Continuous Jets and Backflow Models for the Formation of W50/SS 433 in Magnetohydrodynamics Simulations

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Abstract

The formation mechanism of the W50/SS 433 complex has long been a mystery. We propose a new scenario in which the SS 433 jets themselves form the W50/SS 433 system. We carry out magnetohydrodynamics simulations of the propagation of two side jets using the public code CANS+. As found in previous jet studies, when the propagating jet is lighter than the surrounding medium, the shocked plasma flows back from the jet tip to the core. We find that the morphology of light jets is spheroidal at early times; afterward, the shell and wings are developed by the broadening spherical cocoon. The morphology depends strongly on the density ratio of the injected jet to the surrounding medium. Meanwhile, the ratio of the lengths of the two side jets depends only on the density profile of the surrounding medium. We also find that most of the jet kinetic energy is dissipated at the oblique shock formed by the interaction between the backflow and beam flow, rather than at the jet terminal shock. The position of the oblique shock is spatially consistent with the X-ray and TeV gamma-ray hotspots of W50.

Unified Astronomy Thesaurus concepts: Magnetohydrodynamical simulations (1966)

1. Introduction

Astrophysical jets emitted from gravitational objects such as black holes, neutron stars, and protostars are universal phenomena observed in various layers of the Milky Way. The jets interact with the surrounding interstellar medium (ISM), and the kinetic energy of the jets is therefore transformed into ISM thermal and turbulent energies. Additionally, some of the kinetic energy of jets is given to energetic, nonthermal particles. Microquasar jets are therefore a candidate for cosmic-ray acceleration sites (e.g., Heinz & Sunyaev 2002; Bordas et al. 2009). In particular, Cooper et al. (2020) argued that the cosmic-ray component generated in microquasar jets makes a non-negligible contribution to observed cosmic-ray spectra. However, physical quantities and characteristics of galactic jets are currently not well understood because the angular size of many galactic jets is small compared with the spatial resolution of observations.

The radio nebula W50 is located near the Galactic plane, and it is a rare Galactic object for which high-quality radio observations have been made (Dubner et al. 1998; Gao et al. 2011; Farnes et al. 2017; Broderick et al. 2018). The radio morphology of W50 has two characteristics, namely a circular shell with a diameter of 58′, and lateral extensions, which are called wings, in east–west directions. The X-ray binary SS 433 launches sub-relativistic precessing jets at the center of the shell structure of W50 (Blundell & Bowler 2004; Roberts et al. 2008; Blundell et al. 2018). The jet velocity of SS 433 is \( v_{\text{jet}} = 0.2581 c \), where \( c \) is the speed of light, and the precession period is 164 days (Margon 1984; Margon & Anderson 1989). Additionally, the kinetic energy luminosity of the jets is \( L_{\text{kin.jet}} \sim 10^{39} \text{erg s}^{-1} \) (Brinkmann et al. 2005). The wings are usually associated with the jets because the major axis of W50 is well aligned with jets from SS 433. Polarization observations indicate the existence of a helical magnetic field in the eastern wing (Farnes et al. 2017; Sakemi et al. 2018a, 2018b).

Nonthermal X-ray and gamma-ray observations indicate that the W50/SS 433 system is an efficient site for cosmic-ray acceleration, and emissions have been detected along the major axis of the jets (Brinkmann et al. 1996, 2007; Safi-Harb & Ögelman 1997). Several prominent regions have been identified as X-ray hotspots and are labeled e1, e2, and e3 on the eastern side and w1 and w2 on the western side. In particular, very-high-energy \( \gamma \)-rays (>25 TeV) have been detected from around the e1, e2, and w1 hotspots by the High Altitude Water Cerenkov observatory (Abeysekara et al. 2018). The spectral energy distribution at the hotspots is consistent with the model for the leptonic scenario. This scenario is that relativistic electrons scatter cosmic microwave background photons to TeV energies via the inverse Compton process. In addition, no TeV \( \gamma \)-ray signal from the central binary system has been detected. The hotspots should therefore be in situ particle acceleration sites associated with the SS 433 jets. Moreover, several studies provided observational evidence of \( \gamma \)-ray emissions at MeV–GeV energy levels from not only around X-ray hotspots but also around the spherical shell of W50 (e.g., Sun et al. 2019; Xing et al. 2019). Detailed analysis of over 10 years of GeV gamma-ray data recorded by the Fermi Gamma-ray Space Telescope revealed that the precessional period of the SS 433 jets is linked with the time variability of \( \gamma \)-ray excess in the northern shell of W50 (Li et al. 2020). These observations also strongly support the idea that W50/SS 433 has plausible cosmic-ray acceleration sites. However, it remains unclear whether the outstanding acceleration is due to the interaction between the jet and the supernova remnant (SNR) or just the SS 433 jets themselves.

W50 has a unique radio morphology, called the manatee nebula, and the formation mechanism of the W50/SS 433 system has been debated for many years. One scenario is that W50/SS 433 formed through interaction between the jets of SS 433 and wind bubbles, which were swept up by the stellar wind of the companion star of SS 433 (Begelman et al. 1980;
Konigl 1983). In addition, Asahina et al. (2014) suggested that 
the shell of W50 was formed by winds from an accretion disk 
with a mass accretion rate exceeding the Eddington limit. 
These scenarios pose the problem that it takes a long time for a 
wind explosion to reach 40–50 pc. The most popular scenario is 
that the jets and SNR shell interact. The circular shell of W50 is 
the shell of an SNR, resulting from a supernova explosion at SS 
433’s birth. The interaction between the jets and SNR shell forms 
the elongated wings on either side. A structure protruding from a supernova shell is often found in core-collapse SNRs and looks like the elongated structure of W50 (e.g., Gaensler et al. 1998). Griechener & Soker (2017) 
estimated the additional energy used to create the wings of the core-collapse SNR to be 1%–10% of the explosion energy of 
the supernova under simple geometrical assumptions. 
However, these wings are shorter than the radius of their own SNR. In contrast, the length of the eastern wing of W50 is 
much longer than the radius of the shell. For the wing length to 
be comparable to the shell radius, the additional kinetic energy needed to extend the W50 wing must be the same as 
the supernova explosion energy. Simply assuming that the kinetic energy luminosity of the SS 433 jets is $10^{39}$ erg s$^{-1}$ 
and the explosion energy is $10^{51}$ erg ensures the long-term activity of SS 433 for 10–100 kyr.

