On Black Hole Spins and Dichotomy of Quasars

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Abstract: Most quasars are known to be radio quiet and according to the “spin paradigm”, which connects their radio-loudness with the value of the black hole spin, they must harbor very slowly rotating black holes. On the other hand, quasars are powered by accretion which tends to increase the spin of the black hole. We show that the Blandford-Znajek mechanism is not efficient enough to counteract the spinning up of black holes by an accretion disk, regardless of the accretion rate. We establish conditions under which it is possible to obtain low values of the black hole spin, in the scenario involving a sequence of many accretion events with random angular momenta. Our results are used to select possible evolutionary scenarios which can explain radio bimodality of quasars in terms of the “spin paradigm”.

1 Introduction

One of the most intriguing properties of quasars is the large range and bimodal distribution of their radio-loudness. Quasars can approximately be divided into two classes: radio-loud (RL) quasars and radio-quiet (RQ) quasars, with the RL-quasars having the ratio of their radio to optical fluxes $F_{5\text{GHz}}/F_{\text{B}} \geq 10$ (Kellerman 1989). RL objects are rather rare (they consist only about 10% of the AGN population) and they almost always reside in elliptical galaxies. Despite the differences in radio-loudness, the optical and ultraviolet spectra of RL and RQ objects look very similar (Francis et al. 1993; Zheng et al. 1997). Since the optical-UV radiation is produced by accretion flows, the above indicates that accretion conditions do not differ significantly in these two classes of quasars. This supports the idea that the parameter which determines the power of jets and radio-loudness of quasars is the black hole spin (Blandford 1990). This, so called ‘spin paradigm’, is supported by recent calculations of parameters of Galactic ‘micro-quasars’. Considering the thermal emission and frequency of quasi-periodic oscillations in X-ray binaries,
Zhang et al. (1997) have found that galactic sources with strong jet activities harbour fast-rotating black holes. The spin paradigm seems to be in odds with the interpretation of broad red wings of fluorescent iron line in RQ Seyfert galaxies in terms of reflection model in the Kerr metric (Iwasawa et al. 1996). However, as was recently shown by Reynolds & Begelman (1997), the “Kerr” profiles of the Fe Kα line can be mimicked by radiation scattered by the matter contained in the region between the marginally stable orbit and the horizon of a non-rotating black hole.

The main purpose of this paper is to verify the basic assumption of the “spin paradigm”, which is that the population of quasars on the whole is dominated by objects with low spin black holes. We investigate whether such an assumption can be reconciled with any reasonable evolutionary scenario of super-massive black holes.

2 Equilibrium Spin

We assume simple Kerr geometry in which a black hole in expressed in the terms of its energy-mass, $M$, and angular momentum, $J$. Evolution of the black hole is described by the set of equations (Moderski & Sikora 1996a):

$$c^2 \frac{dM}{dt} = e_{in} \dot{M} - P, \quad (1)$$

$$\frac{dJ}{dt} = j_{in} \dot{M} - \frac{P}{\Omega_F}, \quad (2)$$

$$P \approx \frac{1}{8} \frac{B^2 r_h^4}{c} \Omega_F (\Omega_h - \Omega_F), \quad (3)$$

where $\dot{M} \equiv dM/dt$ is the accretion rate, $e_{in}$ and $j_{in}$ are specific energy and angular momentum of matter at inner edge of the accretion disc, $P$ is the power extracted by the Blandford–Znajek (B-Z) mechanism, $\Omega_F$ is the angular velocity of the magnetic field lines threading the horizon, $\Omega_h$ is the angular velocity of a black hole, and $B$ is the intensity of the magnetic field on the horizon.

