DISTRIBUTION OF FARADAY ROTATION MEASURE IN JETS FROM ACTIVE GALACTIC NUCLEI. II.
PREDICTION FROM OUR SWEETING MAGNETIC TWIST MODEL FOR THE WIGGLED PARTS
OF ACTIVE GALACTIC NUCLEUS JETS AND TAILS

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ABSTRACT

Distributions of Faraday rotation measure (FRM) and the projected magnetic field derived by a three-
dimensional simulation of MHD jets are investigated based on our “sweeping magnetic twist model.” FRM
and Stokes parameters were calculated to be compared with radio observations of large-scale wiggled AGN jets
on kiloparsec scales. We propose that the FRM distribution can be used to discuss the three-dimensional
structure of the magnetic field around jets and the validity of existing theoretical models, together with the
projected magnetic field derived from Stokes parameters. In a previous paper we investigated the basic straight part
of AGN jets by using the result of a two-dimensional axisymmetric simulation. The derived FRM distribution has
a general tendency to have a gradient across the jet axis, which is due to the toroidal component of the magnetic
field generated by the rotation of the accretion disk. In this paper we consider the wiggled structure of the AGN
jets by using the result of a three-dimensional simulation. Our numerical results show that the distributions of
FRM and the projected magnetic field have a clear correlation with the large-scale structure of the jet itself,
namely, three-dimensional helix. Distributions, seeing the jet from a certain direction, show a good matching
with those in a part of the 3C 449 jet. This suggests that the jet has a helical structure and that the magnetic field
-especially the toroidal component—plays an important role in the dynamics of the wiggle formation because it is
due to a current-driven helical kink instability in our model.

Subject headings: galaxies: jets — magnetic fields — MHD — polarization

1. INTRODUCTION

To explain the formation of active galactic nucleus (AGN) jets and other astrophysical jets, various models have been
proposed. Among them, the magnetohydrodynamic (MHD) model is one of the most promising models, since it can explain
both the acceleration and the collimation of the jets (see, e.g., Meier et al. 2001 and references therein). Lovelace (1976) and
Blandford (1976) first proposed the theoretical model of the magnetically driven jet from accretion disks, and Blandford &
Payne (1982) discussed magnetocentrifugally driven outflow from a Keplerian disk in steady, axisymmetric, and self-similar
situations. Time-dependent, two-dimensional axisymmetric simulations were performed by Uchida & Shibata (1985, 1986)
and Shibata & Uchida (1986). They pointed out that large-amplitude torsional Alfven waves (TAWs) generated by the
interaction between the accretion disc and a large-scale magnetic field play an important role. The toroidal magnetic field
propagates along the large-scale magnetic field while squeezing it into a collimated jet shape by the pinching effect of the
Lorentz force. In this paper we refer to this model as a “sweeping magnetic twist model.” After these papers, many

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by a foreground Faraday screen (Taylor 1998; Asada et al. 2002). If this is the case, we can get new information, that is, the line-of-sight component of the magnetic field, and thus can predict the three-dimensional configuration of the magnetic field around the jet, together with the projected magnetic field. Uchida et al. (2004, hereafter Paper I) carried out a two-dimensional axisymmetric simulation and investigated the model counterpart distributions of FRM and the projected magnetic field in the basic straight part of AGN jets. It was described how a systematically helical field configuration is produced in the sweeping magnetic twist model. It was also shown as a result that the model can reproduce fairly well the characteristic distribution of FRM having the gradient across the jet axis (Perley et al. 1984; Asada et al. 2002; Gabuzda & Murray 2004). The systematic FRM gradient was caused by the gradient of the line-of-sight component of the magnetic field. This means that the existence of the helical magnetic field (and the propagation of TAWs) is plausible. On the basis of this success, in this paper the treatment is advanced to the nonaxisymmetric situation, the wiggled structure, in AGN jets.