The interaction between the SS 433 jets and the SNR shell has been studied by conducting hydrodynamic simulations. Velázquez & Raga (2000) conducted a hydrodynamic simulation of jet propagation inside an SNR, as modeled using the analytical Sedov solution. Additionally, they showed that the cocoon gas, which is heated at the jet’s terminal shock, slightly increases the shell expansion velocity near the interaction region. A three-dimensional simulation conducted by Zavala et al. (2008) revealed that the exponential density profile of an ambient ISM identified by H I observations reproduced the length ratio of the eastern and western wings. The reason for the difference in the wing lengths is that a jet propagating into a region of increasing density drastically decelerates. Goodall et al. (2011a) reported results of two-dimensional hydrodynamical simulations for models of several jets propagating in an SNR shell, i.e., precession jets, cone jets, and fireball jets. They suggested that multi-episodic jet activity is needed for the formation of W50. Recently, Milas et al. (2019) performed a high-resolution adaptive-mesh refinement hydrodynamical simulation of precessing jets propagating in an SNR. Their results indicate that precession does not affect the large-scale morphology of W50, while the jets are well collimated at ∼0.068 pc from SS 433 and become hollow (Monceau-Baroux et al. 2015; Milas et al. 2019). Note that Monceau-Baroux et al. (2014) reported that precession would be dynamically important from the SS 433 scale to the sub-parsec scale because the precessing jets transport more kinetic energy into the ISM than do straight jets owing to the increase in the area of interaction between the jets and ISM. These hydrodynamical models for the interaction of the jets and SNR can explain the morphology of W50 within a realistic time, which is 10–100 kyr, in contrast with the wind model. However, there are problems. Although the jet termination regions are expected to be sites of efficient particle acceleration in the SNR and jet scenarios, prominent X-ray emissions are not detected in the terminal regions of the wings. Moreover, there is no physical explanation of where X-ray hotspots form in the intermediate region of SS 433 jets. Goodall et al. (2011a) pointed out differences between simulation results and observations. In particular, the connections between the jet and SNR shell are a smooth transition in contrast with simulation results (see Figure 10 in Goodall et al. 2011a).

In terms of the morphology of continuous jets produced by an active galactic nucleus (AGN), some numerical simulations of light jets, which have a lower density than the surrounding medium, reproduced the structure of the shell and wings (Gaibler et al. 2009; Hodges-Kluck & Reynolds 2011; Rossi et al. 2017). When the jet density is lower than the ISM density, we can use the simple formula of the light jet to estimate the speed of advance. Note that Monceau-Baroux 2014 suggested that multi-episodic jet activity is needed for the formation of W50. Recently, Millas et al. 2019 performed a hydrodynamic simulation of precessing jets propagating in an SNR. Their high-resolution adaptive-mesh refinement hydrodynamical simulations for models of several jets propagating in an SNR can explain the morphology of W50 within a realistic time, which is 10–100 kyr. In contrast with simulation results (see Figure 10 in Goodall et al. 2011a).

The speed of advance of light jets $v_{\text{head}}$ can be determined analytically from the momentum balance at the contact discontinuity between the jets and ISM. The speed of advance is approximately (Krause 2002)

$$v_{\text{head}} = \frac{\sqrt{\rho_j}}{1 + \sqrt{\rho_j}} v_{\text{beam}},$$

where $A$ and $v_{\text{beam}}$ are respectively the ratio of the beam to head area and the beam velocity. Equation (1) indicates that the speed of advance also depends on the ratio of the beam to head area. This ratio is close to unity for a heavy jet ($\eta \sim 1$) and decreases to 0.1 for a light jet ($\eta < 1$) (Krause 2002). Thus, light jets decelerate rapidly, and the propagation enters a nonlinear stage. Meanwhile, the lateral expansion of light jets is well described by the blast-wave equation of motion after the bow shock reaches $\sim R_{\text{jet}}/2\eta^{0.25}$, where $R_{\text{jet}}$ is the jet beam radius (Krause 2003, 2005). Light jets have strong backflows whose plasma continuously goes toward the core, and the jets expand supersonically in the lateral direction. When we simply assume constant energy injection $E = L_{\text{kin,jet}}$ and the density of the homogeneous ISM $\rho_{\text{ISM}}$, the radius of lateral expansion can be written as

$$R_{\text{lateral}} = \left( \frac{5L_{\text{kin,jet}}}{4\pi\rho_{\text{ISM}}} \right)^{1/5} = \left( \frac{5}{4} \frac{\rho_{\text{jet}}^2 v_{\text{beam}}^3}{\rho_{\text{ISM}}} \right)^{1/5},$$

where $L_{\text{kin,jet}} = \pi R_{\text{jet}}^2 \rho_{\text{jet}} v_{\text{beam}}^3$ is the kinetic energy luminosity of the jets. Therefore, $v_{\text{beam}}$, $R_{\text{jet}}$, and $\eta$ are quantities important to the morphology of light jets.

In this paper, we propose new modeling of the magnetohydrodynamics (MHD) of W50/SS 433 generated by jets and backflows. The jets injected during the period 20–90 kyr exist on either side and are light, supersonic, and magnetized. We conduct four simulations for jets with different radii and density ratios, and we present a mechanism for the formation of a shell and wings like those of W50. The remainder of the paper is structured as follows. We describe the basic equations and numerical setup of the jets and ISM in Section 2. In Section 3, we present our four models for MHD simulations. We discuss the results and other formation scenarios of W50/SS 433 in Section 4 and give a summary in Section 5.

