A NUMERICAL MODEL OF HERCULES A BY MAGNETIC TOWER: JET/LOBE TRANSITION, WIGGLING, AND THE MAGNETIC FIELD DISTRIBUTION

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ABSTRACT

We apply magnetohydrodynamic (MHD) modeling to the radio galaxy Hercules A to investigate the jet-driven shock, jet/lobe transition, wiggling, and magnetic field distribution associated with this source. The model consists of magnetic tower jets in a galaxy cluster environment, which has been discussed in a series of our papers. The profile of the underlying ambient gas plays an important role in the jet/lobe morphology. The balance between the magnetic pressure generated by the axial current and the ambient gas pressure can determine the lobe radius. The jet body is confined jointly by the external pressure and gravity inside the cluster core radius $R_c$, while outside $R_c$ it expands radially to form fat lobes in a steeply decreasing ambient thermal pressure gradient. The current-carrying jets are responsible for generating a strong, tightly wound helical magnetic field. This magnetic configuration will be unstable against the current-driven kink mode, which visibly grows beyond $R_c$, where a separation between the jet forward and return currents occurs. The reversed pinch profile of the global magnetic field associated with the jet and lobes produces projected $B$-vector distributions aligned with the jet flow and the lobe edge. An AGN-driven shock powered by the expanding magnetic tower jet surrounds the jet/lobe structure and heats the ambient ICM. The lobes expand subsonically; no obvious hot spots are produced at the heads of lobes. Several key features in our MHD modeling may be qualitatively supported by observations of Hercules A.

Subject headings: galaxies: active — galaxies: individual (Hercules A) — galaxies: jets — methods: numerical — MHD

1. INTRODUCTION

In this paper, we continue our discussion of the dynamics of extragalactic jets in cluster environments within the framework of the “magnetic tower” model (Lynden-Bell & Boily 1994; Lynden-Bell 1996), which we have analyzed in a series of papers. Magnetohydrodynamic (MHD) mechanisms are frequently invoked to model the launching, acceleration, and collimation of astrophysical jets (see, e.g., Ferrari 1998; Meier et al. 2001 and references therein). An underlying large-scale (coronal) poloidal field for producing the magnetically driven jets is almost universally assumed in many theoretical/numerical models. However, the origin and existence of such a galactic magnetic field are still poorly understood.

In contrast with the large-scale field models, Lynden-Bell (Lynden-Bell & Boily 1994; Lynden-Bell 1996) examined the expansion of the local force-free magnetic loops anchored to the star and the accretion disk by using the semianalytic approach. Twisted magnetic fluxes due to the disk rotation make the magnetic loops unstable and splay out at a semiangle of 60° from the rotational axis of the disk. Global magnetostatic solutions of magnetic towers with external thermal pressure were also computed by Li et al. (2001) using the Grad-Shafranov equation in axisymmetry (see also Lovelace et al., 2002; Lovelace & Romanova 2003; Uzdensky & MacFadyen 2006). Full MHD numerical simulations of magnetic towers have been performed in two dimensions (axisymmetric; Romanova et al. 1998; Turner et al. 1999; Ustyugova et al. 2000; Kudoh et al. 2002; Kato et al. 2004a) and three dimensions (Kato et al. 2004b). Magnetic towers are also observed in laboratory experiments (Hsu & Bellan 2002; Lebedev et al. 2005).

The first in our series, Li et al. (2006, hereafter Paper I), described the basic assumptions and approaches in the numerical modeling of magnetic tower jets. The evolution of the tower jets in a constant density/pressure background was examined there. The second in our series, Nakamura et al. (2006, hereafter Paper II), investigated the global structure of magnetic tower jets in a gravitationally stratified atmosphere, in terms of the MHD wave structure, radial force equilibrium, and collimation. A large current flowing parallel to the jet bulk flow plays an essential role in determining the lobe radius, as does the background pressure profile. The third in our series, Nakamura et al. (2007, hereafter Paper III), investigated the stability properties of magnetic tower jets on cluster scales. Current-driven instabilities are responsible for the nonaxisymmetric structures; the external “kink” ($n = 1$) mode grows outside $R_c$, while the internal “double helix” ($n = 2$) mode grows predominantly inside $R_c$. This is the forth in our series of papers to examine nonlinear magnetic tower jets. Here we examine our model’s applicability to an individual source, Hercules A (Her A, 3C 348), by performing three-dimensional (3D) MHD simulations.

