INFLATING FAT BUBBLES IN CLUSTERS OF GALAXIES
BY PRECESSING MASSIVE SLOW JETS

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ABSTRACT

We conduct hydrodynamical numerical simulations and find that precessing massive slow jets can inflate fat bubbles, i.e., more or less spherical bubbles, that are attached to the center of clusters of galaxies. To inflate a fat bubble the jet should precess fast. The precessing angle $\theta$ should be large, or change over a large range $0 \leq \theta \leq \theta_{\text{max}} \sim 30 - 70^\circ$ (depending also on other parameters), where $\theta = 0$ is the symmetry axis. The constraints on the velocity and mass outflow rate are similar to those on wide jets to inflate fat bubbles. The velocity should be $v_j \sim 10^4$ km s$^{-1}$, and the mass loss rate of the two jets should be $2 \dot{M}_j \simeq 1 - 50 \dot{M}_\odot$ yr$^{-1}$. These results, and our results from a previous paper dealing with slow wide jets, support the claim that a large fraction of the feedback heating in cooling flow clusters and in the processes of galaxy formation is done by slow massive jets.

1. INTRODUCTION

Many of the X-ray deficient bubbles in galaxies and clusters of galaxies reside very close to the center of the cluster (or galaxy) and are fully or partially surrounded by a dense shell, e.g., Perseus (Fabian et al. 2000), Abell 2052, (Blanton et al. 2003), Abell 4059 (Heinz et al. 2002), and HCG 62 (Vrtilek et al. 2002; Morita et al. 2006). We term these more or less spherical bubbles ‘fat bubbles’. Fat bubbles are defined by the following properties: (1) Fat bubbles come in pairs, each on opposite sides of the equatorial plane. In some cases there is departure from axisymmetry, and they are not exactly opposite. (2) They touch each other at the center, and by that form an hourglass structure (like the figure ‘8’). One bubble of the hourglass structure is referred to as a fat bubble. (3) The density inside the bubbles is much lower than that of their surroundings (ambient gas). (4) They are fully or partially surrounded by relatively thin shell that is denser than the surroundings. (5) In some cases

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their boundary, on the far side from the center, is open. In classifying planetary nebulae, for example, this structure is referred to as a bipolar nebula. There are many such planetary nebulae that are well resolved in the visible band, and the bipolar structure is well defined. In many cases there are similar structures in planetary nebulae and in clusters of galaxies (Soker & Bisker 2005). The best examples of the hourglass type of structure we aim to study are the bubbles in Perseus (Fabian et al. 2000) and in A 2052, (Blanton et al. 2001). Other cases are cited above and in Soker & Bisker 2006. If the bubble rises through the ICM and do not touch each other any mode, then they are not ‘fat’ any more because they don’t form an hourglass structure anymore. We estimate that $\sim 30 - 50\%$ of the bubbles are, or were, fat bubbles.

In recent years, two and three-dimensional hydrodynamical simulations of jets and bubbles in clusters of galaxies, were conducted to study different aspects of their interaction with the intra-cluster medium (ICM), such as heating the ICM (e.g., Basson & Alexander, 2003; Heinz & Churazov, 2005; Reynolds et al., 2005; Heinz et al., 2006; Vernaleo & Reynolds, 2006; Binney et al., 2007; Ruszkowski et al., 2007; Alouani Bibi et al., 2007; Brüggen et al., 2007). In our studies we aim to understand the conditions leading to the formation of fat bubbles.

In previous papers (Soker 2004, 2006; Sternberg et al. 2007, hereafter Paper I) we proposed that in order to inflate fat bubbles, either the jet’s opening angle has to be large, i.e., wide jets, or the jet is narrow but its axis has to change its direction. The change in direction can result from precession (Soker 2004, 2006), random change (Heinz et al. 2006), or a relative motion between the ICM and the active galactic nucleus (AGN; Loken et al. 1995; Soker & Bisker 2006; Rodríguez-Martínez et al. 2006).

