LONG-TERM EVOLUTION OF AND X-RAY EMISSION FROM A RECOILING SUPERMASSIVE BLACK HOLE IN A DISK GALAXY

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ABSTRACT

Recent numerical relativity simulations have shown that the emission of gravitational waves at the merger of two black holes gives a recoil kick to the final BH. We follow the orbits of a recoiling supermassive black hole (SMBH) in a fixed background potential of a disk galaxy including the effect of dynamical friction. If the recoil velocity of the SMBH is smaller than the escape velocity of the galaxy, the SMBH moves around in the potential along a complex trajectory before it spirals into the galactic center through dynamical friction. We consider the accretion of gas onto the SMBH from the surrounding interstellar medium and estimate the X-ray luminosity of the SMBH. We find that it can be larger than $3 \times 10^{39}$ erg s$^{-1}$ or the typical X-ray luminosity of ultra-luminous X-ray sources, when the SMBH passes the galactic disk. In particular, the luminosity could exceed $\sim 10^{45}$ erg s$^{-1}$, if the SMBH is ejected into the galactic disk. The average luminosity gradually increases as the SMBH spirals into the galactic center. We also estimate the probability of finding recoiling SMBHs with X-ray luminosities of $> 3 \times 10^{39}$ erg s$^{-1}$ in a disk galaxy.

Key words: black hole physics – galaxies: nuclei – ISM: general – X-rays: general

Online-only material: color figures

1. INTRODUCTION

Thanks to recent breakthroughs in numerical relativity, it has been shown that the loss of linear momentum radiated away in the form of gravitational waves induces a large recoil velocity of the merged binary black hole (BH). This would have been happened for supermassive black holes (SMBHs) at the centers of galaxies, if two SMBHs coalesce after a major galaxy merger. Since the maximum velocity would reach $\sim 4000$ km s$^{-1}$ (e.g., González et al. 2007; Campanelli et al. 2007), the SMBH could escape from its host galaxy. However, if the recoil velocity is a little smaller than the escape velocity of the galaxy, the SMBH would orbit in the potential well of the galaxy for a long time. The identification of observational signatures of such recoiling SMBHs is important for studies about the growth of BHs as well as the general relativity.

In addition to direct detection of gravitational waves, a number of ideas have been proposed for detection of observational signatures of recoiling BHs through electromagnetic waves. Kapoor (1976, 1983) indicated that stellar captures can lead to the formation of an accretion disk–star system about the SMBH, and that the emission from the SMBH could be observable. Madau & Quataert (2004) and Loeb (2007) argued that a recoiling SMBH would be observed as an off-nuclear quasar until the gas carried by the SMBH is depleted, although Bonning et al. (2007) found no convincing evidence for recoiling SMBHs carrying accretion disks in the Sloan Digital Sky Survey (SDSS) data. Merritt et al. (2004) indicated that the displacement of a recoiling SMBH transfers energy to the stars in the galactic nucleus and converts a steep density cusp into a core. Volonteri (2007) discussed the influence of the merger and ejection of SMBHs from the galactic centers on the relation of the BH mass and the velocity dispersion of the galaxy. Gualandris & Merritt (2008) indicated that helical radio structures could be observed around a recoiling SMBH because of the oscillation of the SMBH in the core of the host galaxy. Lippai et al. (2008) showed that prompt shocks are created in the gas disk around a recoiling SMBH and that the shocks could result in an afterglow, and the luminosity and characteristic photon energy increase with time. Komreich & Lovelace (2008) discussed that the SMBH displacement may give rise to observable non-axisymmetries in the morphology and dynamics of the stellar and gaseous disk of the host galaxy. de la Fuente Marcos & de la Fuente Marcos (2008) examined the influence of a runaway SMBH passage through intergalactic medium, and indicated that the SMBH is able to ignite star formation efficiently in the wake of its trajectory. Komossa & Merritt (2008) indicated that a recoiling SMBH carries stars, and the electromagnetic flares from the stars that are tidally disrupted by the SMBH would be observable.