Using dimensionless units: $A = cJ/GM^2 \equiv J/J_{max}$, $\tilde{j}_{in} = c j_{in}/GM$, $\tilde{e}_{in} = e_{in}/c^2$ and $\tilde{\Omega} = GM\Omega/c^3$, and noting that $\tilde{\Omega}_h = A/(2r_h)$, we rewrite Eqs. (1), (2) and (3) as

$$\frac{dA}{dt} = \frac{1}{Mc^2} \left( \dot{\mathcal{M}} c^2 (\tilde{j}_{in} - 2A\tilde{e}_{in}) - P \left( \frac{2r_h}{kA} - 2A \right) \right), \quad (4)$$

$$\frac{d\ln M}{dt} = \frac{1}{Mc^2} (\dot{\mathcal{M}} \tilde{e}_{in} - P), \quad (5)$$

$$P \approx \frac{k(k-1)}{32} \frac{G^2}{c^3} A^2 r_h^2 B^2 M^2, \quad (6)$$

where $k = \Omega_F/\Omega_h$. Assuming that the pressure of the black hole magnetic field, $B^2/8\pi$ is balanced by the ram pressure of the innermost parts of an accretion flow,
we obtain
\[ P = \frac{\pi}{4} k(k - 1) \frac{Gm_p c}{\sigma_T} \dot{m} A^2 M = \frac{k(k - 1)}{16} A^2 \dot{m} L_{Edd}, \] (8)

where \( \dot{m} = \dot{M} c^2 / L_{Edd} \), and \( L_{Edd} = 4\pi Gm_p c M / \sigma_T \).

From Eqs. (4) and (8) one can calculate the equilibrium spin \( A_{eq} \) for which \( dA / dt = 0 \). This spin does not depend on accretion rate, and for the maximum efficiency of the B-Z mechanism, i.e. for \( k = 1/2, \ A_{eq} = 0.997 \). Because this value is so high evolution of a black hole for any \( A < 0.9 \) is very well approximated by equation
\[
\frac{dA}{d\ln M} = \frac{(\dot{j}_{in} - 2A \bar{\epsilon}_{in})}{\bar{\epsilon}_{in}}
\] (9)

which is obtained by dividing Eq. (4) over Eq. (5) and assuming \( P = 0 \). Eq. (9) has analytical solution for \( r_{in} = r_{ms} \) (Bardeen 1970) and for \( r_{in} = r_{mb} \) (Abramowicz & Lasota 1980, Moderski & Sikora 1996b), where \( r_{ms} \) is the marginally stable orbit and \( r_{mb} \) is the marginally bound orbit. In particular, it can be shown that initially nonrotating black hole with mass \( M_0 \), after accreting \( \Delta m \) from the disk, will be spun-up to \( A \sim \Delta m / M_0 \). This shows that only those super-massive black holes which accrete from the disk much less than their initial mass can avoid spinning up to high values of \( A \).

3 Switching Between Pro- and Retrograde Accretion Discs

Matter, accreting from the disc which rotates in the opposite direction than the black hole, carries negative angular momentum and reduces the spin of the black hole. We call such a process a ‘retrograde accretion’. This process was shown by Moderski & Sikora (1996b) to be very a efficient mechanism of spinning down a black hole. It suffices to accrete \( \sim 0.2 \) of the initial black hole mass, \( M_0 \), to decelerate the black hole from its maximum spin, \( A_{max} = 1 \), to zero.

Of course, an accretion of larger amount of matter than \( 0.2M_0 \) will spin-up a black hole again, and in order to maintain the low value of the time-averaged spin, the evolution of a black hole must be governed by many “small” (\( \delta m \ll M_0 \)) accretion events. This case is illustrated in Fig. 1, where we show the evolution of the black hole spin for \( \delta m = 0.01M_0 \). The evolution illustrated on this Figure was obtained neglecting the B-Z mechanism, with an assumption that accreting matter forms geometrically thin disc, and that the angular momentum of the disc is randomly switched between two opposite directions.

Fig. 1 shows that after the phase of deceleration, the spin of a black hole fluctuates around zero. We also checked behavior of the population of black holes evolving from the \( A_0 = 1 \) by performing a number of ‘numerical evolutions’ for various \( \delta m \). We have found that the final average spin in the population does not depend on \( \delta m \) but only on the total accreted mass. The average spin of the
Fig. 1. Example of the evolution of the black hole’s spin. Black hole evolves from the maximally rotating state and accretes each time a portion 0.01 of its initial mass.