In Paper I we conducted two-dimensional hydrodynamical simulations of wide jets expanding in the ICM. We found that wide jets can indeed inflate fat bubbles that reside very close to the center of the cluster. For this to occur, we found that the jets should have high momentum flux. Typically, the half opening angle should be $\alpha \gtrsim 50^\circ$, and the large momentum flux requires a jet speed of $v_j \sim 10^4 \text{ km s}^{-1}$, i.e., highly non-relativistic, but supersonic ($v_j \simeq 3000 - 3 \times 10^4 \text{ km s}^{-1}$). Narrow relativistic jets can exist in parallel with the slow wide outflow, but they will not lead to the inflation of fat bubbles. The inflation process involves large 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 $3 \times 10^8 \lesssim T_b \lesssim 3 \times 10^9 \text{ K}$, and that large quantities of the cooling gas in cooling flow clusters are expelled back to the intra-cluster medium and heated up (Soker & Pizzolato 2005). In Paper I we suggested that the magnetic fields and relativistic electrons that produce the synchrotron radio emission might be formed in the shock wave of the non-relativistic jet. Motivated by our earlier
results, in this paper we examine the inflation of fat bubbles by narrow precessing jets.

2. NUMERICAL METHOD AND SETUP

The simulations were performed using the *Virginia Hydrodynamics-I* code (VH-1; Blondin et al. 1990; Stevens et al. 1992), as described in Paper I. We simulated a three-dimensional axisymmetric flow, so practically we simulated a quarter of the meridional plane using the two-dimensional version of the code in spherical coordinates. The symmetry axis of all plots shown in this paper is along the horizontal axis (the x axis) while the equatorial plane is vertical. Radiative cooling and gravity were not included, since the total time of the simulation, \( t_{\text{sim}} \sim 10^7 \) 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 determine whether or not the required bubble is inflated, hence, these omissions are justified.

We used the \( \beta \) model (with \( \beta = 1/2 \)) as the initial density profile of the ICM,

\[
\rho_{\text{ICM}} = \rho_c \left[ 1 + \left( \frac{r}{r_0} \right)^2 \right]^{-3/4},
\]

with \( \rho_c = 2.16 \times 10^{-25} \) g cm\(^{-3} \) and \( r_0 = 100 \) kpc (see Paper I and references therein). The ICM temperature is \( 2.7 \times 10^7 \) K. The box size used in our simulations was 30 kpc \( \times \) 30 kpc (one quarter of the meridional plane). We used a 128 \( \times \) 128 evenly spaced grid. As discussed in Paper I, higher resolution does not change the large scale behavior, thus, this resolution is sufficient for our study. In Figure I we present density maps (logarithm of the density. The density is given in g cm\(^{-3} \).) of two runs with the same parameters but different resolution (128 \( \times \) 128 and 256 \( \times \) 256). This figure clearly shows that the large scale behavior does not change significantly with the increase in resolution. Moreover, we note that in the zone relevant to our simulations, \( r \lesssim 30 \) kpc, the assumption of a constant temperature is reasonable (see fig 1. of Pizzolato & Soker 2005).

The narrow jet was injected at a radius of 0.1 kpc, with constant mass flux \( \dot{M}_j \) (per one jet) and a constant radial velocity \( v_j \), inside a half opening angle \( \alpha = 5^\circ \). Therefore, the total kinetic power of one jet is \( \dot{E}_j = \dot{M}_j v_j^2 / 2 \). The symmetry axis of the jet is at an angle \( \theta(t) \) in respect to the symmetry axis of the problem (the x axis). This is the precessing angle which is a function of time. Because of the axisymmetric nature of our problem, the meaning of a precessing jet in these simulations is that the narrow jet precess around the symmetry axis very rapidly. Namely, the precessing period around the symmetry axis is much shorter than any other relevant time scale in the problem, e.g., the time scale over which \( \theta \) is changing.

