Magnetohydrodynamic Simulations of the Formation of Molecular Clouds toward the Stellar Cluster Westerlund 2: Interaction of a Jet with a Clumpy Interstellar Medium

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Abstract

The formation mechanism of CO clouds observed with the NANTEN2 and Mopra telescopes toward the stellar cluster Westerlund 2 is studied by 3D magnetohydrodynamic simulations, taking into account the interstellar cooling. These molecular clouds show a peculiar shape composed of an arc-shaped cloud on one side of the TeV γ-ray source HESS J1023-575 and a linear distribution of clouds (jet clouds) on the other side. We propose that these clouds are formed by the interaction of a jet with clumps of interstellar neutral hydrogen (HI). By studying the dependence of the shape of dense cold clouds formed by shock compression and cooling on the filling factor of HI clumps, we found that the density distribution of HI clumps determines the shape of molecular clouds formed by the jet–cloud interaction: arc clouds are formed when the filling factor is large. On the other hand, when the filling factor is small, molecular clouds align with the jet. The jet propagates faster in models with small filling factors.

Key words: ISM: clouds – ISM: jets and outflows – magnetohydrodynamics (MHD) – shock waves

1. Introduction

Observations of the CO J = 1–0 transition toward the stellar cluster Westerlund 2 with the NANTEN2 telescope revealed peculiarly shaped molecular clouds around the TeV γ-ray source HESS1023-575 (Fukui et al. 2009): a semicircular molecular cloud (arc-like cloud) on one side of the TeV γ-ray source and a linear molecular cloud (jet-like cloud) on the other. Subsequent high-resolution CO (J = 2–1 and 1–0) observations with the NANTEN2 and Mopra telescopes provided significant details of their distribution at a factor of 2–5 higher resolution, confirming the arc- and jet-like clouds, which are likely associated with HESS1023-575 (Furukawa et al. 2014). These authors argued that the clouds are 1 kpc further away than Westerlund 2, so the arc- and jet-like clouds and HESS1023-575 are not physically connected with Westerlund 2. An obvious explanation of the formation of the arc cloud is a supernova explosion, but the cloud’s noncircular shape suggests that the explosion that formed it should be highly asymmetric. On the other hand, the correlation between the molecular clouds and the TeV γ-ray source indicates that the microquasar jet ejected from the γ-ray source triggered the formation of the molecular clouds. The formation of molecular clouds induced by the microquasar jet was discussed by Yamamoto et al. (2008), in which they reported that molecular clouds found by NANTEN CO observations are aligned with the radio and X-ray jet ejected from the microquasar SS433.

Hydrodynamic (HD) or magnetohydrodynamical (MHD) simulations have been conducted to study the interaction of astrophysical jets with the interstellar medium (ISM). Norman et al. (1982) studied structures of a supersonic jet propagating into a uniform intergalactic medium by 2D axisymmetric HD simulations. They revealed that the propagating jets form structures such as a bow shock ahead of the jet, a jet terminal shock, an internal shock, and a cocoon. Axisymmetric 2D MHD simulations were conducted by a number of authors (e.g., Clarke et al. 1986; Lind et al. 1989; Kössl et al. 1990; Todo et al. 1992). Todo et al. (1993) studied the helical kink instability of a jet interacting with a dense gas cloud by 3D MHD simulations. These simulations were carried out by assuming adiabatic fluid.

The effects of radiative cooling on the propagation of protostellar jets were studied by Blondin et al. (1989, 1990). They carried out axisymmetric 2D simulations taking into account the radiative cooling in the temperature range 10^3 K < T < 10^6 K. They showed that the jet front is cooled in the head of the jet forms a cool shell with temperature T ~ 10^4 K. Axisymmetric 2D MHD simulations of the protostellar jets taking into account radiative cooling were carried out by Frank et al. (1998), Stone & Hardee (2000), and Teuleau et al. (2008).

Asahina et al. (2014) presented the results of 2D axisymmetric MHD simulations of the interaction of a jet and a neutral hydrogen (H I) cloud by taking into account interstellar cooling. They adopted a cooling function applicable to the high-density gas with T < 10^4 K (Inoue et al. 2006). Asahina et al. (2014) showed that the cooling instability triggered by the shock compression of the H I layer forms a dense, cold (<100 K) arc-like cloud along the bow shock ahead of the jet and elongated dense clouds in the sheath surrounding the jet. The mass and the speed of the dense clouds are comparable to those observed in clouds aligned with the SS433 jet.