The morphological structures in AGN jets, such as "wiggles (kinks)" or "bends," are frequently seen not only on kiloparsec scales but also on parsec scales and smaller (Hummel et al. 1992). Such a helical distortion might be caused by either plasma instabilities or precession of jet ejection axis due to the gravitational interaction between binary black holes (BBHs; Begelman et al. 1980), BH/disk, or galaxies. Magnetically driven jets possess a toroidal field component, which is equivalent to an axial electric current, and such "current-carrying" jets are susceptible to MHD instabilities; moreover, Kelvin-Helmholtz instabilities must also be taken into account for jet dynamics. MHD instabilities are usually divided into pressure-driven instabilities and current-driven instabilities (Bateman...
Kelvin-Helmholtz instabilities have been considered for past decades by many theoretical and numerical works (for reviews see Birkinshaw 1991; Ferrari 1998 and references therein). One of the promising possibilities is a magnetic mechanism based on the sweeping magnetic twist model. It was shown by three-dimensional MHD simulations that the formation of the wiggled structure can be explained by the current-driven helical kink instability (Todo et al. 1993). In these simulations, the magnetic field was a force-free helical field from the beginning and the propagation of TAWs was not dealt with. Nakamura et al. (2001) extended the treatment of the sweeping magnetic twist model to the part far from the gravitator and the accretion disk. They investigated the behavior of TAWs propagating far from the AGN core. They showed that the current-driven helical kink instability can explain the production of the observed wiggles. If the mechanism of the wiggles formation is clarified, it can become a clue to the physics of the jet formation.

In this paper we calculate FRM, the projected magnetic field, and the total intensity from the numerical data of an MHD simulation based on our sweeping magnetic twist model and discuss these model counterparts in comparison with an observation. Here we consider the wiggled structure of the jet and thus use the same kind of three-dimensional simulation as in Nakamura et al. (2001). In §2 we describe the application of the model to the distant part of the jet from the AGN core and show the formation of a helical structure of the jet by the current-driven helical kink instability. We introduce the method to calculate model counterparts of observational quantities in §3 and show the results in §4. We discuss a comparison between the calculated distributions and observed ones in §5. The conclusion is summarized in §6.

2. NUMERICAL SIMULATION

The sweeping magnetic twist model was proposed for star-forming jets (Uchida & Shibata 1985; Shibata & Uchida 1986), and it has since then been extended to the case of AGN jets (Uchida & Shibata 1986; Matsumoto et al. 1996; Uchida et al. 1999, 2000; Nakamura et al. 2001) as described in Paper I in some detail. In Paper I we confined ourselves to the straight part of the jet as a first step, by using the two-dimensional axisymmetric model. In the present paper we extend our treatment to the wiggled part of our three-dimensional jet model, in order to compare the model counterpart with the observation. In this section we describe the formation of the wiggled structure due to the current-driven helical kink instability.

2.1. Brief Explanation of the Model—Assumptions and Basic Equations

Figure 1 is the schematic picture of a physical situation we treat in this paper. We consider a primordial large-scale magnetic field and that it is squeezed under an assumption of frozen-in magnetic flux due to the gravitational contraction to form the central AGN core (Figs. 1a and 1b). During the contracting process of the magnetized gas, the toroidal component of the magnetic field is continuously created by the rotation of the intergalactic medium having the angular momentum. As a result, large-amplitude nonlinear TAWs begin to propagate out along the large-scale poloidal field. We expect that this process reaches its maximum as the accretion disk is formed, and the interaction of the rotating accretion disk and the poloidal magnetic field penetrating it reaches its maximum phase (Fig. 1c). In addition, the MHD jets powered by TAWs are emitted in opposite directions along the rotation axis of the disk, which is the direction of the original large-scale poloidal magnetic field.

In the present paper we concentrate our attention on the distant part of the jet from the AGN core. The TAWs finally encounter the ambient medium with a higher density surrounding the large spherical “cavity” from which the mass fell toward the center in the gravitational contraction (Fig. 1d). The Hubble Space Telescope (HST) optical and MERLIN radio observations of a few hundred parsec scale 3C 264 jet...

![Fig. 2.—Radial profile of imposed circular motion (solid line) and inflow (dotted line) at the lower boundary.](Image)

![Fig. 3.—Initial distributions of the density (top), the pressure (initially constant) on the y-z plane (−1.0 ≤ y ≤ 1.0, 0.0 ≤ z ≤ 8.0) at x = 0.0 (middle), and the projected three-dimensional configuration of the initial magnetic field (bottom).](Image)
Fig. 4.—Time evolution of the density on the $y$-$z$ plane at $x = 0.0$ ($-1.0 \leq y \leq 1.0$, $0.0 \leq z \leq 8.0$).
Fig. 5.—Time evolution of the pressure on the y-z plane at $x = 0.0$. 
Fig. 6.—Time evolution of the projected three-dimensional configuration of selected magnetic lines of force.
indicate that the jet has a wiggled structure as a result of interacting with a circular optical cold (dense) “ring,” which may be a true ring, a shell, or a filled spheroid (Baum et al. 1997). This observational result indicates that the interaction between the jet and the ambient medium will affect the jet dynamics and morphology. The existence of denser material ahead of the propagating TAWs causes the deceleration of MHD jets due to the decreasing local Alfvén velocity; the accumulation of the toroidal component of the magnetic field occurs, which may lead to the current-driven helical kink instabilities through this nonlinear process (Nakamura et al. 2001). Even in the case of decreasing density atmospheres, the MHD jets would be subject to the current-driven kink distortions (M. Nakamura & D. L. Meier 2004, in preparation).

