Recurrent Outbursts and Jet Ejections Expected in Swift J1644+57: Limit-Cycle Activities in a Supermassive Black Hole

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Abstract

The tidal disruption event by a supermassive black hole in Swift J1644+57 can trigger limit-cycle oscillations between a supercritically accreting X-ray bright state and a subcritically accreting X-ray dim state. Time evolution of the debris gas around a black hole with mass $M = 10^6 M_\odot$ is studied by performing axisymmetric, two-dimensional radiation hydrodynamic simulations. We assumed the $\alpha$-prescription of viscosity, in which the viscous stress is proportional to the total pressure. The mass supply rate from the outer boundary is assumed to be $\dot{M}_{\text{supply}} = 100 L_{\text{Edd}}/c^2$, where $L_{\text{Edd}}$ is the Eddington luminosity, and $c$ is the light speed. Since the mass accretion rate decreases inward by outflows driven by radiation pressure, the state transition from a supercritically accreting slim disk state to a subcritically accreting Shakura-Sunyaev disk starts from the inner disk and propagates outward in a timescale of a day. The sudden drop of the X-ray flux observed in Swift J1644+57 in August 2012 can be explained by this transition. As long as $\dot{M}_{\text{supply}}$ exceeds the threshold for the existence of a radiation pressure dominant disk, accumulation of the accreting gas in the subcritically accreting region triggers the transition from a gas pressure dominant Shakura-Sunyaev disk to a slim disk. This transition takes place at $t \sim 50/(\alpha/0.1)$ days after the X-ray darkening. We expect that if $\alpha > 0.01$, X-ray emission with luminosity $\gtrsim 10^{44}$ erg s$^{-1}$ and jet ejection will revive in Swift J1644+57 in 2013–2014.

Key words: accretion, accretion disks — black hole physics — hydrodynamics — radiative transfer

1. Introduction

The unusual transient Swift J1644.9+573541 (hereafter Swift J1644+57) found in March 2011 has been interpreted as a tidal disruption event, which enormously increased the accretion rate onto a supermassive black hole in an inactive galactic nucleus at redshift $z = 0.35$ and launched a relativistic jet with Lorentz factor $\Gamma \sim 20$ (Burrows et al. 2011; Zauderer et al. 2011).

The peak isotropic X-ray luminosity of Swift J1644+57 is $L_{\text{iso}} \sim 10^{48}$ erg s$^{-1}$. Although the radiative flux measured in the jet rest frame reduces by a factor $\Gamma^{-2}$, the luminosity in the jet rest frame is still $\sim 10^{46}$ erg s$^{-1}$. Since the mass $M$ of the central black hole of the host galaxy of Swift J1644+57 is estimated to be less than $\sim 2 \times 10^7 M_\odot$ from the variation time scale of the X-ray intensity and the empirical law between the mass of the central black hole and the luminosity of the galactic bulge (Burrows et al. 2011), the jet rest frame luminosity exceeds the Eddington luminosity $L_{\text{Edd}} = 1.25 \times 10^{38} (M/M_\odot)$ erg s$^{-1}$. Therefore, the mass accretion rate $\dot{M}$ at the jet launching stage should exceed the Eddington mass accretion rate $\dot{M}_{\text{Edd}} = L_{\text{Edd}}/c^2$ where $c$ is the light speed. Subsequently, the X-ray luminosity of Swift J1644+57 decreased as $L \propto t^{-5/3}$ (Bloom et al. 2011, but see also Cannizzo et al. 2011 and Tchekhovskoy et al. 2013), which can be explained by decrease of the mass supply rate $\dot{M}_{\text{supply}}$ from the stellar debris (Rees 1988; Phinney 1989; Evans & Kochanek 1989). Swift J1644+57 gives us an opportunity to study the super-Eddington accretion onto a supermassive black hole and the transition from a super-Eddington accretion flow to a sub-Eddington accretion flow.

