Radio Bimodality: Spin, Accretion Mode, or Both?

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A new scenario is suggested to explain a large diversity of the AGN radio properties and their dependence on the galaxy morphology. The scenario is based on the assumption that the growth of supermassive BHs is dominated by the accretion only during the quasar (high accretion rate) phase, otherwise - by mergers with less massive black holes. Following that, BHs are expected to spin much faster in giant ellipticals than in disk galaxies. Within the frame of the spin paradigm this explains the observed relation of the radio-dichotomy with the galaxy morphology. Various theoretical and observational aspects of such a dichotomy are discussed. In particular, the issue of the intermittency and suppression of a jet production at high accretion rates is addressed and a scenario for production of powerful, extended radio sources is drafted.

1 Introduction

Diversity of radio sources associated with AGNs is mainly manifested by a very broad range of radio luminosities $L_R$ and morphology. The most luminous are radio sources powered by AGNs hosted by giant ellipticals (Xu, Livio & Baum 1999). In terms of the radio-to-optical luminosity ratio, $R \propto L_R/L_O$, they are by 2-3 orders radio louder than the most radio luminous AGNs hosted by disk galaxies. This difference holds for a full range of the Eddington-ratio, $\lambda \equiv L_{bol}/L_{EDD}$. Despite such a big difference, maximal radio luminosities of both populations show similar dependence on $\lambda$. Those increase with $\lambda$ but slower than linearly, which implies the opposite dependence of the radio-loudness on $\lambda$, i.e. $R$ increases with decreasing $\lambda$ (Sikora, Stawarz, & Lasota 2007 [SSL07]). While the dependence on $\lambda$ is most likely related to the accretion rate, there must be an additional parameter which has the effect on the jet production efficiency and is correlated with the galaxy morphology. SSL07 postulated that it is the black hole spin. However for this, the two basic questions must be answered: (1) how the cosmological evolution could lead to a black hole spin distribution weighted to much larger spin values in giant elliptical galaxies than in disk galaxies; (2) why most quasars and other high accretion rate AGNs are radio-quiet even if hosting fast spinning black holes. These issues are the topics of sections §2 and §3, respectively, and the work is summarized in §4.

2 Spin vs. galaxy morphology

In order to have the galaxy morphology-related spin bimodality, SSL07 and Volonteri, Sikora & Lasota (2007) proposed the following scenario. They assumed that the growth of the AGN black holes is dominated by accretion: in quasars — by very massive events triggered by major mergers of gas rich galaxies, in AGNs hosted by the disk galaxies — by multi-accretion events with random angular momentum orientation and very small mass portions. They must be smaller than

$$m_{\text{align}} \simeq \xi a \left( \frac{r_g}{r_w} \right) M_{\text{BH}} \sim 10^{-3} \left( \frac{\xi}{0.1} \right) \left( \frac{a}{0.1} \right) \frac{M_{\text{BH}}}{\sqrt{r_w/10 r_g}},$$

which is the minimal mass of the accretion event leading to the alignment of the black hole spin with the angular momentum of the outer portions of an accretion disk, $r_g = G M_{\text{BH}}/c^2$ is the gravitational radius, $r_w$ is the warp radius, $a \equiv J_{\text{BH}}/J_{\text{BH,max}} = c J_{\text{BH}}/GM_{\text{BH}}^2$ is the dimensionless BH spin, $J_{\text{BH}}$ is the BH angular momentum, $M_{\text{BH}}$ is the BH mass, and $\xi \equiv \nu_2/\nu_1$ where $\nu_1$ and $\nu_2$ are viscosities related to the 'planar' and 'vertical' shear, respectively (Papaloizou & Pringle 1983). Only for the accretion events with masses $m_{\text{acc}} < m_{\text{align}}$ the counter-rotating accretion disks avoid a flip to the co-rotating ones, and significantly smaller $m_{\text{acc}}$ is required in order to balance the rate of counter-rotating and co-rotating events — the condition needed to prevent growing BHs against gaining large spins (King et al. 2005; Volonteri et al. 2007). However, such a condition is very difficult to satisfy because accretion disks in AGNs extend at least up to the broad emission line region and their masses are larger than $m_{\text{align}}$ (but $\ll M_{\text{BH}}$). Furthermore, it is observed in some Seyfert galaxies that kiloparsec scale jets are often bent (Gallimore et al. 2006). If these jet bends are caused by the BH-disk alignment process, this also implies $m_{\text{acc}} \geq m_{\text{align}}$.