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4 Some papers refer to “wings” as “ears.”
2. Numerical Setup

We solve ideal MHD equations in the axisymmetric cylindrical coordinate system \((R, \phi, z)\). The equations are
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \tag{3}
\]
\[
\rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p + \frac{B^2}{8\pi} + \frac{1}{4\pi} (\mathbf{B} \cdot \nabla) \mathbf{B}, \tag{4}
\]
\[
\frac{\partial}{\partial t} \left( e + \frac{1}{2} \rho \mathbf{v}^2 + \frac{B^2}{8\pi} \right) + \nabla \cdot \left[ \left( e + p + \frac{1}{2} \rho \mathbf{v}^2 \right) \mathbf{v} - \frac{(\mathbf{v} \times \mathbf{B}) \times \mathbf{B}}{4\pi} \right] = 0, \tag{5}
\]
\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}), \tag{6}
\]
\[
\nabla \cdot \mathbf{B} = 0, \tag{7}
\]
\[
\frac{\partial f}{\partial t} + \nabla \cdot (f \mathbf{v}) = 0, \tag{8}
\]
where \(\rho, \mathbf{v}, p, \mathbf{B}, e,\) and \(f\) are respectively the density, velocity, pressure, magnetic field, internal energy density, and jet tracer function. To distinguish the jets and ISM, the jet tracer function is set equal to unity for the injected jet flow and equal to zero for the ISM. We adopt the ideal gas law and give the internal energy density as \(e = (\gamma - 1)p\), where \(\gamma = 5/3\) is an adiabatic index. The plasma composition is 70% hydrogen and 30% helium by mass so that the mean molecular weight is 1.3. We use the MHD code CANS+ (Matsumoto et al. 2019). The code is based on the HLLD approximate Riemann solver (Miyoshi & Kusano 2005). The code implements fifth-order accuracy in space and third-order accuracy in time. We adopt the hyperbolic divergence cleaning method to reduce numerical errors under the divergence-free condition of the magnetic field (Dedner et al. 2002). The number of cells in our simulation box is \((N_R, N_z) = (1200, 4000)\). The physical dimensions of the box are \(0 \text{ pc} < R < 60 \text{ pc}\) and \(-80 \text{ pc} < z < 120 \text{ pc}\). We thus adopt a uniform grid in both directions, \(\Delta R = \Delta z = 0.05 \text{ pc}\). We apply a symmetric boundary condition at \(R = 0\) and an outflow boundary condition, which sets a zero gradient across the boundary, at other boundaries.

In this work, we assume the distance to SS 433 as 5.5 kpc (Lockman et al. 2007). The ISM around SS 433 thus seems to have a galactic exponential profile (Dehnen & Binney 1998). We adopt a modified exponential density profile for the initial density of the ISM:
\[
\rho_{\text{amb}} = \begin{cases} 
\mu m_p n_0 & (z \gtrsim -20) \\
\mu m_p n_0 \exp \left( -\frac{R}{R_d} - \frac{z + 20}{Z_d} \right) & (z < -20),
\end{cases}
\tag{9}
\]
where \(R_d = 5.4 \text{ kpc}\) is the scale length of the disk, \(Z_d = 30 \text{ pc}\) is the scale height of the Galactic disk, \(n_0 = 0.1 \text{ cm}^{-3}\), \(m_p\) is the proton mass, and SS 433 is located at \(z = 0\) and \(R = 0\). Note that the H\textsc{i} intensity map of the GALFA-H\textsc{i} survey shows that the constant density distribution of the ISM is a reasonable assumption in the eastern region of SS 433 (Peek et al. 2011). The western and eastern directions respectively correspond to the directions \(z < 0\) and \(z > 0\) in this simulation. The ISM is in pressure equilibrium, and the temperature of the ISM is \(10^4 \text{ K}\) at the location of SS 433. We assume that the uniform magnetic field is parallel to the \(z\)-axis and that the plasma \(\beta \equiv p/(B^2/8\pi)\) is 10 \((B \sim 0.59 \mu\text{G})\).

The two side jets are injected by a cylindrical nozzle along the \(z\)-axis at the origin. We adopt a velocity \(v_{\text{jet}} = 7.9 \times 10^6 \text{ cm s}^{-1}\) and initial Mach number \(M_{\text{jet}} = 10\) for the jets in all runs. We make calculations for four models, which have different density contrasts \(\eta = 10^{-2}\) and \(10^{-3}\) and different jet radii \(R_{\text{jet}} = 1\) and 3.33 pc. The jet nozzle length is 2 pc \((|z| < 1 \text{ pc})\). The jet kinetic energy luminosity is thus written as
\[
L_{\text{kin}} = \frac{\pi R_{\text{jet}}^2 \rho_{\text{jet}} v_{\text{jet}}^3}{\eta} = \pi R_{\text{jet}}^2 \rho_{\text{jet}} v_{\text{jet}}^3 \\
\sim 3.1 \times 10^{42} \eta \left( \frac{R_{\text{jet}}}{1 \text{ pc}} \right) \text{ erg s}^{-1}, \tag{10}
\]

We inject a toroidal field \(B_0 = R_{\text{jet}} \text{sgn}(z) \sin^2(\pi R/R_{\text{jet}})\), where \(\text{sgn}\) is the sign function, in the jet nozzle. We set \(\beta = 1\) at \(R = 0.5R_{\text{jet}}\) and hence \(B_{\text{jet}} = 140 \mu\text{G}\) for all runs. The parameters are summarized in Tables 1 and 2.