The X-ray luminosity of Swift J1644+57 dramatically dropped in August 2012, when the luminosity decreased from $L_{\text{iso}} \sim 10^{48}$ erg s$^{-1}$ to that below the detection limit by the Swift satellite. The luminosity just before the transition was obtained by using the observed X-ray flux $F_{0.3-10\text{keV}} \sim 10^{-12.5}$ erg cm$^{-2}$ s$^{-1}$ (Sbarufatti et al. 2012) and the luminosity distance $d_L = 1.88$ Gpc (Burrows et al. 2011). Observations by the Chandra Satellite in November 2012 showed that the X-ray luminosity is about $10^{42}$
erg s$^{-1}$ (Levan & Tanvir 2012). Zauderer et al. (2013) proposed that the accretion disk transited from a supercritically accreting slim disk (Abramowicz et al. 1988) which produces X-ray emitting jets to a geometrically-thin, optically thick Shakura-Sunyaev disk (Shakura & Sunyaev 1973, hereafter SSD), in which jet ejection is shut off. This model is motivated by the observations of galactic black hole candidates, in which jets disappear in high/soft states (Fender et al. 2004; Russell et al. 2011). More recently, Tchekhovskoy et al. (2013) predicted that jets and associated X-ray emission will be revived in 2016–22 when the continuous decrease of the accretion rate triggers the state transition from a high/soft state to a low/hard state, in which the radio emission from jets is observed in galactic microquasars (Fender et al. 2004).

In this Letter, we propose an alternative scenario for the revival of the jets and X-ray emission in Swift J1644+57 on the basis of the limit-cycle model of the disk instability which takes place when the accretion rate is close to the Eddington accretion rate (e.g., Honma et al. 1991; Kato et al. 2008 and references therein). Figure 1 schematically shows the evolutionary track we propose for Swift J1644+57. When the accretion rate exceeds the Eddington accretion rate, the accretion flow stays in the upper, slim disk branch (Abramowicz et al. 1988). As the accretion rate decreases and becomes less than the critical accretion rate for the existence of the slim disk branch, the accretion flow will transit to the SSD (transition denoted by A in Figure 1). Since the luminosity of the accretion flow at this transition point in Swift J1644+57 is $L \sim 1.3 \times 10^{44}$ erg s$^{-1}$ and $L \sim L_{\text{Edd}}$, the black hole mass can be estimated to be $M = 10^6 M_\odot$, which is consistent with the estimation by Burrows et al. (2011).

The transition A takes place in the thermal timescale of the disk $t_{\text{th}} \sim 100 t_{\text{dyn}} \sim 0.1 M / M_\odot$ sec, where $t_{\text{dyn}}$ is the dynamical timescale of the innermost region of the disk. Subsequently, the wave front of the transition propagates in the viscous timescale $t_{\text{vis}} \sim t_{\text{th}} (H/r)^{-2} \sim (0.01 - 0.1) M / M_\odot$ sec in slim disks in which $H/r \sim 0.5$, where $H$ is the half thickness of the disk. The luminosity decreases with this timescale. For the black hole with $10^6 M_\odot$, the timescale is consistent with that of the sudden X-ray drop of Swift J1644+57 in August 2012, in which the upper limit of the timescale of the X-ray drop constrained by the Swift observation is less than $10^6$ sec. Ohsuga (2006, 2007) showed that the transition A takes place when $M_{\text{supply}} \lesssim 100 (L_{\text{Edd}} / c^2)$. Assuming that $M_{\text{supply}}$ from the debris of the disrupted star decreases as proportional to $t^{-5/3}$ (Evans & Kochanek 1989), we estimate that $M_{\text{supply}}$ becomes $\lesssim 100 (L_{\text{Edd}} / c^2)$ at $\sim 1$ year after the maximum mass supply from the debris, which is roughly consistent with the duration between the discovery of Swift J1644+57 in March 2011 and the drastic decrease of X-ray flux in August 2012. In the same way, we estimate that $M_{\text{supply}}$ exceeds the maximum accretion rate for the existence of the gas pressure dominated SSD ($\sim L_{\text{Edd}} / c^2$) for $\sim 10$ years. Therefore, so long as $M_{\text{supply}}$ exceeds this limit, the surface density of the gas pressure dominant SSD increases, and when the radiation pressure exceeds the gas pressure, the disk becomes thermally unstable and transits to the slim disk (track B).

The accretion rate in the slim disk will significantly exceed the Eddington rate because the mass accumulated in the SSD quickly accretes onto the black hole. Radiation hydrodynamic simulations of supercritical accretion flow onto a black hole (e.g., Ohsuga et al. 2005) showed that radiation pressure driven jets and winds are produced during the supercritical accretion. Furthermore, radiation hydrodynamic simulations including Compton cooling (Kawashima et al. 2009, 2012) showed that shock heated region formed around the funnel wall of the radiation pressure supported slim disk (or torus) Comptonizes the soft photons and emits hard X-rays. Therefore, revival of jets and X-ray emission is expected when the transition B takes place in Swift J1644+57.