Fig. 2. Average spin and spread in the population of black hole evolving from $A_0 = 1$ as a function of accreted mass. Average spin is marked with solid line while $1\sigma$ standard deviation in distribution (assuming Gaussian shape) is marked as dotted, dashed and long dashed lines for $\delta m = 0.001, 0.01$ and $0.1M_0$ respectively. Only $+1\sigma$ contours are plotted.

population and standard deviation of the distribution are plotted versus total accreted mass in Fig. 2. Note that results presented in Fig. 1 and 2 hardly depend on the B-Z mechanism, because, as shown in §2, this mechanism is dynamically efficient only for $A \sim 1$.

4 Discussion

The fact that the equilibrium spin of a black hole is very close to the maximal value and does not depend on the accretion rate, implies that evolution of black holes with $A < 0.9$ is strongly dominated by accretion. Taking this into account, and assuming that radio-loudness of quasars is related to the black hole spin, we discuss two possible accretion history scenarios which can eventually lead to the observed radio dichotomy of quasars. The first one (model ‘A’) is based on the assumption that during the entire history of a given quasar, the direction of the rotation of its accretion disk remains constant. The observed excess of RQ-quasars over RL-quasars can then be explained in terms of the spin paradigm only if the quasar population is dominated by objects containing a low spin black hole. Thus, a majority of black holes must be initially formed with a very low spin and the amount of matter accreted from the disk must be much smaller than the initial
mass of the black hole. The second scenario (model ‘B’) is based on the assumption that the history of a quasar can be described by a sequence of accretion events with randomly oriented angular momentum vectors. In this case black holes can be formed with high spin, provided that after their formation, they accrete enough amount of matter to be slowed down to a low spin value.

To quantify the above constraints, we estimate a value of the black hole spin, $A_c$, which corresponds to the radio-to-optical flux ratio $F_{5\text{GHz}}/F_B \sim 10$ dividing quasars into the RL and RQ objects. Assuming that the fraction of jet power converted to radiation is 10%, and that bolometric correction for jet radiation at $\nu_R \sim 5$ GHz is of the same order as that for the accretion disk radiation in the B-band, and noting that $\nu_R/\nu_B \sim 10^{-5}$, we find that $F_R/F_B \sim 10$ corresponds to $P/L_d \sim 10^{-3}$, where $L_d$ is the bolometric luminosity of the accretion disk. Dividing $P$ given by Eq. (8) by $L_d = (1 - \tilde{e}_{in})\dot{M}c^2$, we find

$$\frac{P}{L_d} \approx \frac{k(1 - k)}{16} \frac{A^2}{(1 - \tilde{e}_{in})},$$

and, therefore,

$$A_c \approx \sqrt{16 \times 10^{-3}(1 - \tilde{e}_{in}) k(1 - k)}.$$  \hspace{1cm} (11)

For the maximum efficiency of the Blandford-Znajek mechanism, i.e. $k = 1/2$, and for radiation efficiency of a disk $(1 - \tilde{e}_{in}) \sim 0.1$, Eq. (11) gives $A_c \approx 0.1$.

For $A_c \approx 0.1$, the model ‘A’ is viable provided that 90% of quasars are born with $A < 0.1$ and that the mass of the matter accreted from the disk is less than 0.1 of the initial mass of the black hole. The RL-quasars can therefore be the objects where:

(a) - a black hole is already formed with the high ($A > A_c$) spin, and/or
(b) - a black hole accreted from the disk more than 10% of its initial mass, and/or
(c) - a black hole coalesces with another black hole having a comparable mass.

