LONG-TERM EVOLUTION OF MAGNETIZED BUBBLES IN GALAXY CLUSTERS

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ABSTRACT

We have performed nonlinear ideal magnetohydrodynamic simulations of the long-term evolution of a magnetized low-density “bubble” plasma formed by a radio galaxy in a stratified cluster medium. It is found that about 3.5% of the initial magnetic energy remains in the bubble after ~8 × 10^7 yr, and the initial magnetic bubble expansion is adiabatic. The bubble can survive for at least 8 × 10^9 yr due to the stabilizing effect of the bubble magnetic field on Rayleigh-Taylor and Kelvin-Helmholtz instabilities, possibly accounting for “ghost cavities” as observed in Perseus A. A filament structure spanning about 500 kpc is formed along the path of bubble motion. The mean value of the magnetic field inside this structure is ~0.88 μG at ~8 × 10^9 yr. Finally, the initial bubble momentum and rotation have limited influence on the long-term evolution of the bubble.

Subject headings: galaxies: jets — magnetic fields — methods: numerical — MHD

1. INTRODUCTION

An unsolved problem in active galactic nuclei (AGN) feedback on clusters is how to account for the morphology and stability of buoyant bubbles and their interactions with the ambient intracluster medium (ICM) (McNamara & Nulsen 2007). Fabian et al. (2006) showed that in the Perseus cluster, such bubbles can stay intact far from cluster centers where they were inflated by AGN jets. However, studies of kinetic energy-dominated jets in the purely hydrodynamic limit did not explain the observed long-term persistence of the buoyant bubbles, which are prone to Rayleigh-Taylor and Kelvin-Helmholtz instabilities (RTI and KHI) and fragment entirely within 100 Myr, contrary to observations (but see Reynolds et al. 2005; Pizzolato & Soker 2006; Gardini 2007).

Appreciable magnetic energy has been observed in both cluster and radio lobe plasmas (Owen et al. 2000; Kronberg et al. 2001; Croston et al. 2005). The magnetic fields could play a vital role in the dynamics of the rising bubble, as shown by a series of 2D magnetohydrodynamic (MHD) studies for bubbles of several times 10^9 yr (Brüggen & Kaiser 2001; Robinson et al. 2004; Jones & De Young 2005). Stone & Gardiner (2008) showed that uniform strong magnetic fields do not suppress RTI completely, but sheared fields at the bubble interface quench the instability. This implies that not only the field strength but also the configuration matters for bubble stability. Ruszkowski et al. (2007) did a comprehensive study of the influence of different magnetic field configurations on the stability of a rising bubble. They found that the internal bubble helical magnetic field moderately stabilizes the bubble; however, the bubble has an initial plasma parameter β ≡ (2nT/μB^2) ≫ 1, still in the thermal energy-dominated regime. Recently, Li et al. (2006) proposed a different bubble magnetic field configuration for jet/lobes. Here we adopt the field configuration of Li et al. (2006) and focus on the late stage of the evolution of magnetically dominated bubbles in 3D. We show that this spheromak-like magnetic field configuration strongly stabilizes the instabilities and prevents the bubble from breaking up, possibly forming the intact but detached “ghost cavity” observed in systems such as Perseus A. This Letter is organized as follows. In § 2, we describe the problem setup. The simulation results and discussions are given in § 3.

