Probing a Supermassive Binary Black Hole with MAXI

Hayasaki Kimitake[1], Isobe Naoki[2], Sudou Hiroshi[3], Seta Hiromi[2] and Mineshige Shin[4]

[1]Yukawa Institute for Theoretical Physics, Kyoto University,
Oiwake-cho, Kitashirakawa, Sakyo-ku, Kyoto 606-8502, Japan
[2]RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
[3]Faculty of Engineering, Gifu University, 1-1 Yanagido, Gifu 501-1193, Japan
[4]Department of Astronomy, Kyoto University,
Oiwake-cho, Kitashirakawa, Sakyo-ku, Kyoto 606-8502, Japan
E-mail(HK): kimitake@yukawa.kyoto-u.ac.jp

Abstract

Supermassive black holes are considered to have been coevolved with their host galaxies. This strongly suggests that black hole growth is mainly caused by black hole mergers and subsequent accretion of gas in the course of the galaxy merger. If so, a supermassive binary black hole with a sub-parsec scale separation are inevitably formed before the black holes merge by emitting gravitational radiation. However, there is yet no definitive observational evidence for the supermassive binary black hole in spite of some claims (e.g. quasi-periodic light variations from OJ287). In this paper, we study the smoothed particle hydrodynamics simulations of accretion flows around the sub-parsec scale binary black hole with a moderate orbital eccentricity. In the simulations we consider a triple-disk system composing of two accretion disks around black holes and one circumbinary disk surrounding the two. Here, the circumbinary disk works as a mass reservoir. We confirm that X-ray luminosity from accretion disks significantly depends on the orbital phase because of the eccentric orbit of the binary black hole. Note also that the X-ray luminosity exhibits the double peaks every binary orbit in the case of binary black hole with low mass ratios. Such properties could not only explain a basic feature of light variations from OJ287 but also provide a potentially important observational signature of the sub-parsec binary black hole in active galactic nuclei with MAXI.

Key words: black hole physics – accretion, accretion disks – binaries:general – galaxies:nuclei

1. Introduction

Most galaxies are thought to have supermassive black holes at their centers (Kormendy & Richstone 1995). Supermassive black holes play an important role not only in the activities of active galactic nuclei and quasars but also in the formation and global evolution of galaxies (Margorrian et al. 1998; Ferrarese & Merritt 2000; Grblack holeardt et al. 2000). Since galaxies are well-known to evolve through frequent mergers, this strongly suggests that black hole growth is mainly caused by black hole mergers and subsequent accretion of gas (Yu & Tremaine 2002). If so, a supermassive binary black hole with a sub-parsec scale separation are inevitably formed before two black holes merge by emitting gravitational radiation (Begelman et al. 1980; Milosavljević & Merritt 2001; Mayer et al. 2007).

Despite the general expectation that the binary black hole should form naturally during the course of galaxy formation and evolution, the currently available observational evidence for binary black holes have been largely circumstantial and indirect. These include the detection of X-shaped structures in radio galaxies (Merritt & Ekers 2002), double compact cores with a flat radio spectrum (Rodriguez et al. 2006), and close pairs of active galactic nuclei such as that seen in NGC 6240 (Komossa et al. 2003). As these systems evolve, we expect that their black holes would eventually form a strongly gravitationally bound binary on sub-parsec scales. Such small-scale binaries have been inferred to be present from the quasi-periodic outbursts detected in OJ 287 (Sillanpää 1988; Valtonen et al. 2008) and the proper motions seen toward the compact radio core in 3C 66B (Sudou et al. 2003), but the interpretation of neither case is unambiguous. Quite recently, Bogdanović et al. (2008) and Dotti et al. (2008) proposed the hypothesis that SDSSJO92712.65+294344.0 is a massive binary black hole, by interpreting the observed emission line features as those arising from the mass-transfer stream from the circumbinary disk.