Her A is one of the most powerful double-lobed radio sources in the sky. Its total energy content is approximately $3 \times 10^{49}$ ergs, and it is identified with the central compact diffuse (cD) galaxy of a cluster (Sadun & Hayes 1993) at a low redshift of $z = 0.154$ (Siebert et al. 1999). The X-ray luminosity of $4.8 \times 10^{44}$ ergs s$^{-1}$ (Gizani & Leahy 2004, hereafter GL04) is thought to be due to bremsstrahlung of the very high temperature intracluster medium (ICM). Her A has a peculiar radio structure; the morphology looks like a classical double-lobed Fanaroff-Riley type II (FR II) radio source (Fanaroff & Riley 1974), but it has no compact hot...
spots, instead showing an unusual jet-dominated morphology as in a Fanaroff-Riley type I (FR I) radio source, which was first revealed by Dreher & Feigelson (1984). Furthermore, the two jets in Her A are quite different in appearance. The eastern jet appears to have continuous twisting flows, while the western jet leads to a unique sequence of "rings." The jets in Her A are initially well collimated but flare suddenly at a certain distance from the nucleus. The explanation for the presence of such different structures in the same source is still unresolved in the literature. Her A is not a typical FR I source, either; its jets are well collimated and have knot components. Therefore, Her A might be classified an intermediate case: FR I/II.

Various models have been proposed to explain the formation of the jets and rings in Her A, including both kinematic (Mason et al. 1988; Morrison & Sadun 1996; Sadun & Morrison 2002) and dynamic (Meier et al. 1991; Saxton et al. 2002) points of view. By performing axisymmetric, two-dimensional hydrodynamic simulations, Meier et al. (1991) proposed a model in which an overdense and overpressured jet undergoes a sudden expansion when it becomes highly overpressured compared to the background gas at a certain distance from the core. This causes a subsequent conical expansion, giving rise to the "ice cream cone" shape of the lobe. However, at present, there is nothing in the X-ray observations to suggest that the jet becomes thermally overpressured as required in this model. In Saxton et al. (2002) the formation of ring structure in the western jet was interpreted as the result of ribbonlike, annular shocks propagating through the jet cocoon. These authors also conclude that the absence of hot spots in Her A results from the dynamics of turbulent and entraining backflows in the radio lobe.

Recently, Gizani & Leahy (2003, hereafter GL03) revealed detailed structures of the total intensity, spectral index, polarization, and projected magnetic field in Her A by using multifrequency VLA (Very Large Array) imaging. The jet disruption in the eastern lobe is clearly visible, implying flow instabilities. The projected magnetic field, after correcting for Faraday rotation, closely follows the edges of the lobes, the jets, and the rings; the two lobes have generally similar field patterns. This observational picture may disagree with the turbulent structure inside the lobes suggested by Saxton et al. (2002).

Magnetic field distributions associated with the extragalactic jets and their comparisons with the observations have been examined by using Stokes parameters, the Faraday rotation measurement, and the projected magnetic field (B-vector; e.g., Laing 1981, 2006; Clarke et al. 1989, 1992; Hardee & Rosen 1999, 2002). In general, helical magnetic fields produce asymmetric transverse brightness and polarization profiles; they are symmetrical only if the field is purely toroidal or the jet is at 90° to the line of sight (Laing 1981). Laing et al. (2006) conclude that, to first approximation, the field configuration in an FR I jet over 10 kpc scales is a mixture of toroidal and longitudinal components.

GL04’s ROSAT X-ray observations of the intracluster gas in the Her A cluster have revealed extended X-ray emission coming from a compact source at the center of cluster, out to a radius of 2.2 Mpc. The azimuthally averaged X-ray surface brightness profile is well fitted by a modified King (β) model (King 1972; Cavaliere & Fusco-Femiano 1976), with core radius $R_c = 121 \pm 10$ kpc and $\beta = 0.74 \pm 0.03$. Their X-ray analysis supports the conclusion that the inner jets are confined thermally by the cluster core gas: thermal pressure in the cluster core is almost 10 times larger than the equipartition pressure in the eastern jet with the standard assumptions (including no protons). The radio lobes are largely positioned beyond the X-ray core radius, allowing for projection, so they are expanding essentially into a power-law atmosphere with density falling as $R^{-3.9} \sim R^{-2.25}$, quite close to the $R^2$ profile needed to give the lobes a self-similar structure (Falle 1991).