Recently, Volonteri & Perna (2005) studied the assembly and growth of BHs in a hierarchical structure formation scenario. They computed the luminosity distribution produced by intermediate mass black holes (IMBHs) accreting from their circumstellar medium. Blecha & Loeb (2008) calculated the trajectory of a SMBH ejected in a smooth background potential that includes both a stellar bulge and a gaseous disk (see also Vicari et al. 2007), and estimated the gas accretion rate onto the SMBH as a function of time. Fujita (2008, hereafter Paper I) also calculated the trajectory of a SMBH ejected in a realistic background potential of a disk galaxy. We calculated the accretion rate of gas onto the SMBH from the interstellar medium (ISM) in the galactic disk, and estimated the X-ray luminosity based on a model of a radiatively inefficient accretion flow (RIAF; Narayan 2005). We showed that the luminosity of the SMBH can be comparable to or even larger than those of ultra-luminous X-ray sources (ULXs) observed in galaxies ($L_X \gtrsim 3 \times 10^{39}$ erg s$^{-1}$; Colbert & Mushotzky 1999; Makishima et al. 2000; Mushotzky 2004).

However, in that study, the effect of dynamical friction was not explicitly included. If dynamical friction is effective, the SMBH gradually settles down to the galactic center. Since the accretion rate depends on the density of the surrounding ISM, we expect that the X-ray luminosity increases accordingly. In this
paper, we study the long-term orbital and luminosity evolution of a recoiling SMBH in a disk galaxy, considering the effect of dynamical friction. This paper is organized as follows. Our models and choice of parameters are outlined in Section 2. The results of calculations are presented in Section 3 and discussed in Section 4. Finally, in Section 5, we present our conclusions.

2. MODELS

We consider SMBH mergers in a normal disk galaxy for the sake of simplicity, although the galaxy interaction and merger supposedly affect the original disk. However, the process of the settling of SMBHs between the galaxy merger and the set-in of effective emission of gravitational waves from the SMBHs, which leads to the merger of the SMBHs, has not been understood (e.g., Begelman et al. 1980; Iwasawa et al. 2006). If the timescale of the SMBH merger is long, the galaxy may be significantly relaxed when the recoil occurs (Blecha & Loeb 2008). Anyway, in order to follow the galaxy and SMBH mergers self-consistently, we would need ultra-high-resolution simulations of galaxy mergers that can resolve the settling of SMBHs in the core of the merged galaxy.

The model of a disk galaxy is the same as that in Paper I. The galaxy potential consists of three components, which are a Miyamoto & Nagai (1975) disk, Hernquist spheroid (Hernquist 1990), and logarithmic halo (Binney & Tremaine 2008):

\[
\Phi_{\text{disk}} = -\frac{GM_{\text{disk}}}{\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2}},
\]

\[
\Phi_{\text{sphere}} = -\frac{GM_{\text{sphere}}}{r + c},
\]

\[
\Phi_{\text{halo}} = \frac{1}{2}v_{\text{halo}}^2 \ln \left[ R^2 + \left( \frac{z}{q} \right)^2 + d^2 \right],
\]

where \( R = \sqrt{x^2 + y^2} \) and \( z \) are cylindrical coordinates aligned with the galactic disk, and \( r = \sqrt{R^2 + z^2} \). The parameters are those of the Galaxy. We take \( M_{\text{disk}} = 1.0 \times 10^{11} \ M_{\odot}, M_{\text{sphere}} = 3.4 \times 10^{10} \ M_{\odot}, a = 6.5 \ \text{kpc}, b = 0.26 \ \text{kpc}, c = 0.7 \ \text{kpc}, d = 13 \ \text{kpc}, \) and \( q = 0.9 \). \( v_{\text{halo}} \) is determined so that the circulation velocity for the total potential, \( \Phi = \Phi_{\text{disk}} + \Phi_{\text{sphere}} + \Phi_{\text{halo}} \), is 220 km s\(^{-1}\) at \( R = 7 \ \text{kpc} \) (see Law et al. 2005). Contrary to Paper I, we include dynamical friction in the equation of motion for the SMBH (Chandrasekhar 1943; Binney & Tremaine 2008):

\[
\dot{v} = -4\pi G^2 v_{\text{BH}} \sum_i \rho_i(\dot{X}_i) \ln \Lambda_i \frac{v_{\text{rel},i}}{v_{\text{rel},i}^2} \Phi_{\text{disk}}(\dot{X}_i)_{|z=0}.
\]

