X-RAY EMission FROM A SUPERMassive BLACK HOLE EJECTED FROM THE CENTER OF A GALAXY

YUTAKA FUJITA
Department of Earth and Space Science, Graduate School of Science, Osaka University, 1-1 Machikaneyama-cho, Toyonaka, Osaka 560-0043, Japan

Received 2008 June 25; accepted 2008 August 5; published 2008 August 21

ABSTRACT

Recent studies have indicated that the emission of gravitational waves at the merger of two black holes gives a kick to the final black hole. If the supermassive black hole at the center of a disk galaxy is kicked but the velocity is not large enough to escape from the host galaxy, it will fall back onto the disk and accrete the interstellar medium (ISM). We calculate the orbit of a recoiled black hole in a fixed potential, and thus the luminosity of a black hole depend on the mass of the black hole and the density of the gas surrounding it (see eq. [7]). Since the mass of a stellar-mass black hole is small, its luminosity becomes large enough to be observed only when it plunges into a high-density region such as a molecular cloud. On the other hand, in this Letter, we show that a recoiled supermassive black hole can shine even in the ordinary region of a galactic disk because of its huge mass.

2. MODELS

We calculate the orbit of a recoiled black hole in a fixed galaxy potential. The galaxy potential consists of three components, which are a Miyamoto & Nagai (1975) disk, Hernquist spheroid, and logarithmic halo:

\[ \Phi_{\text{disk}} = -\frac{GM_{\text{disk}}}{\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2}}, \]
\[ \Phi_{\text{sphere}} = -\frac{GM_{\text{sphere}}}{r + c}, \]
\[ \Phi_{\text{halo}} = \frac{1}{2} \frac{v_{\text{halo}}^2}{\Phi_{\text{halo}}} \ln \left[ \frac{R^2 + \left(\frac{z}{q}\right)^2 + d^2}{R^2 + \left(\frac{z}{q}\right)^2 + d^2} \right], \]

where \( R \) \((=x^2 + y^2)^{1/2}\) and \( z \) are cylindrical coordinates aligned with the galactic disk, and \( r = (R^2 + z^2)^{1/2}\). We adopt the parameters for the Galaxy. We take \( M_{\text{disk}} = 1.0 \times 10^{11} M_\odot\), \( M_{\text{sphere}} = 3.4 \times 10^{10} M_\odot\), \( a = 6.5 \) kpc, \( b = 0.26 \) kpc, \( c = 0.7 \) kpc, \( d = 13 \) kpc, and \( q = 0.9\); \( v_{\text{halo}} \) is determined so that the circular velocity for the total potential is 220 km s\(^{-1}\) at \( R = 7 \) kpc (see Law et al. 2005). We solve the equation of motion for the supermassive black hole:

\[ \dot{r} = -\nabla \Phi, \]

where \( \mathbf{v} = (v_x, v_y, v_z) \) is the velocity of the black hole, and \( \Phi = \Phi_{\text{disk}} + \Phi_{\text{sphere}} + \Phi_{\text{halo}} \). The density of the disk is given by

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

(Miyamoto & Nagai 1975). We assume that part of the disk consists of the ISM; its density is represented by \( \rho_{\text{ISM}} = \)
The accretion rate of the ISM onto the supermassive black hole is given by the Bondi-Hoyle accretion (Bondi 1952):

$$\dot{m} = \frac{4\pi G^2 m_{\text{BH}} \rho_{\text{ISM}}}{c_s^2 + v_{\text{rel}}^2 \ln(1 + \lambda)}.$$  \hspace{1cm} \text{(7)}

where $m_{\text{BH}}$ is the mass of the black hole, $c_s$ (10 km s$^{-1}$) is the sound velocity of the ISM, and $v_{\text{rel}}$ is the relative velocity between the black hole and the surrounding ISM. We assume that the orbit of the black hole is confined to the x-z plane ($v_{\text{rel}}^z = 0$). Thus, the relative velocity is simply given by $v_{\text{rel}}^{\text{x,y}} = v_{\text{rel}}^x + \sqrt{v_{\text{rel}}^y^2 + v_{\text{rel}}^z^2}$. The X-ray luminosity of the black hole is given by