3. Numerical Results

3.1. Morphology

The basic structure in all runs has a dynamic behavior similar to that found in previous light-jet simulations (e.g., Ohmura et al. 2020). Therefore, we briefly summarize the basic structure of light jets and then describe the overall morphology of each run in detail. Figure 1 shows maps of the gas density (top) and \(z\)-direction velocity (bottom) for run L-R1 at \(t = 88 \text{ kyr}\). The basic structures of supersonic jets, such as a beam, backflow, cocoon, and thick shell (shocked ISM) are seen. Surrounding plasma mixes into the cocoon owing to Kelvin–Helmholtz (KH) instabilities at the contact discontinuity between the jet gas and shocked ISM. In particular, backflows from the tips of the jet interact with each other, and vortex motions are highly developed in the cocoon. The background density spatially increases at \(z < -20 \text{ pc}\) in the western direction, and the advance of the jet in the western direction thus slows appreciably. The magnetic field distribution and its detail are reported in Section 3.3.
Figure 2 shows the shape of the jet for all runs when the contact discontinuity between the jet and ISM reaches 100 pc. Because the speed of advance of jets depends on the injection condition, the times at which the jets reach 100 pc are different; i.e., H-R3, H-R1, L-R3, and L-R1 are at \( t = 16, 29, 55, \) and \( 88 \) kyr respectively. We here define the outer shape of jets as the contact discontinuity rather than a bow shock. However, it is difficult to identify the contact discontinuity between the jet plasma and shocked ISM because the gases are highly mixed by the KH instability. We therefore define the outer shape as the maximum radius of each \( z \) at which the jet tracer function \( f \) is less than \( 10^{-5} \). An analogous definition has been widely used in previous works on jet propagation (e.g., Gaibler et al. 2009). Here we denote the shell radius and the lengths from the origin to the eastern/western edges of the jet as \( l_R, l_{east}, \) and \( l_{west} \).

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We find that all runs have a circular shell centered on the origin when jets reach ~100 pc. The ratio of $l_{\text{east}}$ to $l_{\text{west}}$ is 100:75 for all runs. Lighter jets such as L-R1 and L-R3 form a larger shell. A lower density ratio corresponds to a lower lateral expansion velocity (see Equation (2)). However, because the kinetic energy luminosity of light jets is less than that of heavy jets, the advance of the light jet becomes much slower than that of the heavy jets. Lighter jets thus have enough time to form a larger circular shell while they propagate a distance of 100 pc. Run L-R1 therefore reproduces the characteristic morphology of W50, including a circular shell and elongated wings. Note that the wings of L-R3 are much wider than those of W50.

### 3.2. Time Evolution

In this section, we describe the time evolution of the jet morphology (Figure 3). Top and bottom panels show L-R1 and L-R3, respectively. Colors denote the shapes at $t = 8, 18, 28, 38, 48, 58, 68, 78, 88$ kyr for run L-R1 and $t = 5, 15, 25, 35, 45, 55$ kyr for run L-R3. In the early period of $t \lesssim 30$ kyr, the shapes of L-R1 and L-R3 are spheroids rather than circular shells. The spheroidal shape is well known from previous simulations and is similar to that of FR II radio sources, such as 3C 452 (e.g., Harwood et al. 2015). We find that a circular shell and wings then form. The region of the wing is filled with back-flowing plasma and it is thus difficult for the region to expand rapidly like the shell. Once the shell and wings have formed, they expand as self-similar evolution.

We next consider what physical parameters determine the speed of advance of the jet. We easily estimate the speed of advance of the jet in the positive $z$-direction by adopting Equation (1). Meanwhile, the density distribution in the western direction exponentially increases, and the gradient effect should thus be included in the expression for the speed of advance:

\[
v_{\text{head}} = \frac{dz}{dt} = \frac{\sqrt{\eta(z)}}{1 + \sqrt{\eta(z)}} v_{\text{beam}}, \quad \eta(z) = \eta_0 \exp \left( \frac{z - 20}{Z_d} \right).
\]

Here, we simply assume that $A = 1$ and $\rho_0, v_{\text{beam}}$ are constant values.

Figure 4 (left) shows the positions of the tips of the eastern/western jets as a function of the time for each run (solid lines) and analytic lines (dashed lines $\eta = 10^{-2}$, dotted lines $\eta = 10^{-4}$) of Equation (1) ($z > 0$) and Equation (11) ($z < 0$, toward the Galactic plane). All of the lines at $z > 0$ (eastern) are not in good agreement with analytic values because the speed of advance decreases rapidly. The area of the jet head increases during the propagation of the jets; i.e., $A$ is decreasing in Equation (1) because vortices grow downstream of the terminal shock. The jets, which have a large radius, have a small deceleration rate for both runs H and L because $A$ remains at unity for a longer time than in the case of jets with a small radius. When a jet propagates toward the Galactic plane (in the western direction), which means the ambient density increases as the distance increases ($z < 0$), Equation (11) well describes the results of runs H-R3 and L-R3.

We next describe the results of the time evolution of radial expansion for each run. Figure 4 (right) shows the shell radius $l_R$ as a function of time for each run (solid lines). Dashed lines are the time evolution of the analytical model (Equation (2)) whose kinetic energy luminosity is $L_{\text{kin,jet}} = 10^{39}, 10^{40}$, and $10^{41}$ erg s$^{-1}$. All runs have $l_R \propto t^{2/5}$ in accordance with the analytical solution. Note that Equation (2) describes the length of the bow shock along the $R$ axis instead of the contact discontinuity. $l_R$ is defined by the position of the contact discontinuity, and the expansion rate in all runs is thus lower than that for Equation (2). Note that the approximation for
Equation (2) is not valid when the density ratio of the ISM to jets is close to unity. Furthermore, jets with larger radii have greater kinetic energy luminosity, and the speed of radial expansion thus depends on the jet’s radius.

To discuss the formation mechanism of shells and cocoon, we focus on the length ratio of the two side jets and the length ratio of the jets and shell radius. In this work, the shell radius of W50 and the lengths from SS 433 to the tips of eastern and western wings are respectively $R_{W50} \sim 48$ pc, $L_{\text{east}} \sim 121.5$ pc, and $L_{\text{west}} \sim 86.5$ pc according to radio observations (Dubner et al. 1998; Goodall et al. 2011a). Thus, $L_{\text{east}}/R_{W50}$ and $L_{\text{east}}/L_{\text{west}}$ are 2.5 and 1.4, respectively. Figure 5 (left) shows the time evolution of the length ratio $l_{\text{east}}/l_{\text{west}}$ for all runs. The dashed and dotted lines are analytic solutions obtained when $\eta = 10^{-2}$ and $10^{-3}$. The numerical results for all runs and analytic solutions show a linear evolution over time.

In this work, we perform calculations until the tip of one side jet reaches 100 pc, but the length ratio, $l_{\text{east}}/l_{\text{west}}$, increases with simulation time. It is thus expected that the length ratio becomes 1.4 when $l_{\text{east}} = 120$ pc, which is consistent with radio observations. Interestingly, the length ratios are roughly the same for all runs when the positions of jets are fixed. These results indicate that $l_{\text{east}}/l_{\text{west}}$ is determined only by the density profile of the ISM.

