Nuclear activity in galaxies driven by binary supermassive black holes

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Summary. Nuclear activity in galaxies is closely connected to galactic mergers and supermassive black holes (SBH). Galactic mergers perturb substantially the dynamics of gas and stellar population in the merging galaxies, and they are expected to lead to formation of supermassive binary black holes (BBH) in the center of mass of the galaxies merged. A scheme is proposed here that connects the peak magnitude of the nuclear activity with evolution of a BBH system. The scheme predicts correctly the relative fractions of different types of active galactic nuclei (AGN) and explains the connection between the galactic type and the strength of the nuclear activity. It shows that most powerful AGN should result from mergers with small mass ratios, while weaker activity is produced in unequal mergers. The scheme explains also the observed lack of galaxies with two active nuclei, which is attributed to effective disruption of accretion disks around the secondary in BBH systems with masses of the primary smaller than $\sim 10^{10} M_\odot$.

1 Binary black holes and nuclear activity in galaxies

Important roles played by galactic mergers and binary black holes in galaxy evolution was first recognized several decades ago [1, 22]. A large number of subsequent studies have addressed the problems of evolution of binary black holes in post-merger galaxies (see [19] for a recent review) and connection between mergers and nuclear activity in galaxies [3, 8, 25]. The correlations observed between the masses, $M_{BH}$, of nuclear black holes in galaxies, the and masses, $M_*$, [18] and velocity dispersions, $\sigma_*$, of the host stellar bulges [6, 7, 26] suggest a connection between the formation and evolution of the black holes and galaxies. Growth of black holes in galactic centers is self-regulated by outflows generated during periods of supercritical accretion [5, 9, 24]. This mechanism offers a plausible explanation for the observed $M_{BH} - \sigma$ relation [11].

Supermassive black holes are expected to form in the early Universe, with multiple SBH likely to be common in galaxies [9]. However, the detailed connection between the SBH evolution and the nuclear activity is somewhat elusive. Observational evidence for binary SBH is largely indirect (see [17, 19] and references therein), with only two double galactic nuclei (NGC 6240 [12] and 3C 75 [23]) observed directly in early merger systems, at large separations. There are no convincing cases for secondary black holes within active
galaxies, although some of them may be hiding among the extranuclear X-ray point sources detected by ROSAT and Chandra. This implies that the activity of secondary companions is quenched at early stages of the merger, possibly due to disruption of the accretion disk.

The nuclear activity depends strongly on the availability of accreting material in the immediate vicinity of a black hole, and AGN episodes are believed to last for $\sim 10^7$–$10^8$ yr. This is likely to be smaller than typical lifetimes of nuclear binary black holes in galaxies. This suggests that nuclear binary black holes 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 can also be connected phenomenologically to different types of AGN. Here, an analytical model is proposed that connects the evolution of central SBH in to the nuclear activity in galaxies.

1.1 BBH evolution

The main constituents of the model are: 1) binary system of supermassive black holes, 2) accretion disk, 3) central stellar bulge. The BBH is described by the masses $M_1$, $M_2$ ($M_1 \geq M_2$) of the two black hole and their separation $r$. The accretion disk is assumed to be a viscous Shakura-Sunyaev disk, with a mass $M_d$. The disk extends from $\rho_{in} R_g$ to $\rho_{out} R_g$, where $R_g$ is the gravitational radius and $\rho_{in} \approx 6$ and $\rho_{out} \approx 10^4$. The central bulge extends over a region of radius $r_\star$ and has a mass $M_\star (M_\star > M_{12} = (M_1 + M_2))$ and a velocity dispersion $\sigma_\star$.

