Magnetohydrodynamic Simulations of a Plunging Black Hole into a Molecular Cloud

Mariko Nomura1,2, Tomoharu Oka1,3, Masaya Yamada3, Shunya Takekawa3,4, Ken Ohsuga5,6,7, Hiroyuki R. Takahashi5, and Yuta Asahina5

1 Department of Physics, Faculty of Science and Technology, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama, Kanagawa 223-8522, Japan; mariko.nomura@keio.jp
2 Astronomical Institute, Tohoku University, Aoba, Sendai 980-8578, Japan
3 School of Fundamental Science and Technology, Graduate School of Science and Technology, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama, Kanagawa 223-8522, Japan
4 Nobeyama Radio Observatory, National Astronomical Observatory of Japan (NAOJ), National Institutes of Natural Sciences (NINS), 462-2 Nobeyama, Minamimaki, Minamisaku-gun, Nagano 384-1305, Japan
5 National Astronomical Observatory of Japan, Osaka, Mitaka, Tokyo 181-8588, Japan
6 School of Physical Sciences, Graduate University of Advanced Study (SOKENDAI), Shonan Village, Hayama, Kanagawa 240-0193, Japan
7 Center for Computational Sciences, University of Tsukuba, Ten-nodai, 1-1-1 Tsukuba, Ibaraki 305-8577, Japan

Received 2017 December 22; revised 2018 April 11; accepted 2018 April 11; published 2018 May 18

Abstract

Using two-dimensional magnetohydrodynamic simulations, we investigated the gas dynamics around a black hole (BH) plunging into a molecular cloud. In these calculations, we assumed a parallel-magnetic-field layer in the cloud. The size of the accelerated region is far larger than the Bondi–Hoyle–Lyttleton radius, being approximately inversely proportional to the Alfvén Mach number for the plunging BH. Our results successfully reproduce the “Y” shape in position–velocity maps of the “Bullet” in the W44 molecular cloud. The size of the Bullet is also reproduced within an order of magnitude using a reasonable parameter set. This consistency supports the shooting model of the Bullet, according to which an isolated BH plunged into a molecular cloud to form a compact broad-velocity-width feature.

Key words: ISM: clouds – ISM: kinematics and dynamics – magnetohydrodynamics (MHD) – methods: numerical

1. Introduction

To date, ~60 stellar mass black hole (BH) candidates have been detected in our Galaxy by X-ray observations (Corral-Santana et al. 2016), while their total number is estimated to be \( \sim 10^{8}–10^{9} \) (Agol & Kamionkowski 2002; Caputo et al. 2017). This sharp discrepancy is due to the extremely low percentage of BHs in close binary systems, in which abundant mass accretion from companion stars activates them. Therefore, almost all BHs in our Galaxy still remain undetected.

An isolated, inactive BH would pull up ambient material, leaving a trace in the interstellar medium as a spatially compact, broad-velocity-width feature. The “Bullet” in the W44 molecular cloud is a candidate for such a BH trace (Sashida et al. 2013). W44 is a supernova remnant (SNR) interacting with an adjacent giant molecular cloud (Claussen et al. 1997; Seta et al. 1998, 2004; Sashida et al. 2013). In the process of investigating the gas kinematics of the W44 molecular cloud, we noticed an extraordinary broad-velocity-width feature (Sashida et al. 2013), the Bullet. Follow-up observations by Yamada et al. (2017), hereafter Y17, have revealed its compact appearance \((0.5 \times 0.8 \text{ pc}^2)\), broad-velocity width nature (\( \Delta V \sim 100 \)) and unique “Y” shape in the position–velocity maps.

The Bullet is intense in CO \( J = 4–3 \) and HCN \( J = 1–0 \) emissions, suggesting that it consists of warm and dense molecular gas. The total kinetic energy of the Bullet is \( \sim 10^{48} \text{ erg} \). This is approximately 1.5 orders of magnitude greater than the kinetic energy of a supernova sharing the small solid angle of the Bullet with respect to the W44 center. Y17 proposed two scenarios of Bullet formation: (1) an expansion model and (2) the shooting model. Both scenarios assume an isolated BH that contributes to the formation of the Bullet. In the expansion model, an additional explosive event triggered by mass accretion onto an isolated BH accounts for the kinematics of the Bullet, but the conversion process from the gravitational energy to the kinetic energy is unclear. The shooting model seems to be more plausible. In this model, the plume of a \( \gtrsim 30 M_\odot \) BH into the high-density layer toward us successfully explains the broad-velocity width as well as the enormous kinetic energy of the Bullet (see Figure 3(b) in Y17). The gas dragged by the plunging BH might correspond to the “Y” shape on the position–velocity map.