We next investigate the time evolution of the ratio of length from the center to the tip of the jet propagation in the eastern direction to the shell radius, $l_{\text{east}}/l_{R}$ (right panel of Figure 5). For all runs, $l_{\text{east}}/l_{R}$ saturates at certain values. The lower-density runs of L-R1 and L-R3 have a constant value of $l_{\text{east}}/l_{R}$ for a long time. These results mean that outer shapes seem to undergo self-similar expansion in the later phase (see Figure 3). The ratio of $l_{\text{east}}$ and $l_{R}$ depends strongly on $\eta$. Although the speed of advance of the jet head is proportional to $\eta$, the speed of radial expansion does not depend on $\eta$. Although the speed of advance is strongly dependent on $\eta$, the speed of radial expansion is weakly dependent on $\eta$. Therefore, $l_{\text{east}}/l_{R}$ is greater when $\eta$ is closer to unity. The ratio of the length of the eastern wing to the shell radius of W50/SS 433 is $l_{\text{east}}/R_{W50} \sim 2.5$, which is consistent with the L-R1 run. In this work, we assume axisymmetric coordinates. We note that the speed of advance in three-dimensional simulations can be higher than that expected from axisymmetric simulations (Perucho et al. 2019).
3.3. Flow and Magnetic Fields

Figure 6 (top) presents the distributions of physical quantities on the jet axis that show the characteristics of shock waves. The red and blue curves present the pressure $\bar{p}$ and velocity gradients ($-\partial \bar{v}/\partial z$) averaged according to

$$\bar{f} = \frac{1}{\pi R_{jet}^2} \int_{0}^{R_{jet}} 2\pi R f \, dR.$$

(12)

The velocity gradient in the direction of propagation roughly represents the magnitude of the shock wave. The bottom panel of Figure 6 shows streamlines of the average velocity. The velocity gradient (blue curve) has many sharp spikes while the pressure distribution has wide-tailed peaks. The two are generally correlated and the peaks are considered as shock waves, such as reconfinement shocks, oblique shocks, and terminal shocks. As an example, we see reconfinement shocks at $z \sim -10, 10,$ and $20$ pc. After the jet propagates far away, it is difficult to identify the origin of each peak because many reflection waves propagate in various directions. However, when including the density and velocity distributions (Figure 1), we can identify the terminal shocks ($z \sim -70, 90$ pc) and oblique shocks ($z \sim -45, 60$ pc) in both side jets. A terminal shock is a location of energy exchange from jet kinetic energy to thermal energy and it produces backflows. When the propagation speed decreases, the backflow becomes turbulent and has circular and arc-like motion (see the bottom panel of Figure 6). The backflow therefore interacts with the beam itself and drives the strong oblique shock (Mizuta et al. 2004). We estimate the size of the backflow vortex in Section 4.1. In our calculation, the oblique shock in the eastern jet releases more kinetic energy than the terminal shock. Meanwhile, the western jet shows the opposite correlation. The background ISM density increases in the western direction, and the conversion efficiency of the jet kinetic energy to thermal energy at the terminal shock in the western direction is therefore higher than that in the eastern direction. The red curve shows that the pressure maximum of the jet head at $z = -75$ pc is three times that of the jet in the eastern direction ($z = 100$ pc).

Figure 7 (left) shows the distribution of toroidal magnetic fields and magnetic energy for run L-R1 at $t = 88$ kyr and the distribution of current density, $j = \nabla \times B$ (right). The magnetic energy is increased by shock compression; in particular, its energy is strongly enhanced downstream of the terminal shock of the western jet. We find three areas in the cocoon in Figure 7 (top left): an area of a positive field (blue), an area of a negative field (red), and an area of a weak magnetic field (white). The two backflows, which are antiparallel toroidal fields, interact in the cocoon, and the gas is mixed by vortices. The magnetic fields are therefore dissipated by magnetic reconnection in this mixing region. Figure 7 (right) shows that the interaction of the two backflows generates current sheets, where particles can be efficiently accelerated by magnetic reconnection. Our results would be affected by an artifact of the axisymmetric condition. If we conduct three-dimensional simulations, turbulence would be generated in the cocoon, which would readily convert toroidal and poloidal fields.

4. Discussion

4.1. Dynamics of Backflow

We here make a simple estimation of the interval of the oblique shocks. Note that the oblique shocks are formed by the
interaction between the beam and backflow. The interval thus corresponds to the size of the backflow vortex \( l_{bf} \). For the eastern jet of L-R1, we assume that the radius \( r_{bf} \) is about 10 pc (see Figure 3). To verify this assumption, we make the simple argument of mass flux conservation. The simulation result gives a \( z \)-direction velocity and density of the backflow of about \( 0.15v_{jet} \) and \( 10^{-4}\rho_{jet} \), respectively. Conservation of mass flux in a hollow cylindrical symmetry gives \( \pi R_{jet}^2 \rho_{jet} v_{jet} = \pi (r_{bf}^2 - r_{jet}^2) \rho_{bf} v_{bf} \). We obtain \( r_{bf} \approx 8R_{jet} = 8 \) pc, and the assumption is reasonable. We assume that the \( R \)-direction velocity is about the speed of sound \( c_{bf} \). To obtain \( c_{bf} \), we first calculate the speed of sound at the hotspot \( c_h \) using the Rankine–Hugoniot condition,

\[
c_h^2 = \frac{5M^4 + 14M^2 - 3}{16M^2} c_{jet}^2,
\]

(13)

where \( M = 10 \) is the Mach number of the jets while \( c_{jet} = M^{-1}v_{jet} \) is the speed of sound of the jets. Note that we ignore the speed of advance because it is much lower than \( v_{jet} \) and \( c_h \). We can estimate \( c_{bf} \) simply using the adiabatic condition:

\[
c_{bf}^2 = \left( \frac{R_{jet}^2}{r_{bf}^2} \right)^{\gamma - 1} c_h^2,
\]