$$L_X = \eta \dot{m} c^2,$$  \hspace{1cm} \text{(8)}

where $\eta$ is the efficiency. Since the accretion rate is relatively small for the mass of the black hole, the accretion flow would be a radiatively inefficient accretion flow (RIAF; Ichimaru 1977; Narayan 2005). In this case, the efficiency follows $\eta \propto \dot{m}$ for $L_x \leq 0.1 L_{Edd}$ where $L_{Edd}$ is the Eddington luminosity (e.g., Kato et al. 1998). Therefore, we assume that $\eta = \eta_{Edd}$ for $m > 0.1 m_{Edd}$ and $\eta = \eta_{Edd} m/(0.1 m_{Edd})$ for $m < 0.1 m_{Edd}$ where $m_{Edd} = L_{Edd}/(c^2 \eta_{Edd})$ (Mii & Totani 2005). We assume that $\eta_{Edd} = 0.1$.

We solved equation (4) with Mathematica 6.0 using a command NDSolve. The black hole is ejected on the x-z plane at $t = 0$. The direction of the ejection changes from $\theta = 0^\circ$ to $90^\circ$, where $\theta = 0^\circ$ corresponds to the z-axis. We calculate the orbit until $t = t_{\text{max}}$, which is chosen to be much larger than the period of revolution and to be smaller than the timescale of dynamical friction. The latter is estimated to be

$$I_{\text{df}} = \frac{v_{\text{rel}}^2}{4\pi G^2 m_{\text{BH}} \rho \ln(\Lambda)}.$$  \hspace{1cm} \text{(9)}

(Binney & Tremaine 2008), where $\rho$ is the total density (disk + sphere + halo). The halo component does not much affect the dynamical friction. Since N-body simulations for a spherically symmetric potential showed that the Coulomb logarithm is $\ln(\Lambda) \sim 2 - 3$ (Gualandris & Merritt 2008), we take $\ln(\Lambda) = 2.5$. The effects of dynamical friction on orbits in a complex potential like the one we adopted would be complicated and ideally should be studied with high-resolution N-body simulations. Thus, equation (9) should be regarded as a rough estimate of the timescale of the dynamical friction.

3. Results

The black hole is placed at the center of the galaxy at $t = 0$. Since we do not know the distributions of mass and initial velocity ($v_0$) of the black hole, we consider situations in which the emission from it would be observed easily. That is, the luminosity of the black hole would be large, and the observable time would be long.

We consider five combinations of $m_{\text{BH}}$ and $v_0$, shown in Table 1. If we take larger $m_{\text{BH}}$ and/or smaller $v_0$, the dynamical friction becomes more effective and the black hole quickly falls into the galaxy center. On the other hand, if we take smaller $m_{\text{BH}}$ and/or larger $v_0$, the luminosity of the black hole becomes too small to be observed (eq. [7]). Moreover, the black hole is not bound to the galaxy, if $v_0$ is too large. The dynamical friction is most effective when $\theta = 90^\circ$. In Table 1, we show the time average of the timescale, $\langle I_{\text{df}} \rangle_{\theta = 90^\circ}$ for $0 < t < t_{\text{max}}$ and $\theta = 90^\circ$.

Figure 1 shows the orbit of the black hole when $v_0 = 600$ km s$^{-1}$ and $\theta = 90^\circ$. Figure 2 shows the luminosity of the same black hole ($m_{\text{BH}} = 3 \times 10^7 M_\odot$). In Table 1, we present the distance of the apastrons from the center of the galaxy ($r_{\text{max}}$) when $\theta = 90^\circ$. It is to be noted that $r_{\text{max}}$ is not much smaller than $r_{\text{lim}}$ when $\theta = 90^\circ$.