One problem is that a native shooting model cannot reproduce the spatial size of the Bullet. This is because the size of the accretion zone, which may correspond to the Bullet size, is described by the Bondi–Hoyle–Lyttleton (BHL) radius (Hoyle & Lyttleton 1939; Bondi & Hoyle 1944; Edgar 2004), \( R_{\text{BHL}} = \frac{2GM_{\text{BH}}}{v^2} \), where \( G M_\odot \), \( c_\odot \), and \( v \) are the gravitational constant, the BH mass, the sound speed, and the velocity of the plunging BH. When \( M_{\text{BH}} \sim 30 M_\odot \) \( c_\odot \sim 1 \text{ km s}^{-1} \) and \( v \sim 100 \text{ km s}^{-1} \), the BHL radius becomes \( \sim 3 \times 10^{-5} \text{ pc} \), which is too small to reproduce the Bullet size \((\sim 0.5 \text{ pc})\).

In this paper, we examine the effect of the magnetic field on the size of the accretion zone around a plunging BH. The magnetic field is frozen in the partially ionized interstellar gas, and the bent shape of the field lines propagates with the Alfvén speed. If the BH plunges into the parallel-magnetic-field layer and the magnetic field lines are caught on the gas in the vicinity of the BH, the gas outside of \( R_{\text{BHL}} \) would be dragged by the plunging BH via the magnetic tension force. This effect may enlarge the size of the accretion zone if the magnetic field is strong enough, which is the case in the W44 expanding shell \((B \sim 500 \mu \text{G}; \text{Hoffman et al. 2005})\). In this case, the lower part of the “Y” shape in the position–velocity map may correspond to the accelerated gas in front of the BH, which is moving with the plunging speed of BH. The upper part of the “Y” shape can be interpreted as the gas around the BH accelerated from the
magnetic tension force, whose velocity may decrease with the distance from the BH.

In order to quantitatively investigate the magnetohydrodynamic (MHD) effect in the shooting model, we simulated the plunging of a BH into a parallel-magnetic-field layer by considering a large-scale gas flow around a stationary BH. A two-dimensional MHD code was employed. In Section 2, we explain the calculation method. The results of the simulations are shown in Section 3. Sections 4 and 5 are devoted to discussions and conclusions.

2. Basic Equations and Models

We calculate the gas dynamics around a plunging BH using MHD simulations in Cartesian coordinates (x, y, z). In our simulations, a BH is located at the center of the coordinate system and ambient gas flows in with high velocity. The basic equations of ideal MHD are

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \tag{1}
\]

\[
\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left( \rho \mathbf{v} \otimes \mathbf{v} + p \mathbf{I} + \frac{B^2}{8\pi} - \frac{B \otimes B}{4\pi} \right) = -\rho \frac{GM_{BH}r}{r^3}, \tag{2}
\]

\[
\frac{\partial (e + \frac{B^2}{8\pi}) + \nabla \cdot \left( (e + p) \mathbf{v} - \frac{\mathbf{v} \times \mathbf{B} \times \mathbf{B}}{4\pi} \right)}{\partial t} = 0, \tag{3}
\]

\[
\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0, \tag{4}
\]

where \(\rho\), \(\mathbf{v}\), \(p\), \(\mathbf{B}\), \(r\), and \(e\) are the mass density, velocity, pressure, magnetic field, distance from the BH, and energy density of the gas written by \(\rho = p/(\gamma - 1) + \rho v^2/2\) with \(\gamma = 5/3\). In our calculations, we assume that the energy dissipation in shock has a timescale comparable to that of the cooling. At each time step, we reset the pressure and the energy density of the gas using an isothermal equation of state, \(p = \rho c_s^2\), where we set a sound speed to \(c_s = 0.91 \text{ km s}^{-1}\), which is consistent with the observed temperature of the Bullet (\(T = 100 \text{ K}\), Y17) and a mean molecular weight of 1.0. The last term of the equation of motion is the gravitational force due to the BH located at the origin.