where \( v = (v_x, v_y, v_z) \) is the velocity of the SMBH, \( \ln \Lambda_i \) is the Coulomb logarithm, and the suffix \( i \) refers to disk, sphere, or halo. The relative velocities are defined as \( v_{\text{rel,disk}} = v - v_{\text{circ,disk}} \), \( v_{\text{rel,sphere}} = v \), and \( v_{\text{rel,halo}} = v \), where \( v_{\text{circ,disk}} \) is the circulation velocity of the disk, which is given by

\[
v_{\text{circ,disk}}^2 = \frac{\partial \Phi}{\partial R} |_{z=0}.
\]

(Binney & Tremaine 2008). The densities are given by

\[
\rho_{\text{disk}} = \frac{b^2 M_{\text{disk}}}{4\pi} \frac{a R^2 + (a + 3\sqrt{z^2 + b^2})(a + \sqrt{z^2 + b^2})^2}{[R^2 + (a + \sqrt{z^2 + b^2})^2]^{1/2}(z^2 + b^2)^{1/2}},
\]

\[
\rho_{\text{sphere}} = \frac{M_{\text{sphere}}}{2\pi r (c + r)^3},
\]

\[
\rho_{\text{halo}} = \frac{v_{\text{halo}}^2}{4\pi G q^2} \frac{(2q^2 + 1)d^2 + R^2 + (2-q^2)z^2}{(d^2 + R^2 + z^2q^{-2})^2}.
\]

(Miyamoto & Nagai 1975; Hernquist 1990; Binney & Tremaine 2008). We assume that part of the disk consists of the ISM; its density is represented by \( \rho_{\text{ISM}} = f_{\text{ISM}} \rho_{\text{disk}} \). For most models we studied, we take \( f_{\text{ISM}} = 0.2 \), which is based on the observations of the Galaxy (e.g., Binney & Tremaine 2008). In Equation (4), the factor \( I(\dot{X}_i) \) is given by

\[
I(\dot{X}_i) = \text{erf}(\dot{X}_i) - \frac{2X_i}{\sqrt{\pi}} e^{-X_i^2},
\]

where \( X_i = v_{\text{rel},i}/(\sqrt{2}\sigma_i) \) and \( \sigma_i \) is the one-dimensional velocity dispersion. For the disk velocity dispersion, we set \( \sigma_{\text{disk}} \propto \rho_{\text{disk}}^z(\mathbf{y}, z = 0) \) (Lewis & Freeman 1989) and fix the normalization by assuming that the disk has a Toomre Q-parameter of 1.5 at \( R = 7 \ \text{kpc} \) (Velazquez & White 1999). For the spheroid and halo, we use the common \( I(\dot{X}_i) \) and the velocity dispersion is

\[
\sigma_{\text{halo}} = \frac{\left(v_{\text{circ,sphere}}^2 + v_{\text{circ,halo}}^2\right)^{1/2}}{\sqrt{2}},
\]

where \( v_{\text{circ,sphere}} \) and \( v_{\text{circ,halo}} \) are the circulation velocities of the spheroid and halo, respectively (Taylor & Babul 2001).

Chandrasekhar’s (1943) formula for the dynamical friction force (the second term in the right side of Equation (4)) was derived assuming an infinite, homogeneous, and unchanging background. It is obviously not true for a SMBH that is kicked out of the galactic center and orbiting in the disk galaxy. However, N-body simulations have shown that it can be applied to various cases if one chooses the Coulomb logarithm appropriately. For a SMBH ejected from the center of a spherically symmetric galaxy, Gualandris & Merritt (2008) showed that \( 2 \lesssim \ln \Lambda \lesssim 3 \) is appropriate. Thus, we set \( \ln \Lambda_{\text{sphere}} = \ln \Lambda_{\text{halo}} = 2.5 \). For a disk galaxy, such N-body simulations have not been performed as far as we know. Instead of a SMBH, the evaluation of Chandrasekhar’s formula has been made for a dwarf galaxy infalling to a more massive disk galaxy. Taylor & Babul (2001) showed that \( \ln \Lambda_{\text{disk}} = 0.5 \) is appropriate. The small value of \( \ln \Lambda_{\text{disk}} \) probably reflects the small ratio of the disk scale height and the size of a dwarf galaxy, which corresponds to the ratio of maximum and minimum effective impact parameters of particles that contribute to the friction force (Taylor & Babul 2001). However, since a SMBH is a point source, we first assume that \( \ln \Lambda_{\text{disk}} = 2.5 \), which is the same as \( \ln \Lambda_{\text{sphere}} \) and \( \ln \Lambda_{\text{halo}} \), and then change the value to see the influence of the uncertainty on results.