The computational domain we report here is also shown in Figure 1d, and it includes a part of the “squeezed” poloidal field near the edge of the density “cavity.” We assume the poloidally magnetized intergalactic medium with a varying Alfvén velocity distribution (i.e., gradually decreasing as the TAWs propagate) due to the existence of a denser shell that represents the edge of the cavity. A continuous cylindrical MHD inflow, powered by TAWs into the “evolved” region of the domain, is specified for all times in the lower “boundary zone.” We note that a quasi-stationary Poynting flux–dominated flow is injected into our calculated region throughout the time evolution.

We adopt the ideal MHD as the governing equations:

\begin{align}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0, \\
\rho \frac{\partial \mathbf{v}}{\partial t} + \rho (\mathbf{v} \cdot \nabla) \mathbf{v} + \nabla p - \frac{1}{4\pi} (\nabla \times \mathbf{B}) \times \mathbf{B} &= 0, \\
\frac{\partial p}{\partial t} + \nabla \cdot (p \mathbf{v}) - (1 - \gamma) p \nabla \cdot \mathbf{v} &= 0, \\
\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) &= 0,
\end{align}

where \( \rho, p, \) and \( \mathbf{v} \) are the density, pressure, and velocity of the gas, respectively, and \( \mathbf{B} \) is the magnetic field. Here \( \gamma \) represents the ratio of specific heats and is equal to 5/3 in this paper.

In Paper I we introduced the effect of gravity in equation (2) in order to consider the launching and accelerating of MHD jets.

![Fig. 7.—Distribution in the x-y plane at z = 4.25. A gray scale and contour show the z-component of the current density, and arrows show the velocity field.](image1)

![Fig. 8.—Three-dimensional distributions of a typical isovalue surface of the specific power, \(-J_z B_z V_z/\rho + J_z B_z V_z/\rho\), and the selected magnetic lines of force at t = 19.0.](image2)
jets near the AGN core. We neglect the gravity term in this equation and concentrate on the dynamics of the propagating MHD jets in this paper.

We normalize all physical quantities by the typical length $L_0$, typical density $\rho_0$, and typical velocity $V_0$. $L_0$ is 10 times as long as the radius with the maximum velocity of the circular motion. Parameters $\rho_0$ and $V_0$ are the density and the Alfvén velocity at the origin, respectively. The total computational domain is taken to be $x_{\text{min}} \leq x \leq x_{\text{max}}$, $y_{\text{min}} \leq y \leq y_{\text{max}}$, and $z_{\text{min}} \leq z \leq z_{\text{max}}$, where $x_{\text{min}} = y_{\text{min}} = -5.10$, $x_{\text{max}} = y_{\text{max}} = 5.10$, $z_{\text{min}} = -1.00$, and $z_{\text{max}} = 12.09$. The numbers of grid points in the simulation reported here are $(N_x \times N_y \times N_z) = (243 \times 243 \times 655)$, where the grid points are distributed non-uniformly in the $x$, $y$, and $z$-directions. The grid spacing is uniform, $(\Delta x, \Delta y, \Delta z) = (0.015, 0.015, 0.015)$ for $|x| \leq 0.99$, $|y| \leq 0.99$, and $z \leq 8.0$, and then stretched by 5% per each grid step for the regions $|x| > 0.99$, $|y| > 0.99$, and $z > 8.0$.

Initial conditions are almost the same as those of Nakamura et al. (2001), but the radial profiles of $V_x$ and $V_z$ (the circular motion and inflow imposed at the lower boundary zone) in this paper are different from those in Nakamura et al. (2001). The profiles in this paper are shown in Figure 2. The initial distributions of the density and the pressure of the gas, as well as the three-dimensional configuration of selected magnetic lines of force, are shown in Figure 3. This figure displays the distributions of the range of $-1.0 \leq y \leq 1.0$, $0.0 \leq z \leq 8.0$.

