bolometric magnitude \(m_{\text{lim}}\) is based on the relation
\[
m_{\text{lim}} = -2.5 \log \frac{F_{\text{lim}}}{F_0},
\]
where \(F_0 = 2.48 \times 10^{-8} \text{ [W m}^{-2}\text{]}\) (see Allen 1973). The value of the bolometric magnitude \(m_{\text{lim}} = 18.9\) adopted here might be somewhat brighter than the limit in the magnitude of actual QSO survey with a specified band of wavelength. However, we should note that the conversion (the bolometric correction) between the magnitude used in observations (e.g. the V-band magnitude \(m_V\) or the B-band magnitude \(m_B\)) and the bolometric magnitude for AGNs is not clear. Thus, it is not worth giving a detailed estimation of the detection limit on the bolometric magnitude here.

In the range with large \(\zeta\), say \(\zeta > 3\), the population of the result plotted as the dot–dashed line decreases considerably as \(\zeta\) increases, compared with the previous result (the solid line) in Fig. 7. This is as expected, because \(L_{\text{lim}}\) is an increasing function of \(\zeta\) in this case. About the dot–dashed line, in the range with small \(\zeta\), say \(\zeta < 2\), the population is overestimated, because \(L_{\text{lim}}\), which corresponds to a fixed apparent magnitude \(m_{\text{lim}} = 18.9\) in the case in Fig. 7), is too small. Such faint nuclei should not be classified as AGNs. To be more realistic, the detection limit \(L_{\text{lim}}\) should be switched from (23) to (25) at the crossing point (\(\zeta = 2.5\) in Fig. 7) of these curves as \(\zeta\) increases.

5 SUMMARY

The purpose of this work is not to present a realistic model that can precisely explain the observation, but to demonstrate properties of a fascinating mechanical model, i.e. the Kerr BH fly-wheel model, and to submit a physical scenario of the evolution of QSOs/AGNs not as a speculation, but as a result of the mechanical process.

We have proposed a magnetohydrodynamic model for the ‘engine’ of QSOs/AGNs: the Kerr BH fly-wheel model (see Section 3 of this paper and Nitta et al. 1991). This engine is driven by the rotation of the BH. The rotation energy of the BH is extracted by an electromagnetic process (magnetic braking). The extracted energy is stored in the magnetosphere in the form of Maxwell stress, and then it produces the plasma outflows.

One might be misled to thinking that the fly-wheel engine is the mechanism for radio-loud activity only, because the released energy produces the outflow. This might come from a strong impression that highly collimated bipolar jets make the double radio lobes. However, from the observational point of view, the presence of outflows are required for other kind of AGNs. For
example, it has been established that broad absorption line (BAL) QSOs also have outflows (the ‘disc wind’ nearly in the plane of the disc, see Murray et al. 1995). From the theoretical point of view, mechanics of the global structure of outflows is argued in much literature. The produced outflows show a wide variety of global structures, e.g. the bipolar jets of radio-loud QSOs/AGNs, the equatorial wind of BAL QSOs, and more (see Nitta 1994). Thus we can say that radio-loud outflows are simply one possibility of the fly-wheel engine.

In the fly-wheel model, we can clarify the properties and evolution of the individual engines (see Section 3) parametrized by BH mass \(m\), initial Kerr parameter \(a\), magnetic field \(B_0\) at the source region and a small dimension-less parameter \(\epsilon\). These engines are assumed to correspond to QSOs/AGNs. If we obtain the statistical properties for these parameters, we can discuss the statistics of an ensemble of QSOs/AGNs. Here we adopt the Press–Schechter formalism for the spatial number density with plausible behaviour of the fly-wheel model.

For simplicity, we assumed the BH formation epoch to be \( t < 1000 \) years, and \( \epsilon = 0.1 \) (the distance of the source region is several times the horizon radius). Thus the evolution depends only on the BH mass \(m\).