Due to the numerical nature of the jets injection, in some cases a fraction of the injected mass does not succeed in mounting our grid and remains in the first cells of the grid. In the
next time step the jet properties are reinserted into these cells and this mass is lost. Moreover, if the jet is precessing, then the movement of the injection zone may increase/decrease the effective opening angle of the jet, in effect changing $\dot{M}_j$, such that only after the simulation we can determine the mass loss rate and kinetic luminosity of the jet. The kinetic luminosity of the jet is constant, and is equal to $5PV/2t$, where $P$ is the pressure and $V$ is the volume inflated after time $t$. We calculated this value at several times for each case, and was taken to be the kinetic luminosity. All tables and plot captions specify the estimated jet luminosity. We consider three basic types of precessing jets:

(i) Fixed precessing angle, i.e., $\theta$ is constant.

(ii) A constant rate of change in the precession angle, i.e., at constant time interval $d\theta/dt$ is constant for $\theta < \theta_{\text{max}}$.

(iii) Random precession, i.e., the jet axis has the same probability to take any direction within a maximum angle $\theta_{\text{max}}$. This is done by taking $d(\cos \theta)/dt$ to be constant.

We studied 12 cases per each precession type (fixed, constant rate change, and random). The parameters of the different cases are given in Tables 1-3.

We used slow massive jets, as have been used before in a number of numerical studies (e.g., Paper I; Alouani Bibi et al. 2007). We further discuss the usage of slow massive jets in section 6.

3. RESULTS: PRECESSION AT A CONSTANT ANGLE

In Figure 2 we show the density map (logarithem of the density. The density is given in g cm$^{-3}$.) at different times for a jet with a fixed precession angle of $\theta = 15^\circ$ in respect to the symmetry axis (Fix2, see Table 1). The jet has a half opening angle of $\alpha = 5^\circ$, $v_j = 7750$ km s$^{-1}$, and $\dot{E}_j \simeq 1.1 \times 10^{44}$ erg s$^{-1}$. For this case the mass injection rate into one jet is $\dot{M}_j \simeq 6M_\odot$ yr$^{-1}$. Namely, the two jets expel mass back to the ICM at a high rate of $\sim 12M_\odot$ yr$^{-1}$. At first the jet inflates a cavity of low density matter in the shape of a torus. At later times the jet is bent towards the symmetry axis, thereafter, it continues its propagation in a manner quit similar to that of a non precessing jet with a $\sim 20^\circ$ half opening angle (see Figure 1 model 2 in Paper I). In this case, it is obvious to see that a fat bubble was not inflated. The arrows in the plot represent the velocity of the flow. For visual clarity we divided the velocities into groups, each represented by an arrow of a predetermined length:
Fig. 1.— Density maps for two runs with the same parameters but different resolution (128 × 128 and 256 × 256) shown at the same time ($t = 27$ Myr). The small scale behavior might differ, but the large scale behavior, which is what we are interested in, does not differ. We emphasize that the x axis is the symmetry axis. In all figures the density is given in g cm$^{-3}$ and in log scale.