$B_z$ decreases gradually along the $z$-axis and tends to $\sim z^{-2}$ for the upper region, and $\rho$ also decreases in the same way but increases again toward the upper boundary. We assume a constant pressure throughout the computational domain and that the plasma $\beta$ (the ratio of gas pressure to magnetic pressure) at the origin is 0.01. The value of the plasma $\beta$ increases along the $z$-axis and exceeds unity at $z = 3.8$. In the decreasing region ($\rho$ and $B$) in the lower part, we have the constant Alfvén velocity ($V_\A = |B|/\rho^{1/2}$) and gradually decreasing distribution of $V_\A$ as $\rho$ increases.

The formation of the wiggled structure is universal independent of the imposed velocity profiles. The clearest difference in the results between Nakamura et al. (2001) and this paper is the time that it takes before the wiggled structure is formed.

### 2.2. Time Evolution

We discuss the dynamical behavior of a typical case in our performed three-dimensional simulations: the growth of a current-driven instability in an MHD jet. Figures 4, 5, and 6 show the time evolution of the density, pressure, and three-dimensional configuration of the selected magnetic lines of force in the $y$-$z$ plane ($-1.0 \leq y \leq 1.0$, $0.0 \leq z \leq 8.0$) at $x = 0.0$. In the early stage ($t = 5.0$), a strongly magnetized
helical jet powered by TAWs advances with a constant velocity into the decreasing poloidally magnetized medium. Our MHD jets have a fast-mode MHD wave front and a slow-mode MHD wave front closely beyond a contact surface. The front of the TAW (a fast-mode MHD wave) begins to be decelerated as a result of the gradually decreasing $V_A$; the accumulation of $B_e/C_30$ occurs behind this wave front ($t = 10.0$). The toroidal magnetic pressure gradient force $d(B^2_e/2)/dz$ becomes large and works effectively at this front, strongly compressing the external medium along this propagating TAW front. The initially “hourglass-shaped” magnetic field becomes “tucked up” behind this wave front ($t = 15.0$). At later stages the front becomes superfast magnetosonic and a strong bow shock (fast-mode MHD shock) is formed. The accumulation of $B_{e}/C_{30}$ causes a concentration of the axial current density $J_z$ near the central ($z$) axis (Fig. 7, left panel), and the magnetic pitch $(|B_{e}/rB_z|)$ becomes large inside the jet. The Lorentz force breaks the quasi-equilibrium balance in the radial direction, and the jet is disrupted ($t = 19.0-20.0$). We have an asymmetric distribution of the current density and projected (in an $x$-$y$ plane) velocity field seen in the right panel of Figure 7. There is a strong correlation between the three-dimensional configuration of the magnetic field and the distribution of specific power due to the radial ($r$) component of the Lorentz force: $-J_0 B_0 V_r/\rho + J_0 B_z V_r/\rho$ (Fig. 8). Therefore, it is confirmed that the distortion of our MHD jet is driven by the current-driven helical kink instability ($m = 1$; Nakamura et al. 2001).

3. METHOD OF CALCULATION OF MODEL COUNTERPARTS

Using the numerical data of the three-dimensional simulation explained in the previous section, we computed the distributions of FRM, the projected magnetic field, and the total intensity seen from different viewing angles.

We computed the FRM distribution by integrating $B \parallel$ along the line of sight although in Paper I we integrated $n_e B_0$. In this paper we intend to consider the effect of the deformed magnetic field configuration and to omit the effect of the dense shell from consideration. To calculate Stokes parameters, we assume the following: (1) radiation processes are dominated by synchrotron radiation, (2) synchrotron self-absorption is negligible, (3) the spectral index $\alpha$ is equal to unity, and (4) the projected magnetic field is perpendicular to the projected electric field. The emissivity of the synchrotron radiation is given by $\epsilon = p B \sin \psi |^{\alpha+1}$, where $B$ is the local magnetic field strength, $\psi$ is the angle between the local magnetic field and the line of sight, and $p$ is the gas pressure. In our simulation the relativistic particles are not explicitly tracked; therefore, we assume that the energy and number densities of the relativistic particles are proportional to the
energy and number densities of the thermal fluid (Clarke et al. 1989; Hardee & Rosen 1999, 2002). The total intensity is then given by the integration of the emissivity along the line of sight as

\[ I = \int \epsilon \, ds \]