The limit-cycle behavior in radiation pressure dominant disks was demonstrated by two-dimensional radiation hydrodynamic simulations by Ohsuga (2006, 2007). The limit-cycle can explain the recurrent bursts in galactic microquasar GRS 1915+105 (Watarai & Mineshige 2003) and IGR J17091-3624 (Altamirano et al. 2011). In this Letter, we would like to apply the limit-cycle model to accretion flows onto a supermassive black hole.

2. Simulation Set-Up

We solve a set of radiation hydrodynamic equations in spherical coordinates ($r$, $\theta$, $\varphi$) assuming axisymmetry. Simulations are carried out by using a global radiation hydrodynamic code (Ohsuga et al. 2005) with improvements by including the effects of Compton cooling/heating.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{Fig1.pdf}
\caption{A Schematic picture of the S-shaped equilibrium curve of black hole accretion disks whose accretion rate is around the Eddington critical rate. The horizontal axis shows the surface density $\Sigma$ of the accretion disk, and the vertical axis represents the accretion rate. The branch shaded in blue shows the thermally and viscously unstable equilibrium curve.}
\end{figure}
The radiative transfer is solved by adopting the flux-limited diffusion approximation (Levermore & Pomraning 1981; Turner & Stone 2001). The hydrodynamical part is solved by Virginia Hydrodynamics One (VH-1) code based on the Lagrange-remap version of piecewise parabolic method (Colella & Woodward 1984). The mass of the black hole is assumed to be $M = 10^6 M_\odot$. General relativistic effects are incorporated by a pseudo-Newtonian potential (Paczyński & Wiita 1980), $\Phi = -GM/(r-r_s)$ where $r_s = 2GM/c^2$ is the Schwarzschild radius, $G$ is the gravitational constant. We adopt the $\alpha$-prescription of viscosity (Shakura & Sunyaev 1973) in which the viscous stress is proportional to the total pressure (gas plus radiation pressure for optically thick plasmas, but gas pressure for optically thin limit: see Ohsuga et al. 2005 in detail) and set $\alpha = 0.1$.

The computational domain is $2r_s \leq r \leq 500r_s$ and $0 \leq \theta \leq \pi/2$. The number of grid points is $(N_r, N_\theta) = (96, 192)$. The grid points are distributed such that $\Delta \ln r = \text{constant}$ and $\Delta \cos \theta = 1/N_\theta$. Mirror symmetry is assumed at the equatorial plane. The initial state is an isothermal hot ($10^{11}$ K), rarefied, optically thin, and spherically symmetric atmosphere. Accretion of the stellar debris is simulated by supplying mass from the outer boundary at $r = 500r_s$ near the equatorial plane ($0.45\pi \leq \theta \leq 0.5\pi$) with a constant rate $\dot{M}_{\text{supply}} = 100L_{\text{Edd}}/c^2$. The injected matter is assumed to be cool ($\sim 10^6$ K) and to have a specific angular momentum corresponding to the Keplerian angular momentum at $r = 100r_s$. At the outer boundary except the mass injection region (i.e., $r = 500r_s$ and $0 \leq \theta < 0.45\pi$), we allow matter to escape freely but not to enter the computational domain. We impose an absorbing boundary condition at $r = 2r_s$.

3. Results of Numerical Simulations

The matter injected from the outer boundary infalls and forms a torus around $r = 100r_s$. We note that the injected mass accumulates around $60r_s$ when the dense disk does not exist in $r < 100r_s$ because the ram pressure of the infalling matter is large enough to push the matter to the region $60-100r_s$. As the angular momentum is distributed by the $\alpha$-viscosity, a geometrically-thin disk is formed. As the surface density of the mass accumulated in the disk exceeds the limit for the existence for the gas pressure dominant SSD, a supercritically accreting slim disk is formed. The top panel of Figure 2 shows the time evolution of the isotropic luminosity $L_{\text{iso}}$ for the face-on observer approximately evaluated as

$$L_{\text{iso}} = 4\pi (r_{\text{out}})^2 F_{r}(r_{\text{out}}, \theta_{\text{min}}),$$