| Run | $\theta$ (deg) | $v_j$ (Km s$^{-1}$) | $L_j$ ($10^{44}$ erg s$^{-1}$) | Morphology | Figure |
|-----|----------------|---------------------|-------------------------------|------------|--------|
| Fix1 | 15$^\circ$ | 7750 | 0.24 | Thin and narrow jet and cocoon | - |
| Fix2 | 15$^\circ$ | 7750 | 1.1 | Thin and narrow jet and extensive cocoon | Fig 2 |
| Fix3 | 15$^\circ$ | 23250 | 0.15 | Very Thin and narrow jet and cocoon | - |
| Fix4 | 15$^\circ$ | 23250 | 1.8 | Thin and narrow jet and extensive cocoon | Fig 5 |
| Fix5 | 30$^\circ$ | 7750 | 0.14 | Fat Bubble | Fig 3 |
| Fix6 | 30$^\circ$ | 7750 | 1.8 | Fat bubble | Fig 4 |
| Fix7 | 30$^\circ$ | 23250 | 1.2 | First torus then spherical cavity at center of cluster | Fig 5 |
| Fix8 | 30$^\circ$ | 69750 | 1.2 | First torus then an ellipsoid cavity at center of cluster | - |
| Fix9 | 60$^\circ$ | 7750 | 0.2 | First torus then an ellipsoid cavity at center of cluster | - |
| Fix10 | 60$^\circ$ | 7750 | 1.8 | Both tori merge to create a 'doughnut' | Fig 5 |
| Fix11 | 60$^\circ$ | 23250 | 0.14 | First torus then an ellipsoid cavity at center of cluster | - |
| Fix12 | 60$^\circ$ | 23250 | 2.2 | First torus then spherical cavity at center of cluster | - |

Table 1: Parameters of the fixed angle precession runs, where, $\theta$ is the angle (in degrees) between the symmetry axis of the jet and the symmetry axis of the problem, $v_j$ is the jet velocity in Km s$^{-1}$, $L_j$ is the jet luminosity in erg s$^{-1}$ (per one jet). The cluster sound speed is 775 Km s$^{-1}$. 
### Constant rate of change in the precession angle

| Run | \( T \) (Myr) | \( v_j \) (Km\ s\(^{-1}\)) | \( L_j \) (10\(^{44}\) erg\ s\(^{-1}\)) | Morphology | Figure |
|-----|----------------|-----------------|-----------------|------------|--------|
| Con1 | 0.1 | 7750 | 1.9 | Fat bubble | [Fig 6] |
| Con2 | 0.1 | 23250 | 1.1 | Thin jet shedding large vortecies | - |
| Con3 | 0.1 | 69750 | 1.8 | Very thin jet and extensive cocoon | [Fig 8] |
| Con4 | 1 | 7750 | 2 | Narrow and elongated cavity (not a fat bubble!!!) | - |
| Con5 | 1 | 23250 | 1.5 | Narrow and elongated cavity | - |
| Con6 | 1 | 69750 | 1.2 | Narrow and elongated cavity | - |
| Con7 | 5 | 7750 | 1.6 | Narrow and elongated cavity extensive backflow | [Fig 9] |
| Con8 | 5 | 23250 | 1.6 | Narrow jet with extensive backflow | - |
| Con9 | 5 | 69750 | 2 | Narrow jet with extensive backflow | - |
| Con10 | 30 | 7750 | 1.8 | Elongated clumpy cavity, extensive backflow | - |
| Con11 | 30 | 23250 | 1.5 | Narrow jet with extensive clumpy cocoon | - |
| Con12 | 30 | 69750 | 1.6 | Narrow jet with narrow clumpy cocoon | - |

Table 2: Parameters of the constant rate of change in precession angle runs. Same parameters as in Table 1. In addition, \( T \) is the precession period in Myr.

### Random change in the precession angle

| Run | \( T \) (Myr) | \( v_j \) (Km\ s\(^{-1}\)) | \( L_j \) (10\(^{44}\) erg\ s\(^{-1}\)) | Morphology | Figure |
|-----|----------------|-----------------|-----------------|------------|--------|
| Ran1 | 0.1 | 7750 | 1.4 | Fat bubble | [Fig 11] |
| Ran2 | 0.1 | 23250 | 2 | Thin jet shedding very large vortecies | - |
| Ran3 | 0.1 | 69750 | 1.5 | Thin jet and cocoon, extensive backflow | - |
| Ran4 | 1 | 7750 | 1.8 | Elongated cavity | - |
| Ran5 | 1 | 23250 | 1.6 | Elongated cavity | - |
| Ran6 | 1 | 69750 | 1.5 | Narrow and elongated cavity extensive backflow | - |
| Ran7 | 5 | 7750 | 1.5 | Elongated clumpy cavity | - |
| Ran8 | 5 | 23250 | 1.8 | Elongated clumpy cavity | - |
| Ran9 | 5 | 69750 | 2 | Elongated clumpy cavity, extensive backflow | - |
| Ran10 | 30 | 7750 | 1.8 | First torus then fat bubble | [Fig 10] |
| Ran11 | 30 | 23250 | 1.5 | First torus then elongate cavity, extensive backflow | - |
| Ran12 | 30 | 69750 | 1.6 | Torus then narrow jet with clumpy cocoon | - |