Other Stokes parameters are given by

\[ Q = \int \epsilon \cos 2\chi' \, ds \]
\[ U = \int \epsilon \sin 2\chi' \, ds \]

where the local polarization angle \( \chi' \) is determined by the direction of the local magnetic field and the direction of the line of sight. Using these \( U \) and \( Q \), the polarization angle \( \chi \) is given by

\[ \chi = \frac{1}{2} \tan^{-1}(U/Q) \]

Finally, the projected magnetic field is determined from the polarization angle \( \chi \) and the polarization intensity \((Q^2 + U^2)^{1/2}\).

Here we separate the Faraday rotation screen and the emitting region, and we performed the integrations only in the emitting region for Stokes parameters and only in the Faraday rotation screen for FRM. We assumed this separation on the basis of the fact that linear dependence of the observed polarization angle on wavelength squared holds in some observations (Perley et al. 1984; Feretti et al. 1999; Asada et al. 2002; Gabuzda & Murray 2004); this would not be the case if the Faraday rotation is caused in the emitting region (Burn 1966). The emitting region and the Faraday rotation screen are deformed into the three-dimensional shape in the helical kink instability. Therefore, we trace the flux tube in its time development by the initial footpoints of magnetic lines of force at the upper boundary of the simulation region. This is reasonable because the footpoints do not move until a wave front arrives. The region that is defined as the Faraday rotation screen is almost corresponding to the magnetic tube to which the circular motion is imposed.

4. RESULTS OF THE NUMERICAL OBSERVATION

4.1. Before the Formation of the Wiggled Structure

Figure 9 shows the FRM distributions at the time before the formation of the wiggled structure \( t = 15.0 \). Black in the map corresponds to a maximum and white to a minimum in each viewing angle case. The FRM distributions have the gradient in the direction perpendicular to the jet axis independent of the viewing angle. This gradient is caused by the toroidal magnetic field propagating as TAWs.

Figure 10 shows the total intensity distributions. When the angle between the jet axis and the line of sight, \( \theta \), is equal to \( 90^\circ \), total intensity has the highest value on the jet axis since both the emissivity and the integration depth of the emitter are maximum. As the viewing angle becomes small, the asymmetry appears as a result of the asymmetry of the emissivity; this is equivalent to the asymmetry of the magnetic field component perpendicular to the line of sight.
Fig. 12.—Calculated model counterparts for the FRM distribution, when seen at (a) 90°, (b) 70°, (c) 55°, and (d) 30°, from the axis (ahead of the jet) at the time after the formation of the wiggled structure ($t = 20.0$). The data of the numerical observation exist inside the area surrounded by the black line.
Fig. 13.—Calculated model counterparts for the total intensity, when seen at (a) $90^\circ$, (b) $70^\circ$, (c) $55^\circ$, and (d) $30^\circ$, from the axis at $t = 20.0$. The data of the numerical observation exist inside the area surrounded by the black line.
Fig. 14.—Calculated model counterparts for the projected magnetic field, when seen at (a) 90°, (b) 70°, (c) 55°, and (d) 30°, from the axis at $t = 20.0$. The bars represent the direction of the projected magnetic field, and the length of the bars represents the polarization intensity.
helical magnetic field; therefore, it is opposite in both sides of the jet whether the emissivity increases or decreases when the viewing angle changes. Figure 11 shows the distributions of the projected magnetic field. It is parallel to the jet axis in almost all regions independent of the viewing angle because the pitch angle of the helical magnetic field is not so large. However, the polarization intensity becomes lower as \( \theta \) becomes small.

4.2. After the Formation of the Wigged Structure

The FRM distributions at the time after the formation of the wiggled structure \((t = 20.0)\) are shown in Figure 12. The gradient across the jet axis is partly seen, but it is not seen in the wiggled structure because the toroidal component of the magnetic field is smaller compared to the field component along the structural axis; i.e., the magnetic field is less twisted around the wiggled structure. Therefore, FRM is large in the structure coming toward us and small in the structure going backward. This means that the FRM distribution in the wiggled structure can strongly reflect its three-dimensional shape. FRM changes suddenly where different parts of the wiggled jet overlap each other as seen by the observer.