It is possible that molecular clouds toward the TeV γ-ray source HESS1023-575 can be formed by the same mechanism. If both arc clouds and jet clouds were formed by the same jet ejection event, the asymmetry of the molecular cloud distribution may be due to the difference in distributions of the H I clouds. In order to better understand the interaction of the jet and the ambient H I gas, we have carried out MHD numerical simulations of the arc clouds and jet clouds and present the results in this paper. We present our simulation models in Section 2 and numerical results in Section 3. Section 4 gives a summary and discussion.
2. Numerical Model

We conduct 3D MHD simulations in Cartesian coordinates \((x, y, z)\). The basic equations of ideal MHD are

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

\[
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot \left( \rho \mathbf{v} \otimes \mathbf{v} + p \mathbf{I} + \frac{\mathbf{B} \otimes \mathbf{B}}{8\pi} - \frac{\mathbf{B} \otimes \mathbf{B}}{4\pi} \right) = \rho \mathbf{F}, \quad (2)
\]

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) \quad (4)
\]

where \(\rho, \mathbf{v}, p, \mathbf{B}\), and \(L\) are density, velocity, pressure, magnetic field, and the cooling function, respectively, and

\[
e = \frac{p}{\gamma - 1} + \frac{\rho \mathbf{v}^2}{2} \quad (5)
\]

is the energy density of the gas. We adopt the cooling function

\[
\rho L = n (\Gamma + n \Lambda) \exp \left\{ - \left[ \max \left( \frac{T}{7000}, -1, 0 \right) \right]^{4} \right\}, \quad (6)
\]

\[
\Gamma = 2 \times 10^{-26} \text{erg s}^{-1}, \quad (7)
\]

\[
\Lambda = 7.3 \times 10^{-21} \exp \left( \frac{-118400}{T + 1500} \right)
+ 7.9 \times 10^{-27} \exp \left( \frac{-200}{T} \right) \text{ erg cm}^{3} \text{s}^{-1} \quad (8)
\]

where \(n, \Gamma, \) and \(\Lambda\) are number density, heating rate, and cooling rate, respectively, and \(T\) is in kelvin. The basic equations and cooling function for interstellar cooling are the same as those in Asahina et al. (2014). In contrast to Blondin et al. (1989, 1990) and Frank et al. (1998), where the radiative cooling in the temperature range \(T > 10^{4} \text{K}\) is taken into account, we consider the cooling of \(\text{H}\text{I}\) gas with temperature \(T < 10^{4} \text{K}\). We cut off cooling at \(T > 10^{4} \text{K}\) because the jet internal plasma is continuously heated by internal shocks (Asahina et al. 2014). Cooling can be significant in the shear between the hot \((T > 10^{6} \text{K})\) jet and the cold \((T \approx 200 \text{K})\) \(\text{H}\text{I}\) cloud but the density and temperature distribution are essentially determined by the cooling at \(T < 10^{4} \text{K}\). Inclusion of the cooling in the range \(10^{4} \text{K} < T < 10^{6} \text{K}\) only leads to thinning of the interface between the hot jet and the cold, dense cloud formed by the cooling instability. In this paper, we neglect thermal conduction. Thermal conduction determines the width of the interface between the warm \((T \approx 10^{4} \text{K})\) gas and the hot plasma \((T > 10^{5} \text{K})\). The thickness of the interface, called Field’s length (Begelman & McKee 1990), is of the order of 1 pc. In this paper, instead of resolving the interface in the temperature range \((10^{4} \text{K} < T < 10^{6} \text{K})\) taking into account thermal conduction, we approximate the interface by a contact discontinuity where the density and temperature jump.

Asahina et al. (2014) studied the dependence of numerical results on the jet speed and showed that the speed of the working surface of the jet is proportional to the square root of the jet speed when the jet mass flux is fixed. The speed of the cold, dense clouds formed around the sheath between the jet and the ambient medium decreases with time, and approaches 0.5 km s\(^{-1}\). In Asahina et al. (2014), a preexisting dense \(\text{H}\text{I}\) region is approximated by a uniform dense layer for simplicity. When the \(\text{H}\text{I}\) region has finite thickness, the speed of the working surface will increase. In this paper, we study the interaction of jets with spherical \(\text{H}\text{I}\) clouds.

We carry out simulations for two models: (i) a large \(\text{H}\text{I}\) cloud and (ii) clumpy \(\text{H}\text{I}\) clouds. The former model extends our previous 2D axisymmetric study on the interaction of a jet and a dense \(\text{H}\text{I}\) layer (Asahina et al. 2014) by taking into account the finite size of the \(\text{H}\text{I}\) cloud and 3D effects. We carry out simulations for a head-on collision in which the center of the cloud is located on the jet axis, and for an off-center collision. We expect that the arc-shaped cloud can be easily formed without assuming a supernova explosion in these models. We confirm that the arc-shaped cloud can be formed in a finite-sized \(\text{H}\text{I}\) cloud via the same cooling instability mechanism as Asahina et al. (2014). The model of clumpy clouds is more realistic than that of a large \(\text{H}\text{I}\) cloud. We mainly carry out simulations by assuming the former model in order to propose a unified model for the arc clouds and jet clouds. Figure 1 shows schematically the interaction of a jet with clumpy \(\text{H}\text{I}\) clouds. When the filling factor of the \(\text{H}\text{I}\) clouds is moderate, the jet will propagate along the channels between the \(\text{H}\text{I}\) clouds (left of Figure 1). On the other hand, when the filling factor is large, an arc-like molecular cloud may be formed (right of Figure 1).