We have discussed the evolution of the luminosity function and the spatial number density in a period \(0 \leq z \leq 5\), and made a qualitative comparison with observations. In the typical case \(n = -0.8\) and \(\xi = 0\), we obtain the evolution of the luminosity function and the spatial number density with plausible behaviour in the period \(0 \leq z \leq 5\) that is consistent with observations. The brighter end of the luminosity function lifts up for \(z > 3\), then it drops, and the curve becomes shorter and steeper for \(0 \leq z \leq 3\) as shown in Figs 5 and 6. In accordance with this behaviour, the spatial number density evolves as shown in Fig. 7.

We should note that these characteristic evolutions obtained in this paper are derived from the evolution of the individual magnetospheric structure in the vicinity of the Kerr BH. This individual evolution is not a speculation but the result based on the MHD picture. In previous works, e.g. Pei (1995), the evolution of individual AGNs is simply an assumption without any mechanical scenario. We have tried to join the intrinsic Kerr BH magnetospheric physics, i.e. the fly-wheel model, with observational facts, and have succeeded in presenting a mechanical model of the evolution, at least qualitatively.

In order to explain the observational facts of \(0 \leq z \leq 5\), a somewhat flat mass function of BHs \((n = -0.8\) in equation 7) and a weak dependence of the magnetic field at the source region on the BH mass \((\xi > -1/2\) in equation 6) are preferred. These values of \(n\) and \(\xi\) should be determined through further physics, however, we do not have a widely accepted model for them, so we have treated them as free parameters in our picture.

6 DISCUSSION

6.1 Simplifications in our model

For simplicity, we assumed the BH formation epoch to be \(z = z_{\text{vir}} = 200\), independent of the BH mass \(m\). From the Compton-drag model (see Sasaki & Umemura 1996), the seed BH can be formed only at the epoch in which the background photon density is sufficiently high. The formation epoch should be \(z > 10^2\). Of course, in the actual case, \(z_{\text{vir}}\) will depend on \(m\). However, when we translate the redshift \(z\) to the cosmic time \(t\) by virtue of the Einstein–de Sitter model, the variation around \(z \sim 200\) corresponds to the order of \(z = 10^{5} [\text{yr}]\), and is negligible compared with the epoch around \(z = 3 \sim (10^9 \text{[yr]})\) in which we are interested. Hence, it seems reasonable to suppose that \(z_{\text{vir}} \sim \text{const}\) independent of \(m\).

We assumed the dependence of the magnetic field \(B_0\) at the source region on the BH mass \(m\) to be \(B_0 \propto m^2\). In the realistic case, \(B_0\) should depend not only on \(m\) but also on the mass accretion rate. This problem is very difficult and still open for discussion at the present time as discussed in Section 6.3. However, to discuss this large problem is beyond the scope of this paper.

We assumed the initial Kerr parameter \(a\) to be \(a/m \sim 1\). Bičák & Dvořák (1980) showed that the extreme Kerr hole does not possess a magnetic field crossing the horizon. This means that the magnetic braking process cannot extract the rotation energy from extreme Kerr holes. Hence we cannot set the initial Kerr parameter as \(a/m = 1\). However, we should note that the exact value of the initial Kerr parameter is not essential. Even if \(a/m = 0.9, 0.5\) or \(0.3\), say, the explosive epoch \(t_{\text{max}}\) is shifted by only a factor of the order of unity. Such magnitude of ambiguity does not matter in our discussion based on an order estimation.

The initial mass function or the initial Kerr parameter function of the ‘protogalactic cloud’ have been discussed in some literature (e.g. Susa, Sasaki & Tanaka 1994, Sasaki & Umemura 1996), but the general relativistic dynamical process of the BH formation from the protogalactic cloud has not been solved. The initial Kerr parameter function may not be important compared with the initial mass function as discussed in above paragraph. Hence we have obtained the initial mass function of the BH from the initial mass function of the protogalactic cloud by assuming that \(10\) per cent of the baryonic mass collapses to form the seed BH.