---

**TABLE 1**

| $m_{\text{BH}}$ (M$_\odot$) | $v_0$ (km s$^{-1}$) | $t_{\text{max}}$ (Gyr) | $I_{\text{df}}$ (Gyr) | $r_{\text{max}}$ (kpc) | $L_{\text{X}}$ (erg s$^{-1}$) | $P_{\text{nu}}$ | $\dot{P}_{\text{nu}}$ |
|--------------------------|-------------------|----------------------|----------------------|----------------------|-------------------------------|-------------|-------------|
| $3 \times 10^7$         | 500               | 0.3                  | 1                    | $1 \times 10^8$      | 0                             | 0           | 0           |
| $1 \times 10^7$         | 500               | 0.3                  | 1                    | $1 \times 10^8$      | 0.064                         | 0.010       | 0           |
|                         | 600               | 1                    | 4.5                  | 3                    | 5 $\times 10^8$               | 0.016       | 0.012       |
|                         | 700               | 2                    | 27                   | 13                   | $8 \times 10^8$               | 0           | 0           |
| $3 \times 10^7$         | 500               | 0.3                  | 1                    | $1 \times 10^8$      | 0.56                          | 0.031       | 0           |
|                         | 600               | 1                    | 1.5                  | 3                    | $1 \times 10^8$               | 0.15        | 0.11        |
|                         | 700               | 2                    | 9.0                  | 13                   | $2 \times 10^8$               | 0           | 0           |

---

**Fig. 1.**—Orbit of a black hole for $0 < t < 1$ Gyr when $v_0 = 600$ km s$^{-1}$ and $\theta = 90^\circ$. [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 2.**—Luminosity of a black hole for $0 < t < 0.5$ Gyr when $m_{\text{BH}} = 3 \times 10^7 M_\odot$, $v_0 = 600$ km s$^{-1}$, and $\theta = 80^\circ$. [See the electronic edition of the Journal for a color version of this figure.]
dependent on $\theta$ for a given $v_0$. We also present the maximum X-ray luminosity of the black hole ($L_{\text{max}}$) when $\theta = 90^\circ$ in Table 1. For a given $m_{\text{BH}}$ and $v_0$, the X-ray luminosity is larger when $\theta$ is closer to $90^\circ$, because the orbit is included in the galactic disk, where $\rho_{\text{ISM}}$ is large.

We found that for $v_0 \approx 600$ km s$^{-1}$, the luminosity reaches its maximum when the black hole passes apastrons and when the apastrons reside in the disk of the galaxy. This is because $v$ decreases, $\rho_{\text{ISM}}$ increases, and thus $m$ increases there (eq. [7]). On the other hand, for $v_0 \sim 700$ km s$^{-1}$, the distance of the apastrons from the galactic center ($r_{\text{max}}$) is always large (Table 1). Thus, even if apastrons reside in the disk, $\rho_{\text{ISM}}$ is small there. Therefore, the luminosity of the black hole reaches its maximum between the apastron and periastron, and $L_{\text{max}}$ is smaller compared with the models of $v_0 \approx 600$ km s$^{-1}$ (Table 1).

Assuming that black holes are ejected in random directions at the centers of galaxies, we estimate the probability of observing black holes with luminosities larger than a threshold luminosity $L_{\text{th}}$. For given $m_{\text{BH}}$ and $v_0$, we calculate 91 evolutions of the luminosity by changing $\theta$ from $0^\circ$ to $90^\circ$ by $1^\circ$ 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 $t_{\text{max}}$. This is the fraction of the period during which the black hole luminosity becomes larger than $L_{\text{th}}$. We refer to this fraction as $f(\theta)$ and show it in Figure 3 when $m_{\text{BH}} = 3 \times 10^7$ M$_\odot$, $v_0 = 600$ km s$^{-1}$, and $L_{\text{th}} = 3 \times 10^{39}$ erg s$^{-1}$. We average $f(\theta)$ by $\theta$, weighting with $\sin \theta$, and obtain the probability of observing black holes with $L_X > L_{\text{th}}$. In Table 1 we present the probability $P_{39}$ when $L_{\text{th}} = 3 \times 10^{39}$ erg s$^{-1}$; for the parameters we chose, $P_{39} \approx 0.056$.