2. PROBLEM SETUP

The background ICM is assumed to be hydrostatic and isothermal. The density and pressure profile is given as ρ = ρ_0 = [1 + (r/R_0)^2]^{-1}, where the parameters κ and R_0 are taken to be 1.0 and 4.0, respectively. The fixed yet distributed gravitational field −∇ψ(R) dominated by the dark matter is assumed (Nakamura et al. 2006). We simulate only the phase after the AGN has inflated a low-density bubble that is in pressure equilibrium with the ICM initially. The static magnetized bubble initially lies at (x_0, y_0, z_0) = (0, 0, 5) with density ρ_0 = 0.1, spherical radius r_0 = 2 for the density profile, and r_0 = 1 for the magnetic configuration. The specific heat γ inside and outside the bubble is taken to be 5/3. Physical quantities are normalized by the characteristic system length scale R_0 = 25 kpc, density ρ_0 = 1.67 × 10^{-26} g cm^{-3}, and velocity V_0 = 6.2 × 10^7 cm s^{-1}. The initial sound speed, C_s|_t=0 = γ^{1/2} ~ 1.29, is constant throughout the computational domain. Other quantities are normalized as follows: time t = 1 gives R_0/V_0 = 38.6 Myr, magnetic field B = 1 gives (2ρ_0V_0^2)^{1/2} = 1.13 × 10^{-5} G, and energy E = 1 gives ρ_0V_0^2/r_0^2 = 2.71 × 10^{58} ergs. The magnetic field setup of the bubble follows Li et al. (2006) with the ratio of toroidal poloidal bubble field α taken to be 1/10, which corresponds to a minimum initial Lorentz force. The latter is reasonable since we want to mimic the situation in which the magnetic bubble has substantially relaxed and detached from the jet tip. The initial total magnetic energy is around 2.0 × 10^{58} ergs. The computational domain is taken to be |x| ≤ 16, |y| ≤ 16, and 0 ≤ z ≤ 32, corresponding to a (800 kpc)^3 box in the actual length scales. The numerical resolution used here is 400^3, where the grid points are assigned uniformly in every direction. A cell δx corresponds to 2.0 kpc. We use “outflow” boundary conditions at every boundary except the boundary at z = 0, where we use “reflecting” boundary conditions, which guarantee that the energy flux through this boundary is zero.

3. RESULTS AND DISCUSSION

Energy and density evolution reveal the different stages of the bubble. Figure 1 (top) presents the time evolution of various energies at the early stage, in which the gravitational energy $E_g = \int \rho \psi dV$ and the internal energy $E_r = \int p (\gamma - 1) dV$, where $dV$ is the infinitesimal volume and the integral is over the entire

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Therefore, where the subscripts 1 and 2 in $E_{\text{v}}$ represent the variables before, at which time the shock wave heats and compresses the medium due to buoyancy. The total energy increases since the bubble accelerates upward due to buoyancy, and the magnetic energy is defined as $E_m$. The initial bubble expansion is approximately adiabatic, for is not strictly satisfied due to numerical diffusion.

The magnetic field suppresses instabilities and therefore the bubble remains intact longer. Figure 2 presents the typical density distribution (logarithmic scale) in 2D x-z slices at $y = 0$ at different times ($t = 0, 7.5, 20, 50, 50, 125$). The white solid contour lines indicate contours of constant magnetic field strength $|B|$. Consistent with Figure 1 [bottom], after $t \geq 50$, the bubble undergoes a slowly decaying oscillation between $z \sim 19$ and $z \sim 24$. We have also performed simulations of an unmagnetized bubble and found that it disintegrates after $t = 20$, whereas the magnetic bubble still clearly differentiates itself from the ambient medium at $t = 200$ (Fig. 2). The formation of an "umbrella" or a thin protective magnetic layer on the bubble working surface suppresses instabilities (Ruszczowski et al. 2007). The stronger magnetic field is also found to move the bubble faster and push the bubble farther away from its initial position. The position of the bubble top as a function of time is shown in Figure 3. This position is calculated by plotting the axial profile of the density along the line of $(x, y) = (0, 0)$ and finding the location of the first density jump from the top of the domain. Comparing the unmagnetized run (dashed line) with the magnetized run (both without initial momentum/rotation), we can see that the rising speed increases from 0.36 to 0.6. Note that the rough estimate of the terminal speed $v_t$, based on the initial gravitational acceleration $g$ and size $r_0$, both position dependent, is $v_t \approx 4/3 (2g r_0)^{1/2} \sim 2$, assuming force balance between buoyancy and viscous drag force at the final stage (McNamara & Nulsen 2007).