(1)

where $r_{\text{out}} = 500r_s$, $\theta_{\text{min}} = 0.03(\pi/2)$, and $F_{r}$ is the radial component of radiative flux measured in the observer frame, i.e., $\mathbf{F} = \mathbf{F}_0 + v\mathbf{E}_0 + \mathbf{v}\cdot\mathbf{P}_0$. Here, $\mathbf{E}_0$, $\mathbf{F}_0$, and $\mathbf{P}_0$ are the radiation energy density, the radiation flux, and the radiation pressure tensor, which are measured in the comoving frame of the fluid, respectively. The bottom panel of Figure 2 shows the mass accretion rate onto the black hole $\dot{M}_{\text{acc}}$, and the mass outflow rate $\dot{M}_{\text{out}}$ defined as

$$\dot{M}_{\text{acc}} = 4\pi(r_{\text{in}})^2 \int_0^1 \rho(r_{\text{in}}, \theta) \max[-v_r(r_{\text{in}}, \theta), 0] d\mu,$$

(2)

$$\dot{M}_{\text{out}} = 4\pi(r_{\text{out}})^2 \int_0^1 \rho(r_{\text{out}}, \theta) \max[v_r(r_{\text{out}}, \theta), 0] d\mu,$$

(3)

where $r_{\text{in}} = 2r_s$, $\mu = \cos \theta$, and $v_r$ is the radial velocity.

In this simulation, a supercritically accreting disk is formed around $t = 38$ day. Distribution of the temperature, density, and velocity at this supercritical stage indicated by (i) in Figure 2 is plotted in the left panel of Figure 3. A radiation pressure dominated geometrically thick disk is formed. The temperature of the disk is $10^{5-6}$ K, so that UV radiation will be dominant. Above the disk, a radiation pressure driven jet with speed $\gtrsim 0.1c$ appears around the rotation axis and an outflow with $\lesssim 0.01c$ appears outside the jet. The temperature of the outflow is $10^{7-8.5}$ K. A Hot region with temperature $\sim 10^8$ K also appears around the funnel wall of the radiation pressure dominant tori near the black hole (see Kawashima et al. 2012). The UV radiation from the disk is expected to be upscattered to X-rays by the inverse Compton scatterings in this hot region. The mass accretion rate at this stage is $10-100L_{\text{Edd}}/c^2$, and the isotropic luminosity exceeds the Eddington luminosity for a black hole with $M = 10^6 M_\odot$. The dotted line in Figure 2 shows the lu-
Fig. 3. Snapshots of the simulation in a super-Eddington phase (left) and in a sub-Eddington phase (right) in $r < 100 r_s$. The horizontal axes represent $R = r \sin \theta$. The arrows in the left panel display the poloidal velocity field of the outflow exceeding $10^{-3} c$ at $r \simeq 25 r_s$ and $\simeq 55 r_s$ in logarithmic scale. The speed for the longest arrow in the figure is $v \sim 0.1 c$.

minosity $\sim 1.3 \times 10^{44}$ erg s$^{-1}$, which corresponds to the isotropic luminosity of Swift J1644+57 when it suddenly dropped in August, 2012.

Although the mass supply rate from the outer boundary is fixed in this simulation, the mass accretion rate decreases between 40 day and 55 day as plotted in the lower panel of Figure 2. The main reason for the decrease of the mass accretion rate near the black hole is the mass outflow in the region $60–300 r_s$ during the super-Eddington phase. We would like to note that the mass outflow rate at $r = 500 r_s$ shown in Figure 2 is smaller than that in $60–300 r_s$ because most of the mass outflowing from this region falls back to the outer disk. When the mass accretion rate becomes smaller than the critical accretion rate for the slim-to-SSD transition (track A in Figure 1), the mass accretion rate and the luminosity drastically decreases, and the accretion flow transits to a gas pressure dominant, geometrically thin, SSD. The distribution of the temperature, density, and velocity after this transition (stage (ii) denoted by a dashed arrow in Figure 2) is shown in the right panel in Figure 3. The disk becomes geometrically-thin, and the jet is shut-off. We note that a geometrically thin disk exists down to $R(= r \sin \theta) \sim 3 r_s$ although it is not visible in the right panel of Figure 3.

The mass accretion rate in this SSD is $0.01–0.1 L_{\text{Edd}}/c^2$. Since the mass accretion rate is much smaller than the mass supply rate $100 L_{\text{Edd}}/c^2$, the mass accumulates in the region around $R \sim 100 r_s$. As the surface density of the disk in this region exceeds the threshold for the SSD-to-slim transition (track B in Figure 1) at $t \sim 100$ day in Figure 2, a supercritically accreting disk is formed, and radiation pressure driven jets and outflows are revived.