This observational evidence motivates us to apply our dynamical magnetic tower jet model to Her A. To our knowledge, no MHD model has been applied to Her A before, although there are several hydrodynamic models, as we have already mentioned. Radio observations suggest that the magnetic fields need to be taken into account to discuss the jet/lobe dynamics in Her A. We believe that a key clue to understanding the transition between the jet and the lobe may be whether or not the inner jets become overpressured during their propagation in the X-ray thermal cluster gas. However, the jet internal pressure may be magnetically, rather than thermally, dominated. This is in contrast to previous models (Meier et al. 1991). Of particular interest here are the jet/lobe transition, wiggling, and magnetic field distribution associated with the eastern jet of Her A, which have not yet been fully discussed in the previous hydrodynamic models of Her A. We do not discuss the formation of rings in the western jet in this paper.

This paper is organized as follows. In § 2, we outline our numerical methods. In § 3, we describe our numerical results. Discussions and conclusions are given in §§ 4 and 5, respectively.

2. NUMERICAL METHODS AND MODEL ASSUMPTIONS

We solve the nonlinear system of time-dependent ideal MHD equations numerically in a 3D Cartesian coordinate system $(x, y, z)$. The basic numerical treatments (including the MHD numerical scheme) are essentially the same as in Papers I, II, and III. We assume an initial hydrostatic equilibrium in the gravitationally stratified medium, adopting an isothermal King model. The magnetic flux and the mass are steadily injected in a central small volume during a certain time period. Since the injected magnetic fields are not force-free, they will evolve as a "magnetic tower" and interact with the ambient medium. The dimensionless system of MHD equations is integrated in time by using the TVD (total variation diminishing) upwind scheme (Li & Li 2003).

Computations were performed on the parallel Linux clusters at the Los Alamos National Laboratory.

2.1. Numerical Setup

We normalize physical quantities with the unit length scale $R_0$, the unit density $\rho_0$, and the sound speed $C_{0}$ as the typical speed in the system. Other quantities are derived from their combinations; e.g., the typical time $t_0$ is $R_0/C_0$. In this paper, we use some observed quantities associated with the source Her A (GL04) in order to determine our normalization units. A central electron density $n_e = 1.0 \times 10^{-2}$ cm$^{-3}$ is adopted in GL04, suggesting quite a dense cluster, as such densities in clusters are typically of the order of $10^{-3}$ cm$^{-3}$ (Jones & Forman 1984). This provides a unit density $\rho_0 = 1.7 \times 10^{-26}$ g cm$^{-3}$. A single-temperature fit with $kT = 4.25$ keV is assumed for the β-model cluster, giving a unit temperature $T_0 = 4.9 \times 10^7$ K, a unit pressure $p_0 = 2.3 \times 10^{-10}$ dyn cm$^{-2}$, and a unit velocity (sound speed) $C_{0} = (\gamma p_0/\rho_0) = 1.2 \times 10^6$ cm s$^{-1}$. Here we choose a unit length $R_0 = 30$ kpc and therefore a unit time $t_0 = 2.4 \times 10^7$ yr. The unit magnetic field $B_0 = (4\pi \rho_0 C_{0}^2)^{1/2} = 53.4 \mu$G. In the King model we use here, we take the cluster core radius $R_c$ to be 120 kpc, corresponding to the normalized core radius 4.0, and take the exponential slope $\kappa$ to be 1.1 ($3/2$ with $\beta = 0.74$) by adopting the observations in GL04.

We use $\rho_0$ and $p_0$ as the initial quantities at the origin $(x, y, z) = (0, 0, 0)$, and thus the normalized $\rho$ and $p$ are set to unity at the
origin in these simulations. The total computational domain is taken to be $|x|, |y|, |z| \leq 15$. The number of grid points in the simulations reported here is 360, where the grid points are assigned uniformly in the $x$, $y$, and $z$-directions. The simulation domain is from $-450$ to $450$ kpc, with $\Delta x = \Delta y = \Delta z = 0.083$, which correspond to $\sim 2.5$ kpc.