The accretion of the surrounding gas onto an isolated BH has been studied by several authors (Fujita et al. 1998; Agol & Kamionkowski 2002; Mii & Totani 2005; Mapelli et al. 2006, and references therein). Most of the previous studies focused on stellar mass black holes (\(~10^3 \ M_{\odot}\)) or IMBHs (\(~10^5 \ M_{\odot}\)). In this study, we consider the accretion on a recoiling SMBH.

The accretion rate of the ISM onto the SMBH is given by the Bondi–Hoyle accretion (Bondi 1952):

\[
m = 2.5\pi G^2 \frac{m_{\text{BH}}^2 m_{\text{ISM}}}{(c_s^2 + v_{\text{rel,disk}}^2)^{3/2}},
\]
where $m_{\text{BH}}$ is the mass of the BH, and $c_s (=10\text{ km s}^{-1})$ is the sound velocity of the ISM. The X-ray luminosity of the BH is given by

$$L_X = \eta \dot{m} c_s^2,$$

where $\eta$ is the efficiency. Since the accretion rate is relatively small for the mass of the BH, the accretion flow would be a RIAF (e.g., Ichimaru 1977; Narayan & Yi 1994; Abramowicz et al. 1995; Yuan et al. 2004). In this case, the efficiency follows $\eta \propto \dot{m}$ for $L_X \lesssim 0.1L_{\text{Edd}}$, where $L_{\text{Edd}}$ is the Eddington luminosity (e.g., Kato et al. 1998). Therefore, we assume that $\eta = \eta_{\text{Edd}}$ for $\dot{m} > 0.1\dot{m}_{\text{Edd}}$ and $\eta = \eta_{\text{Edd}}\dot{m}/(0.1\dot{m}_{\text{Edd}})$ for $\dot{m} < 0.1\dot{m}_{\text{Edd}}$, where $\dot{m}_{\text{Edd}} = L_{\text{Edd}}/(c^2\eta_{\text{Edd}})$ (Mii & Totani 2005). We assume that $\eta_{\text{Edd}} = 0.1$.

We solve Equation (4) with Mathematica 6.0 using a command NDsolve. The algorithm of the integration is automatically chosen. We have confirmed that the fractional energy error that arises in the integration of an orbit per cycle is $\lesssim 10^{-6}$.