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No such difficulties arise if one assumes that the growth of BHs in the disk galaxies is dominated by capturing BHs sinking to the center following mergers of a disk galaxy with dwarf satellite galaxies (Hughes & Blandford 2003; Kendall, Magorrian & Pringle 2003). During such minor mergers, tidal forces from satellite galaxies are too weak to induce the inflow of the gas to the center. The satellite galaxies are stripped of the gas and enter the center from random directions. The process is finalized by a dry minor merger of two very unequal-mass BHs and the sequence of such mergers cause the growth of the BH with a low spin. Cosmological evolution of BHs dominated by the dry BH mergers was simulated by Volonteri (2007) and Berti & Volonteri (2008). They derived much shallower distribution of BH spins than predicted by Hughes & Blandford (2003). The reason is that time scale of dynamical friction which drives the low mass satellite galaxies and their BHs toward the center of the more massive companion is very long and therefore major mergers are initially dominant. However, noting that up to masses $2 \times 10^6 M_\odot$ the BH growth can be dominated by accretion of tidally disrupted stars (Milosavljević, Merritt & Ho 2006), the spin distribution weighted to low values is very likely.

It is worth noting here that significant contribution of BH mergers to the BH mass content of the local Universe is rejected by most AGN-BH evolution models. This is primary because several studies based on the Soltan’s type of argument (Soltan 1982) have shown that in order to reconcile an amount of energy radiated by quasars per co-moving volume with a mass density of BHs in the local universe requires very efficient radiation even if assuming that the BH growth is totally dominated by the accretion (see Wang et al. 2006 and refs. therein). However, the newest results obtained by Shankar, Weinberg & Miralda-Escudé (2007) and Merloni & Heinz (2008) suggest the lower energy requirements. Assuming that the BH growth is strongly dominated by accretion, they found that radiation efficiency is consistent with non-rotating BHs. But these same results can be interpreted in terms of the model where quasars radiate with efficiency corresponding with the fast rotating black holes provided the BH growth in the pre-quasar phase is significantly contributed by BH mergers (Cao & Li 2008). Such an interpretation is fully consistent with the scenario proposed above.

3 Jet activity in the high accretion rate regime

3.1 Intermittency

It has been proposed that there is an analogy between the jet production in X-ray binaries and AGNs (Maccarone, Gallo & Fender 2003). Radio observations of the X-ray binaries indicate a suppression of the jet production at high states (Gallo, Fender & Pooley 2003). However, there are also some ‘sub-states’ during which powerful jets are occasionally produced (Fender, Belloni & Gallo 2004). It was suggested that the low (3-10%) fraction of the radio-loud quasars is also due to the suppression of the jet production and that radio-loud quasars are the products of the intermittent jet activity (Nipoti, Blundell & Binney 2005; Körding, Jester & Fender 2006). Livio, Pringle & King (2003) proposed the model according to which intermittency is connected with stochastic transitions between two accretion modes, the standard one – with angular momentum transmitted outwards by viscous torques within a disk, and the ‘magentical’ one - with the developed large scale poloidal magnetic fields and related MHD jets/winds. SSL07 incorporated this idea into the spin paradigm scenario. They assumed that creation of narrow powerful jets requires both a large BH spin and an efficient collimation mechanism (Sol, Pelletier & Asseo 1989; Begelman & Li 1994) and postulated collimation of the central, Poynting flux dominated outflows by heavier and slower MHD outflows generated intermittently in a disk.