The computational domain is \(-0.5 \text{ pc} \leq x \leq 0.5 \text{ pc}\) and \(-0.5 \text{ pc} \leq y \leq 0.5 \text{ pc}\). We prepare 720 \times 720 grids in the domain for \(M_{BH} = 10^4 M_\odot\), so as to set 7–8 grids in the BHL radius, \(R_{\text{BHL}}\). The resolution is \(~1.4 \times 10^{-3} \text{ pc}\). We also employ \(M_{BH} = 10^3 M_\odot\), \(10^5 M_\odot\), and \(10^{13} M_\odot\). For these cases, we divide the domain into \(7200 \times 7200\), \(2160 \times 2160\), and \(240 \times 240\) grids, corresponding to resolutions of \(~1.4 \times 10^{-4} \text{ pc}\), \(~4.6 \times 10^{-4} \text{ pc}\), and \(~4.2 \times 10^{-3} \text{ pc}\), respectively. The choices of \(M_{BH}\) larger than \(10^3 M_\odot\) are for resolving the BHL radii with the realistic number of computational grids. After performing simulations with four \(M_{BH}\), we check the \(M_{BH}\)-dependence on the size of the accelerated region (Section 4.1, Figure 7).

We show the initial condition of the fiducial model in Figure 1. In the region \(r \geq R_{\text{BHL}}\), the number density and the velocity are set to \(n = n_0\) and \(\mathbf{v} = (0, v_\phi, 0)\). We suppose the situation that a BH plunges into a magnetized layer (high-\(B\) layer) with a relative velocity of \(~100 \text{ km s}^{-1}\). We reproduce this situation by shedding high-\(B\) layer to a stationary BH, because it is difficult to treat a BH moving in the computational box. As the high-\(B\) layer is accelerated by the magnetic pressure before reaching the BH (see also Section 3.1), we choose the initial velocity \((v_\phi, 0)\) so that the plunge velocity becomes \(100 \text{ km s}^{-1}\). For the fiducial model, the initial velocity is set to \((v_\phi, 0) = 50 \text{ km s}^{-1}\). We employ \(n_0 = 10^3 \text{ cm}^{-3}\) to simulate the high-\(B\) (density) layer after the supernova blast wave. This value is between the typical density in molecular clouds and that in the Bullet (Y17). We also perform the simulations for different \(n_0\) and \(v_\phi\) (see Sections 3.2 and 4.1).

In the region \(r < R_{\text{BHL}}\), the density is set to \(n = 0.1 n_0\) and the velocity to zero. On the upstream side \((y \leq -0.2 \text{ pc})\), the magnetic field is set to \(\mathbf{B} = (B_\phi, 0, 0)\), which describes the high-\(B\) layer. We employ \(B_\phi = 50 \mu \text{G}\) based on the previous measurement in the W44 expanding shell (Hoffman et al. 2005). Sections 3.2 and 4.1 describe the other cases. In the downstream side, the magnetic field is set to \(\mathbf{B} = (50 \mu \text{G}, 0, 0)\).

We apply the free boundaries at \(x = -0.5 \text{ pc}, x = 0.5 \text{ pc}, \) and \(y = 0.5 \text{ pc}\). At the boundary \(y = -0.5 \text{ pc}\), the density, \(x\)-component of the magnetic field, and \(y\)-component of the velocity are kept constant \(n = n_0, B_x = B_\phi, \) and \(v_y = v_\phi\). We impose the free boundary conditions for the other variables. This means that the gas is initially flowing, maintaining the initial density and magnetic field strength in \(y \leq -0.5 \text{ pc}\). This situation corresponds to a high-velocity plunging of a BH into a uniform gas cloud. In \(r < R_{\text{BHL}}\), the velocity is fixed to zero so as to reproduce the condition that the gas is trapped by the BH and it traps the magnetic field lines. The density is also kept constant at \(n = 0.1 n_0\) so that the gas flowing into this region accretes onto the BH and does not appear in the computational domain again.

Numerical simulations are carried out by using the MHD code CANS++ (Matsumoto et al. 2016). The code employs the HLLD approximate Riemann solver (Miyoshi & Kusano 2005). We apply second-order spatial accuracy by using monotone upstream-centered schemes for conservation laws (MUSCL; van Leer 1979). A third-order TVD Runge–Kutta scheme is used for solving the time integration. A hyperbolic divergence cleaning method is employed (Dedner et al. 2002).
5.38 \times 10^3 \text{ years}

Magenta dashed lines show the range of integration. The BH is located at the lines and blue arrows show the magnetic field lines. Magenta dashed lines show the range of integration. The BH is located at the center of the coordinate system.