We assumed that the dimensionless small parameter \(\epsilon = m \Omega_0 = 0.1\) in the calculation. This value corresponds to the situation when the source region (the plasma-injection region or the pair-creation region) is located at a radius several times greater than the horizon radius \((\sim 4.6m\) for \(\epsilon = 0.1\)). This might be plausible for the outer gap model of the pair creation. The factor \(\Omega_0\) of the definition of \(\epsilon\) roughly coincides with the Keplerian angular velocity at the source region. If the locus of the plasma source is fixed at a radius several times the horizon radius from the outer gap model, \(\Omega_0\) depends only on \(m\). In the evolutionary model of Nitta et al. (1991), \(m \sim \text{const}\) during the characteristic time-scale of the angular-momentum extraction which is defined as the time-scale of the evolution. Hence we can assume that \(\Omega_0 \sim \text{const}\), thus \(\epsilon \sim \text{const}\), independent of the time.

In our model, each BH suddenly ceases to release energy at \(t = t_{\text{max}}\) corresponding to the situation \(\Omega_0 = \Omega_{\text{crit}}\). If \(\Omega_0\) of a BH magnetosphere distributes in a range, say, \(\Omega_1 < \Omega_0 < \Omega_2\) as a function of the magnetic flux function, the fly-wheel activity gradually ceases on a field line in order of decreasing value of \(\Omega_0\). If this variation of \(\Omega_0\) does not result in the variation of \(\epsilon\) in order of magnitude, it does not affect our qualitative discussion.

In order to relate the time after the formation of black holes and the redshift, we need a cosmological model. In the main
discussion of this paper, we adopt the Einstein–de Sitter model (see equation 11) for simplicity. Of course, the Einstein–de Sitter model is very classical, and recent observational studies of cosmology support the model with the cosmological constant, i.e. the Lemaître model. Here we have to estimate the difference of results between the cases with the Einstein–de Sitter model and the Lemaître model. We provide the look-back times \( t_1(z) \) and \( t_2(z) \) of the epoch with the redshift \( z \) in the Einstein–de Sitter model and the Lemaître model, respectively. If we choose the parameters \( \Omega_0 = 0.1 \) and \( \Lambda_0 = 0.9 \) in the Lemaître model, the look-back time of the black hole formation epoch \((z = 10^9)\) can be estimated as \( t_1 = 1.92 t_1 \). At the epoch \( z = 5 \) in which we are interested here, \( t_2 = 1.83 t_1 \). These differences are simply by a factor of the order of unity. Hence the difference of the results between these two cosmological models does not matter in our discussion because the evolutionary process of our discussion (see Section 3) is based on an order estimation.

6.2 Two types of BH engines

In this paper, our attention is focused on the fly-wheel model. However, BH–accretion disc systems also seem to include another type of engine: the fuel (accretion-powered) engine. The elementary process of the fuel engine is the release of the gravitational energy of the accreting matter, so the activity strongly depends on the mass accretion rate. It is widely believed that the accretion rate is roughly determined by the Eddington limit. This idea is based on a speculation that the regulating stage of the entire accretion process is the final stage, i.e. the accretion onto the BH. However, we do not have any theoretical evidence of how the entire system (i.e. a galaxy) determines the accretion rate. In other words, how the system can remove the angular momentum of the accreting matter resulting in such an accretion rate.

In order to determine the activity of the fuel engine, we must solve the extraction of the angular momentum in a very wide spatial range. If we want to obtain the accretion rate of a range from an angular-momentum-extraction mechanism, we need the accretion rate outside this region where another mechanism may regulate the accretion rate, and so on. This endless chain seems hopelessly difficult to solve completely. Thus, it is so difficult to assemble the angular-momentum-extraction mechanisms of each range into a consistent theory that we have no other way except to treat the final accretion rate on to the BH as a free parameter. This is the point of difficulty in making an evolutionary scenario of QSOs/AGNs based on the fuel model.

In the model adopted in this paper, we do not consider the activity of the fuel engine at all. However, the author believes that coexistence of these two types of engines is indisputable. Even after the fly-wheel engine ceases to release energy, the fuel engine continues to act while the accretion is continued. If we make an appropriate assumption to estimate the luminosity owing to the fuel engine, we should add the contribution of the fuel engine. For simplicity, if we assume a constant energy release of the fuel engine, i.e. the Eddington luminosity (depends only on \( m \)), this luminosity is comparable with the initial luminosity of the fly-wheel engine. In this model, the fuel engine works constantly and the fly-wheel engine works in a period \( t_{\text{max}} \) after the BH formation. Even after the fly-wheel engine dies, the luminosity does not vanish, but decreases to the Eddington luminosity.