For both models, we inject a jet with a radius \(r_{\text{jet}} = 1 \text{pc}\). The jet speed is \(5.8 \times 10^{2} \text{km s}^{-1}\) (Mach 3). The temperature and number density of the jet are \(2 \times 10^{6} \text{K}\) and \(5 \times 10^{-4} \text{cm}^{-3}\), respectively. We determined the temperature and number density so that the jet is thermally stable even when the cooling at \(T > 10^{4} \text{K}\) is considered. The mass flux of the jet, which is \(1.4 \times 10^{18} \text{g s}^{-1}\), is chosen such that it is comparable to the Eddington mass accretion rate for a stellar mass black hole (an order of magnitude smaller than that of the jet ejected from the microquasar SS433). In the initial state, we assume pure toroidal magnetic field \(B_{0} \propto \sin(r/r_{\text{jet}})\) in the jet and \(\beta = p_{\text{gas}}/(B_{0}^2/8\pi) = 100\) at \(r = 0.5 \text{pc}\). The magnetic field is enhanced in the sheath in 2D simulations (Asahina et al. 2014). To confirm that the magnetic field is amplified in 3D simulations as well as in 2D ones, we assume the same condition for the initial magnetic field. The number density and temperature of the \(\text{H}\text{I}\) cloud are \(n_{\text{HI}} = 6.9 \text{cm}^{-3}\) and \(T_{\text{HI}} = 200 \text{K}\), respectively. The warm ISM with a number density of \(0.15 \text{cm}^{-3}\) and a temperature of \(9.3 \times 10^{3} \text{K}\) is assumed to be in pressure equilibrium with the \(\text{H}\text{I}\) cloud.

For a model of a large cloud, we assume a spherical \(\text{H}\text{I}\) cloud whose center is at \((x, z) = (0 \text{pc}, 45 \text{pc})\) for a head-on collision model. For the off-center collision model, the center of the cloud is located at \((x, z) = (2.5 \text{pc}, 45 \text{pc})\). The radius of the cloud is 10 pc. Figure 2 shows the temperature distribution in the initial state in the \(y = 0\) plane for the head-on collision model. The size of the simulation region is \((L_{x}, L_{y}, L_{z}) = (24 \text{pc}, 24 \text{pc}, 60 \text{pc})\) and the number of grid points is \((N_{x}, N_{y}, N_{z}) = (240, 240, 600)\). For a model of clumpy \(\text{H}\text{I}\) clouds, we place spherical \(\text{H}\text{I}\) clumps with radii of 2 pc randomly in the region \(z > 10 \text{pc}\). When an \(\text{H}\text{I}\) clump overlaps with another \(\text{H}\text{I}\) clump, we set the number density...
as $n = 6.9 \text{ cm}^{-3}$ (i.e., density is not simply added) in that region in order to satisfy the condition for thermal equilibrium. The volume filling factor of the H\textsc{i} clumps, defined as the ratio $V_{\text{H}\textsc{i}}/V_{\text{total}}$, is assumed to be 0.2, 0.8, and 0.9, for models F02, F08, and F09, respectively. For the clumpy cloud model with filling factor 0.2, we also carried out simulations for a Mach 4 jet (model F02H) and a Mach 2 jet (model F02L). The jet velocities are $7.7 \times 10^2 \text{ km s}^{-1}$ for model F02H and $3.9 \times 10^2 \text{ km s}^{-1}$ for model F02L. In the initial state for models F02L and F02H, we assume the same density distribution as that for model F02. The size of the simulation region for the model of clumpy clouds is $(L_x, L_y, L_z) = (40 \text{ pc}, 40 \text{ pc}, 60 \text{ pc})$ and the number of grid points is $(N_x, N_y, N_z) = (400, 400, 600)$. For both models, the grid size is $(\Delta x, \Delta y, \Delta z) = (0.1 \text{ pc}, 0.1 \text{ pc}, 0.1 \text{ pc})$. We impose a symmetric boundary condition at $z = 0$, and the other boundaries are assumed to be free boundaries. We apply an MHD code based on the HLLD Riemann solver (Miyoshi & Kusano 2005) with fifth-order spatial accuracy. The spatial

**Figure 1.** Schematic picture of the interaction of a jet with the H\textsc{i} clumps. When the filling factor is small (left), the jet propagating in channels between the H\textsc{i} clumps forms jet-like molecular clouds. When the filling factor is large (right), the jet sweeps the H\textsc{i} clouds and forms an arc-shaped molecular cloud.