Table 1

| Models | $m_{\text{BH}}$ $(M_\odot)$ | $v_0$ (km s$^{-1}$) | $\ln \Lambda_{\text{disk}}$ | $f_{\text{ISM}}$ | $r_{\text{max,60}}$ (kpc) | $L_{\text{max,60}}$ (erg s$^{-1}$) | $\langle t_{\text{df}} \rangle$ (Gyr) | $P_{X,39}$ | $P_{X,39}$ | $P_{1,39}$ | $P_{1,39}$ |
|--------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| A1     | $3 \times 10^6$ | 500             | 2.5             | 0.2             | 1               | $1 \times 10^{38}$ | 0.63             | 0.0058          | 0.0003          | 0               | 0               |
| A2     | $3 \times 10^6$ | 600             | 2.5             | 0.2             | 2               | $5 \times 10^{37}$ | 6.4              | 0.0018          | 0.0010          | 0               | 0               |
| B1     | $1 \times 10^7$ | 500             | 2.5             | 0.2             | 0.7             | $4 \times 10^{39}$ | 0.13             | 0.23            | 0.0027          | 0               | 0               |
| B2     | $1 \times 10^7$ | 700             | 2.5             | 0.2             | 2               | $1 \times 10^{39}$ | 1.3              | 0.0756          | 0.0080          | 0.0033          | 0.0033          |
| B3     | $1 \times 10^7$ | 700             | 2.5             | 0.2             | 10              | $1 \times 10^{38}$ | $>0$             | 0.031           | 0.031           | 0.031           | 0.031           |
| C2     | $3 \times 10^7$ | 600             | 2.5             | 0.2             | 1               | $2 \times 10^{38}$ | 0.16             | 0.58            | 0.0093          | 0.10            | 0.0016          |
| C3     | $3 \times 10^7$ | 700             | 2.5             | 0.2             | 7               | $1 \times 10^{38}$ | 3.7              | 0.31            | 0.15            | 0.22            | 0.11            |
| C4     | $3 \times 10^7$ | 800             | 2.5             | 0.2             | 40              | $4 \times 10^{38}$ | $>10$            | 0.0020          | 0.0020          | 0.0018          | 0.0018          |
| C"2   | $3 \times 10^7$ | 600             | 1.5             | 0.2             | 1               | $2 \times 10^{39}$ | 0.16             | 0.58            | 0.0090          | 0.10            | 0.0016          |
| C"3   | $3 \times 10^7$ | 700             | 1.5             | 0.2             | 7               | $1 \times 10^{38}$ | 3.5              | 0.18            | 0.073           | 0.12            | 0.053           |
| b0     | $1 \times 10^7$ | 400             | 2.5             | 0.2             | 0.7             | $2 \times 10^{39}$ | 3.7              | 0.24            | 0.12            | 0.16            | 0.097           |
| d3     | $1 \times 10^6$ | 700             | 2.5             | 0.2             | 1               | $3 \times 10^{41}$ | 0.066            | 0.95            | 0.0062          | 0.21            | 0.0013          |

3. RESULTS

The SMBH is placed at the center of the galaxy at $t = 0$. The SMBH is ejected on the $x-z$ plane at $t = 0$. The parameters of our models ($m_{\text{BH}}, v_0, \ln \Lambda_{\text{disk}}, f_{\text{ISM}}$) are shown in Table 1. In this section, we consider models in which the SMBH neither falls into the galactic center too quickly through dynamical friction nor escapes from the galaxy (models A1–C4 in Table 1). The mass of the SMBH is $3 \times 10^6$ to $3 \times 10^7 M_\odot$, which is comparable to or somewhat larger than that of the SMBH at the center of the Galaxy ($\sim 3.7 \times 10^6 M_\odot$; Schödel et al. 2002; Ghez et al. 2005). The direction of the ejection changes from $\theta = 0^\circ$ to $90^\circ$, where $\theta = 0^\circ$ corresponds to the $z$-axis. The initial velocity of the SMBH is $v_0 = 500–800 \text{ km s}^{-1}$.

We stop the calculation if (1) $t = 10 \text{ Gyr}$ or if (2) $r < 10 \text{ pc}$ and $v < 1 \text{ km s}^{-1}$ is satisfied. We define the time when the condition (2) is satisfied as $t_{\text{df}}$. Figures 1–3 show the trajectories of the SMBHs for models A1, B2, and C3, respectively. Although the SMBHs are ejected on the $x-z$ plane at $t = 0$, they are not confined to the plane because of the circulation of the galactic disk and dynamical friction. Figures 4–6 show the distance from the galactic center ($r$) and the luminosity of the SMBHs ($L_X$) for models A1, B2, and

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1. http://support.wolfram.com/mathematica/mathematics/numerics
ndsolvereferences.en.html
Figure 2. Same as Figure 1 but for model B2.

(A color version of this figure is available in the online journal.)

Figure 3. Same as Figure 1 but for model C3.

(A color version of this figure is available in the online journal.)

Figure 4. (a) Distance from the galactic center and (b) the luminosity of the SMBH for model A1 for $0 < t < t_D$ when $\theta = 60^\circ$.

(A color version of this figure is available in the online journal.)
and $C_3$, respectively ($0 < t < t_{\text{df}}$ and $\theta = 60^\circ$). The distance gradually decreases through the dynamical friction. The infall of the SMBHs accelerates as $t$ approaches $t_{\text{df}}$. The luminosity on average increases as the SMBHs spiral into the galactic center, where $\rho_{\text{ISM}}$ is large. In Table 1, we present the maximum distance from the center of the galaxy when $\theta = 60^\circ$ ($r_{\text{max,60}}$). We note that the maximum radius is not much dependent on $\theta$.