In theoretical view, Hayasaki et al. (2007), using a smoothed particle hydrodynamics (SPH) code (Benz 1990a,b; Bate et al. 1995), studied the accretion flow from a circumbinary disk onto the supermassive binary black hole with a semi-major axis $a = 0.1$ pc. They found that mass transfer occurs from the circumbinary disk to the supermassive binary black hole in two steps. First, the initially circularized circumbinary disk becomes elongated due to the azimuthal $m = 2$ component of the binary potential. The gas density then grows at the two points closest from the black holes. Next, when the gas reaches beyond the potential barrier of the binary, inflow is initiated so that the gas freely inspirals onto each of the black holes. The viscosity of the circumbinary disk is ineffective for the mass transfer process because the viscous timescale is much longer than the orbital period. For binary black hole systems on sub-parsec scales, the viscous timescale of the circumbinary disk can be written as

$$\frac{\tau_{\rm vis}}{P_{\rm orb}} \sim 7.31 \times 10^5 \left(\frac{0.1}{\alpha_{\rm SS}}\right)\left(\frac{10^3\ {\rm K}}{T}\right)\left(\frac{M_{\rm bh}}{10^8\ M_\odot}\right)\left(\frac{0.1\ {\rm pc}}{a}\right), \quad (1)$$

where $\alpha_{\rm SS} = 0.1$ is the Shakura-Sunyaev viscosity parameter (Shakura & Sunyaev 1973), $M_{\rm bh}$ is the total black hole mass, and a is the semi-major axis, respectively. The inner edge of the circumbinary disk is assumed to be at the $1:3$ resonance ($\sim 2.08a$), where the viscous force is balanced with the tidal/resonant force of the binary (Artymowiciz & Lubow 1994). The circumbinary disk is assumed to follow an isothermal equation of state.

The mass transfer rate significantly depends on the binary orbital phase in eccentric binaries, whereas it shows little variation with orbital phase in circular binaries. In both cases the mass transfer from the circumbinary disk to the central binary inevitably leads to the formation of an accretion disk around each of the black holes. Hayasaki et al. (2008) have, furthermore, performed a new set of simulations at higher resolution with an energy equation based on the blackbody assumption, adopting the same set of binary orbital parameters we had previously used (Hayasaki et al. 2007) ($a = 0.1$ pc, eccentricity $e = 0.5$, and mass ratio $q = 1.0$). By this two-stage simulation, it is possible to investigate the behavior of accretion disks around black holes.

2. Periodic light variations from two accretion disks

We describe the detail of the first-stage simulation as in Hayasaki et al. (2008). In order to reduce computational time and to significantly improve the resolution, we confine the simulations only to the accretion flow around the supermassive binary black hole by supplying mass periodically from the outer boundary condition, which is constructed from the SPH particles captured by the black holes (Hayasaki et al. 2007). The capture radii correspond to the effective gravitational radii $0.8r_{\rm L}$, where $r_{\rm L}$ is the innermost common gravitational radius of the binary potential for a circular binary. The number of SPH particles is $37,200$ at the end of the simulation. To reduce the fluctuation noise, the data are folded on the orbital period over $0 \le t \le 100$, where the unit of time is $P_{\rm orb} \simeq 296$ yr. The orbital phase dependence of the mass transfer rate obtained by this procedure is shown by the solid line in Figure 1.

In the second-stage simulation, we model the mass transfer process from the circumbinary disk to the supermassive binary black hole by injecting gas particles at a given phase-dependent rate We assume that the gravitational energy of the particles is converted to heat by the standard SPH viscosity (Monaghan & Gingold 1983). and is locally radiated away as a blackbody. The two black holes have an accretion radius $5 \times 10^{-3}a$, which is the radius of the inner boundary of the simulation that corresponds to $r_{\rm in} \simeq 104 r_{\rm bh}$, where $r_{\rm bh}$ is the Schwarzschild radius of a black hole with mass $5.0 \times 10^7\ M_\odot$. The mass accretion rate at this radius is shown by the dotted line in Figure 1. It is noted that from the figure that the mass accretion rate shows a single peak every orbital period. The X-ray luminosity corresponding to the mass accretion rate is significantly sub-Eddington.