Table 3: Parameters of the random change in precession angle runs. Same as in Table 2.
(i) \(0.1c_s < v_j \leq 0.5c_s\) - shortest,

(ii) \(0.5c_s < v_j \leq c_s\),

(iii) \(c_s < v_j \leq 5c_s\),

(iv) \(5c_s < v_j \leq 10c_s\) - longest for the \(M = 10\) case,

(v) \(10c_s < v_j \leq 30c_s\) - longest for the \(M = 30\) case,

where \(c_s = 775\) km s\(^{-1}\) is the speed of sound. For visual clarity we also omitted velocities of \(v_j \leq 0.1c_s\). This division is true for all plots shown in this paper.

In Figure 3 we show the density map at different times for a jet at a fixed precession angle of \(\theta = 30^\circ\) (Fix5, see Table 1), with a half opening angle of \(\alpha = 5^\circ\), \(v_j = 7750\) km s\(^{-1}\), and \(\dot{E}_j \simeq 1.4 \times 10^{43}\) erg s\(^{-1}\). In a similar manner to the former case, the jet initially inflates a torus shaped cavity, and later it is bent towards the symmetry axis. In contrast to the former case we see that at \(t = 45\) Myr the jet has inflated a bubble that together with the contra-bubble will form a bipolar structure. The bubble in this case is much closer to being spherical than bubbles in runs that we consider unsuccessful in forming fat bubbles (they don’t form a bipolar structure). Even at \(t = 60\) Myr the cavity can still be termed an elongated bubble. In contrast to the bubbles we showed in Paper I, there is no flow of low density matter towards the equatorial plane, which is in good agreement with observations. For the same parameters, but with a luminosity of \(\sim 2 \times 10^{44}\) erg s\(^{-1}\) (Fix6, see Table 1), we also got a fat bubble of low density, as shown in Figure 4. In contrast to the lower luminosity case, we see a non-negligible flow of low density matter towards the equatorial plane, which is not in very good agreement with observations. At early time a torus, rather than a fat bubble, is inflated. At present, we know of no observations of such bubbles.