Depending on whether the supermassive black holes are formed mostly from the gas cloud or from stellar cluster they may acquire higher or lower initial spin. In the giant ellipticals, where formation of the nucleus is much faster and presumably involves larger amounts of gas than in spirals, the growth of a black hole can be dominated by a collapse of a gas cloud. A formation of a black hole from a gas cloud is most likely accompanied by a formation of a massive disk. High accretion rate from such a disk can well support strong magnetic fields in rapidly rotating black holes and, together with a jet powered by the rotating black hole, it can create the phenomenon of the RL-quasars. This high accretion phase is limited by the amount of matter left in the disk after the black hole formation process, and later, when the accretion rate drops, an advection dominated disk can be formed (Rees et al. 1982, Narayan & Yi 1995, Abramowicz et al. 1995). In such a disk, the radiation efficiency is very low, and since the spin of the black hole does not change, the radioludness, $P/L_d$, reaches very high values. These objects are good candidates for FRI radiogalaxies.
If all black holes are formed with low spin, the option (b) or (c) applies. In this case about 10% of black holes must be spun-up in later evolutionary phases. High values of a spin can be reached by a coalescence of supermassive black holes, as proposed by Wilson & Colbert (1995), or by accretion of more than 100% of their initial mass from the disk. These two scenarios are expected to follow a merger of two galaxies, at least one of them gas rich. The total mass accreted during $10^8$ years (what is a typical life-time of RL-quasars deduced from the radio spectra) with the rate $10^8 M_{\odot}$ yr$^{-1}$ (required to produce observed UV luminosities) is enough to spin-up black holes with masses $\leq 10^9 M_{\odot}$ up to $A \sim 1$.

For the model ‘B’, black holes can be spun-down and maintained with a low value of a spin by an accretion disk which changes direction of the rotation. Thus, the population of quasars can be dominated by objects containing black holes with a spin $A < A_c$, even if their initial spin is high. However, as one can deduce from Fig. 2, the total accreted mass, required to spin-down a black hole to $A < A_c \simeq 0.1$, is $> 1 M_0$, and number of accretion events required to maintain a low spin is larger than 100. Such accretion events may be due to matter delivered to the very central region by molecular clouds. Spinning down the black hole can also be provided by capturing black holes with masses $10^6 M_{\odot}$, which are predicted to be formed in recombination era due to Jeans instability of the primary condensations (Loeb 1993). In the model ‘B’, the RL-quasar phenomenon can be related to coalescence of black holes and/or to giant accretion events induced by galaxy mergers (as in the model ‘A’), as well as to the formation of black holes with high initial spin.

The above considerations have implications on the range of radio-loudness of RL-quasars. For $0.1 \leq A < 1$ and for the maximum efficiency of the B-Z mechanism, the ratio $P/L_d$ spans the range $10^{-3} - 10^{-1}$, which corresponds to the range of the radio-to-optical flux ratio $10 - 10^3$ covered by most RL-quasars (Bischof and Becker 1997). There is, however, a number of RL-quasars with the radio-to-optical flux ratio corresponding to $0.1 < P/L_d \simeq 1$, and such high radio-loudnesses require super-Eddington accretion rates, with $\dot{m}$ in the range $10 - 100$ (note that for super-Eddington accretion rates $L_d \simeq \text{const} = L_{\text{Edd}}$ and, therefore $P/L_d \propto \dot{m}$). Somewhat smaller $\dot{m}$ is allowed, if one takes into account that for quasars with the highest ratio $L_R/L_B$, the intrinsic value of $L_B$ is higher than observed due to the extinction in the quasar (Baker 1997).

Finally, we would like to emphasize that basic constraints on accretion history of quasars, imposed by the assumption that the radioloudness is scaled by the square of the black hole spin, depend on how strong is the magnetic field of the black hole that can be supported by an accretion flow. Unfortunately, this problem has not yet been solved. In this paper, we assumed that the maximum magnetic field is limited by the ram pressure of accretion flow very closely to the horizon. This leads to a higher value of $A_{eq}$ than in the case when the magnetic pressure is balanced by radiation or gas pressure in the disk (Moderski & Sikora 1996a; 1997). However, for radiation pressure dominated disks, the equilibrium spin $A_{eq} > 0.1$ and our main conclusions remain the same.

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