Figure 2. Density map (top panel) in the $x$-$y$ plane and column density map in the $x$-$v_y$ plane (bottom panel) at $t = 5.38 \times 10^3$ years for $M_{\text{BH}} = 10^4 \text{ M}_\odot$, $v_0 = 50 \text{ km s}^{-1}$, $n_0 = 10^5 \text{ cm}^{-3}$, and $B_{\phi 0} = 500 \mu\text{G}$. In the top panel, black lines and blue arrows show the magnetic field lines and the velocity field. Magenta dashed lines show the range of integration. The BH is located at the center of the coordinate system.

3. Results

3.1. Fiducial Model

Figure 2 shows the results for $M_{\text{BH}} = 10^4 \text{ M}_\odot$, $v_0 = 50 \text{ km s}^{-1}$, $n_0 = 10^5 \text{ cm}^{-3}$, and $B_{\phi 0} = 500 \mu\text{G}$ (the fiducial model). In this case, the gas is accelerated to $v_y \sim 100 \text{ km s}^{-1}$ by the magnetic pressure before the high-$B$ layer reaches the BH. This velocity corresponds to the plunging speed of the BH in the shooting model (hereafter, we call it the inflow velocity, $v_{\text{in}}$). The top panel shows the density map at $t = 5.38 \times 10^3$ years when the high-$B$ layer passes $\sim 0.4 \text{ pc}$ after reaching the BH.

In the region $|x| \gtrsim 0.36 \text{ pc}$, the gas flows as it is not affected by the magnetic tension force. Near the BH ($|x| \lesssim 0.36 \text{ pc}$), the high-density and low-velocity region (accelerated region) appears and forms an arcuate shape at the side facing the BH (see the yellow region at $-0.2 \text{ pc} \lesssim y \lesssim 0.2 \text{ pc}$). At the front of the BH, gas is compressed and the velocity is accelerated (accelerated toward the negative direction). In this area, the magnetic field is enhanced to $\sim 600-3000 \mu\text{G}$. This is because gas is frozen into the magnetic field and the field lines are caught on the gas dammed up in $r < R_{\text{BHL}}$. At the front of the BH, the magnetic pressure strongly accelerates the gas, and at both sides of the BH, the magnetic tension force due to the curved magnetic field lines contributes to the acceleration. The following flow collides with the accelerated flow inducing shock.

The bottom panel of Figure 2 shows a position–velocity $(x$–$v_y$) map. We divide the $v_y$-axis into grids of the width $\Delta v_y = 5 \text{ km s}^{-1}$. The color represents the column density of the gas in each velocity grid. The column density is integrated along the $y$-axis over the range $-0.25 \text{ pc} \lesssim y \lesssim 0.25 \text{ pc}$ (between the magenta dashed lines in the top panel of Figure 2) in order to focus on the velocity structure around the BH.

In the region far from the BH ($|x| \gtrsim 0.36 \text{ pc}$), the bulk of the gas has a velocity of $\sim 100 \text{ km s}^{-1}$, because of less influence of the magnetic field at this time. In the region $|x| \lesssim 0.36 \text{ pc}$, another velocity component appears at $v_y \lesssim 100 \text{ km s}^{-1}$. The $v_y \sim 100 \text{ km s}^{-1}$ component is contributed by the less-dense gas in the upstream side ($y \lesssim -0.18 \text{ pc}$). The low-velocity component ($v_y < 100 \text{ km s}^{-1}$) makes a “Y” shape on the $x$–$v_y$ map. The widths of the “Y” shape in the $x$-direction ($d$) and in the $v_y$-direction ($\Delta v_y$) are $\sim 0.72 \text{ pc}$ and $\sim 115 \text{ km s}^{-1}$, respectively. This component is contributed by the dense gas in the accelerated region around the BH. $v_y < 0$ component is contributed by the gas in the vicinity of the BHL radius, which falls into the BH along the magnetic field.

Figure 3 shows the time evolution of the size of the accelerated region, which corresponds to the size of the “Y”

![Figure 3](image-url)
shape on the \( x-v_y \) map, \( d \). Here, \( \Delta t \) is the time measured from the moment that the high-\( B \) layer reached the BH. Using the speed of the flow (\( \sim 100 \text{ km s}^{-1} \)), the time is converted to the width of the layer that passed through the BH, \( L \). The size increases in proportion to \( \Delta t \) and \( L \). The best-fitting line (the solid black line) is \( d/\text{pc} = 2.05 \times 10^{-4} \Delta t \text{yr}^{-1} \) \( (d = 1.8L) \). This shows that the accelerated region expands with the Alfvén speed at the vicinity of \( R_{\text{BH}}, \sim 200 \text{ km s}^{-1} \), which is roughly 5.8 times the Alfvén speed in the high-\( B \) layer.