Figure 13 shows the total intensity distributions. Behind the fast-mode MHD shock front, toroidal magnetic field is accumulated and magnetic field is strengthened. It leads the emissivity to increase and the total intensity to become high. On the other hand, the intensity is not so high in the wiggled structure, where the magnetic field is less twisted around the wiggled structure. However, as the viewing angle becomes small, the intensity in the wiggled structure increases because the structure that lies on this side and that on the back side overlap on the same ray. This means that the integration depth of the emitter increases. For the same reason, the polarization intensity gets higher in the wiggled structure (Fig. 14). The projected magnetic field is along the structural axis of the jet on the whole. In the wiggled structure, the projected field appears transverse to the global jet axis (z-axis).

5. DISCUSSION

In this section we discuss the comparison between the calculated distributions shown in the previous section and those in the 3C 449 jet. Figure 15 shows the distributions of FRM and the projected magnetic field in part of the 3C 449 jet (Feretti et al. 1999). As we go along the jet, the color in the FRM distribution starts from blue, changes to deep blue, jumps to yellow, and changes to red at an edge of the jet (a bending point) on the right-hand side. The parallel projected magnetic field exists widely where the color in the FRM distribution is yellow or red.

Figure 16 shows the color FRM distribution of Figure 11c and the projected magnetic field distribution \((\theta = 55^\circ)\) in the wiggled structure. The structure takes the form of a three-dimensional helix. The structure going upward almost perpendicularly to the line of sight corresponds to the yellow part. The projected magnetic field in the wiggled structure is almost parallel. This is caused by the following: the structure going from left to right on the back side and that from right to left on this side appear to overlap partly (see Fig. 17).

As stated in § 3, we omitted the effect of the dense shell from consideration. Here we demonstrate the effect of the dense shell. Figure 18 shows the FRM distribution in the wiggled structure calculated by the integration of \(n_e B_\parallel\). The characteristics of the distribution are the same so that it can be said that the dense shell does not qualitatively affect the distribution so much in this case.

Feretti et al. (1999) estimated the jet velocity and the inclination of the line of sight by the ratio of \(P_{c,obs} \) to \(P_{c,exp}\), where \(P_{c,obs}\) is the observed core radio power at 5 GHz and
$P_{\text{exp}}$ is the power inferred from the total radio power at 408 MHz. From such estimation, they concluded that an initial jet velocity is 0.9$c$ and a jet inclination to the line of sight is 82°5. However, these values were obtained from the information near the core. It is likely that the jet is bent in some places. Birkinshaw et al. (1981) estimated from the polarization intensity along the jet that the inclination of the north jet in 3C 449 is 53°. This inclination is almost the same as that at which we can reproduce the characteristics of the observation.

These similarities between the calculated distributions and the observed ones suggest that the two-dimensional wiggle in the observation is due to the projection of a three-dimensional helical structure onto the plane of the sky. It is also suggested that the structure that lies on this side (yellow) hides the structure on the back side. The reddish part corresponds to the part coming toward us in the helix. If this is the case, it is highly likely that the magnetic field (especially the toroidal component) plays an important role not only in the emission but also in the dynamics of the jet formation because the
wiggle formation is caused by the accumulation of the toroidal field. It is also suggested that the FRM distribution can be a sensitive clue for telling which of the proposed models is the correct one.

Because it is not obvious how much the Faraday screen, which is irrelevant to the jet itself, contributes to the value of rotation measure, it is not possible to predict the value of FRM. It is, however, possible to estimate the difference between the maximum and the minimum of rotation measure. In our simulation, the scale of the wiggled structure is almost equal to the length unit of the simulation. The integration depth of the Faraday screen is about twice as long as the length unit. The rotation measure is given by \( \text{FRM}(\text{rad m}^{-2}) = 8.1 \times 10^{8} n_{e} (\text{cm}^{-3}) B_{\|} \), where \( n_{e} \) is the electron density, \( B_{\|} \) is the line-of-sight component of the magnetic field, and \( L_{FS} \) is the integration depth of the Faraday screen. In our calculation, \( L_{FS} \) is twice as long as \( L_{\text{wiggled}} \), where \( L_{\text{wiggled}} \) is the scale of the wiggled structure. If the maximum of the rotation measure (\( \text{FRM}_{\text{max}} \)) is made by \( B_{\|} = (B) \) and the minimum of the rotation measure (\( \text{FRM}_{\text{min}} \)) by \( B_{\|} = (-B) \), then \( \text{FRM}_{\text{max}} - \text{FRM}_{\text{min}} = 3.2 \times 10^{8} n_{e} (B) L_{\text{wiggled}} \).