Supermassive binary black holes are generally considered to have unequal black hole masses. For example, a binary black hole system in OJ287 is indicated to have an extreme mass ratio $q \le 0.1$ (Valtonen et al. 2008). We have, therefore, performed the two-stage simulations with the shorter semi-major axis, $a = 0.01$ pc, the orbital eccentricity $e = 0.5$, and the mass ratio $q = 0.1$ (Hayasaki & Mineshige 2008). In the first-stage simulation, we calculate the mass transfer rate from the circumbinary disk to the effective gravitational radius of each black hole as the averaged values over $40 \le t \le 100$, where the unit of time is $P_{\rm orb} \simeq 9.4$ yr. The orbital phase dependence of the mass transfer rate of the primary black hole (hereafter, the primary transfer rate), and of the mass transfer rate of the secondary black hole (hereafter, the secondary transfer rate) are shown by the dashed line and the solid line in Figure 2a, respectively.

Next, we have performed the second-stage simulation with both the primary transfer rate and the secondary transfer rate. Here, each black hole has an accretion radius $5 \times 10^{-3}a$. The mass accretion rates at this radius are also shown in Figure 2a, where the dotted line shows the mass accretion rate on to the primary black hole (hereafter, the primary accretion rate), and the dash-dotted line shows the mass-accretion rate on to the secondary black hole (hereafter, the secondary accretion rate). Figure 2b shows the snapshot of the accretion flow around the supermassive binary black hole at the periastron of the 10th binary orbit. The white cross and the white asterisk on the density map indicate the mass supply points from the circumbinary disk to the primary black hole and from the circumbinary disk to the secondary black hole, respectively.

From the figures, we confirm the formation of each accretion disk around black hole. These disks are significantly non-axisymmetric. The accretion disk around the primary black hole is much larger than the accretion disk around the secondary black hole. While the averaged secondary transfer rate during one orbital period is about 4.8 times higher than that of the primary transfer rate, the averaged secondary accretion rate are about 2.7 times higher than that of the primary accretion rate. These indicate that the system does not reach the quasi-steady state yet. Since the secondary accretion rate shows double peaks during one orbital period and is larger than the primary accretion rate with a single peak, the X-ray light variation would exhibit double peaks every orbit.

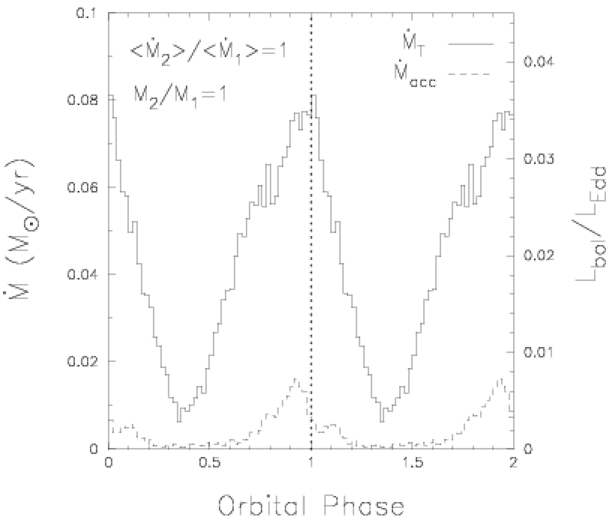

Fig. 1. Orbital phase dependence of the mass transfer rate $\dot{M}_{\rm T}$ from the circumbinary disks to the effective common gravitational radius of the black holes, and of the mass accretion rate $\dot{M}_{\rm acc}$ at the inner simulation boundary $r_{\rm in} = 5.0 \times 10^{-3} a$, of the primary black hole. The right axis shows the bolometric luminosity $L_{\rm bol}$ corresponding to the mass transfer and mass accretion rate with the energy conversion $\eta = 0.1$, normalized by the Eddington luminosity $L_{\rm Edd}$ for a total black hole mass $M_{\rm bh} = 1.0 \times 10^8\ M_\odot$, where η is defined by $L_{\rm bol} = \eta \dot{M}_{\rm bh} c^2$.

3. Summary and Discussion

We have studied the mass transfer process and/or mass accretion process around the supermassive binary black hole in the equal mass binary and unequal mass binary with the low mass ratio. In the equal mass binary, the X-ray lightcurve has a single peak during one orbital period, whereas the X-ray lightcurve shows double peaks in the binary black hole with low mass ratio $q = 0.1$. Each X-ray luminosity is significantly sub-Eddington in the early stage of the evolution of the accretion disks.