The evolution of the BBH is described in terms of reduced mass, $\tilde{M}$, and reduced separation, $\tilde{r}$ of the binary. The reduced mass is defined as $\tilde{M} = 2 M_2 / M_{12}$. This definition implies $\tilde{M} = 0$ for $M_2 = 0$ and $\tilde{M} = 1$ for $M_2 = M_1$. If $q = M_2 / M_1$ is the mass ratio in the system, then $\tilde{M} = 2 q / (1 + q)$. The reduced separation is given by $\tilde{r} = r / (r + r_c)$, where $r_c$ is the separation at which the two black holes become gravitationally bound (this happens at $\tilde{r} = 1/2$). Binary systems have $\tilde{r} \leq 1/2$, while unbound pairs of SBH have $\tilde{r} > 1/2$.

1.2 Accretion disk disruption in binary black holes

Two SBH in a merger galaxy are expected to form a binary system at a separation $r_c = r_\star (M_{12} / M_\star)^{1/3}$, with an initial orbital speed $v_{init} = \sigma_\star (M_{12} / M_\star)^{1/3}$. Assuming that the relative speed of the two black holes reaches asymptotically its Keplerian value, the approach speed can be defined as $v_{app}(r) = \sigma_\star (r_\star / r)^{1/2} (M_{12} / M_\star)$. Both black holes are assumed to have active accretion disks at early stages of the merger. The separations $r_d$ at which the accretion disks are disrupted and eventually destroyed can be estimated for each of the two black holes by equating the approach speed to the
Keplerian velocity at the outer edge of the disk: \( v_{k,\text{out}} = c/\sqrt{\rho_{\text{out}}}. \) This yields \( r_d = \rho_{\text{out}} r_c (\sigma_\star / c)^2 (M_{12} / M_\star)^2. \) The bulge mass and velocity dispersion must satisfy the \( M_{\text{BH}} - \sigma_\star \) and \( M_{\text{BH}} - M_\star \) relations \([11]\). The resulting reduced separation is \( \tilde{r}_d = 1/(1 + \xi), \) where \( \xi = M_1/[1.86 \times 10^7 M_\odot \rho_{\text{out}} \phi^2 (2 - \tilde{M})^3] \) and \( \phi \) is the collimation angle of the outflow carrying the excess energy and angular momentum from the immediate vicinity of the black hole. This corresponds to a critical mass \( M_{\text{eq}} = 1.86 \times 10^7 M_\odot \rho_{\text{out}} \phi^2 \) for which an equal mass binary system will undergo disk destruction at the time of gravitational binding (at \( \tilde{r}_d = \tilde{r}_c = 1/2. \) In systems with \( M_1 < M_{\text{eq}} \) the destruction of accretion disk around the secondary will occur before the formation of a gravitationally bound system. For typical values of \( \rho_{\text{out}} \approx 10^4 \) and \( \phi = 0.1-0.3, \) \( M_{\text{eq}} \) reaches \( 10^9-10^{10} M_\odot. \) It implies that most of active galaxies formed by galactic mergers should undergo destruction of the disk around the secondary BH before or during the formation of a gravitationally bound systems. Since masses of the nuclear black holes in galaxies rarely exceed \( 10^{10} M_\odot, \) this offers a natural explanation for the observed lack of active galaxies with double nuclei, since it predicts that \textit{in most galaxies with binary black hole systems the secondary companion will be inactive.}

Denoting \( \epsilon_1 = M_1/M_{\text{eq}}, \) the disruption distances are

\[
\tilde{r}_{d1} = \left(1 + \frac{\epsilon_1}{M_1^2(2 - M_1)}\right)^{-1} \quad \text{and} \quad \tilde{r}_{d2} = \left(1 + \frac{\epsilon_1}{(2 - M_1)^3}\right)^{-1},
\]

for the primary and secondary black hole, respectively. A circumbinary disk can exist at orbital separations smaller than \( \sim G M_1 \rho_{\text{out}} c^{-2}. \) These three characteristic distances are shown in left panel of Fig. 1 for \( M_1 = M_{\text{eq}}. \)