### 3.2. Parameter Dependence

Each panel of Figure 4 is the same as that of Figure 1, but the parameters are different from the fiducial model. Figures 4(a) and (b) show the results in the case of \( M_{\text{BH}} = 10^{15} M_\odot \) and \( 10^{15} M_\odot \). In both figures, the overall structures are quite similar to the result of the fiducial model. In Figure 4(a), the size and the velocity width of the “Y” shape in the \( x-v_y \) map are \( d \sim 0.70 \text{ pc} \) and \( \Delta v_y \sim 100 \text{ km s}^{-1} \), respectively. In Figure 4(b), these values are \( d \sim 0.78 \text{ pc} \) and \( \Delta v_y \sim 130 \text{ km s}^{-1} \). These results show that the position–velocity structure is almost independent of the BH mass (see also Figure 2).

Figure 4(c) shows the results for the weak magnetic field, \( B_{\text{d0}} = 158 \mu \text{G} \). In order to adjust the inflow velocity to \( v_{\text{in}} \sim 100 \text{ km s}^{-1} \), which is the same as the other cases, we set the initial velocity to \( v_y0 = 90 \text{ km s}^{-1} \). The other parameters are the same as those of the fiducial model. The density map shows that the accelerated region around the BH is small, \( |x| \lesssim 0.15 \text{ pc} \). For this parameter set, the magnetic field lines are sharply bent by the ram pressure of the flow, as the magnetic field strength is weak. As a result, in the \( x-v_y \) map, the size of the “Y” shape is \( d \sim 0.3 \text{ pc} \). The velocity width of the “Y” shape is almost the same as that of the fiducial model, but the matter located at \( x \sim 0 \) is concentrated in the narrow velocity range \( -15 \) to \( +15 \text{ km s}^{-1} \). This is because the gradient of the magnetic field strength is large at the front of the BH, and the flow is rapidly decelerated.

Figure 4(d) is the same as Figure 2 except that \( B_{\text{d0}} = 158 \mu \text{G} \) and \( n_0 = 100 \text{ cm}^{-3} \). The size of the accelerated region is larger than that of Figure 4(c) and comparable to that of Figure 2. In this case, the magnetic field is weak, but the ram pressure of the flow is also small due to the low density. As a consequence, the magnetic field lines draw gentle curves near the BH. In the \( x-v_y \) map, the column density in each cell is smaller than that of the fiducial model, but the position–velocity structure is very similar to that of Figure 2.

### 4. Discussions

#### 4.1. Size of Accelerated Gas

Figures 5(a) and (b) show the size of the “Y” shape on the \( x-v_y \) map, \( d \), as a function of the Alfvén speed in the high-\( B \) layer, \( v_A = B_{\text{d0}}/\sqrt{4\pi n_0} \), when \( L = 0.2 \) and 0.4 pc. In order to survey the \( v_A \)-dependence, we employ \( n_0 = 10^5 \text{ cm}^{-3} \), \( 10^6 \text{ cm}^{-3} \), \( 10^7 \text{ cm}^{-3} \), and \( 100 \text{ cm}^{-3} \) while the magnetic field strength is set to \( B_{\text{d0}} = 500 \mu \text{G} \) (red squares). In addition, we investigate the position–velocity structures for \( B_{\text{d0}} = 50 \mu \text{G}, 158 \mu \text{G}, 500 \mu \text{G}, \) and \( 1.58 \text{ mG} \) when the density is...
$n_0 = 10^3 \text{ cm}^{-3}$ (blue triangles). Here, the BH mass is kept constant $M_{\text{BH}} = 10^4 \text{ M}_\odot$. The initial velocity $v_\odot$ is adjusted to set the inflow velocity to $v_{\text{in}} \sim 100 \text{ km s}^{-1}$ before the high-$B$ layer reaches the BH. Both Figures 5(a) and (b) show that the sizes are similar to each other if the Alfvén speeds have the same value, regardless of the combination of the density and the magnetic field strength. The size increases in proportion to the Alfvén speed and the best-fitting lines are $d/pc = 0.012v_A/\text{km s}^{-1}$ and $d/pc = 0.021v_A/\text{km s}^{-1}$ for $L = 0.2 \text{ pc}$ and $0.4 \text{ pc}$ (the solid black lines).