**Figure 2.** Temperature distribution in the initial state in the $y = 0$ plane. We add the large spherical H\textsc{i} cloud.
accuracy is achieved by applying the WENO-Z (Borges et al. 2008) and monotonicity-preserving schemes (Suresh & Huynh 1997) adopted in Minoshima et al. (2015).

3. Numerical Results

3.1. Results for the Model of a Large Cloud

Figure 3 shows a result for the model of a head-on collision at $t = 10.5$ Myr in the $y = 0$ plane. The shock-compressed HI cloud is cooled to about 50 K by the cooling instability, and a cold, dense sheath, indicated by the dark blue region, is formed. This result is similar to that of 2D simulations in which an infinitely thick HI layer is assumed. The cold, dense sheath is thinnest around the head of the jet, where the thickness is 0.6–0.7 pc. The sheath is resolved by six or seven grids. The width of the interface between the cool sheath and the warm gas where $10^3 \text{ K} < T < 10^4 \text{ K}$ is determined by Field’s length of the warm gas ($\sim 0.1$ pc). It is beyond the scope of this paper to carry out simulations including thermal conductivity to resolve Field’s length. In this simulation, although we do not consider heat conduction, the interface width is comparable to 0.1 pc because the grid size is 0.1 pc. The interface can become thinner if we carry out higher-resolution simulations, but the density of the cold sheath will not change because its thickness is sufficiently larger than Field’s length of the warm gas. As Asahina et al. (2014) showed, the magnetic field is enhanced in the sheath to a strength 6–7 times larger than that injected into the boundary at $z = 0$, which corresponds to $\beta \sim 20$. The effect of the magnetic field is small since the plasma beta is higher than 1. The region between the jet terminal shock and the jet–cloud interface becomes turbulent, and the cocoon expands in the direction perpendicular to the jet axis. This radial expansion produces an arc-like cold, dense cloud.

We computed the column number density of atomic hydrogen (Figure 4(a)) and of H$_2$ (Figure 4(b)) observed from the $+z$ direction. To compute the H$_2$ number density, we assume solar abundance and neglect background UV radiation (e.g., Richings et al. 2014), and estimate $2n_{\text{H}_2}/n$ in the range $10 \text{ K} < T < 200 \text{ K}$ from Figure 4 in Richings et al. (2014) assuming $\log(2n_{\text{H}_2}/n) \propto \log n$ and interpolating for $n$ between $2n_{\text{H}_2}/n = 1$ when $n > 10^2 \text{ cm}^{-3}$ and $2n_{\text{H}_2}/n = 0.5 \text{ min} [1, (T/50)^{-1.16}]$ when $n = 1 \text{ cm}^{-3}$. This method is the same as in Asahina et al. (2014).

We used the X-factor $N(\text{H}_2)/W(12\text{CO}(J = 1–0)) = 1.6 \times 10^{20} \text{ cm}^{-2}/(\text{K km s}^{-1})$ (Hunter et al. 1997) adopted in Furukawa et al. (2014). The column number density is high in the sheath. The peak column number densities for atomic hydrogen and molecular hydrogen ahead of the jet are $N \sim 1 \times 10^{21} \text{ cm}^{-2}$ and $N(\text{H}_2) \sim 0.4 \times 10^{21} \text{ cm}^{-2}$, respectively. The peak of the integrated intensity of the H 121 cm line is about $10^3 \text{ K km s}^{-1}$ (McClure-Griffiths et al. 2005). The column number density for atomic hydrogen is estimated to be $1.8 \times 10^{21} \text{ cm}^{-2}$ by using the conventional factor $1.8 \times 10^{18} \text{ cm}^{-2}/(\text{K km s}^{-1})$. The peak column number density in the simulations is comparable to that in H 1 observations. The peak H$_2$ column density is smaller than the value of $N(\text{H}_2) \sim 2.7 \times 10^{21} \text{ cm}^{-2}$ obtained by CO observations. This is because the width of the region of high column density in our simulations ($\sim 10$ pc) is about half that observed. Furthermore, the velocity dispersion is about 2 km s$^{-1}$ in the simulation, which is about half that observed.

Figure 5 shows the temperature distribution for the off-center collision model at 10.5 Myr in the $y = 0$ plane. The HI cloud cools down as the cloud is compressed by the jet. An arc-like cold, dense region is formed in the off-center collision model as well as in the head-on collision model. Figure 6 shows the distribution of the column density for the off-center collision model. Although some asymmetry appears, the peak column densities are almost the same as those for the head-on collision model. These numerical results indicate that the arc-like cloud can be formed even when the jet collides with a large cloud off-axis.