We investigate the effect of the magnetic field on bubble stability in more detail. Following Nakamura et al. (2007), we first compute the evolution of various energies, $E_{\text{m}}, E_{\text{v}}, E_{\text{d}}, E_{\text{T}}, E_{\text{g}}, E_{\text{t}}, E_{\text{p}}$, and $E_{\text{total}}$. The total energy is defined as $E_{\text{total}} = E_{\text{m}} + E_{\text{v}} + E_{\text{d}} + E_{\text{T}}$, where the kinetic energy is defined as $E_{\text{k}} = \int 1/2 \rho v^2 \, dV$ and the magnetic energy is defined as $E_m = \int B^2/2 \, dV$. At the early stage ($t \leq 5$), the kinetic energy increases since the bubble accelerates upward due to buoyancy, and the magnetic energy decreases due to work done in expansion from the weak initial Lorentz force and conversion to shock and wave energy (Nakamura et al. 2006). The gravitational energy increases because there is a net outward mass flow in the axial direction. The passage of the shock wave heats and compresses the ICM and alters its pressure gradient. The total energy $E_{\text{total}}$ is almost constant before $t \sim 10$, at which time the shock and wavefront reach the boundary. Conservation of the total energy for $t \leq 10$ is not strictly satisfied due to numerical diffusion. The initial bubble expansion ($t \leq 20$) is approximately adiabatic, which gives $E = Vp \propto V^{1-\gamma}$, where $V$ is the bubble volume. Therefore $E_{\text{k}}/E_{\text{v}} = (V/V_0)^{1/3}$, where the subscripts 1 and 2 indicate the initial and final states, respectively. At $t = 20$, the radius of the bubble has increased from 2 to ~5, which gives $E_{\text{k}}/E_{\text{v}} \sim 16\%$, roughly matching the amount of magnetic energy in the bubble (20% from Fig. 1 [top]). For later times (Fig. 1 [bottom]), fitting with $E_m(t)/E_{m,0} = \exp (-t/\tau_{\text{dis}})$, we have (1) a fast dissipation stage ($t \leq 10$) when magnetic energy dissipation time $\tau_{\text{dis}} \sim 11$ and (2) a slow dissipation stage ($t \geq 10$) when $\tau_{\text{dis}} \sim 114$. Both times are much smaller than the numerical dissipation time $\tau_{\text{visc}}$ at the corresponding stages (see discussions at the end of this section). The kinetic energy is oscillating while it is decaying slowly, which can be understood as follows. Gravity pulls the bubble down to the denser ICM, compressing the bubble and causing an increase in magnetic energy (since the magnetic flux is nearly conserved). This results in the magnetic energy oscillating in phase with the kinetic energy with period $\sim 90 (3.5 \times 10^5 \text{yr})$. At $t = 200$ after several periods of decaying oscillations, about 3.5% of the initial magnetic energy remains.

Fig. 2.—Density (in logarithmic scale) in the x-z plane as a function of time ($\alpha = 10^\circ$). The white solid contour lines indicate the magnetic field strength $|B|$. Shown are $t = 0, |B| \in [0, 1.976]; t = 7.5, |B| \in [0, 0.830]; t = 20, |B| \in [0, 0.400]; t = 50, |B| \in [0, 0.328]; t = 100, |B| \in [0, 0.159]; t = 125, |B| \in [0, 0.156]. |B| = 1 \mu G$. All plots have five contour levels.
study KHI of the bubble. At both sides of the bubble, the magnetic field is almost uniform, not twisted like at the top of the bubble. From linear analysis, the instability criterion for non-axisymmetric KHI surface modes is (Hardee & Rosen 2002)