The injections of magnetic flux and mass, and the associated energies, are the same as those described in Paper I. The ratio between the toroidal and poloidal fluxes of the injected fields is characterized by a parameter $\alpha = 25$. The magnetic field injection rate is described by $\gamma_B$ and is set to be $\gamma_B = 1$. The mass is injected at a rate of $\gamma_p = 0.1$ over a central volume with a characteristic radius $r_p = 0.5$. Magnetic fluxes and mass are continuously injected for $t_{ini} = 3.0$, after which the injection is turned off. These parameters correspond to a magnetic energy injection rate of $\sim 2.7 \times 10^{46}$ ergs s$^{-1}$ and an injection time $\sim 72$ Myr. The energy injection rate used here has a range similar to that of other hydrodynamic simulations with the jet power $(2 \times 10^{45}) - (2 \times 10^{46})$ ergs s$^{-1}$ (Saxton et al. 2002). We use the outflow boundary conditions at all outer boundaries. Note that for most of the simulation duration, the waves and magnetic fields stay within the simulation box, and all magnetic fields are self-sustained by their internal currents.

2.2. Formulation of Synthetic Observation Images

Based on our simulations, we make synthetic observation images to compare with the real observations of Her A (GL03). The synthetic radio telescope observations presented here were produced using a modified form of the synthetic observation technique first described in Tregillus et al. (2001). Here we provide an overview of the key points relevant to the present investigation; a complete description of the technique is provided in Tregillus (2002).

Our method utilizes the vector magnetic field structures evolved self-consistently within these MHD calculations and a relativistic electron momentum distribution, $f(p)$, chosen by fiat during postprocessing. The function $f(p)$ is defined over eight logarithmically spaced momentum bins. Each bin has an associated slope value, $q$, and within each bin the distribution is a power law ($f \sim p^{-q}$). However, slope values may vary between bins, making it possible to specify non-power-law distributions, such as would be appropriate for cases where radiative aging is significant. The specified distribution functions are free to vary from location to location within the simulated flows, as is expected to be the case in real radio galaxies. We note that although these distributions are not derived self-consistently within the computed flows, as has been done in previous works (Tregillus et al. 2001, 2004), imposing it as a postprocessing step does provide a measure of flexibility in our investigations.

In this paper we choose the sign convention such that $\alpha > 0$, and the flux density $S_\nu \propto \nu^{-\alpha}$. For the present investigations, which do not incorporate the effects of radiative aging and reacceleration, we applied a spatially uniform momentum slope value $q = 4.5$ throughout the simulated source. This corresponds to a synchrotron spectral index $\alpha = 0.75$, which is consistent with the observed range of spectral indices within individual radio galaxies. For example, GL03 mapped the spectral index distribution in Her A between $1.3$ and $4.8$ GHz, finding $0.6 \leq \alpha_{1.3} \leq 2.0$, with the flattest values within the western jet and the steepest values along the lobe edges. They also found $\alpha_{4.8} = 4.3$ in portions of the eastern jet. Our choice, $\alpha = 0.75$, is also consistent with typical hot spot spectral index values $\alpha_{1.4} = 4.3$ in the sample of 3CR sources studied by Alexander & Leahy (1987).

The local number density of energetic electrons varied with the local magnetic energy density (i.e., $n_e \propto B^2$). This approach represents a partitioning relationship between the field and particle energies, such as is posited by minimum-energy arguments (Miley 1980). However, the overall scaling was chosen such that the energy density of relativistic electrons was far less than the magnetic energy density (i.e., we assume our simulated object is out of equipartition, which is consistent with the lack of dynamical feedback from the electrons in these calculations).

Given information about the local magnetic field and the local distribution of energetic electrons, we compute a synchrotron emissivity $j_\nu$ in every zone of the computational grid. As given by Jones et al. (1974) the emissivity is

$$j_\nu = j_{\nu,0} \frac{4\pi e^2}{c} f(p_0) p_0^{\alpha} \left(\frac{v_B}{\nu}\right)^{\alpha} v_B.$$  

(1)

The spectral index $\alpha$ is related to the local electron momentum index $q$ via $\alpha = (q - 3)/2, v_B = eB\sin\Omega/(2\pi m_e c)$, where $\Omega$ projects the local field onto the sky, and $j_{\nu,0}$ is an order-ununity dimensionless constant, defined in Jones et al. (1974). For a selected observing frequency, $\nu$, the distribution, $f(p_0)$, and the index, $q$, are determined for each point on the numerical grid by establishing the relevant electron momentum from the relation $p_0 = [2\nu/(3v_B)]^{1/2}$, with $p_0$ in units $m_ec$.