3.2. Results for the Model of Clumpy H I Clouds

Figures 7(a)–(c) show the results for model F02 at 5.0 Myr, model F08 at 8.5 Myr, and model F09 at 12.5 Myr, respectively. Since the jet propagates along the channels between the HI clumps, it breaks up into branches; cold, dense clumps, indicated by dark blue, are formed by shock compression.

The maximum number density is 150–300 cm$^{-3}$ for all the models. The number density is high in the region where HI clumps are compressed by the jet. As time goes on, the high-density region moves in the $+z$ direction. At the sides of the jet, the number density of the condensed gas decreases to 20–30 cm$^{-3}$. This result is consistent with the observation that the CO
emission is weaker near the TeV $\gamma$-ray source. For all the models, the maximum number density gradually decreases with time because the turbulence in the head of the jet decreases the ram pressure at the working surface.

Figure 8 shows the $v_y$ distribution in the $y = 0$ plane. The jet changes its direction after it collides with a clump at $z = 35$ pc for models F02 and F08, and at $z = 45$ pc for model F09.

For both column number densities, the peak appears ahead of the jet. The peak of the column number density for atomic hydrogen is of the order of $10^{21}$ cm$^{-2}$ and that for $H_2$ is about $0.4 \times 10^{21}$ cm$^{-2}$.

In the early stage, the interface between the jet ($v > c_{s,\text{jet}} \sim 200$ km s$^{-1}$) and the ambient gas is sharp for the velocity distribution, where $c_{s,\text{jet}}$ is the sound speed of the jet in the injection region. In the later stage, the interface is broadened by turbulence excited around the head of the jet. The beam has a velocity comparable to the injection velocity of the jet and extends to $z = 30$ pc, 35 pc, and 40 pc for models...
F02, F08, and F09, respectively, in the last stage. These positions correspond to the position at which the jet collides with H I clumps (see Figure 7). Since the jet becomes turbulent after collision with a clump, its speed gradually decreases and forms a broader interface for the velocity between the jet and the ambient medium.

Figure 9(a) shows the temperature distribution for model F02L at $t = 7.5$ Myr. The beam breaks up at $z = 25$ pc and the jet is deflected at $z = 35$ pc. On the other hand, the beam extends to $z = 40$ pc for model F02H (see Figure 9(b)). The deflection of the jet by the clump is smaller in model F02 than in model F02. Since the jet power becomes large for jets with higher speed, the bow shock becomes stronger and the ram pressure increases. The colder, denser clumps are formed in model F02H. For example, the maximum number densities are about $5 \times 10^3$ cm$^{-3}$ for model F02H at $t = 3.75$ Myr, 250 cm$^{-3}$ for model F02 at $t = 5.0$ Myr, and 30 cm$^{-3}$ for model F02L at $t = 7.5$ Myr. The minimum temperatures are about 30 K for model F02H, 50 K for model F02, and 100 K for model F02L.

Figures 10(a) and (b) plot the maximum $z$ of the region where $\nu > 200$ km s$^{-1}$. The curves coincide for models F02, F08, and F09 when $z < 10$ pc because the jet propagates in the region without H I clumps. For model F02, the jet propagates faster than for models F08 and F09 since the filling factor is smaller for model F02. However, the jet for model F08 is not always faster than that for model F09 because the H I clumps are located randomly in the initial state. For model F02L, the propagation of the beam stops since the beam breaks at $z = 30$ pc.

The propagation speed of the jet depends on the density distribution of the ISM. Since the dynamical pressure of the jet is equal to that of the ambient medium with density $\rho_{\text{ISM}}$ and that of the H I clump with density $\rho_{\text{H I}}$ in the rest frame of the working surface (e.g., Todo et al. 1992), we estimate the propagation speed of the working surface as

$$v_{w,\text{H I}} = \frac{v_{\text{jet}}}{f_{\text{H I}}} \sqrt{\frac{\rho_{\text{jet}}}{\rho_{\text{H I}}}}, \quad (9)$$

$$v_{w,\text{ISM}} = \frac{v_{\text{jet}}}{f_{\text{ISM}}} \sqrt{\frac{\rho_{\text{jet}}}{\rho_{\text{ISM}}}} \quad (10)$$

where $v_{w,\text{H I}}$ and $v_{w,\text{ISM}}$ are the propagation speeds of the jet in the H I cloud and in the warm ISM, respectively. Substituting our simulation parameters into Equations (9) and (10), we obtain $v_{w,\text{H I}} = 2.5$ km s$^{-1}$ and $v_{w,\text{ISM}} = 17$ km s$^{-1}$ when $r_{\text{ws}}$ is 2 pc. The propagation timescale is estimated to be

$$t = \frac{fL}{v_{w,\text{H I}}} + \frac{(1 - f)L}{v_{w,\text{ISM}}} \quad (11)$$

where $f$ is the volume filling factor of the H I clouds and $L$ is the length scale of the jet. In the region $z < 10$ pc, since the filling factor of the H I clouds is 0, the propagation timescale is 10 pc/$v_{w,\text{ISM}} = 0.56$ Myr. If we assume that $L$ is