Intermittent production of jets is imprinted in radio morphology of some radiogalaxies. Best examples are represented by galaxies with double-double radio structures (see Saikia, Konar & Kulkarni 2006 and refs. therein). However, it is not clear whether this intermittency is related to the changes of a disk accretion mode taking place at the approximately constant accretion rate, or is reflecting a modulation of the accretion rate, e.g. by thermal-viscous instabilities (Siemiginowska & Elvis 1997) or combination of the magnetorotational and gravitational instabilities in the outer portions of the accretion disk (Menou & Quataert 1997). Furthermore, existence of the double-double radio morphologies shows that the radio activity of jets launched in the two different epochs overlap in time which means that the duty cycle is too large to interpret the radio-quiet quasars as those appearing between phases of a jet production turn-off. One could postulate that in most cases the duty cycle is much smaller, corresponding with the percentage of radio-loud quasars, but this would imply the period of a total quasar phase exceeding the Salpeter time already after the first cycle. More promising are models involving much shorter time scales of intermittency. They were suggested to explain an excess of the number density of compact symmetric objects over the number density predicted assuming that all these objects represent initial stages of expanding double radio sources. In the variant of a large duty-cycle the excess results from a delay of the expansion (Reynolds & Begelman 1997), in the variant of a small duty cycle the excess is explained by postulating that most of double radio sources die at young ages (see Kunert-Bajraszewska & Marecki 2007 and refs. therein). Only in the latter case the intermittency can be reconciled with the very small percentage of radio-loud quasars. Furthermore, detection of core-jet structures in all lobe dominated radio-quasar indicates that there are no turn-offs of a jet production in quasars with large scale radio
structures (Hough et al. 2002). Hence, these exceptional objects, constituting about 3% of all quasars (de Vries, Becker & White 2006; Lu et al. 2007), must follow a different evolutionary scenario than others. It is suggested below.

3.2 Quasars with powerful large scale jets

Noting that it is much easier to develop large scale magnetic fields in geometrically thick disks than in geometrically thin disks (Livio, Ogilvie & Pringle 1999), I assume that the MHD winds/jets which collimate the central outflows are generated only if innermost portions of the accretion disk or at least their surface layers are inflated. The inflation can be induced intermittently by thermal instabilities (Janiuk, Czerny & Siemiginowska 2002), or supported permanently by energy transfer from the fast rotating BH to the disk. The latter is expected to work efficiently in objects with BH spins $a > a_{eq}$, where $a_{eq}$ is the maximum spin reachable via the accretion process. Specifically: without any coupling and radiation $a_{eq} = 1$ (Bardeen 1970); with the radiation drag $a_{eq} \approx 0.998$ (Thorne 1974); with the magnetic coupling computed for MHD accretion disks with a moderate geometrical thickness $a_{eq} \approx 0.93$ (Gammie, Shapiro & McKinney 2004); and smaller if counting the extraction of the BH energy and angular momentum via the Blandford-Znajek mechanism operating in an open magnetic field configuration (Moderski, Sikora & Lasota 1998).

Let consider now formation of quasars by two types of major mergers, one involving two gas-rich disk galaxies, and one where the disk galaxy is merged with a giant elliptical. In both cases the merger of two BHs presumably proceeds within a dense, massive gas disk formed in the center of two colliding galaxies. Such a disk helps to drive the hardening of the BH binary on scales where stellar dynamical friction is already inefficient and gravitational radiation is still inefficient (Begelman, Blandford & Rees 1980; Dotti, Colpi & Haardt 2006; but see Cuadra et al. 2008). The disk helps also to avoid the ejection of the merged BHs from the center of the merging galaxies, by inducing the alignment of the BH spins with the orbital spin prior to their coalescence, via the mechanism discussed at the beginning of §2 (Bogdanović, Reynolds & Miller 2007). With such a configuration, a merger of two BHs with low initial spins and mass ratio between 1:4 and 1:1 leads to formation of the BH with the spin enclosed in the range between $\sim 0.5$ and $\sim 0.7$ (Rezzolla et al. 2007). Then, due to the accretion from the disk, BHs are spun-up to $0.8 < a_{eq} < 0.9$. However, if one of the merging galaxies is elliptical, hence already hosting the high spin BH, a BH merger remnant will emerge with a spin $a \sim 0.96 > a_{eq}$. Following that we postulate that radio-loud quasars are the ‘2nd generation quasars’, triggered by collision of two galaxies with one already being the product of the previous major merger event. This hypothesis is consistent with recent studies of galaxy morphologies of radio-loud quasars vs. radio-quiet quasars (Wolf & Sheinis 2008). They show that all radio-loud quasars reside in giant ellipticals while morphologies of galaxies hosting PG quasars are consistent with ongoing mergers of two gas-rich galaxies.