Figures 7–9 show the evolutions of $|z|$, $v_{\text{rel,disk}}$, and $L_X$ for $0 < t < 0.1 t_{\text{df}}$ for models A1, B2, and C3, respectively ($\theta = 60^\circ$). The luminosity of the SMBHs ($L_X$) increases instantaneously, when they pass the galactic disk. The heights of the spikes in Figures 7(c), 8(c), and 9(c) are uneven. This is because the luminosity $L_X$ depends on both $v_{\text{rel,disk}}$ and $\rho_{\text{ISM}}$ (see Equation (11)), and the latter strongly depends on $z$. In Table 1, we present the maximum X-ray luminosity of the SMBHs for $\theta = 60^\circ$ and $t < 0.2 t_{\text{df}}$ ($L_{\text{max,60}}$). The luminosity $L_{\text{max,60}}$ is larger for larger $m_{\text{BH}}$ and smaller $v_0$. In some of the models of $m_{\text{BH}} \geq 1 \times 10^7 M_\odot$, $L_{\text{max,60}}$ reaches $3 \times 10^{39}$ erg s$^{-1}$, which is the Eddington luminosity of a stellar mass BH ($\sim 20 M_\odot$) and is often used as a threshold of ULXs (Colbert & Mushotzky 1999; Makishima et al. 2000; Mushotzky 2004). When $m_{\text{BH}}$ and $v_0$ are given and $\theta$ is not fixed, the X-ray luminosity before the SMBHs are affected by dynamical friction tends to be larger when $\theta$ is closer to $90^\circ$, because their trajectories are included in the galactic disk, where $\rho_{\text{ISM}}$ is large. However, the tendency is not clear when $\theta \lesssim 80^\circ$, because their orbits are scattered in the asymmetric potential of the galaxy. Thus, the maximum luminosity does not much depend on $\theta$. Figures 7–9 indicate that when the SMBH is especially bright, the relative velocity between the SMBH and the surrounding ISM (or stars) is $v_{\text{rel,disk}} \sim v_{\text{crit}}$ ($\sim 220$ km s$^{-1}$), which means that the SMBH passes the apocenter of its orbit ($v \sim 0$) close to the galactic plane. It could be used as a clue to find the traveling SMBH observationally, if atomic line emission associated with the X-ray source is detected and the velocity is estimated through the Doppler shift.

In Table 1, we present the average of $t_{\text{df}}$, which is referred to as $\langle t_{\text{df}} \rangle$; we calculate 30 orbits and corresponding $t_{\text{df}}$ by changing $\theta$ from $3^\circ$ to $90^\circ$ by $3^\circ$ at a time, and average $t_{\text{df}}$ by $\theta$, weighting with $\sin \theta$. Table 1 shows that $\langle t_{\text{df}} \rangle \gtrsim 0.1$ Gyr for models A1–C4, and that $\langle t_{\text{df}} \rangle$ is smaller for larger $m_{\text{BH}}$ and smaller $v_0$.

Following Paper I, we estimate the probability of observing SMBHs with luminosities larger than a threshold luminosity $L_{\text{th}}$, assuming that SMBHs are ejected in random directions at the centers of galaxies. For each model, we calculate 30 evolutions of the luminosity by changing $\theta$ from $3^\circ$ to $90^\circ$ by $3^\circ$ at a time. Then, we obtain the period during which the relation $L_X > L_{\text{th}}$ is satisfied for each $\theta$, and divide the period by $t_{\text{df}}$. This is the fraction of the period during which the BH luminosity becomes larger than $L_{\text{th}}$. We refer to this fraction as $f(\theta)$. We average $f(\theta)$ by $\theta$, weighting with $\sin \theta$, and obtain the probability of observing SMBHs with $L_X > L_{\text{th}}$. In Table 1, we present the probability $P_{39>39}$ when $L_{\text{th}} = 3 \times 10^{39}$ erg s$^{-1}$. For models A1–C4, $P_{39>39} = 0.0018–0.58$.