Once the synchrotron emissivity is known for every numerical zone, we compute surface brightness maps for optically thin emission via line-of-sight integrations. We can similarly obtain the Stokes $Q$ and $U$ parameters for the synchrotron emission, as well as the correction for Faraday rotation through the source, making detailed polarimetric studies possible. We write the resulting data in FITS format and analyze it using conventional observational packages (MIRIAD and KARMA; Gooch 1996).

3. RESULTS

Our magnetic tower model has been applied to Her A. In particular, our goal is to reproduce large-scale structures in the jets: the jet/lobe transition, the nonaxisymmetric deformation, and the projected magnetic field distribution associated with the jets and lobes, as observed in GL03.

Figure 1 shows a snapshot of the gas pressure $p$ in the $x$-$z$ cross section at $t = 8.0$ (192 Myr). As we have examined in Papers II and III, the global structure of the magnetic tower consists of a well-collimated “jet body” and radially extended “lobes” in the gravitationally stratified atmosphere. A transition from the narrow jet to the fat lobe occurs at the cluster core radius. This interesting property is confirmed in recent observations (GL03; GL04). Several key features in these magnetic tower jets (the MHD wave structures, the heating process at the tower front, the cylindrical radial force equilibrium at the tower edge, and the dynamic collimation process) are similar to the results of Paper II (see also Fig. 1 of Paper II for details of the time evolution). The helically twisted magnetic tower has a closed current system that includes a pair of current circuits. Each circuit contains a forward electric current path (the jet flow itself, with its toroidal magnetic field, toward the lobe) and a return current (along some path back to the active galactic nucleus [AGN] core). The global picture of a current-carrying jet with a closed current system linking the magnetosphere of the central engine and the hot spots was introduced by Benford (1978, 2006) and applied to AGN double-lobed radio sources. As seen in Figure 1, the high-pressure material of the ambient gas seems to follow the edge of the jet near the bottom of each lobe. But this is not the case; the local pressure enhancement occurs inside the lobes. In the jet and lobe system,
the axial currents drive the current-driven instabilities; it eventually produces a magnetic reconnection process even in our ideal MHD assumption (that the magnetic field will dissipate numerically). As a result, some local heating may occur, but it never dramatically affects the dynamics of jet propagation.

For a full 3D visualization of the magnetic lines of force, the reader is referred to Paper III. The basic behavior of the helically twisted magnetic field in the present paper appears similar to that in Paper III. The magnetic tower jet has a well-ordered helical field configuration, with a wiggled central helix going up along the central axis and a loosely wound helix coming back at the outer edge of the magnetic tower. The outer edge of the magnetic tower can be identified as a tangential discontinuity without the normal field component. The interior of the tower (lobe) is separated from the nonmagnetized external gas via this discontinuity. At the tower edge, the outward-directed magnetic pressure gradient force is roughly balanced with the inward-directed thermal pressure gradient force. On the other hand, at the core part of the jet body, a quasi-force-free equilibrium is achieved. In the context of magnetically controlled fusion systems, the helical field in the magnetic tower can be regarded as the reversed field pinch (RFP) profile.

The jet axial current and the ambient gas pressure can together determine the radius of the magnetically dominated lobes (Paper II). That is, the internal gas pressure plays a minor role in the lobes (even if the thermal pressure is greater than the nonthermal pressure; Morganti et al. 1988) as is typically seen in FR I radio galaxies (Croston et al. 2003). The Alfvén speed becomes large (about 3 times the local sound speed), while the plasma β (≡2ρ/B²) becomes small (β ≤ 0.1) inside the density cavities due to the expansion of magnetic fluxes. As we have already discussed in Paper II, it is remarkably noted that the expanding tower launches a preceding hydrodynamic shock in the ICM, which may be associated with AGN-driven shocks seen in recent X-ray observations (Forman et al. 2005; Nulsen et al. 2005; Fabian et al. 2006).

