Mergers and binary systems of SMBH

in the context of nuclear activity and galaxy evolution

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Abstract

Galaxy evolution and nuclear activity in galaxies are likely to be connected with the cosmological evolution of super-massive black holes (SMBH) in the galactic nuclei. Galaxies are expected to merge frequently over the course of their formation and cosmological evolution, leading to the the formation of binary systems of SMBH. Binary SMBH are likely to play a crucial role in formation and evolution of active galactic nuclei (AGN). The dynamic evolution of a binary SMBH may be a key factor affecting a large fraction of the observed properties of AGN and galaxy evolution. In this framework, different classes of AGN can be related in general to 4 different evolutionary stages in a binary SMBH: 1) early (merger) stage; 2) wide pair stage; 3) close pair stage; and 4) (pre)coalescence stage. This scheme can be connected with a variety of observational properties that can be explained by the binary SMBH scenario: differences of radio and optical luminosities of different classes of AGN, long-term and short-term variability, quasi-periodic nuclear flares, and formation of relativistic outflows in AGN and their apparent morphology and kinematics.

Introduction

Mergers are expected to occur frequently over the course of galaxy evolution. Formation of binary (or multiple) systems of SMBH is a likely outcome of galactic mergers. Binary black hole (BBH) systems should therefore play an important role in the nuclear activity in galaxies, since the latter is believed to be closely related to SMBH. BBH systems may provide a mechanism necessary for instilling and supporting high accretion rates over timescales implied by large-scale relativistic outflows produced in AGN. Evolutionary stages of BBH systems may also be connected with different types of AGN identified.

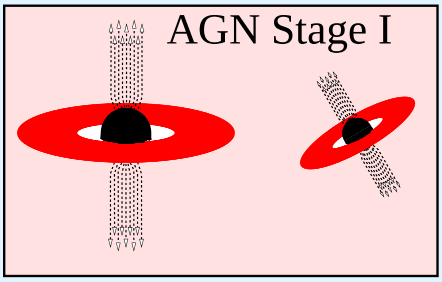
Evolution of BBH depends (to the first order) on the mass ratio of the individual black holes, mass and velocity dispersion of the central stellar cluster and – to a lesser degree – on the density, velocity and distribution of gas and dust in the circumnuclear regions. For AGN, physical conditions in the gas and dust component play more important role as they determine largely the rate at which matter is converted into energy.

A connection between nuclear activity and BBH evolution is therefore not straightforward. It depends on a number of factors and parameters, and may be essentially non-linear in its character. Numerical simulations are probably the best tool for exploring the parameter space involved.

However, analytical work may be successful in identifying the main trends and directions that a co-evolution of AGN and BBH may take. A good starting point for this work is provided by a number of studies of BBH dynamics (e.g. Begelman, Blandford, Rees 1980 and subsequent works) and interaction of supermassive black holes with nuclear environment in galaxies (e.g. Dokuchaev 1991, Polnarev & Rees 1994).

On the basis of the available studies of the BBH systems in galaxies, it is possible to formulate a hypothesis that connects distinct stages of the binary evolution to characteristic types of AGN and galactic morphology associated with them.

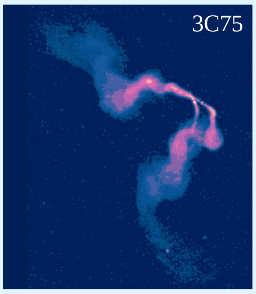
The proposed connection between BBH evolution and AGN is not necessarily unique and exclusive, but it should provide a viable skeleton for building up more complex and detailed models relating nuclear activity to the properties of multiple black holes in active galaxies. In particular, it would be important to investigate joint cosmological evolution of active galaxies and supermassive BBH embedded into their nuclei.

