INFLATING FAT BUBBLES IN CLUSTERS OF GALAXIES BY WIDE JETS

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ABSTRACT

We conduct two-dimensional hydrodynamical simulations of jets expanding in the intra-cluster medium (ICM). We find that for a fat, i.e., more or less spherical, bubble attached to the center to be formed the jet should have high momentum flux and a large opening angle. Typically, the half opening angle should be $\alpha \gtrsim 50^\circ$, and the large momentum flux requires a jet speed of $v_j \sim 10^4$ km s$^{-1}$. The inflation process involves vortices and local instabilities which mix some ICM with the hot bubble. These results predict that most of the gas inside the bubble has a temperature of $3 \times 10^8 \lesssim T_b \lesssim 3 \times 10^9$ K, and that large quantities of the cooling gas in cooling flow clusters are expelled back to the intra-cluster medium, and heated up. The magnetic fields and relativistic electrons that produce the synchrotron radio emission might be formed in the shock wave of the jet.

Subject headings:

1. INTRODUCTION

Chandra and XMM-Newton X-ray observations of clusters of galaxies reveal the presence of X-ray-deficient bubbles in the inner regions of many cooling flow clusters of galaxies, groups of galaxies, and elliptical galaxies. The hot gas in the centers of many galaxies and clusters of galaxies is a strong X-ray emitter, often this emission is strong enough to have a dynamical role: the gas cools radiatively to very low temperatures ($T < 10^4$ K), and some hotter gas from regions further out must flow inward to keep the overall hydrostatic equilibrium in a process dubbed cooling flow. The high-resolution X-ray observations of XMM–Newton and Chandra show that the amount of gas cooling to very low temperatures is lower than the amount of hot gas which has a short cooling time. This implies that some heating mechanism must be at work to counterbalance the radiative losses. It is widely agreed that a major role is played by the jets and bubbles formed by the active galactic nucleus (AGN; see review by Peterson & Fabian 2006) operating at the cluster core. Therefore, understanding the bubble formation is an important key to understand cooling flows. In some cases the pairs of bubbles touch the center and are almost spherical (“fat” bubbles), with a typical hourglass shape (e.g., Perseus, Fabian et al. 2000; A 2052, Blanton et al. 2003).

The basic condition for a jet to inflate a fat bubble is that the jet’s head will reside inside the bubble during the inflation phase. For that to occur, it has to be proposed that the either the jet’s opening angle is large (Soker 2004), or the jet is narrow but its axis changes its direction. The change in direction can result from precession (Soker 2004, 2007), random change (Heinz et al. 2006), or a relative motion between the ICM and the AGN (Loken et al. 1995; Soker & Bisker 2006; Rodriguez-Martinez et al. 2003).

As far as we know, none of the previous numerical simulations of jets expanding from the center could inflate fat bubbles attached to the AGN. The simulations by Basson & Alexander (2003) come close to forming two fat, almost spherical, bubbles, but the bubbles are too elongated. The need to understand the formation of fat bubbles by AGN jets was emphasized in a recent meeting on cooling flows in galaxies and clusters of galaxies (Pratt et al. 2007).

In this paper we report our success to inflate fat bubbles attached to the center by two-dimensional hydrodynamical numerical simulations.

2. NUMERICAL METHOD AND SETUP

The simulations were performed using Virginia Hydrodynamics-I (VH-1; Blondin et al. 1990; Stevens et al. 1992). The code uses finite-difference techniques to solve the equations of an ideal inviscid compressible fluid flow. We used the two-dimensional version in spherical coordinates. Namely, there is an azimuthal symmetry, and the calculations are performed in only one quarter of the meridional plane. In the present paper we study the effect of spreading the ejected matter over a large solid angle, namely, using a wide jet. For that purpose a 2D code is adequate. More realistic 3D code will result in more realistic fine-detail structures, but will not change the conclusions regarding the conditions on inflating fat bubbles. Radiative cooling and gravity were not included, since the total time of the simulation, $< 10^7$ yr, is somewhat shorter than the gravitational time scale, and much shorter than the radiative cooling time. This preliminary report aims to emphasize the jet properties that determines whether the required bubble is inflated, and hence these omissions are justified.

The initial density profile of the ICM is spherical, with a commonly used (e.g., Vernaleo & Reynolds 2006) profile of

$$\rho_{\text{ICM}} = \rho_c [(1 + (r/r_0)^2)^{-3/4}].$$

In the runs described here we take $\rho_c = 2.16 \times 10^{-25}$ g cm$^{-3}$, and $r_0 = 100$ kpc (Rodriguez-Martinez et al. 2006). The ICM temperature is $2.7 \times 10^7$ K. Since we study the inner region, the ICM density is practically constant in the region we simulate $\rho \approx \rho_c$.

The jet is injected at a radius of 0.1 kpc, with constant mass flux and constant radial velocity $v_j$ inside a half opening angle $\alpha$ (measured from the symmetry axis to
the edge). The total kinetic power of one jet is \( \dot{E}_j = M_j v_j^2 / 2 \), where \( M_j \) is the mass outflow rate in one jet.