The orbital periods of the fiducial cases simulated here are prohibitively long for the lifetime of the MAXI $\sim 5\,$yr, even the case with $a = 0.01\,$pc. However, the generic features of the triple-disk BBH system discussed would remain unchanged for other orbital periods, which, from Kepler's third law, can be made shorter by reducing the binary separation and/or increasing the masses of the black holes. In addition, Hayasaki (2008) recently showed that the binary has enough a short period to coalesce within a Hubble time due to the emission of gravitational radiation by disk-binary interaction in the triple disk system. This study suggest that a supermassive binary black hole with an orbital period $\sim P_{\rm orb} = 1\,$yr exists in an active galactic nuclei. We expect that such the very short binary black hole will be detected by MAXI.

The authors thank YITP in Kyoto University, where this work was extensively discussed during the YITP-W-05-11 on September 20–21, 2005, the YITP-W-06-20 on February 13–15, 2007, and the YITP-W-07-19 on January 8-11, 2008. The simulations reported here were performed using the facility at the Centre for Astrophysics & Supercomputing at Swinburne University of Technology, Australia and at YITP in Kyoto University. This work has been supported in part by the Grants-in-Aid of the Ministry of Education, Science, Culture, and Sport and Technology (MEXT; 30374218 K.H., 14079205 K.H. & S.M.), and by the Grant-in-Aid for the 21st Century COE Scientific Research Programs on "Topological Science and Technology" and by the Grant-in-Aid for the Global COE Program "The Next Generation of Physics, Spun from Universality and Emergence" from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

References

Artymowicz, P., & Lubow, S. H. 1994 ApJ., 421, 651

Bate, M. R., Bonnel, I. A., & Price, N. M. 1995 MNRAS., 277, 362

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

Benz, W. 1990, in Numerical Modeling of Nonlinear Stellar Pulsations: Problems and Prospects, ed. R. J. Buchler (Dordrecht: Kluwer), 269

Benz, W., Bowers, R. L., Cameron, A. G. W., & Press, W. H. 1990 ApJ., 348, 647

Bogdanović, T., Eracleous, M., & Sigurdsson, S, 2008 (arXive:0809.3262)

Dotti, M., Montuori, C., Decarli, R., Volonteri, M., Colpi, M., & F. Haardt, 2008 (arXive:0809.3446)