Figure 2 exhibits physical quantities along the z-axis at t = 3.0 (t = 72 Myr). The magnetic-tower-driven hydrodynamic shock front can be seen around z ~ 6.4 in the profiles of ρ, C_s, and V_z. The sound speed jumps by 27% (the temperature ħ = [x C_s²]) increases by 61%) in the postshocked region due to the shock compression. The magnetic tower front, which is identified as the lobe front, is located at z ~ 5.2. There is another MHD wave front at z ~ 4.5, where an increase in C_s (also density/pressure) is accompanied by a decrease in magnetic pressure (not shown in Fig. 2), indicating the reverse MHD slow mode. At later times, this can steepen into a MHD slow shock that causes a compression (heating) at the head of the magnetic tower as seen in Figure 1 (see also Fig. 2 and § 3.1 of Paper II for details).

Figure 3 displays the positions of the shock and lobe fronts as a function of time along the z-axis (propagating toward the positive direction). The shock front has a constant propagation speed V_sh ~ 2.1 (2.52 × 10⁸ cm s⁻¹) that implies a Mach number ~1.63. On the other hand, the magnetically dominated lobe front expands subsonically. This lobe front also has a quasi-constant propagation speed V_{LB} ~ 1.5 (1.8 × 10⁸ cm s⁻¹) that implies a Mach number ~0.91 (C_s increases up to ~1.64 in shocked ICM; see also Fig. 2).

The current-carrying magnetic tower jet, which possesses a highly wound helical field, is subject to the current-driven instability (CDI). Although the destabilization criteria will be modified by the ambient gas and the RFP configuration of the tower, we find that the propagating magnetic tower jets can develop the nonaxisymmetric CDI modes. As seen in Figure 4, both the internal elliptical (m = 2) mode like the “double helix” and the external kink (m = 1) mode grow to produce the wiggles at different locations (see also Paper III for details). We see no disruption owing to shear-driven, Kelvin-Helmholtz modes and/or the pressure-driven interchange modes.

Figure 5 shows the synthetic radio synchrotron intensity at 5 GHz, along with the polarization magnetic field vectors. The wiggled structures can be seen in both the jet and the lobe. Filamentary structures also appear beyond R_e. The projected magnetic field is aligned with the jet and along the lobe edge. The
magnetic tower model produces polarization features that are qualitatively consistent with those seen in the Her A observations of GL03. Furthermore, our dynamical solution of magnetic tower’s evolution may give a self-consistent explanation to a feasible magnetic configuration discussed in nondynamical models having a “spine” \( (B_\phi > B_z \text{ inside the lobe}) \) and “sheath” \( (B_z > B_\phi) \) structure in an FR I jet over 10 kpc scales as discussed in Laing (1981, 2006).

The image contrast in our synthetic synchrotron surface brightness map is approximately 2000:1 between the brightest pixels (beams) near the central core and the faintest regions inside the lobes. Outside the small bright core region, the image contrast is roughly 200:1.

When the synthetic 5 GHz synchrotron map is scaled to an angular size comparable to that of Her A, the brightest pixel (beam) in the synthetic 5 GHz surface brightness map is 875 mJy beam\(^{-1}\). However, away from the small, bright region near the core, the jets generally exhibit flux densities on the order of 30–70 mJy beam\(^{-1}\), the central sheath exhibits flux densities in the range 20–30 mJy beam\(^{-1}\), and the darkest parts of the lobes exhibit \( \lesssim 1.0 \) mJy beam\(^{-1}\).

Our simulated source exhibits a fractional linear polarization, \( m \), at 5 GHz ranging from a few percent in the most magnetically...
tangled portions of the lobes to \( m \approx 30\% \sim 50\% \) on the lobe edges. These values are consistent with those typically observed in radio galaxies (Bridle & Perley 1984; Muxlow & Garrington 1991) as well as with the \( m \)-values reported in GL03 for Her A at 4848 MHz. Fractional polarization values exceed 60\% (roughly twice that reported in GL03) in small, isolated pockets in the sheath around the central jet and near the central core, which may indicate insufficient computational resolution near the core for properly capturing cellular depolarization. In regions outside the magnetized lobes, where the ambient medium in our computational domain has been mildly perturbed by expansion of the magnetic tower, the degree of polarization approaches 72\%. This is the expected result for a region with a uniform magnetic field and a uniform power-law distribution of nonthermal electrons with \( q = 4.5 \) (Rybicki & Lightman 1979).