Except for the wiggled structure, there are some differences. First, the total and polarized intensities enhance beyond the wiggled structure in the model counterparts, while this is not seen in the observation. The enhancement of the intensities in the model counterparts is due to the accumulation of the toroidal magnetic field. This is equivalent to the enhancement of the current density. It is therefore likely that the magnetic reconnection takes place. The magnetic reconnection is the dissipation of the magnetic field so that the strength of the magnetic field decreases and the intensities can also decrease. For more exact discussion, resistive MHD simulations are necessary. Second, the projected magnetic field is longitudinal at the side near the core in the model counterparts, while it is transverse in the observation. It is remarkable that the transverse field was obtained in Paper I, in which the jet near the core was dealt with. We therefore think that the simulations simultaneously solving the formation, propagation, and destabilization of the jet are necessary.

It can be said that the influence of the establishment of the validity of the magnetic model, especially the sweeping magnetic twist model, will be extremely large. This claims that the dynamics of the jet formation, including the collimation and the destabilization in large scale, is due to the operation of the magnetic field. Since there is no local source for this large energy to do the job in the part of the space where the wiggles of the jets are seen (closer to the hot spots at the tip of long jets), the energy should come all the way from the AGN core. We also claim that the energy dumped in the hot spots and the radio lobes is carried by the Poynting flux. In MHD models, the toroidal component is generated and its propagation carries the Poynting energy; therefore, the models are plausible. The generation of the toroidal magnetic field may be due to either the rotation of the accretion disk (Blandford & Payne 1982; Uchida & Shibata 1985) or the effect of the rotating black hole (Blandford & Znajek 1977; Koide et al. 2000). This means that a large amount of energy is flowing out from the core part of an AGN (although we cannot yet say exactly whether that comes from the inner edge of the accretion disk or from the black hole). If we accept this, the major bearer of energy flowing out is, even in the AGN core itself, large-amplitude TAWs, and even very high Lorentz factor phenomena will be a product of the energetic TAWs.

6. CONCLUSIONS

We performed a three-dimensional MHD simulation based on our sweeping magnetic twist model, which was applied to the situation far from the AGN core by Nakamura et al. (2001). In the sweeping magnetic twist model, the disk rotation generates the toroidal magnetic field and it propagates into two directions along a large-scale magnetic field as toroidal Alfvén waves (TAWs). In this paper the situation in which TAWs are propagating far from the gravitator was dealt with. It was assumed that there is a lower Alfvén velocity region ahead of the propagating TAWs. The toroidal magnetic field becomes accumulated after TAWs enter the low Alfvén velocity region. This causes the growth of the current-driven helical kink instability and the wiggled structure is formed.

We also calculated the observational quantities (FRM, Stokes, \( I, Q, \) and \( U \) parameters) by integrating the numerical data along the line of sight. The Faraday rotation screen and the emitting region were defined separately. The integration for FRM was done only in the Faraday rotation screen and that for Stokes parameters only in the emitting region. The projected magnetic field was determined from \( Q \) and \( U \).

Before the formation of the wiggled structure, the FRM distribution has a gradient across the jet axis. An asymmetry in the total intensity distribution exists, except for the case in which \( \theta \) is equal to 90°. The same features are seen in the results of Paper I, and these features can explain some observations (Perley et al. 1984; Asada et al. 2002; Gabuzda & Murray 2004). The projected magnetic field is parallel to the jet axis because the pitch angle of the helical magnetic field is not so large.

After the formation of the wiggled structure, the FRM distribution has a clear correlation with the large-scale structure of the jet itself. This is caused by the following: the magnetic field becomes less twisted around the wiggled structure as a result of the current-driven helical kink instability. This is equivalent to the fact that the magnetic field is almost along the structural axis of the jet in the wiggled structure. The total and polarization intensities are low in the wiggled structure when the jet inclination to the line of sight is large. However, they become higher as the jet inclination becomes small because the structure on the back side and that on the front side of the three-dimensional helix overlap on the same ray as seen by the observer. We found that when we see the jet at a certain angle, we can reproduce the characteristics of the observation of the 3C 449 jet (Feretti et al. 1999).

This suggests that the FRM distribution could be strongly affected by the magnetic field in or around the jet and that the jet has a helical structure. If this is the case, we also suggest that the magnetic field (especially the toroidal component) plays an important role in the formation of astrophysical jets.