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**Figure 6.** (a) Column number density of atomic hydrogen and (b) column number density of H$_2$ and the CO intensity at $t = 10.5$ Myr observed from the $-y$ direction for the off-center collision model. For both column number densities, the peak value appears ahead of the jet. The peak values of the column number density are almost the same as those in the head-on collision model.
the length of the beam at \( z > 10 \) pc, \( L = 38 \) pc for model F02, \( L = 25 \) pc for model F08, and \( L = 35 \) pc for model F09. We obtain a propagation timescale \( t = 5.1 \) Myr for model F02, \( t = 8.5 \) Myr for model F08, and \( t = 12.7 \) Myr for model F09.

The mean propagation velocity of the jet, evaluated as

\[
v_{\text{prop}} = \frac{L}{t} = \left( \frac{f}{v_{\text{ws,H I}}} + \frac{1-f}{v_{\text{ws,ISM}}} \right)^{-1}
\]

for models F02, F02H, F02L, F08, and F09 is estimated to be \( v_{\text{F02}} = 7.9 \) km s\(^{-1}\), \( v_{\text{F02H}} = 10.5 \) km s\(^{-1}\), \( v_{\text{F02L}} = 5.3 \) km s\(^{-1}\), \( v_{\text{F08}} = 3.0 \) km s\(^{-1}\), and \( v_{\text{F09}} = 2.7 \) km s\(^{-1}\), respectively.

Figures 11(a) and (b) show the mean propagation speed of the jet after it collides with the H I clumps. The mean propagation speed, which is defined as \( (z(t) - z(1 \text{ Myr})/t - 1 \text{ Myr}) \), decreases and approaches the propagation speed estimated above. In the last stage, it is about \( 6 \) km s\(^{-1}\) for model F02, \( 10 \) km s\(^{-1}\) for model F02H, \( 2 \) km s\(^{-1}\) for model F02L, and \( 3 \) km s\(^{-1}\) for models F08 and F09. For models F02H, F08, and F09, the propagation velocity is comparable to the value estimated from Equation (12). For models F02 and F02L, it becomes smaller than the estimated values of \( 7.9 \) km s\(^{-1}\) and \( 5.3 \) km s\(^{-1}\). This is because the jet propagates obliquely after colliding with the H I clumps at \( z = 30 \) pc, and the decrease in velocity in the head of the jet decreases the ram pressure at the working surface.

Figures 12(a)–(c) show the column number density observed from the azimuth angle \( \phi = 140^\circ \) for models F02, F08, and F09, respectively. Shock compression by the jet occurs in various places where the jet sweeps the clouds. Therefore, cold, dense clouds are distributed more widely than in the model of a large H I cloud (see Figures 4 and 6). For model F09, an H I cavity is formed in the region \( 10 \) pc < \( z < 30 \) pc. The peak column number density is of the order of \( 10^{21} \) cm\(^{-2}\), which is consistent with that in H I observations.
Figures 13(a)–(c) show the column number density of H$_2$ and the CO intensity observed from the azimuth angle $\phi$ = 140°. The peak of the CO intensity is located in the regions where the jet swept the H$_1$ clouds at $z$ $<$ 30 pc for model F02, 30 pc $<$ $z$ $<$ 35 pc for model F08, and 35 pc $<$ $z$ $<$ 45 pc for model F09. The peak CO intensity is about 2.5 K km s$^{-1}$, which is smaller than that in CO observations. For model F09, the CO distribution approaches that in the arc clouds. The numerical results indicate that as the filling factor increases, the distribution of the molecular clouds approaches that in the arc-like clouds. The dispersion of the line-of-sight velocity is 1–2 km s$^{-1}$, which is comparable to that in the model of a large HI cloud and is half that in observations of the jet cloud.

Let us compare the numerical results for the model of clumpy HI clouds F09 shown in Figure 13 with the off-center collision model shown in Figure 6. The arc-like shape of the dense, cold region, the peak column number density, and the slightly asymmetric distribution of the column number density in model F09 are similar to those in the off-center collision model, but the dense region is more clumpy and wider in the model of clumpy clouds than in the off-center collision with a large cloud.