4. DISCUSSION

4.1. Shock and Lobe Expansions

We discuss some features of the shock and lobe expansions in the simulation by comparing with observations. A Chandra X-ray image of the Her A cluster shows that it has cavities and a shock front associated with the powerful radio lobes (Nulsen et al. 2005). Unusually, these cavities show no clear connection to the radio sources, while many cavities are associated with radio sources in other cluster cases (e.g., McNamara et al. 2000), indicating that they might be ghost cavities (e.g., McNamara et al. 2001).

The observation of Nulsen et al. (2005) reveals a shock front surrounding the Her A radio source. It is elongated in the direction of the radio lobes and appears to be a cocoon shock (Scheuer 1974). Their fitting of a simple hydrodynamic model to the surface brightness profile gives a Mach number for the shock front of \( \sim 1.65 \) and its total energy is estimated at \( \sim 3 \times 10^{51} \) ergs (mean mechanical power \( \sim 1.6 \times 10^{46} \) ergs s\(^{-1}\)). As we examined in § 3, the magnetic tower drives a hydrodynamic shock front in the ambient ICM. The derived Mach number \( M \sim 1.63 \) matches quite well to our observation, and our energy inputs are also in qualitatively reasonable range.

As the radio lobes of Her A lack anything resembling hot spots, it seems likely that they are expanding at around the sound speed, and so are confined by the thermal pressure of the ambient ICM, rather than by strong shocks (GL04). To our knowledge, there may be no direct result revealing the lobe expansion speed of the Her A radio lobes, but we discuss general properties of expanding lobes in a radio galaxy based on the argument of Kraft et al. (2006). It is believed that the radio lobes are greatly overpressurized relative to the ambient medium, indicating sharp X-ray surface brightness discontinuities or large jumps in gas temperature at the lobe edges. A high Mach number (\( M \sim 8.5 \)) shock is detected around the southwest radio lobe of Centaurus A (Kraft et al. 2003).

However, there is no evidence of overpressurized lobes for FR I or low-power FR II radio galaxies, including Her A (GL04) and 3C 388 (Kraft et al. 2006). If thermal conduction in the ICM is efficient (an order of the Spitzer value), then shocks may be nearly isothermal and thus difficult to detect (Fabian et al. 2006). However, Chandra observations suggest that the thermal conduction (and viscosity) of the ICM is orders of magnitude below the Spitzer value (e.g., Vikhlinin et al. 2001; Kraft et al. 2003). Thus, some lobes, including Her A, may be inflating transonically and subsonically (i.e., \( M \leq 1 \)). Based on hydrodynamic arguments of a buoyant bubble, \( M \sim 0.6 \) in M87 (Churazov et al. 2002) and \( M \sim 0.5 \sim 0.9 \) in 3C 388 (Kraft et al. 2006) are estimated. Our numerical result indicates that the magnetically dominated lobe expands subsonically with \( M \sim 0.91 \), as discussed in § 3. This would also match the observationally preferable picture.

4.2. Lobe Size

We next discuss the radial size of the lobes \( r_{\text{lobe}} \) as based on our model (Paper II). The poloidal magnetic fluxes and the poloidal current \( I_p \) in the lobes remain well collimated around the central axis even after the system has fully evolved. This implies that the toroidal magnetic fields in the lobe region are distributed roughly as

\[
B_\phi \sim I_p / r. 
\]

When the lobe experiences sufficient expansion, we can expect \( |B_\phi| \sim |B_\phi| \) at the outer edge of the RFP configuration (Freidberg 1982). The magnetic and background pressures tend to balance each other at the tower edge. Thus, we can expect that

\[
\frac{B_\phi^2 + B_z^2}{2} \sim B_\phi^2 \sim p_e, 
\]

where \( p_e \) is the external gas pressure at the tower edge. By combining equations (2) and (3), we have

\[
B_\phi^2 \sim \left( \frac{I_p}{r_{\text{lobe}}} \right)^2 \sim p_e, 
\]

which gives

\[
r_{\text{lobe}} \sim l_p p_e^{-1/2}. 
\]

