Intermittent Activity of Jets in AGN

Aneta Siemiginowska¹, Bożena Czerny², Agnieszka Janiuk², Łukasz Stawarz³, Matteo Guainazzi⁴, Annalisa Celotti⁵, Giulia Migliori⁵ and Olaf Tengstrand⁴

Abstract.
Large scale X-ray jets that extend to > 100 kpc distances from the host galaxy indicate the importance of jets interactions with the environment on many different physical scales. Morphology of X-ray clusters indicate that the radio-jet activity of a cD galaxy is intermittent. This intermittency might be a result of a feedback and/or interactions between galaxies within the cluster. Here we consider the radiation pressure instability operating on short timescales (< 10⁵ years) as the origin of the intermittent behaviour. We test whether this instability can be responsible for short ages (< 10⁴ years) of Compact Symmetric Objects measured by hot spots propagation velocities in VLBI observations. We model the accretion disk evolution and constrain model parameters that may explain the observed compact radio structures and over-abundance of GPS sources. We also describe effects of consequent outbursts.

1. Introduction
The idea of intermittency is not new. Some observational evidence was given already in early 60-ties. For example Burbidge & Burbidge (1965) suggested intermittent outbursts of NGC1275 the cD galaxy in the center of Perseus A cluster. Kellermann (1966) derived the intermittency timescales of ~ 10⁴ − 10⁶ years required for the production of relativistic particles responsible for the observed synchrotron spectra in radio sources and quasars. Signatures of the past recurrent activity in nuclei of normal galaxies were presented by Bailey & Clube (1978), but their paper was not really noticed and has only 24 citations to date. Shields & Wheeler (1978) examined quasar models and suggested that their accumulate the mass during quiescent periods and then through the instability they transfer the mass onto a central black hole during a short period of an outburst of the activity. These are just a few examples of the AGN intermittency that has been considered since the early days of studies of the nuclear emission in galaxies. It is now that we are looking closely at this behaviour as

¹Harvard-Smithsonian Center for Astrophysics, 60 Garden St, Cambridge, MA 02138, USA
²Copernicus Astronomical Center, Bartycka 18, 00-716 Warsaw, Poland
³KAVLI/Stanford University, Stanford, CA 94305, USA
⁴European Space Astronomy Center of ESA, P.O. Box 78, Villanueva de la Canada, E-28691, Madrid, Spain
⁵SISSA/ISAS, Via Beirut 2-4, I-34151, Trieste, Italy
it becomes evident that it is an important component to our understanding of the evolution of structures in the universe. However, there are still many open questions about the origin of the intermittent behaviour. Is it related to the unsteady fuel supply, or accretion flow? Are there many quiescent and outburst phases? What is the mechanism regulating the intermittent behaviour?

Observations show a range of timescales for the AGN outbursts. Quasar lifetimes estimated based on large samples of SDSS quasars are of order of $10^7$ years (Martini & Weinberg 2001). Signatures of outbursts in recent observations of X-ray clusters indicated similar timescales (see McNamara & Nulsen 2007, for the review). However, episodes of activity on timescales shorter than $< 10^5$ years have been also observed for example in compact radio sources (Owsianik et al. 1998; Reynolds & Begelman 1997) or as light echos in nearby galaxies (Lintott et al. 2009). In this review we will focus on the short timescales of the intermittent jet activity. We discuss the radio source evolution, observational evidence for the intermittent activity and present the model for the origin and nature of the short term activity based on the accretion disk physics.

2. Jets and Compact Radio Sources

Jets provide the evidence for energetic AGN outflows. They highlight the fact that the energy released in the nuclear region in the close vicinity of a black hole can influence the environment at large distances. They also trace the source age and activity timescales. In many recently discovered X-ray jets associated with powerful quasars the continuous X-ray jet emission extends to hundreds of kpc distances from the core (Siemiginowska et al. 2002; Sambruna et al. 2002; Harris & Krawczynski 2006). These jets are straight, sometimes curved or bent, and have many knots. For example in PKS 1127-145 jet associated with z=1.18 quasar the separation and size of the knots may indicate separate outbursts of jet activity with timescales $\sim 10^5$ years (Siemiginowska et al. 2007).

Host galaxy scale jets, smaller than $< 10$ kpc provide a direct information about the jet interactions with the ISM and feedback. Compact radio sources that are entirely contained within the host galaxy represent the initial phase of radio source growth and they are young. The most compact Gigahertz Peaked Spectrum (GPS) sources have linear radio sizes below $\sim 1$ kpc. Their age can be probed directly by studying the expansion velocity of symmetric radio structures and it is typically less than $10^5$ years (Polatidis & Conway 2003; Gugliucci et al. 2005). Compact Steep Spectrum (CSS) radio sources are slightly larger, but still contained within the host galaxy. Their age is given by synchrotron ageing measurements and is smaller than $10^5$ years (Murgia et al. 1999).