4. DISCUSSION

We have found that a supermassive black hole that had been recoiled at the center of a disk galaxy could be observed in the galactic disk with an X-ray luminosity of $L_X \approx 10^{39}$ erg s$^{-1}$. One of the candidates of such objects is ultraluminous X-ray sources (ULXs) observed in disk galaxies (Colbert & Mushotzky 1999; Makishima et al. 2000; Mushotzky 2004). They are found in off-nuclear regions of nearby galaxies and their X-ray luminosities exceed $3 \times 10^{39}$ erg s$^{-1}$, which are larger than the Eddington luminosity of a black hole with a mass of $\sim 20 M_\odot$. If ULXs are stellar-mass black holes, they might be explained by anisotropic emission (Reynolds et al. 1997; King et al. 2001), slim disks (Watarai et al. 2001), or thin, super-Eddington accretion disks (Belgennier 2002). On the other hand, there is some evidence that they are IMBHs, at least for some of them (Miller et al. 2004; Cropper et al. 2004).

Considering their X-ray luminosities and off-center positions, some of the ULXs might be the recoiled supermassive black holes. However, the fraction of supermassive black holes in the ULXs would not be large. Schnittman & Buonanno (2007) 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 $\sim 500$–700 km s$^{-1}$. Since the ejection speed is smaller for mergers with larger mass ratios and smaller spin values, the actual fraction would be smaller. Moreover, in our model, the time-corrected probability of observing black holes with $L_X > 3 \times 10^{39}$ erg s$^{-1}$ is $P_{39} \approx 0.1$, where $P_{39}$ is obtained by averaging $\min\{f(\theta)\}$, $t_{\text{max}}\bar{f}(\theta)\bar{t}_{\text{max}}$ by $\theta$, weighting with $\sin \theta$, and $t_{\text{max}}$ ($\sim 10$ Gyr) is the age of a galaxy (Table 1). Here we note that $t_{\text{max}}$ should be regarded as the upper limit of the actual timescale, because $t_{\text{max}}$ should decrease through the dynamical friction every time the black hole passes the dense region of the galaxy. Furthermore, our model indicates that a traveling supermassive black hole needs to have a mass comparable to the one currently observed at the galactic center in order to have large $L_X$. It is unlikely that a galaxy would have undergone many mergers of black holes with such masses. The number of such mergers that a galaxy has undergone would be $N \approx 1$. Thus, the probability that a galaxy has a traveling supermassive black hole with a luminosity comparable to that of ULXs is $\sim 1 \times 10^{-2}$.

In fact, current radio observations seem to show that ULXs observed so far are not supermassive black holes. Our model predicts that the X-ray luminosity of a supermassive black hole traveling through the galaxy is comparable to the typical X-ray luminosity of a LINER ($\sim 4 \times 10^{39}$–$5 \times 10^{41}$ erg s$^{-1}$; Terashima et al. 2002). LINERs seem to show core radio emission and many even have detectable jets (Nagar et al. 2005). On the other hand, radio observations have shown that no ULX has been detected with an unresolved radio core (Mushotzky 2004). Moreover, it has been shown that the optical luminosities of ULXs tend to be smaller than their X-ray luminosities (e.g., Ptak et al. 2006), which is inconsistent with typical RIAF spectra (e.g., Yuan et al. 2004). Thus, it is unlikely that most of the ULXs are the supermassive black holes traveling through the galaxies.

However, the recoiled supermassive black holes could be found through future extensive surveys. Our model predicts that the X-ray-luminous black holes should not be observed far from the centers of the host galaxies (say $\approx 10$ kpc), because $\rho_{\text{ISM}}$ should be small there (§ 3). Our model also predicts that the relative velocity between the X-ray source and the surrounding ISM and stars is $v_{\text{rel}} \approx v_{\text{cir}}$. If atomic line emission associated with the X-ray source is observed, the velocity could be estimated through the Doppler shift. Instead of X-rays, Macaron (2005) argued that radio detections may be best to search for isolated accreting black holes. The detailed analysis of the spectra and the time variability would be useful to determine the masses of the black holes (Mushotzky 2004). In the future, statistical studies could observationally constrain the probability of the mergers of black holes and the recoil.