Figure 4 shows the propagation of the transition wave between the slim-to-SSD (orange to blue) and the SSD-to-slim disk (blue to orange). Here the mass accretion rate is computed by

$$M(r) = 4 \pi r^2 \int_0^1 \rho(r, \theta) \max[-v_r(r, \theta), 0] d\mu. \quad (4)$$

The slim-to-SSD transition denoted by (a) in Figure 4 starts around $t = 125$ day in the inner disk, and the transition completes in the outer disk at $t = 126$ day. The transition starts from the inner region, because significant fraction of the accreting mass is ejected by radiation pressure driven outflows, so that accretion rate decreases in the inner region. Then, the state transition propagates outward in the viscous timescale. On the other hand, the SSD-to-slim disk transition denoted by (b) in Figure 4 starts in the outer region and propagates inward.
4. Summary and Discussion

We have shown by two-dimensional axisymmetric radiation hydrodynamic simulations that when the accretion rate from the debris of a tidally disrupted star is around $M_{\text{supply}} \sim 100L_{\text{Edd}}/c^2$, recurrent outbursts and jet ejections take place. We assumed the $\alpha$-viscosity in which the viscous stress is proportional to the total pressure. As the mass accretes, supercritically accreting slim disk and radiation pressure driven jets are formed. As the accretion rate near the black hole decreases by this outflow, the state transition from the slim disk to the geometrically thin Shakura-Sunyaev disk takes place. This transition drastically decreases the luminosity, and turns off the jet ejection.

During the slim disk phase, X-rays can be emitted by the inverse Compton scatterings of soft photons by hot electrons around the funnel wall at the footpoint of the jet and in the outflow. We computed the Compton y-parameter for a face-on observer by integrating the Thomson opacity from $z = 400r_s$ down to the point where the effective optical depth $\tau_{\text{eff}} = 1$ for each radius and found that $y \gg 1$ during the slim disk phase. The spectral bump around 1keV in Swift J1644+57 observed by Swift (Saxton et al. 2012) may be explained by the Comptonization of UV disk photons in the Compton-thick outflow. On the other hand, during the SSD phase, it does not contribute to the luminosity except small regions around $R = 5r_s$, where $y$ sometimes exceeds unity. Therefore, we expect that the radiation at this stage is mostly emitted in UV, and the X-ray luminosity is small. The inverse Compton scatterings in the small region where $y > 1$ may be the origin of the X-ray emission with luminosity $L_X \sim 10^{42}\text{erg s}^{-1}$ observed by the Chandra satellite in November, 2012.

The duration of the sub-Eddington accretion is $\sim 50$ days when $\alpha = 0.1$. We employed $\alpha = 0.1$ to save the computational time. Three-dimensional MHD simulations of the growth of the magneto-rotational instability in radiatively inefficient disk indicate that $0.01 < \alpha < 0.1$ (e.g., Hawley 2000; Machida et al. 2004; Hawley et al. 2011). Three-dimensional local radiation MHD simulations indicates that $\alpha > 0.01$ (Hirose et al. 2009a,b). If we assume $\alpha = 0.01$, the duration of the subcritical accretion phase is $\sim 500$ days because the viscous timescale is proportional to $\alpha^{-1}$. We expect, therefore that the revival of X-ray emission and jet ejection will take place within $\sim 500$ days after the sudden darkening in August 2012.

Finally, let us discuss the difference of observational features between the jet revival models for Swift J1644+57, i.e., between the model proposed by Tchekhovskoy et al. (2013) and our alternative model. When the jet is re-launched, the super-Eddington accretion will take place again in our model, while the radiatively inefficient accretion flow will appear in the model by Tchekhovskoy et al. (2013). According to our model, the photon spectral shape will be similar to that before the dramatic darkening, and the luminosity will exceed the Eddington luminosity again. On the other hand, according to the model by Tchekhovskoy et al. (2013), the spectral state is expected to be similar to that of lower-luminosity blazars, and the luminosity measured in the jet rest frame will be significantly lower than the Eddington luminosity. In addition, the time at which the revival of the jet starts is earlier in our model than in their model. In subsequent papers, we would like to confirm the timescale for the revival of the jet by carrying out simulations without assuming $M_{\text{supply}} = \text{constant}$. The spectral calculations by post-processing the simulation data also remain as a future work.

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