3. RESULTS

In Figure 1 we show the density maps at two times and for two jets with the same power and velocity (hence the same mass outflow rate) but different opening angles. In Model 1 the half-opening angle is \( \alpha = 70^\circ \), the power of one jet is \( \dot{E}_j = 10^{44} \text{ erg s}^{-1} \), the initial jet’s speed is \( v_j = 7750 \text{ km s}^{-1} \), and hence the mass outflow rate in one jet in Model 1 is \( 5 \text{ M}_\odot \text{ yr}^{-1} \). Model 2 differs from Model 1 only in the half opening angle \( \alpha = 20^\circ \). In Figure 2 we show the temperature map of Model 1 at \( t = 5 \text{ Myr} \).

Let us examine Figures 1 and 2 for Model 1 at \( t = 5 \text{ Myr} \). The very low density region close to the \( x \)-axis and the center is the region where the jet is freely expanding. Two shocks are seen in the figures. The forward shock running through the ICM has an elliptical shape, extending in the figures from \( x = 8.2 \text{ kpc} \) to \( y = 7.2 \text{ kpc} \). The reverse shock, where the freely expanding jet is shocked, is seen as an almost vertical line at \( x \simeq 2.3 \text{ kpc} \).

Model 3 has the same jet’s power and opening angle, but it differs from Model 1 in having a jet faster by a factor of 3 (\( v_j = 2.32 \times 10^4 \text{ km s}^{-1} \)), and hence a mass outflow rate lower by a factor of 9. Model 4 has the same jet’s power, but it differs from Model 1 in having a faster jet, by a factor of 9, of \( v_j = 6.97 \times 10^4 \text{ km s}^{-1} \), and hence a mass outflow rate \( \dot{M}_j = 0.065 \text{ M}_\odot \text{ yr}^{-1} \), lower by a factor of 81 than that in Model 1. In Model 5 the jet’s speed is as in Model 1, but the power and mass outflow rate are lower by a factor of 10, i.e., \( \dot{E}_j = 10^{43} \text{ erg s}^{-1} \). The density maps of these jets are presented in Figure 3 at times as indicated in each panel.

As evident by Figures 1 and 2 fat bubbles attached to the center are formed only with wide (\( \alpha \gtrsim 50^\circ \)) and slow (\( v_j \simeq 5,000 - 30,000 \text{ km s}^{-1} \)) jets, as in Models 1 and Model 3. The case of model 5 is marginal. The jet is too weak to blow a large fat bubble. More energetic jets, for the ambient medium used by us, can blow fat bubbles, if they wide and slow enough. We also run a model where both the ambient density and the mass outflow rate, hence power, were 0.33 times their values in Model 1 (this is more appropriate to the case in Perseus). Beside small numerical differences, the results are the same as in Model 1. Therefore, models with a power of \( 10^{42} - 10^{43} \text{ erg s}^{-1} \) can still blow fat bubbles if the ambient medium density is proportionally lower than what used here in Model 1.

In all panels we see the vortices on the sides of the jet, developed by the back-flowing jet’s material (termed “cocoon”), and Kelvin-Helmholtz instabilities (Norman et al. 1982). It is well-known (e.g., Loken et al. 1992) that narrow jets interacting with their environment form cylindrically shaped cocoons (e.g., Krause 2004, 2005; O’Neill et al. 2004).

The structure of the cocoon and its width depends on the Mach number and density contrast between the jet and the environment as well (Krause 2003). Rosen et al. (1999) found that relativistic jets have small cocoons, while slow jets develop large cocoons. Therefore, lower velocities increase the cocoon size in jets, as we also find
Fig. 1.— Comparison of wide and narrow jets. In Model 1 and Model 2 the power of one jet is $E_j = 10^{44}$ erg s$^{-1}$, and the initial jet’s speed is $v_j = 7750$ km s$^{-1}$. The initial jet’s half opening angle in Model 1 is $\alpha = 70^\circ$, and in Model 2 it is $\alpha = 20^\circ$. The horizontal lower edge is the symmetry axis, while the left side is the equatorial plane; only quarter of the meridional plane is shown. The density scale is on the right side of each panel (note the different scaling between the panels), in log $\rho$(g cm$^{-3}$).

Fig. 2.— The temperature map of Model 1 at $t = 5$ Myr. Scale is in log $T$(K).

Here. However, the simulations cited above did not lead to the formation of fat bubbles attached to the center, the wide jet’s angle used here for the slow jets, lead to the desired morphology, containing the following components:

1. A fat, very low density cavity.
2. A dense shell surrounding the cavity from all directions, including in the equatorial plane (adding gravity might enhance the dense shell concentration there).
3. A slow shock of the dense shell. The average speed of the forward shock between $t = 2.5$ Myr and $t = 5$ Myr in Model 1 is $\sim 1400$ km s$^{-1}$, which corresponds to a Mach number of $\sim 2$.

Inclusion of magnetic fields in the simulations might reduce the instability, making a smoother boundary for the bubble. Inclusion of heat conduction could lead to the evaporation of denser filaments penetrating into the bubble.