(14)

where we assume that the radius of the hotspot is the same as the radius of the jet. The \( R \)-direction velocity is therefore evaluated as

\[
c_{bf} = v_{jet} \sqrt{ \frac{R_{jet}^2}{r_{bf}^2} } \left( \frac{5M^4 + 14M^2 - 3}{16M^4} \right)^{1/2} \sim 0.12v_{jet}.
\]

(15)

This value is close to the \( z \)-direction velocity of backflow \( v_{bf} \), which is about \( 0.15v_{jet} \) (see Figure 1). The oscillating time of the \( R \)-direction backflow is \( \tau = r_{bf}/c_{bf} \) and the interval of oblique shocks is thus evaluated as

\[
l_{bf} = 2\tau v_{bf} \sim 25 \text{ pc}.
\]

(16)

This value is roughly consistent with our numerical result. The bottom panel of Figure 6 shows that the backflow departs from \( z = 90 \) pc and arrives at \( z = 65 \) pc, where a strong oblique shock is excited. However, the actual dynamics of the beam and backflow are more complex and many weak shocks are thus excited along the beam.

### 4.2. Synchrotron Emission

We create a pseudo-synchrotron image of W50/SS 433 using physical values from MHD simulations. To calculate the synchrotron emissivity, we convert the two-dimensional axisymmetric cylindrical coordinates to three-dimensional Cartesian coordinates and assume a viewing angle of 78°8. We calculate and integrate the emissivity at each cell along the line of sight direction:

\[
I = \int \mathcal{J}_{\text{sync}} ds,
\]

(17)

where \( I \) and \( \mathcal{J}_{\text{sync}} \) are respectively the synchrotron intensity and emissivity. Our simulations do not model the evolution of nonthermal electrons, and hence some assumptions are needed to calculate the synchrotron emissivity. One is that the spectral index is uniform everywhere. The other is that the number density of nonthermal electrons is proportional to the gas density and thermal energy density. Under these assumptions, the synchrotron emissivity is given by (Jun & Norman 1996)

\[
\mathcal{J}_{\text{sync}} = \mathcal{C}_1(\nu) \rho^{1-2\alpha} p^{2\alpha} B_\perp^{\alpha+1},
\]

(18)

where \( \mathcal{C}_1, B_\perp, \nu, \) and \( \alpha \) are a normalized constant, the magnetic field component in the plane of the sky, the frequency of radiation, and the spectral index, respectively. We adopt \( \alpha = 0.52 \) because some radio observations provide the flatter spectrum in the eastern wing of W50 (Dubner et al. 1998; Gao et al. 2011). The calculation of polarized emissions is beyond the scope of this paper due to axisymmetry.

Figure 8 (left) shows the synchrotron intensity map at \( t = 88 \) kyr for run L-R1. The synchrotron power depends strongly on magnetic energy, and a weak emission is thus observed along with the shell (see Figure 7). The bright region in the western wing is around the oblique shocks and the termination shock. Small bright spots on the jet axis are formed by oblique shocks, whose spacing is defined by Equation (16). We can see the wide bright area both in the west and east wings, which consist of thin filaments. The accumulated
magnetic field along the contact discontinuity is the origin of these bright regions. We consider that these bright spots correspond to X-ray hotspots of SS 433. For example, the magnetic filament around \((R, z) = (10, 80)\) is the origin of the bright filament closest to the eastern end. On the other hand, because the magnetic field around the terminal shock is diffused, there is no X-ray radiation around that region.

The synchrotron intensity map obtained from numerical simulation is similar to X-ray observations of W50 (Brinkmann et al. 1996, 2007; Safi-Harb & Ögelman 1997). In particular, the positions of X-ray hotspots of W50 (e1, e2, w1, and w2) are consistent with those in the numerical results. The oblique shocks are thus thought to be rather efficient particle accelerators, in contrast with the terminal shocks in the long-term evolution of jets. Sudoh et al. (2020) and Kimura et al. (2020) constructed an analytic model for nonthermal leptonic and hadronic emission from knots in SS 433 jets, and their results suggest that the X-ray observation can be reproduced by synchrotron emission when the acceleration process is efficient.

We next discuss the distribution of electrons emitting radio waves in W50/SS 433. One main difference between microquasar jets and AGN jets is the outburst age, i.e., the age of relativistic electrons in the jet cocoon. The synchrotron cooling time \(t_c\) of nonthermal electrons in the microquasar jets is \(t_c \sim 1.9 \times 10^3 B^{-2} E^{-1}_z\) s, where \(E_z\) is the energy of electrons. The magnetic field strength of the eastern and western wings is about 1–100 \(\mu G\) (Safi-Harb & Ögelman 1997) and the cooling timescale is thus estimated as \(t_c \sim 100\) kyr when the frequency is 1 GHz and the magnetic field is 100 \(\mu G\). The plasma created around the terminal or oblique shock is thus not cooled to a few GeV and emits radiation at a centimeter wavelength. We calculate the shocked particle content in W50/SS 433, \(\mathcal{F}\), to integrate the tracer function, \(f\):

\[
\mathcal{F} = \int_{\text{LoS}} f \, ds.
\]

Figure 8 (right) is the same as Figure 8 (left) but we display a map of the distribution of jet particles. The plasma accumulates in the cocoon after passing the terminal shock and oblique shocks. The lifetime of electrons for synchrotron radiation is much longer than the jet active time (simulation time), and relativistic electrons in the shell can thus emit continually. The intensity is lower in both wings than in the shell because relativistic electrons are advected by backflow so that there are fewer electrons in both wings. This characteristic is also found for the radio emission of the eastern wing. Another radio characteristic of the eastern wing is an extended radio filament in the terminal region. In addition, Brinkmann et al. (2007) found an X-ray ring in this region, which corresponds spatially to the terminal shock of the SS 433 jet. However, our numerical result indicates that the shock size is only a few parsecs. The filament is thus formed by the backflow of the terminal shock. Additionally, Sakemi et al. (2018a) reported the existence of helical fields that coil the eastern wings. This result is consistent with our backflow scenario. We next discuss the shell emissions of W50. We find that magnetic reconnection generates current sheets in the shell (see Figure 7), and reaccelerated electrons in current sheets provide prominent radio emission. This radio emission corresponds to the filament structure in the southern region of W50; otherwise, the MeV \(\gamma\)-ray emission observed in the northern region of W50 is explained by this acceleration scenario. In this simulation, we assume an axisymmetric condition and the magnetic field in the shell of W50 is thus exhausted by magnetic reconnection. However, if we carry out three-dimensional simulations, the magnetic field can be stored in the shell because the flow can escape easily in any direction. The synchrotron emission from the shell would therefore be enhanced.