\[ \Delta V > V_s = \left( \frac{\rho + \rho_b}{\rho_b} \right) \left( \frac{4\pi \rho_b \rho}{B^2 + B_z^2} \right)^{1/2}, \]

where \( \Delta V \equiv |V_a - V| \) is the velocity shear and \( V_a \) is the surface Alfvén speed. The subscripts \( b \) and \( e \) indicate the bubble and external medium, respectively. The nonaxisymmetric body modes would be important if (Hardee & Rosen 1999) (1) \( V_b > V_e \) in which \( V_b \) is the fast magnetosonic speed; or (2) \( C_s V_s (C_s^2 + V_b^2)^{1/2} < V_s < V_e \) in which \( V_s \) is the Alfvén speed and \( V_e \) is the slow magnetosonic speed. The definitions of \( V_b \) are \[ V_b = \left( \frac{1}{2} \left( C_s^2 + V_b^2 \right) \pm \left( C_s^2 + V_b^2 \right)^{1/2} - 4C_s^2 V_b^2 \cos \theta \right)^{1/2}. \]

Since we focus on the \( x \)-direction only, \( V_b \cos \theta \) are taken to be \( B_z^2/\rho \). Figure 4 (top) displays the transverse distribution of the bulk flow speed \( V = (v_x^2 + v_y^2 + v_z^2)^{1/2} \), the density \( \rho \), and the magnetic field strength \( B \) at \( t = 7.5 \) at \( z = 8.0 \). A distinct velocity shear is identified at \( x \sim 3.5 \). Across this shear, \( \Delta V \approx 0.75 \) and \( V_{ba} \approx 0.85 \). The inequality \( \Delta V < V_{ba} \) holds. This means that the KHI surface modes are completely suppressed. Figure 4 (bottom) displays the transverse distribution of \( V, V_b, \) and \( V_e \) at \( t = 7.5 \) at \( z = 8.0 \). We see that the bulk flow \( V \) lies between \( V_b \) and \( V_e \). The inequality \( V_b < V < V_e \) is satisfied in the body of the buoyant bubble. This rules out the KHI body modes as well.

RTI could also be suppressed by the magnetic field. For the idealized case of two conducting fluids separated by a contact discontinuity with a uniform magnetic field parallel to the interface undergoing constant acceleration \( g \), Chandrasekhar (1961) demonstrated that RTI on a scale \( L \) parallel to the field requires \( B < B_s = [Lg(\rho_b - \rho)]^{1/2} \), in which \( \rho_b \) and \( \rho \) are the densities in the heavy and light fluids, respectively. Modes perpendicular to the field are unaffected. At the top of the bubble \( (z \sim 11.6) \) (Fig. 5), \( \rho_b \) and \( \rho \) are found to be 0.15 and 0.06, respectively, and the gravitational acceleration \( g \) is calculated to be 0.95. If \( L \) is chosen to be the computation domain size, the maximum possible mode wavelength in the simulation, then the critical magnetic field strength is \( B_c \sim 1.6 \), which is larger than the magnetic field \((\sim 0.8)\) at that location. This means that only part of the parallel modes is suppressed regardless of the perpendicular modes. This is not consistent with the simulation results. However, as pointed out in Stone & Gardiner (2008), the twisting nature of the bubble field at the top of the bubble introduces a current sheet at the surface, and the changes in the direction of the field at the interface must be on very small scales to inhibit the interchange modes. A more detailed study of this effect is beyond the scope of this Letter and will be the subject of future study.

Our simulation also provides one possible explanation of the morphology and origin of the large-scale magnetic field and the generation of “ghost cavities” observed in many clusters. As in Robinson et al. (2004), a magnetized high-density tail remains as the bubble rises (Fig. 2). The tails have an elongated morphology (Fig. 2), resembling Hα filaments, which is found to indicate the history of the rising bubble. Interestingly, the magnetic field also helps stabilize this “filament” as it is still
for inspecting the RTI modes.

