Rising jet-inflated bubbles in clusters of galaxies

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ABSTRACT

We conduct two-dimensional axisymmetric (referred to as 2.5D) hydrodynamical numerical simulations of bubble evolution in clusters of galaxies. We inflate bubbles using slow, massive jets with a wide opening angle, and follow their evolution as they rise through the intracluster medium. We find that these jet-inflated bubbles are quite stable, and can reach large distances in the cluster while maintaining their basic structure. The stability of the jet-inflated bubble comes mainly from the dense shell that forms around it during its inflation stage, and from the outward momentum of the bubble and shell. On the contrary, bubbles that are inserted by hand on to the grid and not inflated by a jet, i.e. an artificial bubble, lack these stabilizing factors; therefore, they are rapidly destroyed. The stability of the jet-inflated bubble removes the demand for stabilizing magnetic fields in the bubble.

Key words: galaxies: clusters: general – cooling flows – galaxies: jets.

1 INTRODUCTION

Many clusters of galaxies harbor bubbles (cavities) devoid of X-ray emission, e.g. Perseus (Fabian et al. 2000) and Abell 2052 (Blanton et al. 2001). These low-density bubbles are inflated by the jets launched by the active galactic nuclei (AGN) sitting at the centres of these clusters.

The estimated ages of most bubbles (Birzan et al. 2004) are about one order of magnitude larger than the characteristic time of the Rayleigh–Taylor (RT) instability to destroy them. This observation has prompted many authors (e.g. Brüggen & Kaiser 2001; Jones & De Young 2005; Kaiser et al. 2005) to invoke an ordered magnetic field at the edge of the bubble, or to consider the effects of viscosity (Reynolds et al. 2005), to stabilize the bubble against the RT instability. Indeed, numerical simulations of non-magnetic bubble evolution show them to be disrupted quite rapidly (e.g. Brüggen & Kaiser 2001; Brüggen 2003; Robinson et al. 2004; Ruszkowski, Brüggen & Begelman 2004a,b; Jones & De Young 2005; Reynolds et al. 2005; Pavlovski et al. 2008; Ruszkowski et al. 2008). Adding magnetic field makes the bubble more stable (e.g. Robinson et al. 2004; Jones & De Young 2005; Ruszkowski et al. 2007). However, it is not clear if magnetic fields can indeed supply the required stability (Ruszkowski et al. 2007). In the simulations cited above, the bubbles were injected at off-centre locations by a prescribed numerical procedure. This is, of course, not the way bubbles are formed in clusters. Evidence suggests that these bubbles are formed by jets. We term these type of bubbles that were inserted numerically artificial bubbles. Different in that respect are the tower jet model simulations conducted by Nakamura, Li & Li (2006 also Diehl et al. 2008), which did follow the evolution of a jet and a bubble. None the less, we find some problems with this model, e.g. the angular momentum that is assumed in the jet is too large.

Jets can inflate bubbles if their opening angle is large (i.e. wide jets), or if they are narrow but their axis changes its direction (Soker 2004, 2006; Sternberg, Pizzolato & Soker 2007; Sternberg & Soker 2008). The change in direction can result from precession (Soker 2004, 2006; Sternberg & Soker 2008), random change (Heinz et al. 2006) or a relative motion between the intracluster medium (ICM) and the AGN (Loken et al. 1995; Rodríguez-Martínez et al. 2006; Soker & Bisker 2006). The outcome of a wide jet and a rapidly precessing jet is the same (Sternberg & Soker 2008). For numerical reasons, we conduct a study where we inflate bubbles with wide jets, and not with precessing jets. We use jets with Mach number of 10. Much faster jets form elongated bubbles, rather than ‘fat’ bubbles, i.e. bubbles with axes ratio close to unity. In addition, much faster jets cause back flow of hot gas that fills the region between the two bubbles, and therefore lead to the formation of one elongated bubble (Sternberg et al. 2007). In this Letter, we limit ourselves to comparing the evolution of jet-inflated bubbles (i.e. bubbles inflated solely by jets and not by a prescribed numerical procedure) with artificial bubbles, in the goal of emphasizing the necessity to inflate bubble self-consistently. For that the description of the numerical code is brief, and we present only one case out of the several we simulated.