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near future because they are very important and scientifically rewarding. This means that with those we can determine the correct model if our claim above is correct. We would therefore urge high-quality observations of the FRM distribution, to seek for the clues of the mechanism of jet formation. Numerical computations were carried out on VPP5000 at the Astronomical Data Analysis Center of the National Astronomical Observatory, Japan, which is an interuniversity research institute of astronomy operated by the Ministry of Education, Culture, Sports, Science, and Technology.

REFERENCES

Asada, K., Inoue, M., Uchida, Y., Kameno, S., Fujisawa, K., Iguchi, S., & Mutoh, M. 2002, PASJ, 54, L39
Bateman, G. 1980, MHD Instabilities (Cambridge: MIT Press)
Baum, S. A., et al. 1997, ApJ, 483, 178
Begelman, M. C., Blandford, R. D., & Rees, M. J. 1980, Nature, 287, 307
Birkinshaw, M. 1991, in Beams and Jets in Astrophysics, ed. P. A. Hughes (Cambridge: Cambridge Univ. Press), 278
Birkinshaw, M., Laing, R. A., & Peacock, J. A. 1981, MNRAS, 197, 253
Blandford, R. D. 1976, MNRAS, 176, 465
Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883
Blandford, R. D., & Zhidenko, R. L. 1977, MNRAS, 179, 433
Burn, B. J. 1966, MNRAS, 133, 67
Clarke, D. A., Norman, M. L., & Burns, J. O. 1989, ApJ, 342, 700
Eilek, J. A., & Owen, F. N. 2002, ApJ, 567, 202
Feretti, L., Perley, R., Giovannini, G., & Andernach, H. 1999, A&A, 341, 29
Ferrari, A. 1998, ARA&A, 36, 539
Gabuzda, D. C., & Murray, E. 2004, in ASP Conf. Ser., Future Directions in High-Resolution Astronomy, ed. J. D. Romney & M. J. Reid (San Francisco: ASP), in press (astro-ph/0309668)
Hardee, P. E., & Rosen, A. 1999, ApJ, 524, 650
———. 2002, ApJ, 576, 204
Hummel, C. A., et al. 1992, A&A, 257, 489
Koide, S., Meier, D. L., Shibata, K., & Kudoh, T. 2000, ApJ, 536, 668
Kudoh, T., Matsumoto, R., & Shibata, K. 1998, ApJ, 508, 186
Laing, R. A. 1981, ApJ, 248, 87
Lovelace, R. V. E. 1976, Nature, 262, 649
Matsumoto, R., Uchida, Y., Hirose, S., Shibata, K., Hayashi, M., Ferrari, A., Bodo, G., & Norman, C. 1996, ApJ, 461, 115
Meier, D. L., Koide, S., & Uchida, Y. 2001, Science, 291, 84
Nakamura, M., Uchida, Y., & Hirose, S. 2001, NewA, 6, 61
Ouyed, R., & Pudritz, R. E. 1997, ApJ, 482, 712
Perley, R. A., Bridle, A. H., & Willis, A. G. 1984, ApJS, 54, 291
Shibata, K., & Uchida, Y. 1986, PASJ, 38, 631
Stone, J. M., & Norman, M. L. 1994, ApJ, 433, 746
Taylor, G. B. 1998, ApJ, 506, 637
Todo, Y., Uchida, Y., Sato, T., & Rosner, R. 1993, ApJ, 403, 164
Uchida, Y., Kigure, H., Hirose, S., Nakamura, M., & Cameron, R. 2004, ApJ, 600, 88 (Paper I)
Uchida, Y., Nakamura, M., Hirose, S., Uemura, S. 1999, Ap&SS, 264, 195
Uchida, Y., Nakamura, M., Miyagoshi, T., Kobayashi, T., Makawa, T., & Hirose, S. 2000, in IAU Symp. 195, Highly Energetic Physical Processes and Mechanisms for Emission from Astrophysical Plasmas, ed. P. C. H. Martens, & S. Tsuruta (San Francisco: ASP), 213
Uchida, Y., & Shibata, K. 1985, PASJ, 37, 515
———. 1986, Canadian J. Phys., 64, 507
Usyugova, G. V., Koldoba, A. V., Romanova, M. M., Chechetkin, V. M., & Lovelace, R. V. E. 1995, ApJ, 439, L39