5. CONCLUSION

We have shown that a supermassive black hole ejected from the center of the host disk galaxy will return to the galactic disk, if the initial velocity is smaller than the escape velocity of the galaxy. The black hole accretes the surrounding ISM.
and the resulting X-ray luminosity can reach $\approx 10^{39}$ erg s$^{-1}$, when it passes the apastrons in the disk. Although the luminosity of a recoiled supermassive black hole is comparable to that of ultraluminous X-ray sources (ULXs), it is unlikely that many of the observed ULXs are the supermassive black holes.

I would like to thank the anonymous referee for useful comments. I am grateful to H. Tagoshi and T. Tsuribe for useful discussion. Y. F. was supported in part by Grants-in-Aid from the Ministry of Education, Culture, Sports, Science, and Technology of Japan (20540269).

REFERENCES

Agol, E., & Kamionkowski, M. 2002, MNRAS, 334, 553
Begelman, M. C. 2002, ApJ, 568, L97
Binney, J., & Tremaine, S. 2008, Galactic Dynamics (2nd ed; Princeton: Princeton Univ. Press)
Blecha, L., & Loeb, A. 2008, MNRAS, in press (arXiv:0805.1420)
Bondi, H. 1952, MNRAS, 112, 195
Campanelli, M., Lousto, C., Zlochower, Y., & Merritt, D. 2007, ApJ, 659, L5
Colbert, E. J. M., & Mushotzky, R. F. 1999, ApJ, 519, 89
Cropper, M., Soria, R., Mushotzky, R. F., Wu, K., Markwardt, C. B., & Pakull, M. 2004, MNRAS, 353, 1024
Fujita, Y., Inoue, S., Nakamura, T., Mannoto, T., & Nakamura, K. E. 1998, ApJ, 495, L85
González, J. A., Hannam, M., Hannam, Sperhake, U., Brügmann, B., & Husa, S. 2007, Phys. Rev. Lett., 98, 231101
Gualandris, A., & Merritt, D. 2008, ApJ, 678, 780
Ichimaru, S. 1977, ApJ, 214, 840
Kato, S., Fukue, J., & Mineshige, S. 1998, Black-Hole Accretion Disks (Kyoto: Kyoto Univ. Press)
King, A. R., Davies, M. B., Ward, M. J., Fabbiano, G., & Elvis, M. 2001, ApJ, 552, L109

Agol, E., & Kamionkowski, M. 2002, MNRAS, 334, 553
Begelman, M. C. 2002, ApJ, 568, L97
Binney, J., & Tremaine, S. 2008, Galactic Dynamics (2nd ed; Princeton: Princeton Univ. Press)
Blecha, L., & Loeb, A. 2008, MNRAS, in press (arXiv:0805.1420)
Bondi, H. 1952, MNRAS, 112, 195
Campanelli, M., Lousto, C., Zlochower, Y., & Merritt, D. 2007, ApJ, 659, L5
Colbert, E. J. M., & Mushotzky, R. F. 1999, ApJ, 519, 89
Cropper, M., Soria, R., Mushotzky, R. F., Wu, K., Markwardt, C. B., & Pakull, M. 2004, MNRAS, 353, 1024
Fujita, Y., Inoue, S., Nakamura, T., Mannoto, T., & Nakamura, K. E. 1998, ApJ, 495, L85
González, J. A., Hannam, M., Sperhake, U., Brügmann, B., & Husa, S. 2007, Phys. Rev. Lett., 98, 231101
Gualandris, A., & Merritt, D. 2008, ApJ, 678, 780
Ichimaru, S. 1977, ApJ, 214, 840
Kato, S., Fukue, J., & Mineshige, S. 1998, Black-Hole Accretion Disks (Kyoto: Kyoto Univ. Press)
King, A. R., Davies, M. B., Ward, M. J., Fabbiano, G., & Elvis, M. 2001, ApJ, 552, L109