2 NUMERICAL METHOD AND SETUP

The simulations were performed using the Virginia Hydrodynamics-I code (VH-1; Blondin et al. 1990; Stevens, Blondin & Pollock 1992), as described in Sternberg et al. (2007). Radiative cooling was not included. We study a three-dimensional axisymmetric flow with a two-dimensional grid (referred to as 2.5D). We simulate...
of the meridional plane using the two-dimensional version of the code in spherical coordinates. The symmetry axis of all the plots shown in this Letter is along the \( x \) (horizontal) axis. Due to the fact that this is a Letter, in order to minimize the space required to show the plots, and due to the fact that the results of both halves of the simulated domain were either identical or exhibit the same large-scale and stability behavior, we exhibit only a quarter of the meridional plane (half of the simulated domain).

In contrast to our previous Letters, where gravity was omitted, we added gravity to the simulations. We assume a dark matter halo with a density profile as is given in Navarro, Frenk & White (1996). The dark matter is not affected by the evolution of the baryonic matter, therefore, the gravitational potential is constant,

\[
\Phi_{\text{NFW}}(r) = 4\pi r_s^3 \delta_c \rho_{\text{crit}} \frac{G}{c^2} \left[ 1 - \frac{\ln(r/r_s + 1)}{r/r_s} \right],
\]

where \( r_s \equiv \frac{\nu}{c} \) is a scale radius, \( r_v \) is the virial radius, \( c \) is the concentration factor, \( \delta_c = \frac{200}{3 \ln(1 + c)} \) and \( \rho_{\text{crit}} = \frac{3H^2}{8\pi G} \) is the critical density of the Universe at \( \alpha = 0 \).

We set the initial density profile of the gas to maintain hydrostatic equilibrium (e.g. Makino, Sasaki & Suto 1998), i.e.

\[
\rho_{\text{gas}}(r) = \rho_{\text{gas},0} \rho = \rho_{\text{gas},0} e^{-\frac{r}{r_v} + 1},
\]

where \( b = 4\pi r_s^2 \delta_c \rho_{\text{crit}} \mu m_p G / k T_v \). \( T_v = \frac{\sigma T_s M_v}{R_{\text{vir}} c^2} \) is the virial temperature and \( M_v \) is the virial mass. The unperturbed ICM temperature is \( 2.7 \times 10^7 \) K. We use a 256 \( \times \) 256 grid, evenly spaced in the azimuthal direction. In the radial direction, the grid was partitioned using a geometric series with a common ratio of 1.0015 allowing for better resolution in the inner part of the simulated domain. More detail will be given in a forthcoming Letter where an extended parameter space will be explored.

![Density and velocity map for the jet-inflated bubble at \( t = 0 \).](image)

**Figure 1.** Density and velocity map for the jet-inflated bubble at \( t = 0 \), the time the jet is shut-off. The density scale is on the right-hand side in logarithmic scale and cgs units. The arrows represent the velocity of the flow: \( 0.1c_s < v_j \leq 0.5c_s \) (shortest), \( 0.5c_s < v_j < c_s \) and \( v_j > c_s \) (longest in this case). Here, \( c_s = 775 \text{ km s}^{-1} \) is the sound speed of the undisturbed ICM.

We simulate the evolution of a bubble inflated by a jet, and compare it to the evolution of bubble introduced manually to the grid (an artificial bubble). The jet is injected at a radius of 0.1 kpc, with constant mass flux of \( \dot{M}_j = 5 M_\odot \text{ yr}^{-1} \) (per one jet) and a constant radial velocity of \( v_j = 7750 \text{ km s}^{-1} \), inside a half opening angle of \( \alpha = 70^\circ \). The total power of the two jets is \( E_{\text{jet}} = 2 \times 10^{44} \text{ erg s}^{-1} \). The jet was active for a period of \( \Delta t_j = 10 \text{ Myr} \), from \( t = -10 \text{ Myr} \) until \( t = 0 \), when the jet was completely shut-off.