Figure 6 shows the distribution of \( p \) along a transverse line at \( z = 8.5 \) (255 kpc), when the lobe has a maximum radius (after 192 Myr, as in Figs. 1 and 4). We can see that the external gas pressure begins to decrease around \( x \sim 5 \) (150 kpc) toward the central (z) axis. The pressure cavity corresponds to the lobe of
our magnetic tower. We can estimate the lobe radius $r_{\text{lobe}}$ predicted by equation (5) from physical quantities in simulation. From Figure 2, we take $J_x \sim 3 (4.5 \times 10^{-24} \text{ A cm}^{-2})$ within a radius $r \sim 0.75$ (22.5 kpc), which makes $I_x \sim 1.68 (5 \times 10^{17} \text{ A})$. As suggested by Figure 4, we estimate $p_{\text{e}} \sim 0.11 (2.5 \times 10^{11} \text{ dy cm}^{-2})$ for the external gas pressure. We therefore obtain $r_{\text{lobe}} \sim 5.2$ or roughly 156 kpc. Thus, we find that the depression radius in Figure 6 is qualitatively consistent with $r_{\text{lobe}}$ and is comparable with the physical scale seen in radio observations (GL03). Based on this numerical result, we estimate that one simulated lobe of Her A may contain a total energy $\sim 1.8 \times 10^{49} \text{ ergs}$, out of which $\sim 1.0 \times 10^{49} \text{ ergs}$ are in magnetic energy, $\sim 1.4 \times 10^{49} \text{ ergs}$ are in kinetic energy, and $\sim 6.6 \times 10^{46} \text{ ergs}$ are in thermal energy. In order to explain the lobe radius by this magnetically dominated lobe system, an axial current $\sim 5 \times 10^{17} \text{ A}$, flowing along the jet central axis, is needed.

5. CONCLUSIONS

By performing 3D MHD simulations, we have investigated the nonlinear dynamics of magnetic tower jets in a galaxy cluster environment. In this fourth paper of the series, we have applied our numerical modeling of the magnetic tower to a specific source, Hercules A.

To our knowledge, this is the first discussion of Her A jet using a magnetohydrodynamic model. Projected magnetic field distributions associated with the jets and lobes of Her A have been revealed in recent radio observations, and therefore the dynamics including magnetic fields plays a role in understanding this source. In the present paper, we have investigated the jet-driven shock, jet/lobe transition, wigging, and projected magnetic field distribution of Her A, and in general, these features can be explained by our magnetic tower model.

Our conclusions are summarized as follows.

1. A transition from the narrow jet to the fat lobe occurs at the cluster core radius. This interesting feature is also confirmed in recent observations (GL03; GL04). In our models, the tightly collimated helical field configuration of a magnetic tower jet expands abruptly beyond the core radius due to the decreasing external gas pressure. Thus, the pressure profile of the surrounding ICM plays an important role in determining the morphology of a magnetic tower jet.

2. The expanding magnetic tower jet produces the preceding hydrodynamic shock wave in the ambient ICM. This can be interpreted as an AGN-driven shock in X-ray observations, and the derived shock Mach number is identical to the observational result of Nulsen et al. (2005). The magnetic tower lobes expand subsonically, and thus no hot spots are produced at the end parts of lobes. This may be a general understanding of FR I or low-power FR II radio galaxies (Kraft et al. 2006).

3. The size of the magnetic tower lobe can be accurately estimated from the jet axial current and the external gas pressure at the lobe edge. The estimated lobe size derived by our numerical simulation is qualitatively comparable with the physical scale seen in GL03. In our model, if the background gas has a steep slope ($\beta$) in the King profile, the magnetic jet can potentially lead to a huge magnetic tower lobe.

4. Magnetic tower jets, which have a reversed magnetic pinch profile, are subject to current-driven instabilities. Specifically, the apparent distortions by the nonaxisymmetric kink mode are visible at the jet body inside the lobe rather than the central core. By expanding the lobe, the edge of the axial currents could be freed from the exciting external kink mode; this situation may be suppressed inside the cluster core radius.

5. The synthetic polarimetry of our magnetic tower jets is consistent with the gross polarization features observed in the jets of Her A. The magnetic tower model produces projected $B$-vector distributions that are similar to those observed in the global extragalactic jet/lobe system, especially along the jets and the lobe edges.

6. Magnetic tower jets may produce a self-consistent picture of the field configuration discussed in several nondynamical models of FR I jets. This model consists of a toroidally dominated spine inside the lobe and a poloidally dominated sheath at the lobe edge (a closed poloidal magnetic flux with a toroidal magnetic component, rather than a vector-ordered helical configuration; Laing et al. 2006).

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