### 4.3. SNR Evolution

Previous studies have suggested that the SNR produced by the compact object SS 433 formed the shell structure of W50, and we thus discuss the difference in radial expansion between our backflow scenario and SNR scenarios. We next compare the features of radio emissions of W50/SS 433 with those of other SNRs. We mention again that the shell diameter is \(D = 96\) pc. The typical evolution of an SNR is described in the Sedov phase (i.e., the adiabatic phase). An expanding SNR is then described by the snowplow phase when radiative losses become important. We assume that the shell of W50 is in the Sedov phase and radiative cooling is thus negligible. Note that the radial expansion of the Sedov phase is faster than that of the snowplow phase. The shell radius of the SNR develops in the Sedov phase as 

\[
R = \frac{3}{2} \left( \frac{E_{\text{SNR}}}{\rho_{\text{ISM}} v^2} \right)^{1/2},
\]

where \(E_{\text{SNR}}\) is the initial explosion energy of the SNR. The dashed lines in Figure 9 show the radius of the SNR as a function of time for...
three different values of the ISM density. We simply assume that the ISM has a constant density $\rho_{\text{ISM}} = 1m_p$, $0.1m_p$, and $0.01m_p$ g cm$^{-3}$ and $E_{\text{SNR,51}} = 10^{51}$ erg. When the ISM density is greater than $0.1m_p$, it takes more than 100 kyr to reach a shell radius of 48 pc. The ISM is thus about $0.01m_p$, which is a very low density with which to form the W50/SS 433 shell. However, we note that W50/SS 433 is located near the Galactic plane, and H I emissions are observed around W50 (Peek et al. 2011; Sakemi et al. 2021). Such a low-density environment is thus unlikely. In another case, we believe that the W50 nebula formed in a high-power explosion ($E_{\text{SNR}} \gg 10^{51}$ erg), such as a hypernova or multiple supernovas. In contrast, we plot the time evolution of the radial expansion for the light jets for jet kinetic energy luminosity $L_{k,39} = 10^{39}$ erg s$^{-1}$ in Figure 9. The approximate solution of the radial expansion of jets is $R \propto t^{2/5}$. We mention again that the Sedov solution is proportional to $t^{2/5}$. The radius obtained using the jet model becomes larger than that obtained using the SNR model when the total energy exceeds the supernova explosion energy, $E_{\text{SNR}} = 10^{51}$ erg. The time is about $t \sim 40$ kyr for these model settings. In the case of jets instead of an SNR, the shell of W50 reaches 48 pc within 100 kyr when the ISM is $0.1m_p$ g cm$^{-3}$. Therefore, jets having long-term activity, for which a lifetime of $> 10$ kyr is expected, are a good candidate for the formation mechanism of W50/SS 433.

We next discuss radio observations of typical SNRs and W50/SS 433. Galactic SNRs have a radio observational relationship between the radio surface brightness and the diameter of the SNR, the so-called radio surface-brightness-to-diameter relationship ($\Sigma_{R-D}$) (e.g., Pavlovic et al. 2014). Figure 10 displays the $\Sigma_{R-D}$ relationship at 1 GHz for Galactic SNRs (blue circles and green diamonds) and W50/SS 433 (red star). The figure shows that W50/SS 433 is prominent and has a large size compared with Galactic SNRs. We note the observations of four prominent Galactic SNRs (CTB 37A, Kes97, CTB 37B, and G65.1+0.6) interacting with molecular clouds, which enhances radio emissions. The wings of W50 have a radio surface brightness comparable to that of the shell of W50 (Dubner et al. 1998). Previous hydrodynamical simulations clearly showed that the jetted gas and the gas-related supernova explosions are separated; in particular, the jetted gas is not distributed around the shell region (e.g., Goodall et al. 2011a). Although some observations suggest that there are molecular clouds associated with jets in the western wing of W50 (Yamamoto et al. 2008; Liu et al. 2020), there is no critical evidence of interacting molecular clouds, which would accelerate nonthermal particles. Additionally, the jet-cloud interaction is not strong and it thus does not enhance radio emissions throughout the western wing. Therefore, the origin of the prominent emission from the shell of W50 is not the same as that of other prominent SNRs.

Finally, we mention that the shell of W50 maintains a nearly perfectly circular structure. Stafford et al. (2019) investigated the relationship between the radio morphology and the sizes (ages) of SNRs. They found that larger (older) SNRs are more elliptical and/or elongated because the inhomogeneous ISM, turbulent structure, and molecular clouds affect their morphology. As we mentioned above, W50 is in a large size (old) category if its shell comprises SNRs.
In this section, we compare our results with those of Goodall et al. (2011a). We first mention that the radial expansion of the SNR is too fast in the simulations conducted by Goodall et al. (2011a) compared with the Sedov solutions and hydrodynamical simulations of SNRs. They assumed that the kinetic energy of SNRs is $\sim 10^{51}$ erg and the ISM density is $\sim 0.1$ cm$^{-3}$, and the shell radius of SNRs reaches 50 pc within 20 kyr. They might have underestimated the normalization of the kinetic energy of SNRs by an order of magnitude. We also mention the speed of advance of jets in Goodall et al. (2011a).

As an example, model Jet1 in Goodall et al. (2011a) has a young age of 2.2 kyr when the jet crosses the tip of the eastern wing. The average speed of advance of model Jet1 almost maintains the launch velocity of 0.26$c$ from SS 433, i.e., 120 pc/2.2 kyr $\sim$ 0.18$c$. Thus, the advance of model Jet1 does not decelerate. Note that the results of kinematical studies of the radio observations of W50 indicate that an upper limit to the proper motion of the radio filaments of the eastern wing is 0.0405$c$ (Goodall et al. 2011b). Jets that do not decelerate must be comparable to or greater than the ISM in density. Some previous numerical simulations have modeled protostar jets for heavy jets (e.g., Ustamujic et al. 2016). However, numerical and observational studies of AGN jets and microquasar jets suggest that extensive cocoons develop when the surrounding medium is lighter than the medium of the jets.