We would like to estimate the filling factor of HI clouds at the side of the jet clouds by applying Equation (11). The jet propagation timescale for the jet cloud should be the same as that for the arc cloud, and is given by

$$f_{jc} = \frac{L_{ac}}{L_{jc}} + \left(1 - \frac{L_{ac}}{L_{jc}}\right)\left(\frac{v_{ws,ISM}}{v_{ws,H1}} - 1\right)^{-1}$$

where subscripts “jc” and “ac” denote the parameters for the jet cloud and arc cloud, respectively. We assumed that the jet parameters and density of the ISM and HI cloud are the same for the jet cloud and arc cloud. If we solve for $f_{jc}$ and use Equations (9) and (10), Equation (13) becomes

$$f_{jc} = f_{ac} \frac{L_{ac}}{L_{jc}} + \left(1 - \frac{L_{ac}}{L_{jc}}\right)\left(\frac{\rho_{H1}}{\rho_{ISM}} - 1\right)^{-1}$$

This equation does not depend on the jet parameters. When $L_{jc} = 90$ pc, $L_{ac} = 40$ pc, and we assume that the densities of the ISM and HI clouds are the same as in our simulations, we obtain

$$f_{jc} \sim 0.44 f_{ac} + 0.17.$$ 

Since 0 $\leq$ $f_{ac}$ $\leq$ 1, the range of $f_{jc}$ is 0.17 $\leq$ $f_{jc}$ $\leq$ 0.61. The numerical results indicate that when $f_{ac}$ > 0.9, an arc-like molecular cloud is formed. As a result, we obtain 0.57 $\leq$ $f_{jc}$ $\leq$ 0.61. The ages of the jet cloud and arc cloud are estimated to be a few million years. Substituting $t = 2$ Myr, $v_{ws} = 2$ pc, $f = 0.6$, $L = 90$ pc, and the density of the jet...
assumed in our simulation into Equations (9)–(11), we obtain $v_{\text{jet}} \sim 6.6 \times 10^3$ km s$^{-1}$. The kinetic energy injected by the jet is of the order of $10^{36}$ erg s$^{-1}$.

4. Summary and Discussion

We carried out 3D MHD simulations of the interaction of the jet with interstellar H I clouds for two models: a large H I cloud and clumpy H I clouds. The density distribution of the H I clouds affects the jet propagation and the shape of the cold, dense clouds formed by the jet–cloud interaction. When the jet collides with the large H I cloud, the jet sweeps the H I gas, and the arc-like cold, dense cloud and H I cavity are formed. When the jet interacts with the clumpy H I clouds, the jet breaks up into branches and the cold, dense clouds are distributed more broadly than in the model of a large H I cloud. When the volume filling factor is large, an H I cavity is formed and the shape of the dense clouds becomes more arc-like. The density distribution of the interstellar H I clouds determines the shape of the molecular clouds formed by the jet compression.

Let us compare our results with CO observations (Furukawa et al. 2014). The velocity dispersion of the molecular clouds formed by the jet–cloud interaction depends on the jet speed. From Equation (9), the radial velocity is proportional to $v_{\text{jet}} \sqrt{\rho_{\text{jet}}/\rho_{\text{H I}}} = \sqrt{2E_{\text{jet}}/\rho_{\text{H I}}}$, where $E_{\text{jet}}$ is the kinetic energy density of the jet. In our simulation, $E_{\text{jet}} = 1.42 \times 10^{-12}$ erg cm$^{-3}$, $\rho_{\text{H I}} = 1.15 \times 10^{-23}$ g cm$^{-3}$, the jet speed $v_{\text{jet}} = 5.8 \times 10^3$ km s$^{-1}$, and the kinetic energy flux is $2.34 \times 10^{33}$ erg s$^{-1}$. The velocity dispersion of molecular clouds obtained by numerical simulations when $E_{\text{jet}}/\rho_{\text{H I}} = 1.23 \times 10^{14}$ erg g$^{-1}$ is about 2 km s$^{-1}$. To explain the observed velocity dispersion of $\sim 4$ km s$^{-1}$, we need $E_{\text{jet}}/\rho_{\text{H I}} \sim 5.0 \times 10^{11}$ erg g$^{-1}$ if the velocity dispersion is produced by
speed is studied by carrying out simulations for a Mach 4 jet (model F02H) and a Mach 2 jet (model F02L) in Section 3. Let us discuss the dependence on a jet speed faster than Mach 4. Around the jet head, the velocity dispersion of the cold clumps is proportional to $v_{\text{jet}}$ (see Equation (9)). The cold clumps are no longer accelerated by the ram pressure of the jet after the jet head crosses them. At this stage, we can estimate the velocity dispersion by using Equation (18) in Asahina et al. (2014). The velocity of cold clumps is roughly proportional to $v_{\text{jet}}^{2/3}$. For instance, the velocity dispersion can be about 200 km s$^{-1}$ around the jet head if the jet velocity is 0.2$c$, which is about 100 times larger than that in our simulations. Outside the jet head, the velocity dispersion can be 4–8 km s$^{-1}$. This velocity dispersion is consistent with observations. Asahina et al. (2014) showed that the shape of the interface between the cocoon and the cold sheath is independent of the jet velocity if the jet length is the same. Therefore, the shape of the cold clouds can be almost the same even if we change the jet velocity when the filling factor is large. When the filling factor is moderate or small, the shape of the cold clouds depends on how much the jet is reflected by the H$\text{I}$ clumps. When the jet velocity is large, the cold clouds can be distributed linearly around the jet axis since it is hard for the jet to be deflected by collision with clumps.