3. Evolution of Radio Sources

Tengstrand et al. (2009) discuss the XMM-Newton and Chandra X-ray Observatory observations of a complete sample of compact GPS galaxies. All these sources are unresolved in X-rays, but they are very powerful in both the radio and X-rays bands. In Figure 1 we mark the location of GPS galaxies in radio vs. X-ray luminosity plane. We also mark the locations of the large scale FRI and FRII sources. The GPS sources cover an upper right corner of that diagram.
Figure 1. Radio sources in the radio luminosity vs. X-ray luminosity plane. FRI are marked with empty circles and FRII with squares. Compact radio sources from [Tengstrand et al. (2009)] are marked by large black circles in the upper right-hand part of the diagram. The regression lines for the FRI sources is marked with dashed line and for FRII with dash-dot-dash lines. The solid line is the fit to the compact sources with the lower X-ray luminosity. The evolutionary tracks towards FRI and FRII sources are marked.

and the plotted regression lines indicate possible evolutionary path for the GPS sources to grow into large scale radio sources. However, it is unclear which way and how the evolution of the GPS radio sources proceeds. Are they fade in radio and X-rays simultaneously or maybe only the radio fades while the X-ray emission remains unchanged indicating that the X-ray emission process is independent of the radio one? On the other hand maybe the GPS sources remain in this part of the diagram due to repetitive outbursts. [O’Dea & Baum (1997)] show that there is an overabundance of compact radio sources, so they need to be short-lived or intermittent rather than evolving in a self-similar manner to explain their numbers. [Reynolds & Begelman (1997)] proposed a phenomenological model with the recurrent outbursts on timescales between $\sim 10^4 - 10^5$ years lasting for $\sim 3 \times 10^4$ years that fits the observed numbers of radio sources and their sizes.

There is additional growing evidence for the AGN intermittent activity. Morphology of large radio galaxies with double-double or triple-triple aligned structures show repetitions on scale of $\sim 10^5 - 10^6$ years (see for example [Brocksopp et al. (2007)]). Some nearby radio galaxies show a younger radio structures embedded in a relic radio halo (e.g. 4C+29.30 [Jamrozy et al. 2007]). Recent Chandra observations of X-ray clusters show signs of AGN outbursts on timescales of $10^7$ year, e.g. Perseus A [Fabian et al. (2003)], M87 [Forman et al. (2003)],
However, the origin of intermittent activity has not be determined so far. Mergers operate on long timescales and can be important in X-ray clusters, especially at high redshifts. Unstable fuel supply due to feedback may play a significant role on the long timescales. Instabilities in the accretion flow related to the accretion physics have been shown to operate on long (Shields & Wheeler 1978; Siemiginowska et al. 1996; Janiuk et al. 2004) and short timescales (Janiuk et al. 2002; Czerny et al. 2009) depending on the nature of the instabilities.

4. Outbursts of the Activity due to Accretion Disks Instabilities

Accretion disk instabilities have been studied and shown to operate in binary systems. The ionization instability that causes large amplitude ($\Delta L \sim 10^4$) outbursts in galactic binaries on timescales between 1 and 1000 years may operate in accretion disks around supermassive black holes. It can cause huge outbursts on timescale $10^6 - 10^8$ years and influence the evolution and growth of a central black hole (Siemiginowska et al. 1996). The radiation pressure instability studied in microquasars causes moderate amplitude variability on short timescales. The time-dependent disk models that include this instability support the observed correlation between luminosity variations and jet activity in microquasar (Fender & Belloni 2004). In fact the radiation pressure instability is the only quantitative mechanism explaining the observed variability in GRS1915+105 (Janiuk et al. 2000, Navakshin et al. 2000, Janiuk et al. 2002, Merloni & Navakshin 2006, Janiuk & Czerny 2007). Scaling the observed outbursts with timescales of 100-2000 sec in this $\sim 10 M_\odot$ system to $10^9 M_\odot$ galactic size black hole gives the variability timescales between 300-6000 years.

Figure 2 shows the standard stability curve in the surface brightness vs. effective temperature plane with the stable solutions for an $\alpha$ viscosity accretion disk. In the region dominated by radiation pressure the disk is unstable. The viscous heating cannot be compensated by the radiative cooling and some additional cooling of the disk in a form of an outflow, an advection towards the black hole or the energy dissipation in the corona can stabilize the disk. The solid dots show the evolutionary “track” of the local disk in the unstable region. This model includes the outflow that transports away the excess heating energy allowing the disk to transfer to a lower temperature stable state (Janiuk et al. 2002, Czerny et al. 2009).