We also estimate the age-corrected probability of observing SMBHs with $L_X > L_{\text{th}} = 3 \times 10^{39}$ erg s$^{-1}$, which is obtained by averaging min$[t_{\text{df}}, t_{\text{age}}] f(\theta)/t_{\text{age}}$ by $\theta$, weighting with $\sin \theta$, where $t_{\text{age}}$ is the age of a galaxy and we assume that $t_{\text{age}} = 10$ Gyr. We refer to the age-corrected probability as $P_{39>39}$ and show it in Table 1.

4. DISCUSSION

We have found that a SMBH that had been ejected from the center of a disk galaxy could be observed in the galactic disk with an X-ray luminosity of $L_X \gtrsim 3 \times 10^{39}$ erg s$^{-1}$. The
luminosity gradually increases as the SMBH settles down to the galactic center through dynamical friction.

In Section 3, we follow the evolution until the SMBH spirals down to $r = 10$ pc. However, if $r$ is too small, the SMBH cannot be discriminated from the one that would have been sitting at the galactic center without being affected by a recoil. Therefore, we estimate the probability of observing SMBHs with $L_X > L_{th} = 3 \times 10^{39}$ erg s$^{-1}$ and $r > 1$ kpc, and call it $P_{1,3,39}$. We also calculate the time age-corrected one ($\tilde{P}_{1,3,39}$).

Since $P_{1,3,39}$ and $\tilde{P}_{1,3,39}$ are derived by adding another condition $r > 1$ kpc to $P_{3,39}$ and $\tilde{P}_{3,39}$, respectively, it is natural that $P_{1,3,39} \ll P_{3,39}$ and $\tilde{P}_{1,3,39} \ll \tilde{P}_{3,39}$ (Table 1). As is mentioned in Section 2, dynamical friction of a massive point particle orbiting in a disk galaxy has not been studied very much. Thus, there is some uncertainty about the Coulomb logarithm we should take. Therefore, we change the value of $\ln \Lambda$ disk to estimate the uncertainty. Models C2 and C3 are respectively the same as models C2 and C3 except for $\ln \Lambda_{\text{disk}}$. For these models, we set $\ln \Lambda_{\text{disk}} = 1.5$. Table 1 shows that there is not much difference between the results of models C2 and those of C2. This is because the maximum distances to the apocenters are $\lesssim 1$ kpc, where the spheroidal component is dominant, and the SMBH is not greatly affected by the dynamical friction from the galactic disk. On the other hand, $P_{3,39}$, $\tilde{P}_{3,39}$, $P_{1,3,39}$, and $\tilde{P}_{1,3,39}$ for models C3 and C3 are significantly different, because the SMBH is ejected outside the spheroid. The differences are especially made by that of the orbits of $\theta \sim 90^\circ$. When $\theta \sim 90^\circ$, the SMBH is ejected into the galactic disk. If the dynamical friction from the disk is very effective, the SMBH moves along with the disk ($v_{\text{rel,disk}} \sim 0$) and does not easily fall into the galactic center. This actually happens for model C3 ($t_{\text{df}} > 10$ Gyr when $\theta = 90^\circ$; Figure 10(a)). In this case, the SMBH continues to accrete the ISM in the disk and is bright for a long time (Figure 10(b)). Since this SMBH is very bright ($L_X \gtrsim 10^{35}$ erg s$^{-1}$), it could be easily observed if such SMBHs actually exist. For model C3, the dynamical friction from the disk is not strong enough to hold back the SMBH from the infall even when $\theta = 90^\circ$.

We also consider the uncertainty of the ISM fraction $f_{\text{ISM}}$. Model C3a is the same as model C3 but for $f_{\text{ISM}} = 0.1$. For parameters we adopted, the accretion efficiency is $\dot{m} < 0.1 \dot{m}_{\text{Edd}}$ in most cases. Therefore, we obtain $L_X \propto \dot{m} \propto \rho_{\text{ISM}} \propto f_{\text{ISM}}^2$ (Equations (11) and (12)), which means that the X-ray luminosity in model C3a is one-fourth of that in model C3. Accordingly, $P_{3,39}$, $\tilde{P}_{3,39}$, $P_{1,3,39}$, and $\tilde{P}_{1,3,39}$ in model C3a are smaller than those in model C3, respectively. However, the differences are not large, because $L_X$ changes rapidly.