The radius of the H$\text{I}$ clumps does not affect the propagation of the jet when the filling factor is close to 0 or 1. However, it can affect it when the filling factor is moderate. When the width of the H$\text{I}$ clumps is smaller than the radius of the working surface of the jet, the jet propagates in channels between the H$\text{I}$ clumps and breaks up into numerous branches. When the radius of the H$\text{I}$ clumps is larger than the radius of the working surface, the jet approaches that for the models with large filling factor.

In this paper, we assumed that the H$\text{I}$ clumps are not threaded by the magnetic field in the initial state. When the magnetic field is strong, shocked H$\text{I}$ clumps are hard to shrink in the direction perpendicular to the magnetic field. However, they can shrink along the magnetic field. The preexisting magnetic field can affect the shape of the cold clumps.

HESS J1023-575 is observed in both the high-energy band (above 2.5 TeV) and the low-energy band (0.7–2.5 TeV). The timescales for cooling by the pp interaction and diffusion of the relativistic particles are estimated to be about $5 \times 10^{3}$ yr and $2 \times 10^{3}$ yr, respectively, by Furukawa et al. (2014). If the arc and jet clouds and the TeV $\gamma$-ray source are produced by a single object, a supernova remnant or a pulsar wind nebula is not likely as the origin for the TeV $\gamma$-ray source since the diffusion timescale of the relativistic particles is shorter than the age of the arc and jet clouds (a few million years). A microquasar jet that is active over 1 Myr can explain both the age of the arc and jet clouds and the lifetime of the relativistic particles. Furukawa et al. discussed that averaged power injected to the relativistic protons needs to be $\sim 10^{37}$ erg s$^{-1}$ when the diffusion time is $2 \times 10^{3}$ yr in order to explain the energy of TeV $\gamma$-ray emission. In the low-energy band (0.7–2.5 TeV), TeV $\gamma$-rays are also detected toward the jet clouds. The cooling and diffusion timescales are estimated to be $6 \times 10^{4}$ yr and $7 \times 10^{3}$ yr, respectively. Assuming the diffusion timescale of $7 \times 10^{3}$ yr, the averaged power injection needs to be $\sim 8 \times 10^{33}$ erg s$^{-1}$. These estimations indicate that we need to consider a higher-energy jet than that in our simulations.
The peak of the column number density is about $10^{21}$ cm$^{-2}$ in our simulations while the column number density estimated from H I 21 cm line observations (McClure-Griffiths et al. 2005) is about $1.8 \times 10^{21}$ cm$^{-2}$. The peaks of the H$_2$ column number density of the arc cloud and jet cloud are $2.7 \times 10^{21}$ cm$^{-2}$ and $1.7-4.8 \times 10^{21}$ cm$^{-2}$, respectively, in observations. The peak is about $0.4 \times 10^{21}$ cm$^{-2}$ in our simulations for both the model of a big HI cloud and the model of clumpy HI clouds. One reason why numerical results gave a smaller H$_2$ column density is that the density of the HI clouds is smaller in our simulations. For example, when we consider that the HI clouds are twice as dense as the HI clouds in simulations, the peak of the column number density can double and the peak of the H$_2$ column number density can become about four times higher, since we estimate from Richings et al. (2014) that the ratio of H$_2$ to the total number density is roughly proportional to the total number density in the range $1 \text{ cm}^{-2} < n < 10^2 \text{ cm}^{-2}$. Another reason can be uncertainty of the X-factor. In this paper, we used $N(\text{H}_2)/W(\text{^{12}CO}) = 1.6 \times 10^{20} \text{ cm}^{-2}/(\text{K km s}^{-1})$ (Hunter et al. 1997) obtained from observations made with the Energetic Gamma-Ray Experiment Telescope. The X-factor is estimated to be $2.8 \times 10^{20} \text{ cm}^{-2}/(\text{K km s}^{-1})$ from X-ray observations (Bloemen et al. 1986), $(1.9 \pm 1.1) \times 10^{20} \text{ cm}^{-2}/(\text{K km s}^{-1})$ from infrared observations (Reach et al. 1998), and so on. Thus the X-factor has an uncertainty in the range $1-3 \times 10^{20} \text{ cm}^{-2}/(\text{K km s}^{-1})$.

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