Figure 3 shows the luminosity variations due to the radiation pressure instability occurring in a disk around $M_{BH} = 3 \times 10^8 M_\odot$ black hole with a steady flow of matter with the rate $\dot{M} = 0.1 \dot{M}_{Edd}$, where $\dot{M}_{Edd}$ is the critical accretion rate corresponding to the Eddington luminosity. The outbursts are separated by $3 \times 10^4$ years as required by Reynolds & Begelman model. For a different black hole mass and accretion rates the outbursts timescales and durations are different. In general the effects of the instability depend on the size of the unstable disk region which scales with accretion rate. Also, there is a lower limit to the accretion rate for this instability to operate because the radiation pressure instability occurs when $P_{rad} > P_{gas}$. In the systems with $M_{BH} > 10^8 M_\odot$ and accretion rates below a few percent of the critical Eddington accretion rates the instability does not occur and the disk is stable.
Figure 2. Surface density vs. effective temperature relation, e.g., the local stability curve at $10R_g$ for an accretion disk with the viscosity scaled with gas and total pressure as $\sqrt{P_{\text{gas}}P_{\text{tot}}}$. The viscous heating is balanced by cooling through the processes listed on the right hand side. The regions at lower temperatures are dominated by the gas pressure, while the upper branch becomes unstable when the radiation pressure dominates. Upper curves shows different solutions that include parametrized outflow stabilizing the disk. The top curve shows the solution for the advective slim disk. Green solid qdots indicate solutions obtained during time-dependent model calculation (see Janiuk et al. 2002 for details).

We associate the outbursts caused by the radiation pressure instability with the ejections of radio jets. The predicted timescales for the outbursts durations and repetitions are in agreement with the observations (Wu 2009) of compact radio sources.

5. Consequences

There are several implications of the intermittent jet activity.

The repetitive outbursts have potentially a very strong impact on the ISM. The repetitive shocks on timescales shorter than the relaxation timescales may keep the ISM warm, and also more efficiently drive the gas out of the host galaxy.

There exists an intrinsic limit to the size of a radio source given by the timescales.

Evolution of a radio source proceeds in a non self-similar way. The outbursts repeat regularly every $10^3 - 10^6$ years. The jet turns-off between each outburst. Each radio structure may represent one outbursts and a young source will indicate a new outburst. However, the timescales for fading of a radio source are longer than the separation timescales between the outbursts, and we should observe the fossil radio structure in addition to the compact one. 10% of GPS
sources have faint radio emission on large scales, that is typically explained as a relic of the other active phase (Stanghellini et al. 2005).

What is the radio source evolution between the outbursts? The jet turns off between each outburst and then the pressure driven expansion continues until the radio source energy is comparable to the thermal energy of the heated medium. If the outburst lasts about \( \sim 1000 \) years then the radio source does not expand beyond the host galaxy. The hot spots can only travel to a distance of \( \sim 300 \) pc before the jet turns off and then the pressure driven expansion drives the radio structure only to a distance of 3 kpc for the typical ISM density and jet power. At this point the re-collapse of the radio source starts and it continues for about a Myr if there is no another outburst. In order for the source to escape its host galaxy the outburst needs to last longer than \( \sim 10^4 \) years.

Re-collapse phase is typically longer than the repetition timescale and a “tunnel” made by the jet will not close between outbursts. It means that the repetitive jets outbursts will propagate into a rarified medium. As the timescales between outbursts are long we expect to observe fading compact radio sources with no active nucleus.

For high accretion rates (\( > 0.02 \dot{M}_{\text{Edd}} \)) the jet outbursts can be governed by the radiation pressure instabilities. The observed radio power suggests high accretion rates that are consistent with the requirement for the instability to operate. Thus the number of compact size radio sources with can be explained by the outbursts with timescales consistent with the radiation pressure instability.

There are some open issues related to the theoretical understanding of the disk instability. The effects of the instability depend on the disk viscosity. The standard Shakura & Sunyaev disk is unstable in the case of viscosity scaling...
with total pressure while it is stable for the viscosity scaled with the gas pressure. In the case of the MRI viscosity the local disk simulations support some scaling of the effective torque with pressure. However, the effect of the radiation pressure instability is not clear in the global MHD simulations, although very recent simulations by Hirose et al. (2009) confirm the existence of the instability. Observationally the behaviour of microquasars strongly supports the radiation pressure explanation for the outbursts.

6. Conclusions and Future Perspectives

Observations indicate a complex behaviour of radio sources: continuous jets, signatures of repetitive outbursts in separated radio components, or the statistic of radio sources. The source complex behaviour may reflect different regimes of the accretion flow that depend on the black hole mass and accretion rate. We also note that for some parameters the radio source may never leave the host galaxy.

Large samples of radio sources are needed for statistical studies. We should be able to determine the number of sources, their lifetimes and sizes. We also need more sources with measurements of their age as well as indications for the intermittency in the sources radio morphology. Such data should be available in the future with the new radio surveys that probe fainter, low power compact sources that might be in the fading phase.

Acknowledgments. AS thanks the organizers for the invitation to the meeting. This research is funded in part by NASA contract NAS8-39073. Partial support for this work was provided by the NASA grants GO5-6113X, GO8-9125A and NNX07AQ55G.

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