Figure 6 shows the size, $d$, as a function of the inverse of the inflow velocity, $1/v_{\text{in}}$, when $L = 0.4 \text{ pc}$. We employ four different inflow velocities, $v_{\text{in}} = 50, 100, 150, \text{ and } 200 \text{ km s}^{-1}$, whose corresponding initial velocities are $v_\odot = 0, 50, 100, \text{ and } 150 \text{ km s}^{-1}$ (black squares). In these calculations, $M_{\text{BH}}, n_0, \text{ and } B_0$ are the same as those of the fiducial model. The size increases as the inflow velocity decreases and this relation is fitted by $d/pc = 72/(v_{\text{in}}/\text{km s}^{-1})$ (the solid black line). The decrease of the inflow velocity suppresses the ram pressure of the flow. This leads the magnetic field lines drawing gentle curves and the large accelerated region.

Figure 7 shows the $M_{\text{BH}}$-dependence of the size, $d$, when $L = 0.4 \text{ pc}$. We calculate the position–velocity structures for $M_{\text{BH}} = 10^7 \text{ M}_\odot, 10^{10} \text{ M}_\odot, 10^4 \text{ M}_\odot, \text{ and } 10^{15} \text{ M}_\odot$ (black squares), while the other parameters are same as those of the fiducial model. This figure shows that the size hardly depends on the BH mass at least in the range $10^7 \text{ M}_\odot \lesssim M_{\text{BH}} \lesssim 10^{15} \text{ M}_\odot$. The best-fitting line is $d/pc = 0.51(M_{\text{BH}}/\text{M}_\odot)^{0.438}$ (the solid black line). If we extrapolate this relation in the low-mass range, a “Y”-shaped structure with a size of $\sim 0.5 \text{ pc}$ is produced by a BH of $M_{\text{BH}} \sim 10 \text{ M}_\odot$.

From Figures 3, 5(a) and (b), 6, and 7, we find that the size, $d$, depends mainly on $v_A, v_{\text{in}}, \text{ and } L$, besides having a weak dependence on $M_{\text{BH}}$. The size is approximately determined by $d = aL/M_A$, where $a$ is a proportionality constant, and $M_A$ is the Alfvén Mach number in the high-$B$ layer, $M_A = v_{\text{in}}/v_A$. We derive $a = 5.1$ from the results of $M_{\text{BH}} = 10^7 \text{ M}_\odot$. The size of $L/M_A$ is the scale of the warped magnetic field lines when the high-$B$ layer passed $L$ after reaching the BH. This is derived from the balance between the magnetic tension force and the ram pressure of the flow. The proportionality constant, $a(>1)$, shows an enhanced Alfvén speed and a decreased velocity around the BH.

### 4.2. Comparison with Observations

Our results show that the plunging of the BH into the high-$B$ layer reproduces the characteristic “Y” shape on the position–velocity map of the Bullet in the W44 SNR. Here, we quantitatively compare our results to the two objects, the W44.
Bullet (Y17) and the small high-velocity compacts clouds (HVCCs) detected near the Galactic nucleus (HCN−0.009−0.044 and HCN−0.085−0.094; Takekawa et al. 2017, hereafter T17) The small HVCCs have the velocity widths of $\Delta v \gtrsim 60$ km s$^{-1}$ and the sizes of $\sim$1 pc. The high-velocity components originate from the dense molecular clouds. Although the “Y” shape is not resolved, the position–velocity structure of the small HVCCs is similar to that of the W44 Bullet.

In Figure 8, we compare the theoretical predictions based on our results and the observations on the $d$–$v_{in}$ plane. We plot the constant $v_A L$ lines employing the relation $d = 5.1 L / M_\lambda$ (the solid lines) as well as the size and the velocity width of the Bullet and the small HVCCs (gray regions). Here, on the basis of our simulations, we assume that the velocity width is comparable to the inflow velocity. We find that both the Bullet and the small HVCCs are located in the range $10 \gtrsim v_A L \gtrsim 20$, which can be rewritten as $5(L/pc)^{-1}(n/cm^{-3})^{1/2} \lesssim B/\mu G \lesssim 9(L/pc)^{-1}(n/cm^{-3})^{1/2}$.

The value of $v_A L$ can also be estimated from the observations. In the case of the Bullet, employing $B = 500 \mu G$ (Hoffman et al. 2005), $n = 10^4$ cm$^{-3}$ (Y17), and $L = 0.1$ pc, which is the thickness of thin filaments detected in W44 (Jones et al. 1993), we obtain $v_A L \sim 1.1$ pc km s$^{-1}$. This is consistent with the value predicted by our results within an order of magnitude. In the case of the small HVCCs, the typical magnetic field strength in the central region of our Galaxy is $B \sim 500 \mu G$ (e.g., Morris & Serabyn 1996) and the density of the molecular cloud is $n \sim 10^3$ cm$^{-3}$ (Guesten & Henkel 1983). We assume that $L$ is comparable to the HVCC size and is smaller than the size of the molecular cloud, $L \sim 1$–5 pc. As a result, we obtain $v_A L \sim 3.5$–17.3 pc km s$^{-1}$. This is comparable to or slightly smaller than the theoretical prediction.