In Section 2, the fly-wheel model is characterized by the fact that its mechanism can be clarified by the closed discussion in the vicinity of the BH. However, this statement might be somewhat of an exaggeration. The fly-wheel engine seems to be related to the fuel model at the point at which the magnetic field \( B_0 \) at the source region may depend on the accretion rate, \( B_0 \) is provided as the magnetic field strength averaged on a larger macroscopic scale than the scale of turbulence generated in the accretion disc. Such a large-scale magnetic field should be amplified by the accretion. The accretion plasma carries the frozen magnetic field into the inner magnetosphere and compresses it. Against this process, small but finite resistivity dissipates the magnetic field. Then the saturated level of the magnetic field strength is determined by the equilibrium of the compression and the dissipation. Unfortunately, this problem has not been solved yet as discussed in the next section. Hence we have assumed that \( B_0 \) depends on the BH mass \( m \) like equation (6) because the accretion rate seems to depend on \( m \).

6.3 Ambiguity of the fly-wheel power estimation

Ambiguities still remain about the estimation of the power of the fly-wheel activity mainly owing to the following two reasons. The first is that there are some theoretical ambiguities about the estimation of the magnetic field strength near the BH. The second is the ambiguity of the innermost magnetospheric structure of the BH–accretion disc systems, especially about whether the field lines crossing the horizon (or the innermost region of the accretion disc) are open towards infinity or closed loop-like ones.

The poloidal magnetic field strength is traditionally estimated by an intuition of a principle of equipartition between the magnetic energy density and the gravitational one or the thermal one (see e.g. Shakura & Sunyaev 1973). Recent numerical studies based on the non-linear evolutionary process of the resistive MHD seem to support the result from the equipartition. For example, Matsumoto et al. (1997) conclude that the predominantly toroidal magnetic field is amplified by a differential rotation of the disc and the plasma \( \beta \)-value of \( \beta \approx 10 \) can be achieved. If there is significant magnitude of the poloidal magnetic field, the saturation level will be larger and \( \beta \approx 1 \) might be achieved.

While this conjecture of equipartition is now widely accepted, there is still room for disagreement about this point. Recently Livio, Ogilvie & Pringle (1999) critically assessed the efficiency of the Blandford–Znajek (BZ) process (the magnetically dominated case of the BH fly-wheel model) compared with other disc activities. They re-consider the field strength in the innermost region of BH–disc system. In their result, the power of the BZ process is dominated by the fly-wheel or the fuel (viscous heating) power of the innermost region of the accretion disc. The problem of the saturated strength of the poloidal magnetic field is still an open question.

However, we should note that the energetics of the fly-wheel process depend not only on the strength of the magnetic field but also on the inner magnetospheric structure of the BH–disc systems. The extracted Poynting energy flux resulting from the fly-wheel process is carried along the poloidal magnetic field lines, and will be converted to the kinetic energy of plasma outflow at some distant region from the horizon. Hence, only open magnetic field lines can take place in the energy extraction towards very distant regions. For example, Nitta et al. (1991) give a schematic figure for the innermost magnetospheric structure (see fig. 3 of that paper). In their result, the magnetic field lines
connecting to the innermost region of the disc are closed (a loop-like structure connecting the BH and the disc), and do not contribute to the energy extraction. Open field lines emanate from a high-latitude region of the BH and the outer part of the disc. In this case, the discussion of Livio et al. (1999) should be altered.

Thus, efficiency of the fly-wheel process is closely combined with the disc dynamo process and the magnetospheric structure of the innermost region. These are very important but still open questions in the current state, and to argue this point would take us too far from the purpose of this paper.