Ferrarese, L., & Merritt, D. 2000 ApJ., 539, L9

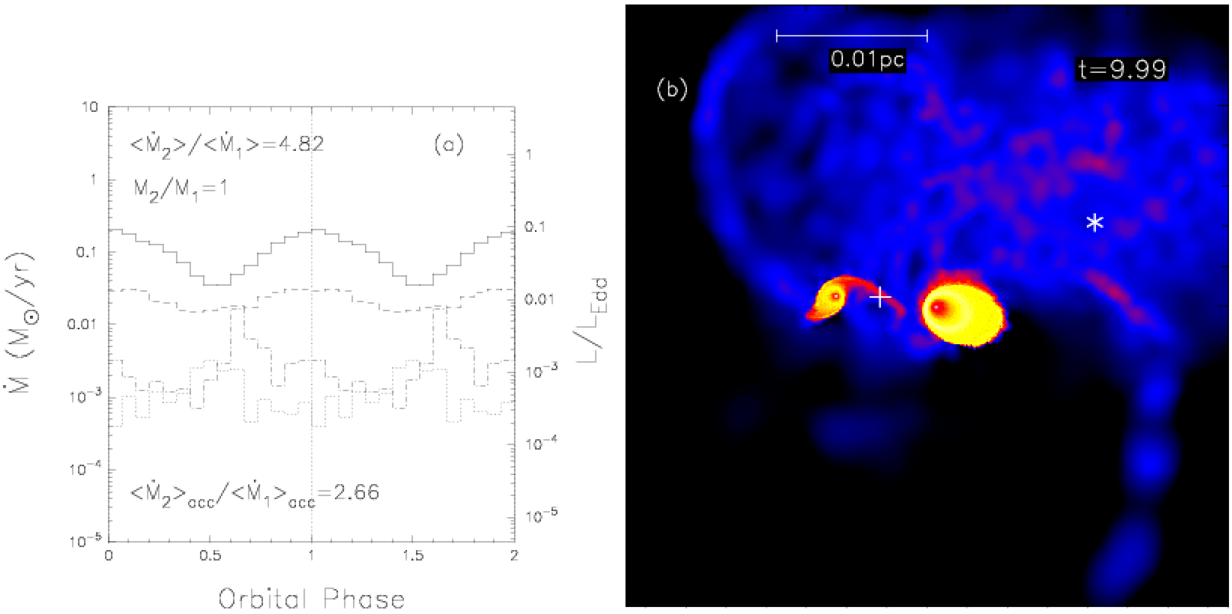

Fig. 2. *(a)* Orbital phase dependence of the mass transfer rate from the circumbinary disk to the effective common gravitational radius of each black hole, and of the mass accretion rate at the inner simulation boundary $r_{\rm in} = 5.0 \times 10^{-3} a$, of the black holes. The solid-line and dashed line show the mass transfer rate to the secondary black hole and the mass transfer rate to the primary black hole, respectively. The dotted line and the dash-dotted line show the mass accretion rate to the secondary black hole and the mass accretion rate to the primary black hole, respectively. In the right side of the panel, $< \dot{M}_2 > / < \dot{M}_1 >$, M_2/M_1, and $< \dot{M}_2 >_{\rm acc} / < \dot{M}_1 >_{\rm acc}$ show the ratio of the mass transfer rates, the mass ratio, and the ratio of the mass accretion rates. *(b)* Density maps of the two accretion disks around the supermassive binary black hole rotating with $P_{\rm orb} \sim 9.4\,{\rm yr}$, $e = 0.5$, and $q = 0.1$ at the periastron. Panel shows on a logarithmic scale the surface density contours over a range of 5 orders of magnitude. The white cross and the white asterisk indicate the positions of the mass input by the boundary condition. The supermassive binary black hole is rotating in a counterclockwise direction. The time and a length scale are shown in the top-right of the panel and the top-left of the panel, respectively. The total number of SPH particles is $112,297$ in the end of the simulation.

Hayasaki, K., Mineshige, S., & Sudou, H. 2007 PASJ., 59, 427

Hayasaki, K., Mineshige, S. & Ho, C.L. 2008 ApJ., 682, 1134

Hayasaki, K & Mineshige, S. 2008 Origin of matter and evolution of galaxies: The 10th International Symposium on Origin of Matter and Evolution of Galaxies: From the Dawn of Universe to the Formation of Solar System. (AIP Conference Proceedings), 1016, 406

Hayasaki, K. 2008 PASJ., in press (arXive0805.3408)

Komossa, S., Burwitz, V., Hasinger, G., Predehl, P., Kaastra, J. S., & Ikebe, Y. 2003 ApJ., 582, L15

Kormendy, J. & Richstone, D. 1995 ARA&A, 33, 581

Magorrian, J., et al. 1998 AJ., 115, 2285

Mayer, L., Kazantzidis, S., Madau, P., Colpi, M., Quinn, T., & Wadsley, J. 2007, Science, 316, 1874

Merritt, D., & Ekers, R. D. 2002, Science, 297, 1310

Milosavljević, M., & Merritt, D. 2001 ApJ., 563, 34

Monaghan J. J., & Gingold, R. A. 1983, J. Comput. Phys., 52, 374

Rodriguez, C., Taylor, G. B., Zavala, R. T., Peck, A. B., Pollack, L. K., & Romani, R. W. 2006 ApJ., 646, 49

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

Shakura, N. I., & Sunyaev, R. A. 1973 A&A., 24, 337

Sillanpää, A., Haarala, S., Valtonen, M., Sundelius, B., & Byrd, G. G. 1988 ApJ., 325, 628

Sudou, H., Iguchi, S., Muratai, Y., & Taniguchi, T. 2003, Science, 300, 1263

Valtonen, M. J., Lehto, H. J., Nilsson, K., Heidt, J., Takalo, L. O., Sillanpää, A., Villforth, C., Kidger, M., Poyner, G., Pursimo, T., Zola, S., Wu, J.-H., Zhou, X., Sadakane, K., Drozdz, M., Koziel, D., Marchev, D., Ogloza, W., Porowski, C., Siwak, M., Stachowski, G.; Winiarski, M., Hentunen, V.-P., Nissinen, M., Liakos, A., Dogru, S. 2008 Nature., 452, 851

Yu, Q., & Tremaine, S. 2002 MNRAS., 335, 965