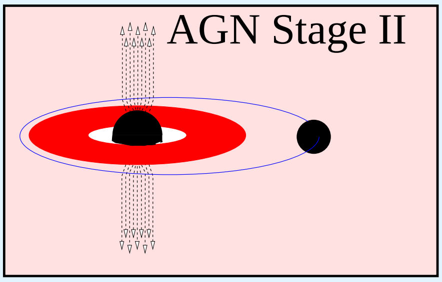


Low–power AGN

Individual galaxies or early mergers (while both BH retain their accretion disks). Timescale and intensity of nuclear activity would depend on the conditions in the central regions (see Dokuchaev 1991), and it is likely that cavity is formed around the BH, producing a "starving", low–power AGN. If galaxies were formed at redshifts $z \sim 5-10$, the peak of single BH activity in galaxies is likely to occur at $z \sim 1$. Around this redshift, AGN with single SMBH may represent a (probably small) fraction of quasars and FR II type radio galaxies. At later epochs a single SMBH in the center of a galaxy is expected to reduce its fueling rate to $F \lesssim 10^{-3}\,[\dot{\mathrm{M}}_{\mathrm{Edd}}]$, and support a typical luminosity of $L \lesssim L_{\mathrm{Edd}}F \approx 10^{43} M_8\,\mathrm{erg/s}$. This activity would be similar to that found in a typical Seyfert galaxy.

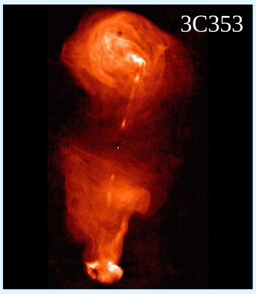
An onset of a merger of two galaxies should not have an immediate effect on environment of each of the SMBH, and the activity should remain weak during merging and relaxation of the galactic cores, which is expected to last for $\simeq 10^8$ years, (Roos 1981, Polnarev & Rees 1994). Main manifestations of nuclear activity: weak pc-scale and kpc-scale jets (this includes, possibly, most FR I type objects); weak broad line regions; very weak variability (particularly, on short timescales).

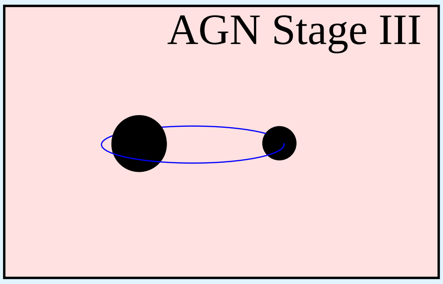




High–power AGN

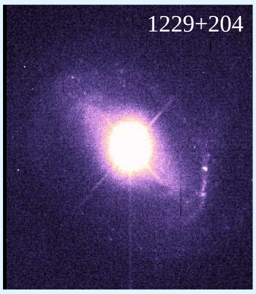
After the merger, the BHs sink rapidly toward the center of the stellar distribution (CSD) and form a gravitationally bound system, with typical orbital separations $r_{\mathrm{b}} \sim 1-10\,\mathrm{pc}$ and initial orbital velocities $v_{\mathrm{init}} \sim 10-100\,\mathrm{km/s}$ (depending on the mass and velocity dispersion of the the central stellar cluster as well as on the masses of the BHs themselves). Dynamical friction would reduce the orbital separation to $r_{\mathrm{b}} \sim 0.1-1\,\mathrm{pc}$, and the smaller BH would eventually lose its accretion disk. It would move around the larger BH on a nearly circular orbit ($e \rightarrow 0$). The orbital motion will align effectively the inner part of the accretion disk with the orbital plane, and cause periodical disruptions of the disk. Interaction of the BBH with the stars and gas in the nuclear region is expected to increase the fueling rate by a factor of 10–100 (Dokuchaev 1991), bringing the accretion rate close to $\dot{M}_{\mathrm{Edd}}$. This would support a luminosity of $\lesssim 10^{46}\,\mathrm{erg/s}$ on timescales of $\sim 10^8$ years, and produce an archetypical high-power AGN in an elliptical galaxy. BBH systems at this stage should produce strong pc-scale and kpc-scale jets; strong broad line regions, and pronounced variability on timescales $\tau_{\mathrm{var}} \sim 10^2$–$10^4$ days. This type of activity is probably present in most of the quasars and FR II radio galaxies.