6.4 Discrimination of QSOs

As discussed in Section 4, in the fly-wheel model, we can only estimate the total output power of the engine, and we cannot discuss the spectrum of resultant radiation. Hence the only way to distinguish QSOs/AGNs from normal galaxies is to set a criterion, say $L_{\text{lim}}$, on the bolometric luminosity. Here we suppose that the entire released energy is perfectly converted to radiation, and assume that the engines that have luminosity greater than $L_{\text{lim}}$ can be treated as QSOs/AGNs. This simplified procedure is obviously far from the actual QSO number-counting studies. In future studies, the problem of the resultant spectrum of the radiation should be solved. This is possible only if we solve the physics of plasma outflows being generated by the fly-wheel engine. This is, needless to say, one of the most difficult open questions in the magnetospheric astrophysics.

From Fig. 7, the locus of the peak of population strongly depends on the criterion $L_{\text{lim}}$. If we set a smaller $L_{\text{lim}}$, the peak shifts to a smaller $z$. This means that if we survey AGNs in deeper, we will find more and more faint AGNs including low-mass BHs. These may correspond to Seyferts. However, we should note if the mass of the central BH is too small, the nucleus activity is dominated by its host galaxy. Such objects may not be classified as QSOs/AGNs. In this meaning, the criterion $L_{\text{lim}} = 10^{38.9}$ or $10^{38.7}$ [W] adopted in this paper might be plausible, because these values dominate the typical luminosity of normal galaxies $10^{37}$ [W] (Andromeda galaxy).

6.5 Similarity of radio-loud and radio-quiet AGNs

Similarity between all kinds of AGNs is widely accepted from the observational point of view. The spectral energy distribution (SED) of radio-loud AGNs and radio-quiet AGNs are quite similar except for the radio range (see e.g. Elvis et al. 1994). We also cannot find any intrinsic difference in the evolution of the spatial number density of the optically selected QSOs, the flat and steep spectrum sources and radio-loud QSOs (see Shaver et al. 1996). These observational evidences of similarity implicitly suggest the universality of physical process of QSOs/AGNs.

As mentioned in Section 5, the author believes that the fly-wheel model is applicable not only for radio-loud AGNs. The variation of AGNs might be caused from the variation of proper parameters (BH mass, BH angular velocity, magnetic field strength, etc.). The difference of parameters will lead to different structures of outflows (see Nitta 1994). We may expect that outflows having different structures will produce different types of spectrum of the radiation. However, the correspondence between the global structure of the outflow and a resultant spectrum of radiation is still unclear. This is a problem for future research.

6.6 Other scenarios of the fly-wheel activity

There are other scenarios that make the Kerr BH the central BH of QSOs/AGNs. Here we mention two of them: the merging of BHs and the spin ups by accretion.

Wilson & Colbert (1995) discussed the formation of AGN BHs by a merging process. They tried to explain the difference between radio-loud and radio-quiet AGNs. As is well known, the number fraction of radio-loud AGNs is only 10 per cent of the total AGNs, and radio-loud galaxies are mainly observed as elliptical galaxies. From these points, they supposed that radio-loud AGNs are merger events of BHs. The merging of two galactic nuclei produces a quickly rotating Kerr BH, and a period after merging, the Blandford–Znajek process acts and shows radio-loud activity. Similarly, Moderski & Sikora (1996) hypothesized making a rapidly rotating BH by very large mass accretion.

The scenarios discussed in these papers are alternative ones. Another possibility is that the fraction of radio-loud to radio-quiet AGNs may be related to the probability of making jet-like outflow. The fly-wheel engine can form various structures of outflows (see Nitta 1994). If well-collimated jet-like structure which is nearly perpendicular to the galactic disc is formed, this will be observed as a radio-loud AGN (or radio galaxy, see Urry & Padovani 1995), because the terminal shock in the jet will be located far from the galactic disc owing to very low ambient matter density in this direction. If equatorial wind is formed, this will be BAL QSO (see, e.g., Cohen et al. 1995 or Murray et al. 1995). Of course, these are simply speculations, because we do not have widely accepted physics for the structure formation of plasma outflows yet. Anyway, as we do not have an authorized theory, we must try to test the various possibilities.