The difference between our results and the observations might be caused by the uncertainty of the coefficient, $a \sim 5.1$, in the relation $d = aL / M_\lambda$. The coefficient, $a$, approximately corresponds to the ratio of the Alfvén speed at $r \sim R_{BHL}$ to that of the high-$B$ layer at the initial condition. It is difficult to accurately evaluate the Alfvén speed in the vicinity of $r \sim R_{BHL}$, because we ignore the dynamics in $r < R_{BHL}$ and assume the simple conditions $n = 0.1 n_0$ and $v_\phi = 0$. The magnetic field strength and the density near the BH would change if we consider the realistic magnetic structure around the BH and the feedback from the accretion flow such as radiative heating. In that case, there is the possibility that the coefficient, $a$, increases by several times to ten times, and the size of the Bullet would be well explained by the relation $d = aL / M_\lambda$.

We found that the size of the accelerated region is almost independent of the BH mass (Figure 7). This result indicates that “Y”-shaped position–velocity structure with $d \sim 0.5$ pc can be reproduced by the plunging of a stellar mass BH. Here, we estimate the total luminosity of the BH based on the BHL accretion model. Assuming $M_{BH} = 10 M_\odot$, $n = 10^4$ cm$^{-3}$, and $v_{in} = 100$ km s$^{-1}$, the total luminosity is estimated to be $L_X = 0.06 M_{BH} c^2 \sim 2 \times 10^{34}$ erg s$^{-1}$, where $M_{BH}$ is the BHL accretion rate (e.g., Edgar 2004). This luminosity is consistent with the absence of the X-ray counterpart in ROSAT All Sky Survey (RASS; Haakonsen & Rutledge 2009). If we assume the BHL accretion rate and standard accretion disk (Shakura & Sunyaev 1973), non-detection of the X-ray counterpart in the RASS indicates that the mass of the plunging BH is less than $\sim 100 M_\odot$. Note that the accretion rate would be smaller than $M_{BH}$ because the magnetic field suppresses the mass accretion rate (Lee et al. 2014). In addition, the accretion disk might become radiation inefficient accretion flow (Narayan & Yi 1994). In such cases, a BH mass larger than $100 M_\odot$ is acceptable. In order to calculate the accurate accretion rate and corresponding X-ray luminosity, the three-dimensional MHD and/or radiation hydrodynamics simulations in the small scale around the BH are necessary. Detection of an X-ray counterpart with modern X-ray imaging telescopes (such as Chandra) will provide a strong support for our scenario.
As a first step of the theoretical approach to the Bullet, we performed the two-dimensional simulations on the \(x\)-\(y\) plane \((z = 0 \text{ plane})\). In three-dimensional simulations, the gas and magnetic field behaviors in the \(z = 0\) plane are expected to be similar to those in the two-dimensional simulations. This is because the gas and magnetic field lines far from the \(z = 0\) plane \((z \gg R_{\text{BH}})\) do not affect those in the \(z = 0\) plane. The three-dimensional MHD simulations of BHL accretion in a small computational domain show the bow shock similar to our results (Lee et al. 2014), supporting that our two-dimensional simulations, at least qualitatively, well reproduce the gas and magnetic field behaviors in the \(z = 0\) plane. In the three-dimensional simulations, the magnetic pressure in the \(z\)-direction might lower the density and magnetic field strength near the BH, and thereby reduce the size of the accelerated region in \(z = 0\) plane. Investigating these three-dimensional effects will be important and interesting future work.

In our simulations, we assumed a simple parallel-magnetic-field layer, although magnetic fields in molecular clouds are not highly ordered. The unordered fields may produce the asymmetric “Y” shape, and the size of the accelerated region might slightly change. More accurate measurements of the magnetic field configuration near the Bullet and the simulations employing realistic settings may be interesting future works.