We study the effects of additional variations in the initial bubble speed by having (1) an initial uniform injection speed or (2) an initial uniform rotation \( \omega \). Nakamura et al. (2008) reported that the radio lobe accelerates. It is conceivable that part of the initial magnetic energy of the bubble accelerates cosmic rays. Throughout the lifetime of a cluster, there could be multiple AGNs injecting jets/lobes into the ICM. Both the cosmic rays and the remaining magnetic fields (distributed over large scales) could provide the energy sources for phenomena such as radio relics and radio halos that have been observed for a number of clusters (Ferrari et al. 2008).

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Fig. 5.—Axial profiles in the \( z \)-direction of several quantities at \( t = 7.5 \) with \( (x, y) = (0, 0) \). The density \( \rho \) and the magnetic field strength \( B \) are shown for inspecting the RTI modes. Visible at \( t = 200 \). Nipoti & Binney (2004) argued that thermal conduction has to be strongly suppressed in the ICM; otherwise, such cold filaments would be rapidly evaporated. As in Ruszkowski et al. (2007), our results provide a possibility that thermal conduction may be locally weaker in the bubble wake, thus preventing or slowing down filament evaporation. The magnetic field is distributed between \( z \sim 2.5 \) and \( z \sim 25 \) at \( t = 200 \) with peak value around 0.156 (\( \sim 1.8 \) \( \mu \)G) or mean value around 0.078 (\( \sim 0.88 \) \( \mu \)G), close to the estimates of wider cluster fields (Carrilí & Taylor 2002; Taylor et al. 2002). This large-scale (\( \sim 500 \) kpc) magnetic field structure also mimics the morphology of the second class (“Phoenix”) of “radio relics” elongated from the cluster center to the periphery observed in A115 (Govoni et al. 2001). The simulation results mean that the magnetic bubble rising from \( \sim 125 \) kpc with an initial magnetic energy of \( 2 \times 10^{59} \) ergs will spread magnetic fields between \( 62.5 \) kpc \( \leq z \leq 600 \) kpc and keep a magnetized bubble between \( 475 \) and \( 600 \) kpc for at least \( 8 \times 10^{10} \) yr. Therefore one could reproduce the intact but detached “ghost cavity” observed in some systems as Perseus A.

Real radio lobes possess complex, jet-driven flows, different from the static bubble that we use for our initial conditions. We study the effects of additional variations in the initial bubble by having (1) an initial uniform injection speed \( v_{\text{inj}} \) or (2) an initial uniform rotation \( \omega \). Nipoti & Binney (2004) argued that thermal conduction has to be strongly suppressed in the ICM; otherwise, such cold filaments would be rapidly evaporated. As in Ruszkowski et al. (2007), our results provide a possibility that thermal conduction may be locally weaker in the bubble wake, thus preventing or slowing down filament evaporation. The magnetic field is distributed between \( z \sim 2.5 \) and \( z \sim 25 \) at \( t = 200 \) with peak value around 0.156 (\( \sim 1.8 \) \( \mu \)G) or mean value around 0.078 (\( \sim 0.88 \) \( \mu \)G), close to the estimates of wider cluster fields (Carrilí & Taylor 2002; Taylor et al. 2002). This large-scale (\( \sim 500 \) kpc) magnetic field structure also mimics the morphology of the second class (“Phoenix”) of “radio relics” elongated from the cluster center to the periphery observed in A115 (Govoni et al. 2001). The simulation results mean that the magnetic bubble rising from \( \sim 125 \) kpc with an initial magnetic energy of \( 2 \times 10^{59} \) ergs will spread magnetic fields between \( 62.5 \) kpc \( \leq z \leq 600 \) kpc and keep a magnetized bubble between \( 475 \) and \( 600 \) kpc for at least \( 8 \times 10^{10} \) yr. Therefore one could reproduce the intact but detached “ghost cavity” observed in some systems as Perseus A.