The spherical artificial bubbles was inserted in its full size at \( t = 0 \) with its volume and (constant) density about equal to that of the jet-inflated bubble at \( t = 0 \). The initial bubble’s radius and density were set to \( R_{\text{ab}} = 4.5 \text{ pc} \) and \( \rho_{\text{ab}} = 10^{-26} \text{ g cm}^{-3} \), respectively. We made several tests. We ran cases with initial artificial-bubble density three times larger, and three times smaller, than \( \rho_{\text{ab}} \). We also ran cases with numerical grid with half and twice the resolution (i.e. \( 128 \times 128 \) and \( 512 \times 512 \), respectively) compared to our standard resolution. We were witness to only small differences between the runs with different resolutions and initial bubble density. Namely, our results and conclusions are not sensitive to the numerical details.

With the parameters used here, the bubble temperature is \( \sim 10 \) times higher than the ambient temperature. We can use a somewhat higher jet velocity that will result in a lower bubble density (Hinton, Dominko & Pope 2007) and in a higher bubble temperature (see Sternberg et al. 2007 and Sternberg & Soker 2008). This will be examined in future Letter.

### 3 RESULTS

In Fig. 1, we show the density and velocity map of the jet-inflated bubble at \( t = 0 \). There are some flow structures which characterize the jet-inflated bubble, and that are not present in the case of the artificial bubble. As we will see below, these are crucial for the...
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Figure 2. The evolution of the jet-inflated bubble (left-hand column) and the artificial bubble (right-hand column), at three times as indicated. In the evolution of the jet-inflated bubble, the jet was active from $t = -10\,\text{Myr}$ until $t = 0$, when the jet was completely shut-off. The artificial bubble was introduced as a spherical bubble with a constant density at $t = 0$.

The evolution of the bubble. (i) There is a dense shell around the bubble. (ii) The bubble and the dense shell have radial momentum. In particular, the shell’s front is relatively dense and has an outward velocity. (iii) There is a circular flow, a vortex, around the lowest density region in the bubble. (iv) Although the jet was shut-down, the jet material along the path form the centre to the bubble still exists. In reality, the jet is gradually shut-down (even if on a short-time-scale), which results in low-density material behind the bubble, hence, this is a real feature.

In Fig. 2, we compare the evolution of the jet-inflated bubble with that of an artificial bubble. As is well documented in many non-magnetic simulations of artificial bubbles (e.g. Churazov et al. 2001; Robinson et al. 2004; Jones & De Young 2005; Reynolds et al. 2005), as the bubble rises a vortex from below forms a flow along the axis that penetrates the bubble from below. This flow leads to the destruction of the bubble. In the case of an artificial bubble, this occurs over a short distance and the bubble clearly loses its shape.

With the more realistic jet-inflated bubble, the situation is very different.

(i) RT instability modes are seen on the front of the artificial bubble. The jet-inflated bubble does not suffer from such instabilities at early times. This is a result of the outflow velocity of the dense shell in front of the bubble. This interface is stable during the inflation phase (Soker, Blanton & Sarazin 2002; Pizzolato & Soker 2006), and the stability is maintained as long as the low-density bubbles does not support the dense ICM against gravity.

(ii) The jet-inflated bubble reaches a much larger distance in the cluster before it starts losing its shape, as compared with the artificial bubble. This is a result of the momentum of the bubble and the dense shell around it.
(iii) The jet material that lags behind the bubble, partially fills the region along the symmetry axis. Our numerical grid forces the flow to be exactly axisymmetric. In a more realistic three-dimensional flow, we expect this region to be spread around the symmetry axis, such that in projection the bubble will still be observed as a more or less spherical bubble. In the case of an artificial bubble, this region is filled with ICM dense gas, and in projection the bubble will appear as a torus. In addition, in a future Letter we intend to follow Reynolds et al. (2005) and increase the viscosity. We expect the higher viscosity to reduce the flow of dense matter along the symmetry axis.