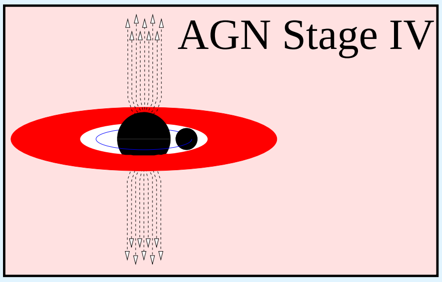




Radio–quiet AGN

At orbital separations $r_{\mathrm{b}} \sim 10^{-2}-1\,\mathrm{pc}$, the BBH system hardens, and interaction of the secondary BH with the accretion disk intensifies so that it may lead to severe disruptions or even complete destruction of the disk. A turbulent activity must ensue in the nuclear region, which would be manifested by highly variable, thermal emission in the optical and high-energy band. The level of radio emission should be reduced substantially, as it is produced in jets which will not be generated during this stage. One could expect that the fueling rate would be somewhat reduced, and the resulting luminosities would reach up to $\lesssim 10^{45}\,\mathrm{erg/s}$. This should be a relatively short stage, lasting for $\lesssim 10^8$ years. An AGN at this stage is likely to be recognized as a "radio quiet" QSO (however, the "radio quietness" does not necessary imply this particular situation, as there are several possible factors potentially capable of stopping the jet production in AGN). A particular tracer of this stage of the BBH system would be very low levels of non-thermal X-ray and optical emission and absence of strong variability induced by the accretion disk. A typical AGN at this evolutionary stage should therefore have no jets, exhibit strong broad line region and strong, multi band variability on timescales $\tau_{\mathrm{var}} \sim 10^0$–$10^3$ days.





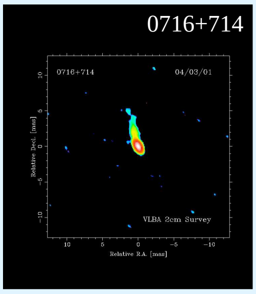
Intraday variable AGN

At separations $r_{\mathrm{b}} \lesssim 10^{-2}\,\mathrm{pc}$, gravitational radiation becomes the most important evolutionary factor. With $r_{\mathrm{b}} \gg r_{\mathrm{acc}}$, it is possible that an accretion disk is formed again around the BBH. Luminosities of up to $\lesssim 10^{45}\,\mathrm{erg/s}$ should be expected. This evolutionary stage is not likely to exceed $\sim 10^7$ years. A typical AGN at this stage would be an intraday variable source (with prominent variability on timescales $\tau_{\mathrm{var}} \sim 10^{-1}$–$10^3$ days), with pc-scale radio jets, (and possible kpc-scale relics), and a prominent broad line region. At least some of the variability observed must arise from the GR effects and rapid orbital motion in the system.

Maximum brightness temperature. GR effects and orbital motion will strongly modulate the emission, which would lead to variability on timescales that correspond to brightness temperatures of up to

$$T_{\mathrm{b,max}} = 5.58{\cdot}10^{11} \Delta S_{\mathrm{var}} \delta^{2-\alpha} \left[\frac{\lambda_{\mathrm{obs}} D_{\mathrm{L}} (\mu^3+\mu^2)^{1/5}}{M_8 (1+z)^2}\right]^2 ,$$

where μ is the mass ratio of the binary and δ is the Doppler factor of the emitting material. **Example:** 0917+624 (Kraus et al. 1999): $z = 1.446$, $\Delta S_{\mathrm{var}} = 0.14\,\mathrm{Jy}$, $\tau_{\mathrm{min}} = 0.285\,d$ at $\lambda_{\mathrm{obs}} = 6\,\mathrm{cm} \Rightarrow \ T_{\mathrm{b,obs}} = 1.4\cdot10^{19}\,\mathrm{K}$. Model estimate: $T_{\mathrm{b,max}} = 4\cdot10^{20}\,\mathrm{K}$, for $M_{\mathrm{bh}} = 10^7 \mathrm{M}_{\odot}$, $\mu = 1$, $\delta = 1$. Implies $h \approx 5\cdot10^{-16}$ at $\nu_{\mathrm{grav}} \approx 4\cdot10^{-4}$ (LISA threshold: $h \approx 10^{-20}$)



References

Begelman, M. C., Blandford, R. C., Rees, M. J. 1980, Nature, 287, 307.

Dokuchaev, V. I. 1991, MNRAS, 251, 564.

Kraus, A. et al. 1999, A&A, 352, 107.

Polnarev, A. G., Rees, M. J. 1994, A&A, 283, 301.

Roos, N. 1981, A&A, 104, 218.

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