In most of the cases that we ran we ended up with either a narrow jet, as shown in upper panel of Figure 5 (Fix4, see Table 1), or with a fat bubble with a significant flow of low density matter to the equatorial plane (in effect a spherical or ellipsoid cavity at the center of the cluster), as shown in the middle panel of Figure 5 (Fix7, see Table 1). In some of the cases with \(\theta = 60^\circ\) (Fix10, see Table 1) the torus inflated by the simulated jet merged at the equatorial plane with the torus of the unsimulated jet (we remind the reader that we imposed reflecting boundary conditions in the equatorial plane). In effect we got a large low density torus, with an elliptic cross section, at the equator as shown in the lower panel of Figure 5. For the sake of clarity we state that all of these cases are not in agreement with observations. Therefore, large constant precessing angle \(\theta \gtrsim 40^\circ\), cannot form the observed fat bubbles. In all cases the typical temperature of the low density gas in the cavities or cocoon was \(10^8\) K \(\lesssim T_b \lesssim 10^9\) K.
Fig. 2.— Density maps (logarithem of the density $[\text{g cm}^{-3}]$) for a jet at a fixed precession angle $\theta = 15^\circ$ (Fix2, see Table 1), given at three different times ($t = 2.5$, 5, and 20 Myr). The jet has a half opening angle of $\alpha = 5^\circ$, an injected velocity of $v_j = 7750 \text{ km s}^{-1}$, and power of (one jet) $\dot{E}_j \approx 1.1 \times 10^{44} \text{ erg s}^{-1}$. Only one quarter of the meridional plane is showed, as the other three are symmetric to it. The $x$-axis (horizontal) is the symmetry axis, while the $y$-axis (vertical) is in the equatorial plane. The arrows represent the velocity of the flow: $0.1c_s < v_j \leq 0.5c_s$ (shortest), $0.5c_s < v_j \leq c_s$, $c_s < v_j \leq 5c_s$, and $5c_s < v_j \leq 10c_s$ (longest in this case).
Fig. 3.— Density maps for a jet at a fixed precession angle of $\theta = 30^\circ$ (Fix5, see Table 1), with a half opening angle of $\alpha = 5^\circ$, $v_j = 7750 \text{ km s}^{-1}$, and $\dot{E}_j \simeq 1.4 \times 10^{43} \text{ erg s}^{-1}$. The cavity inflated by the jet reaches a more or less spherical shape at $t \sim 45 \text{ Myr}$, and remains spherical, though a little elongated even at $t = 60 \text{ Myr}$. The equatorial plane (vertical in the figures) remains devoid of low density matter, in good agreement with observations. There are no numerical fluctuations in the equatorial boundary either, unlike along the symmetry axis (horizontal axis). The arrows represent the velocity of the flow as in Figure 2.
4. RESULTS: A CONSTANT RATE OF CHANGE IN THE PRECESSION ANGLE

Figure 6 shows the density maps for a precessing jet with a constant rate of change in the precession angle (i.e., $\theta \propto t$, where the symmetry axis of the jet changes in the range $5^\circ \leq \theta \leq 65^\circ$). We remind the reader that in all cases presented here, the jet is assumed to precesses rapidly around the symmetry axis, so it rotates in the $\phi$ direction many times while $\theta$ is being changed; the $\phi$ coordinate is not calculated in the simulations. The case shown in this figure has a precession period $T_{\text{prec}} = 0.1$ Myr (Con1, see Table 2). This period is much shorter than the typical expansion time of the bubble formed. As a result of that the narrow jet’s interaction with the ICM resembles that of a wide opening angle jet with a half opening angle of $\sim 70^\circ$ (Paper I). For comparison, in figure 7 we show the case of a wide angle jet taken from Paper I. As can be seen in figure 6 at short times of ($t \lesssim 5$ Myr) the low density bubble is more or less spherical and there is almost no flow of low density matter to the equatorial plane. At longer times of $t \sim 10$ Myr, the flow of low density matter to the equatorial plane is substantial, though the cavity itself can still be termed a fat bubble. We conclude that for these parameters a fat bubble is formed. The difference in the volume of the bubbles is due to the fact that the actual $\dot{M}$ of the wide angle case was slightly smaller then that of the precessing case, and therefore the bubble inflated by it was slightly smaller (this is due to the numerics associated with the jet injection, as elaborated in section 2).

Figure 8 shows the case with higher jet velocity of $v_j = 23250$ km s$^{-1}$, $T = 0.1$ Myr, $\dot{E}_j \simeq 1.2 \times 10^{44}$ erg s$^{-1}$ (Con2, see Table 2). As with wide jets (Paper I), fast jets of $v_j \gtrsim 20,000$ km s$^{-1}$ (the exact speed limit depends on the other parameters) do not form fat bubbles, but rather the jets propagated close to the axis of symmetry (the $x$ axis) in the manner of a narrow jet with an extensive cocoon.