### 1.3 Peak luminosity of AGN

The peak magnitude of the nuclear activity in a galaxy hosting a binary black hole system can also be connected with the reduced mass and orbital separation of the two black holes. Assuming that the accretion rate increases proportionally to the tidal forces acting on stars and gas on scales comparable to the accretion radius, \( 2 G M_{\text{bh}} / \sigma_\star^2, \) the peak luminosity from an AGN can be crudely estimated from

\[
L_{\text{peak}} = L_0 \left(1 + \frac{\tilde{M} \tilde{M}}{2 - \tilde{M} \tilde{r}^2}\right),
\]

where \( L_0 \) is the “unit” luminosity of a typical single, inactive galactic nuclei. The peak luminosities calculated in this fashion are plotted in the right panel of Figure 1 for the entire range of \( \tilde{M} \) and \( \tilde{r}. \)

The peak luminosity increases rapidly with increasing \( \tilde{M} \) and decreasing \( \tilde{r}, \) and it reaches \( L_{\text{peak}} = 1000 L_0 \) for an equal mass binary SBH at \( r \approx 0.03 r_c. \) This corresponds most likely to powerful quasars residing in elliptical
Fig. 1. Properties of binary black holes in the $\tilde{M}$–$\tilde{r}$ plane ($\tilde{r} = 1/2$ signifies the capture distance at which a pair of black holes becomes gravitationally bound). **Left:** Reduced separations for the disruption distance of the accretion disks around the secondary (solid line) and the primary (dashed line) black holes. The separations are calculated for $M_1 = M_{eq}$. Above the $\tilde{r}_{d2}$ line, both black holes retain accretion disks, while only one accretion disk (around the primary) exists. The dotted line shows the limiting distance below which a circumbinary disk may exist. This becomes feasible at $\tilde{M} \lesssim 0.2$. **Right:** Peak luminosities of AGN calculated for a range of values of the reduced mass $\tilde{M}$ and reduced distance $\tilde{r}$ in binary systems of SBH in the centers of galaxies. Equal luminosity contours are drawn at a logarithmic step of 0.1, starting from a unit luminosity $L_0$ marked by the vertical line at $\tilde{M} = 0$.

Galaxies. At the same $\tilde{r}_c$, an unequal mass binary, with $\tilde{M} = 0.15$, will only produce $L_{\text{peak}} \approx 10L_0$, which would correspond to a weak, Seyfert-type of active nucleus. Assuming that galaxies are distributed homogeneously in the $\tilde{M}$–$\tilde{r}$ diagram, this scheme implies that about 70% of all galaxies should be classified as inactive, while the Seyfert-type of galaxies, with $L_{\text{peak}} = 10$–100 $L_0$, should constitute 25% of the galaxy population, and the most powerful AGN, with $L_{\text{peak}} > 100$ $L_0$, should take the remaining 5%. It shows that the most powerful AGN with $L_{\text{peak}} > 1000$ $L_0$ should be found in binary SBH with nearly equal masses of the primary and secondary black holes. Binary SBH with smaller secondary companions should produce (at the peak of their nuclear activity) weaker, Seyfert-type AGN. Evidence exists in the recent works [13, 14] that the nuclear luminosity does indeed increase with the progression of the merger, but more systematic and detailed studies are required.
2 Conclusion

The model described above can be applied effectively to high-resolution optical studies and data from large surveys that can be used to obtain estimates of the nuclear luminosities and black hole masses in active galaxies. The most challenging task is to assess the state of the putative binary, since the secondary black holes are very difficult to detect. For wide binaries, Direct evidence may be sought in galaxies with double nuclei and extranuclear compact sources. Close binaries can probably be identified only indirectly, through periodic perturbations caused by the secondary companion. Other indicators, such as flattening of the galactic nuclear density profile due to BBH \cite{Merritt:2005}, can also be considered. Once the binary separations have been estimated, it would be possible to populate the $\dot{M} - \hat{r}$ diagram and study whether different galactic and AGN types occupy distinctively different areas in the diagram.

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