Soker’s (2004) formula predicts that wider jets will more easily form fat bubbles, as we find here. However, that formula predicts also that faster jets are more likely to inflate fat bubbles, contrary to our finding. The reason for the discrepancy is that Soker (2004) assumed that the jet has already reached a large distance of few kpc or more from the center. This is the case in the simulations conducted by Vernaleo & Reynolds (2006), where bubbles were inflated at a distance of 400 kpc from the center, agreeing with the estimate of Soker (2004; see Soker 2007). However, for a given jet’s kinetic power a higher velocity implies a lower momentum flux, and hence the jet is recollimated by the pressure formed as it interacts with the ICM. This is clearly seen in Model 4, which starts with a wide angle, but is soon recollimated to a narrow jet that expands to a large distance without forming a fat bubble.

4. DISCUSSION AND SUMMARY

We showed that slow wide jets (Model 1 and Model 3) can inflate fat bubbles attached to the center. Morphologically, these resemble the structures observed in some cooling flow clusters like A 2052 and Perseus. This by itself does not imply that these bubbles are inflated by wide jets, as there is still the possibility that these are inflated by jets with varying axis (Soker 2004, 2007; Heinz...
et al. 2006). Our controversial finding might be that the jet should be highly sub-relativistic (but still of high Mach number), with a typical velocity of $v_j \sim 10^4$ km s$^{-1}$. This leads to a bubble temperature of $T_b \simeq 3 \times 10^8 - 3 \times 10^9$ K. Our motivation and justifications for using relatively slow massive jets are as follows.

1. Equipartition arguments applied to the bubble systems in several cooling flow clusters suggest that the pressure in the radio lobes is an order of magnitude less than the surrounding thermal gas pressure (e.g., Hydra A, McNamara et al. 2000; Perseus, Fabian et al. 2000; A 2052, Blanton et al. 2001). Therefore, as noted by these authors, a likely solution is that there is a good amount of thermal pressure in the bubbles, resulting from gas at several tens of keV (several $10^8$ K). Sanders & Fabian (2007) constrain the amount of hot thermal plasma in the temperature range $7 - 70 \times 10^5$ K in the bubbles of Perseus. For this cluster, their result is consistent with our model provided that the jet speed is $v_j \gtrsim 2 \times 10^5$ km s$^{-1}$.

2. Nearby Seyfert galaxies have slow outflows of $\sim 1000$ km s$^{-1}$ (e.g., Crenshaw & Kraemer 2007). It has been claimed (Behar et al. 2003) that these are the large-angle high mass loss rate winds observed directly in Seyfert 2’s. There are also claims for faster winds in brighter quasars (24000 km s$^{-1}$). Pounds et al. 2003; but see Kaspi & Behar 2006) for which mass estimates are still unavailable. Possibly, UV broad absorption line quasars (BALQS) may be related to the winds simulated in this work, although they have not been observed in any of the known cooling flow clusters and their entrained mass is unknown.

3. On the theoretical side, Binney (2004) argued that in many cases the relativistic jet carries a small fraction of the mass and energy in the outflow. In their jet simulations Omma et al. (2004) take $v_j = 10^4$ km s$^{-1}$ and a jet mass outflow rate of $2 M_{\odot}$ yr$^{-1}$. There are other models which predict slow ($\sim 10^4$ km s$^{-1}$) winds (e.g., Begelman & Celotti 2004).

4. Soker & Pizzolato (2005) proposed a scenario in which a large fraction, or even most, of the gas cooling to low temperatures of $T < 10^4$ K in cooling flow clusters directly gains energy from the central black hole. In Model 1, the mass outflow rate in each jet is $5 M_{\odot}$ yr$^{-1}$, or $10 M_{\odot}$ yr$^{-1}$ in the two jets. Therefore, it is possible that the inflation of fat attached bubbles occur when mass outflow rate is so high, that it must occur in cooling flow clusters.

Dunn et al. (2006) argue that the jets in Perseus (a cluster with a clear indication of radio bubbles) are dominated by electron-positron plasma. This result might be controversial, as other authors (Celotti & Fabian, 2003) prefer baryon-dominated, not lepton-dominated jets. Anyhow, even a lepton-dominated jet would not be at odds with our claim that the bulk of the energy is thermal. The conclusions of Dunn et al. (2006) apply at the base of the jet (on parsec scales), which does not exclude a baryonic contamination of the outflow further out. In the present framework, therefore, the bulk of the energy input by the jet may be thermal, with $\sim 10\%$ of the energy budget in magnetic fields and relativistic particles, in agreement with the observations of the cluster’ cavities in the radio band (e.g. Clarke et al. 2003 and references therein).

If the acceleration of electrons in ICM shocks is as efficient as that in supernova remnant shocks of few $10^3$ km s$^{-1}$ as suggested by Loeb & Waxman (2000), then we can expect $\sim 5\%$ of the post shock energy to be converted to relativistic electrons and magnetic fields. This is sufficient to account for the radio synchrotron emission inside bubbles (Birzan et al. 2004, and references therein).

We thank John Blondin for his great help with the numerical code. This research was supported by the Asher Fund for Space Research at the Technion. It is a pleasure to thank Ehud Behar for useful discussions.

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