In the case of constant rate of change in the precession angle, the jet spends equal time in small and large precession angles. At small precession angle the jet has more momentum per unit area, making it easier for the jet to break through the denser ICM. This can be seen in simulation with longer precession periods, e.g., $T_{\text{prec}} \gtrsim 1$ Myr (not shown here) where at small precession angles the jet’s propagation is easier than at larger angles, resulting in a propagation along the symmetry axis, i.e., in the resemblance of a narrow jet, as can be seen for example in Figure 9 (Con7, see Table 2). No fat bubble is formed for a too long precession period. In all cases simulated in this section the typical temperature of the low density gas in the cavities or cocoon was of the order $10^8$ K $\lesssim T_b \lesssim 10^9$ K.
5. RESULTS: RANDOM PRECESSION

A more physically acceptable change in the precession angle is one in which the jet covers a constant solid-angle per unit time, i.e., \( d(\cos \theta)/dt \) is constant. Because the precession period about the symmetry axis is assumed to be very short, the jet spends longer periods of time at larger angles, in respect to the symmetry axis, than at small ones. The shorter time spent at small angles reduces the break-through period along the symmetry axis, as experienced in the uniform change in precession angle case (section 4). The reduction in the break-through period allows more matter to spread farther from the symmetry axis, in effect inflating a fat bubble of low density matter. This can be seen in Figure 10 which shows the density map of a randomly precessing jet with a precession period of \( T_{\text{prec}} = 30 \) Myr (Ran10, see Table 3). The other parameters are \( v_j = 7750 \) km s\(^{-1}\), \( \dot{E}_j \simeq 1.8 \times 10^{44} \) erg s\(^{-1}\), and the boundary of the precession angle (of the jet’s axis) are \( 5^\circ < \theta < 45^\circ \). The jet starts its precession off-axis and inflates a toroidal cavity as seen at \( t = 10 \) Myr. At \( t = 20 \) Myr we see that the cavity is in the shape of a fat ellipsoid bubble. At \( t = 25 \) Myr the bubble is more or less spherical with a radius \( R \sim 20 \) kpc. There is a flow of low density matter to the equatorial plane, but it is minimal.

As in the constant rate of change case, the random precessing jet with a short precessing period, \( T_{\text{prec}} = 0.1 \) Myr (Ran1, see Table 3) resulted in an interaction with the ICM similar to that of a wide jet with a half opening angle of \( \alpha \sim 50^\circ \). Figure 11 shows the density maps for this case. All along the simulation the cavity inflated by the jet is more or less spherical, though at \( t = 25 \) Myr it gets a little elongated. In contrast to observations there is a flow of low density matter to the equatorial plane.

For higher velocity jets (\( v_j \gtrsim 2 \times 10^4 \) km s\(^{-1}\)) the results (not shown here) of the interaction between the jet and ICM are the propagation of the jet close to the symmetry axis (i.e., a narrow jet with a cross section radius of \( 1 - 2 \) kpc) with an extensive cocoon of low density matter shed by the propagating jet in the form of vortices. The cross section radius, of the jet and the cocoon, is typically \( 3 - 5 \) kpc.

Over all, we conclude that rapidly and randomly precessing massive slow jets can inflate fat bubbles, similar to those inflated by wide jets (Paper I). In all cases the typical temperature of the low density gas in the cavities or cocoon was of the order \( 10^8 \leq T_b \leq 10^9 \) K.

6. DISCUSSION AND SUMMARY

We showed that precessing slow jets can inflate fat bubbles attached to the center of the galaxy clusters. By slow jets we refer to supersonic but highly non-relativistic jets. In
our axisymmetrical simulations the 3D problem can be simulated with a 2D grid, and the
simulations were of jets precessing rapidly in the $\phi$ coordinate around the symmetry axis
(the $\phi$ coordinate is not included in our simulations). Namely, the rotation time of the jet’s
axis around the symmetry axis (the $x$ axis in our figures) is much shorter than the time over
which the precessing angle $\theta$ varies. the length of our simulations was chosen to match the
$10 - 50$ Myr age of most observed bubbles (Birzan et al. 2004; McNamara & Nulsen 2007).