3.3 Radio-intermediate quasars

A large fraction of radio-loud quasars is compact (de Vries et al. 2006; Lu et al. 2007). Some of them are as radio-luminous as extended double radio sources. They are presumably connected with the intermittently launched jets and are represented by compact symmetric objects. But most of radio detected quasars have intermediate radio luminosities and it is not clear whether their radio activity is powered by jets. Their radio emission may originate, e.g. in shocks formed by the collision of the uncollimated central outflows with the interstellar medium. This suggestion is supported by observations of broad-absorption-line (BAL) quasars. These objects are preferentially found in intermediate-radio quasars with core dominated radio structures (Liu et al. 2008). If assuming that their BAL systems result from the loading of the unconfined central outflows by the cold filaments in the broad emission line region, the lack of BALs in radio-loud quasars with extended structures can be explained by the fact that in such quasars central outflows form well collimated jets which are spatially separated from the broad emission line region. In this picture, intermediate radio quasars may represent the tail of the radio-quiet population of quasars (Zamfir, Sulentic & Marziani 2008) and the lack of radio emission in most quasars can be explained assuming that in most cases central outflows are effectively slowed down by the mass entrainment and do not form the terminal shocks.

3.4 Radiogalaxies

High accretion rate radio galaxies with extended FRII type double radio structures are represented by so-called broad-line-radio-galaxies (BLRG), with optical morphology of giant ellipticals. They are as radio-luminous as radio loudest quasars, and on the radio-loudness vs. Eddington-ratio plot form smooth extension of radio-loud quasars toward lower $\lambda$’s (SSL07). They, similarly to radio-loud quasars, constitute only a small fraction of AGNs hosted by giant ellipticals. Most are radio intermediate or weak (Kauffmann, Heckman & Best 2008) and the cause can be the same as proposed for quasars, i.e. the lack of collimation of the central outflow.

3.5 Seyfert galaxies

According to the scenario sketched in §2, AGNs in disk galaxies, are not related to any specific merger process but are occasionally triggered by gravitational instabilities secularly developed in the galactic disks fed by the gas stripped from the satellite galaxies and by the cold streams from the halo (Johansson, Naab & Burkert 2008;
Bournaud, Jog & Combes 2007). As observations of Seyfert galaxies indicate most of these AGNs radiate at intermediate rates which combined with their lifetimes give the mass increment not enough large to spin-up BHs significantly. However there is a category of Seyfert galaxies, called NLS1 (narrow-line Seyfert 1) which accrete at very high rates and, therefore, like quasars may host fast spinning BHs. Interestingly, as recent surveys show, some of NLS1s are radio-loud (Yuan et al. 2008). The radio-loud fraction of NLS1 is smaller than the radio-loud fraction of quasars which may indicate a lower duty cycle of the intermittent jet production in NLS1 or that not in all of them the high accretion lasts sufficiently long to significantly spin-up BHs.

4 Summary

Radio studies of AGNs at low accretion rates indicate that AGNs hosted by elliptical galaxies are on average by 2-3 orders radio louder than AGNs hosted by disk galaxies (see SSL07 and refs.therein). This can be interpreted in terms of the spin paradigm assuming that BHs in the elliptical galaxies gain during their evolution much larger spins than BHs in the disk galaxies. SSL07 and Volonteri et al. (2007) assumed that growth of BHs in all galaxies is dominated by accretion and showed that low spin BHs in disk galaxies may be due to their accretion history composed of many small mass accretion events with random angular momenta. However noting that masses of accretion disks in Seyfert galaxies are larger than the upper mass limit per the assumption that initial collimation of the centrally produced jets can be provided by MHD jet/wind from the inflated innermost portions of the accretion disk and that such inflation may persist for very long time if supported by the transfer of the energy from the fast rotating BH to the disk. This transfer is expected to be efficient if the BH is spinning with $a > 0.99$, and it is argued that such a spin is available in the 2'nd generation of quasars, i.e. following a major merger of a giant elliptical (a product of the past quasar event) with a gas-rich disk galaxy.

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