5. Conclusions

Performing the MHD simulations, we investigated the gas dynamics around a BH plunging into a molecular cloud with a parallel-magnetic-field. We found the following results:

1. The MHD effects enlarge the accelerated region compared to the native shooting model, and the acceleration region expands within \(|\mathbf{v}| \lesssim 0.36 \text{ pc}\) when \(L = 0.4 \text{ pc}\) for the fiducial model \((M_{\text{BH}} = 10^4 M_\odot, B_{z0} = 500 \mu G, n_0 = 10^3 \text{ cm}^{-3}, \text{ and } v_{\text{in}} = 100 \text{ km s}^{-1})\).
2. When \(L = 0.4 \text{ pc}\), the accelerated gas exhibits a “Y” shape with a size of \(d \sim 0.72 \text{ pc}\) and a velocity width of \(\Delta v \sim 115 \text{ km s}^{-1}\) on the \(x-y\) map for the fiducial model.
3. The size of the accelerated gas increases in proportion to the time (the distance traveled in the layer, \(L\)).
4. Our simulations show that the size of the “Y” staple is almost independent of the BH mass and stellar mass BH \((M_{\text{BH}} \lesssim 100 M_\odot)\) is preferred for the Bullet if we assume the BHL accretion rate and the standard accretion disk.
5. The size of the “Y” shape is approximately determined by \(d = 5.1L/M_{\Delta}\).
6. Our model can reproduce the “Y” shape and the velocity width on the position–velocity map of the W44 Bullet.
7. The size of the “Y” shape expected from the model is consistent with that of the Bullet within one order of magnitude.
8. Our model can explain the velocity width and the size of the small HVCCs in the Galactic center.

The foregoing results support the shooting model of the Bullet and the small HVCCs and indicate that the MHD effects are necessary to reproduce the size of the accelerated gas. There is a possibility that the plunging of the isolated BH into the molecular cloud be responsible for the formation of the extraordinary high-velocity component.

Numerical computations were carried out on Cray XC30 at the Center for Computational Astrophysics, National Astronomical Observatory of Japan. This work is supported in part by JSPS Grant-in-Aid for Scientific Research (B) (15H03643 T.O., 15K05036 K.O.), for Young Scientists (17K14260 H.R.T.), and for Research Fellow (15J04405 S.T.). This research was also supported by MEXT as “Priority Issue on Post-K computer” (Elucidation of the Fundamental Laws and Evolution of the Universe) and JICFuS.

References

Agol, E., & Kamaionkowski, M. 2002, MNRAS, 334, 553
Bondi, H., & Hoyle, F. 1944, MNRAS, 104, 273
Caputo, D. P., de Vries, N., Patruno, A., & Portegies Zwart, S. 2017, MNRAS, 468, 4000
Claussen, M. J., Frail, D. A., Goss, W. M., & Gaume, R. A. 1997, ApJ, 489, 143
Corral-Santana, J. M., Casares, J., Muñoz-Darias, T., et al. 2016, A&A, 587, A61
Dedner, A., Kemm, F., Kröner, D., et al. 2002, JCoPh, 175, 645
Edgar, R. 2004, NewAR, 48, 843
Gusten, R., & Henkel, C. 1983, A&A, 125, 136
Haakonsen, C. B., & Rutledge, R. E. 2009, ApJS, 184, 138
Hoffman, I. M., Goss, W. M., Brogan, C. L., & Claussen, M. J. 2005, ApJ, 627, 803
Hoyle, F., & Lyttleton, R. A. 1939, PCPS, 35, 405
Jones, L. R., Smith, A., & Angelini, L. 1995, MNRAS, 265, 631
Lee, A. T., Cunningham, A. J., McKee, C. F., & Klein, R. I. 2014, ApJ, 783, 50
Matsumoto, Y., Asahina, Y., Kudoh, Y., Y., et al. 2016, arXiv:1611.01775
Miyoshi, T., & Kusano, K. 2005, JCoPh, 208, 315
Morris, M., & Serabyn, E. 1996, ARA&A, 34, 645
Narayan, R., & Yi, I. 1994, ApJ, 428, L13
Sashida, T., Oka, T., Tanaka, K., et al. 2013, ApJ, 774, 10
Seta, M., Hasegawa, T., Dame, T. M., et al. 1998, ApJ, 505, 286
Seta, M., Hasegawa, T., Sakamoto, S., et al. 2004, AJ, 127, 1098
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 19, 337
Smith, A., Jones, L. R., Watson, M. G., et al. 1985, MNRAS, 217, 99
Takekawa, S., Oka, T., Iwata, Y., Tokuyama, S., & Nomura, M. 2017, ApJL, 843, L11
van Leer, B. 1979, JCoPh, 32, 101
Yamada, M., Oka, T., Takekawa, S., et al. 2017, ApJL, 834, L3