Panferov (2017) constructed a model combined with the theory of the dynamics of SNRs, wind bubbles, and jets for the formation of W50. Their jet model was based on turbulent jets in Landau & Lifshitz (1987). In the case of a wind bubble, if the binary system of SS 433 is a super-Eddington accretion, the age of the wind bubble needs to exceed 300 kyr to produce the large shell of W50. They also modeled the dynamics of SNRs in the Sedov phase and snowplow phase, describing the dynamics using the fitting function of Kim & Ostriker (2015). They argued that the age of W50 as an SNR is at least 97 kyr, which agrees with our results in Figure 9. The main result of Panferov (2017) is that the shell of W50 formed in a supernova explosion about 100 kyr ago, and the SS 433 jets produced both wings and pushed up the pre-existing SNR within 27 kyr. However, hydrodynamical studies showed that interaction between the jets and SNR does not push up the shell of W50 in the radial direction (Goodall et al. 2011a). Therefore, some other mechanism is needed for the model of Panferov (2017) to exchange energy efficiently between the jets and SNR shell.

### 4.4. Comparison with Other W50/SS 433 Formation Scenarios

In this section, we compare our results with those of Goodall et al. (2011a). We first mention that the radial expansion of the SNR is too fast in the simulations conducted by Goodall et al. (2011a) compared with the Sedov solutions and hydrodynamical simulations of SNRs. They assumed that the kinetic energy of SNRs is $\sim 10^{51}$ erg and the ISM density is $\sim 0.1$ cm$^{-3}$, and the shell radius of SNRs reaches 50 pc within 20 kyr. They might have underestimated the normalization of the kinetic energy of SNRs by an order of magnitude. We also mention the speed of advance of jets in Goodall et al. (2011a).

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### 5. Summary

We conducted a series of axisymmetric MHD simulations of two side jets to study the parameter dependence for the formation of shell and wings of the W50/SS 433 system. We argue that light and supersonic jets can produce the shell and wing morphology in a backflow scenario. The main results of this work are as follows.

1. At an early time ($t \lesssim 30$ kyr), the morphology of light jets ($\eta < 10^{-3}$) had a spheroidal shape. Afterward, the shell and wings formed and they expanded under self-similar evolution. In contrast, slightly heavy jets ($\eta \sim 10^{-2}$) cannot form a large shell because the advance is too fast compared with the radial expansion.
2. Jets having a large radius do not decelerate like jets with a smaller radius. Moreover, larger jets provide much kinetic energy luminosity, and the radial expansion of
the cocoon thus becomes fast. We can therefore produce wings and a shell of arbitrary size by appropriately selecting parameters, such as the jet radius and density contrast.

3. The exponential ISM profile produces the asymmetric wings observed for W50/SS 433 in previous works (Zavala et al. 2008; Goodall et al. 2011a; Millas et al. 2019). We find that the length ratio between the eastern and western wings, \( l_{\text{east}} / l_{\text{west}} \), is roughly the same for all runs when the positions of jets are fixed. Thus, \( l_{\text{east}} / l_{\text{west}} \) is determined only by the density profile of the ISM. Furthermore, our runs using the ISM profile of our model provide an asymmetric shape that is consistent with observations.

4. The main challenge to the jet scenario is the requirement for the prolonged activity of the jets. Run L-R1 requires activity lasting more than 100 kyr to result in the observed size of W50. The speed of advance and the speed of radial expansion respectively depend on the density contrast and density of the ISM. Therefore, if the ISM is slightly lower than 0.1 cm\(^{-3}\), our scenario overcomes the issues noted above.

5. A large amount of jet kinetic energy is converted into thermal energy for jets propagating in the Galactic plane because these jets interact with the high-density ISM. The interaction between the backflows and beams drives strong oblique shocks at the intermediate point of beams. The positions of oblique shocks correspond to X-ray hotspots of W50. Meanwhile, highly turbulent flows drive magnetic reconnection, which generates current sheets in the shell region where the two backflows have interacted.

6. We discussed the jet scenario and SNR scenario. For an SNR interpretation, an extremely low-density atmosphere, \( n_{\text{ISM}} \ll 0.1 \text{ cm}^{-3} \), or a high-energy explosion, \( E_{\text{SNR}} \gg 10^{51} \text{ erg} \), is required for the SNR’s forward shock to reach about 50 pc. Moreover, the shell of W50 is larger and much more prominent than that of other Galactic SNRs. Although the jet scenario depends strongly on the activity time and the total amount of energy, the shell of W50 could have been formed by backflow within a period of 100 kyr. Notice that our numerical results can explain the morphology of W50/SS 433, but they do not entirely rule out the SNR scenario.

Future work should treat some of the key physics that we have ignored. First, three-dimensional effects affect the dynamics of jets. The speeds of advance in three-dimensional simulations are higher than those in axisymmetric simulations, and turbulence is generated by non-axisymmetric motions. Second, we ignored winds from the companion star and/or accretion disk. The interaction between winds and jets might positively affect the formation of the shell of W50. If SS 433 is an ultraluminous X-ray source, then the state of the accretion disk is a supercritical accreting flow. Radiation hydrodynamics simulations of supercritical accretion flow suggest that strong winds \((\sim 10^{16} \text{ erg s}^{-1})\) can be driven by radiation pressure (Kawashima et al. 2009). From an observational viewpoint, some ultraluminous X-ray sources have bubbles on the scale of a few tens of parsecs, similar to the case for W50 (e.g., Pakull et al. 2010; Berghea et al. 2020). Finally, we need to implement the precession of jets. However, we mention again that the precessions do not affect the large-scale morphology of W50 because the jets are well collimated within 0.1 pc from SS 433 and they become hollow (Millas et al. 2019).

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