In some literature, the fuel process (accretion from disc) and the fly-wheel process (Blandford–Znajek process) are simultaneously considered (see, for example, Moderski & Sikora 1996 and Ghosh & Abramowicz 1997). In these models, the accretion contributes to spin up the BH, but the BZ process suppresses it. On the contrary, Nitta et al. (1991) imply that MHD accretion on to the Kerr BH extracts the angular momentum and spins down the rotation of the Kerr BH when $\Omega_0 < \Omega_{\text{crit}}$ (see Section 3). This is a natural result of MHD accretion on to the Kerr BH (see Takahashi et al. 1990).

One might think that they are contrary to each other. However, the author does not think so. Moderski & Sikora (1996) and Ghosh & Abramowicz (1997) start with a slowly rotating BH ($\Omega_{\text{f}} > \Omega_{\text{crit}}$); on the contrary, Nitta et al. (1991) assumes a quickly rotating BH ($\Omega_{\text{f}} \ll \Omega_{\text{crit}}$). This difference comes from the difference in the concepts of the models. However, we should note that this difference is essential.

In our model, the energy source of the Kerr BH fly-wheel engine is inherently obtained from the rotation energy of the central BH. The origin of this energy is the tidal interaction during the collapse of the protogalactic cloud with other density fluctuations. Once the fly-wheel engine starts to act, the rotation energy monotonically decreases, and stops at the state $\Omega_{\text{f}} = \Omega_{\text{crit}}$.

On the other hand, in other models, accretion energy converts to the fly-wheel type activity, and they relate to the radio-loud activity. For example, the central BH is normally in a state of slow rotation; however, if coalescence of BHs (Wilson & Colbert 1995) or very large mass accretion (Moderski & Sikora 1996) occurs, the central BH spins up and the fly-wheel engine starts to wok. In these models, the energy source is, consequently, the accretion energy.

6.7 Dormant quasar: Fornax A

Let us notice a splendid example, Fornax A (NGC 1316, see Iyomoto et al. 1998), which seems clearly to show properties of the fly-wheel engine. In general, we cannot observe the evolution of a galaxy because of its very long lifetime; however, Fornax A is a particular case in which we can obtain evidence of the evolution for the last 0.1 Gyr. This is a radio galaxy with double radio lobes. The nucleus should be active (> $4 \times 10^{34}$ [W] in 2–10 keV X-ray luminosity) at least 0.1 Gyr ago, while the present activity is ‘dormant’ ($2 \times 10^{33}$ [W] in 2–10 keV X-ray luminosity).

We can guess the reason for this based on the fly-wheel model as follows. The fly-wheel engine was still active 0.1 Gyr ago, and the nucleus ejected plasma outflows (bipolar jets) and made the radio lobes. At an epoch within the past 0.1 Gyr, the fly-wheel engine ceased to work and the nucleus became dormant. The radio lobe can emit radiation within a period determined by the Synchrotron cooling time without the energy supply from the fly-wheel engine. In this sense, the fly-wheel engine of Fornax A is not a ‘dormant’ one but a ‘dead’ one, if it is without some mechanisms to spin up the central BH again. However, the fuel engine can act after the fly-wheel activity ceases. This corresponds to the present nucleus activity. In this case, the peak fly-wheel activity is an order of magnitude greater than the fuel activity. This is a result from our model with $\epsilon \sim 0.1$.

ACKNOWLEDGMENTS

The author wishes to thank Drs K. Aoki, K. Okoshi, S. Satoh, S. Kameno, T. M. Yamamoto and T. Totani, and Mr Y. Tutui at National Astronomical Observatory of Japan for their helpful comments and criticisms. The author also thanks the anonymous referee for comprehensive comments on possible improvements.

REFERENCES

Nitta S., 1994, PASJ, 46, 217
Schmidt M., Schneider D. P., Gunn J. E., 1995, AJ, 110, 60
Tanaka Y. et al., 1995, Nat, 375, 659

This paper has been typeset from a \TeX/La\TeX file prepared by the author.