(iv) It seems that the vortex inside the jet-inflated bubble (Fig. 1) stabilizes the sides of the bubbles as it rises. We see no sign of instabilities there, neither RT nor Kelvin–Helmholtz.

(v) There is a low density–high temperature (high entropy) gas lagging behind the bubble in a disrupted flow. This gas is mixed with the ICM and increase its entropy. What we find here is a relatively efficient way to heat the ICM.

We would like to state that our results also support past conclusions that simulations of feedback in cooling flow clusters have to be more realistic and incorporate, among other things, a more realistic jet (Vernaleo & Reynolds 2006). The inflation of the bubbles by the jet, and not by predescribed numerical recipe, might be one of the missing ingredients needed to make these simulations more real.

4 DISCUSSION AND SUMMARY

When the realistic jet-inflation process of bubbles is considered, there are two stabilizing processes. (i) During the inflation phase, the bubble is RT stable because the bubble–ICM interface is decelerating and expanding (Soker et al. 2002; Pizzolato & Soker 2006). (ii) The outward momentum of the bubble and the dense shell around it imply that the low-density bubble does not need to support a dense gas above it during the outward motion to large distances. This implies that the interface is RT stable. The result of these processes is that the bubbles can rise to large distances from the cluster’s centre while still maintaining their general structure, without the need to invoke stabilizing magnetic field. Therefore, it is crucial that in the study of low-density bubbles in clusters of galaxies, the bubbles will be self-consistently inflated, rather than introduced artificially. It also seems that the vortex within the jet-inflated bubble suppresses instabilities on the sides of the rising bubble.

Our results show that the inflating jet, even if completely shut-down, results in a high-entropy gas extending from the centre to the bubble. This high-entropy gas mixes with the ICM. This mixing is a relatively efficient channel to heat the ICM. As seen at late times in Fig. 2, the volume filled by the ‘fractal’ high-entropy gas is non-negligible.

The inflation of large, more or less spherical, bubbles close to the centre of the cluster (termed ‘fat’ bubbles) requires the jet to be slow, \( v_j \sim 10^4 \text{ km s}^{-1} \ll c \), and the mass-loss rate to be relatively large, \( \sim 1-5 \times 10^4 \text{ M}_\odot \text{ yr}^{-1} \) (Sternberg et al. 2007; Sternberg & Soker 2008). In these Letters, we already mentioned AGN observations that support such a high mass-loss rate, and listed some previous theoretical studies based on such an outflow. We here add that recent observations suggest that in many clusters, cooling flow does exist as the radiative cooling is not completely prevented (O’Dea et al. 2008). Namely, gas radiatively cools to low temperatures. Revaz, Combes & Salome (2008) conducted numerical simulations and use them to suggest that cold blobs of gas participate in the feedback heating in cooling flow clusters, as suggested by Pizzolato & Soker (2005). Over all, it seems that high mass-loss rate in jets might occur quite often in cooling flow clusters, as suggested by the moderate cooling flow model (Soker & Pizzolato 2005). Another issue is the opening angle of the jet. We note that most observed jets are narrow. However, as discussed in Sternberg & Soker (2008), it is possible that much of the energy and mass reside a wider and slower outflow, i.e. the narrow jet is the centre of a wider jet. Our prediction of a wide, or rapidly precessing, jet will have to be tested in the future.

Putting the results of this Letter on a broader view, the usage of slow massive jets, that are either wide of rapidly precessing, can account for some basic properties of cooling flow clusters: (i) recycling of gas that cool from the ICM and flows towards the centre. (ii) Formation of fat bubbles close to the centre. (iii) Allowing the bubble to rise to large distances (the results of this Letter). (iv) Efficiently transfer energy form the central accreting black hole to the ICM.

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