For comparison, we also investigate a model with a smaller initial velocity (model b0), because we consider a Milky-Way-type galaxy, which is generally expected to experience minor mergers rather than major mergers. In such cases, large recoil
velocities as adopted above would not be common. A model with a larger SMBH mass is also considered (model d3). Figures 11 and 12 show the trajectories of the SMBHs for models b0 and d3, respectively. Their ejection angles are \( \theta = 60^\circ \). In these models, \( v_0 \) is too small (model b0), or \( m_{\text{BH}} \) is too large (model d3) for the SMBH to be ejected from the spheroidal component of the galaxy. Thus, it would be difficult to recognize them as recoiling SMBHs, if their host galaxies are moderately distant. The SMBHs are almost confined to the \( x-z \) plane, because the dynamical friction from the spheroidal component overwhelms that from the galactic disk. Table 1 shows that \( P_{3e39} \) for models b0 and d3 is relatively large because of small \( v_0 \) and large \( m_{\text{BH}} \), respectively. The SMBHs set back to the galactic center in only several orbital periods (\( t_{\text{df}} \sim 0.01 \) and 0.07 Gyr, respectively).

Since we have included the effect of dynamical friction when we consider the evolution of \( L_X \), we can constrain the probability to find SMBHs with \( L_X > L_{\text{th}} \) more precisely than Paper I. It has been estimated that for comparable mass binaries with dimensionless spin values of 0.9, only \sim 10\% of all mergers are expected to result in an ejection speed of \( \sim 500-800 \) km s\(^{-1}\) (Schnittman & Buonanno 2007; Baker et al. 2008). Since the ejection speed is smaller for mergers with large mass ratios and smaller spin values, the actual fraction would be smaller.

Although we consider the mergers of BHs with the masses currently observed at the centers of disk galaxies, it is unlikely that a galaxy would have undergone many mergers of BHs with such masses (e.g., Enoki et al. 2004; Micic et al. 2007). The number of such mergers that a galaxy has undergone would be \( N \lesssim 1 \). Thus, since \( \tilde{P}_{3e39} \), \( \tilde{P}_{1,3e39} \lesssim 0.1 \) (Table 1), the probability that a disk galaxy has a traveling SMBH with a luminosity comparable to or larger than that of ULXs is \lesssim 1 \times 10^{-2}\.

Since the probability is not so large, extensive surveys would be required to find the SMBHs running in the galactic disks. In the future, it would be interesting to study whether the probability is larger than that of finding SMBHs immediately after the ejection from the galactic centers with velocities of \( > 1000 \) km s\(^{-1}\) (e.g., Loeb 2007). Since the SMBHs ejected into galactic disks are very bright (Figure 10(b)), they could be
observed even in distant galaxies. As was discussed in Paper I, observations in bands other than X-rays would also be useful to detect the SMBHs orbiting in disk galaxies and discriminate them from IMBHs.

5. CONCLUSION

We have investigated the trajectory of a SMBH ejected from the galactic center through the emission of gravitational waves at the merger of two BHs. We included the effect of dynamical friction. For a disk galaxy comparable to the Galaxy, the orbit decays on a timescale of $\gtrsim 10^8$ yr if the initial velocity of the SMBH is $\sim 500$–800 km s$^{-1}$ and the mass is $\sim 10^7 M_\odot$. The SMBH accretes the surrounding ISM when it passes the galactic disk. Since the accretion rate is larger when the relative velocity between the SMBH and the ISM is smaller, the accretion rate is the largest when the SMBH passes the apocenter of its orbit that reside in the galactic disk. Assuming that the accretion flow is a RIAF, we estimated the X-ray luminosity of the SMBH. We found that the X-ray luminosity can reach $L_X \gtrsim 3 \times 10^{39}$ erg s$^{-1}$, which is comparable to or even larger than those of ULXs. In particular, the X-ray luminosity would reach $L_X \gtrsim 10^{45}$ erg s$^{-1}$, if the SMBH is ejected into the galactic plane. Since the probability of finding the traveling SMBHs with $L_X \gtrsim 3 \times 10^{39}$ erg s$^{-1}$ in a disk galaxy is $\lesssim 0.01$, extensive surveys would be required to find them.

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