The main criteria we find for the inflation of fat low density bubbles by precessing jets are:

1. The jet’s velocity should be $v_j \sim 10^4$ km s$^{-1}$. Using our results obtained here and our
   results from Paper I, we conclude that the range over which slow jets can inflate fat
   bubbles is $3000$ km s$^{-1} \lesssim v_j \lesssim 2 \times 10^4$ km s$^{-1}$. Jets with higher velocities form narrow
   expanding jets with extensive cocoons. These jet velocities form bubbles with interior
temperatures of $10^8$ K $\lesssim T_b \lesssim 10^{10}$ K.

2. For a jet with a fixed precession angle $\theta$ (measured from the the symmetry axis; $x$ in our
   figures), this angle should not be too small or too large. A small angle causes the jet to
   propagate along the symmetry axis, and a large angle leads to the bending of the jet
   towards the equatorial plane. The constraint on the precessing angle is $30^\circ \lesssim \theta \lesssim 50^\circ$

3. The jet should spend more time at large angles in order to reduce the break-through
   along the symmetry axis that happens when it’s precessing angle is small. This favors
   a case with random precession, i.e., the jet axis covers constant solid angle per unit
   time and the precessing angle is bound in the range $0^\circ \leq \theta \leq \theta_{\text{max}} \simeq 50^\circ$.

4. For any prescribed precession behavior and parameters that can form a fat bubble, the
   maximum precessing angle should be quite large, $\theta_{\text{max}} \sim 30 - 70^\circ$.

5. The slow velocity and large energy of the jet inflating fat bubbles require that the two
   opposite jets carry large amount of mass. The two jets together can expel back to the
   ICM a mass at a rate of $\dot{M}_{\text{back}} \simeq 1 - 50 M_\odot$ yr$^{-1}$.

Let us elaborate on these points, and on the physics behind them. As discussed in
previous papers (Soker 2004; 2006; Paper I), the basic condition for a jet to inflate a fat
bubble is that the jet’s head will reside inside the bubble, or, if the jet’s head is outside the
bubble, that the jet’s head will not ”run away” from the expanding bubble. For example, in
the case of constant large precessing angle (Run ’Fix10’ in Figure 5), the jet’s head revolves
around the symmetry axis but at a large distance. It inflates a local low density region, a
torus around the axis. But this torus expands too slowly to inflate a fat bubble. Namely,
the motion of the jet’s head is too fast for the expanding shocked gas. This condition for
the jet’s direction not to escape from the expanding bubble formed by its shocked material
is given in equation (17) of Soker (2006). This explains why the precessing angle cannot be
too large (point 2 above).

The same principle holds for the jet’s head not to expand too fast in the radial direction.
If the expansion of the jet is concentrated within a small solid angle, e.g., a small precession
angle, the large momentum flux (ram pressure) will result in a jet’s head that moves radially
faster than the expansion of the shocked gas. A long bubble will be formed instead of a fat
bubble. This explains points 3 and 4 above and the lower limit on the precessing constant
angle in point 2. Qualitatively, this condition on the solid angle of the expanding jet is given
by equation (14) in Soker (2004) that was derived for a wide jet instead of a precessing jet,
and was shown to hold in the numerical simulations of wide jets (Paper I).

Regarding point 1 above. If the jet’s speed is too low, for a given energy it is too dense.
As a result of that, the bubble expands too slowly and the jet’s head moves radially too
fast. This is also seen by equation (14) in Soker (2004), and was shown to hold for wide jets
(Paper I). If the jet’s material is too fast, the shocked jet’s gas expands much faster than
the jet’s head. In that case the shocked low density gas fills the entire inner region, and
the two opposite jets form a large elliptically-shaped bubble instead of a bipolar (hourglass)
structure of two fat bubbles. This is very similar to the case of wide angle (Paper I). Note
that in some of the simulations no dense ICM gas is left in the equatorial plane near the
center (e.g., Figure 5, see also Paper I). This shows that dense ICM in the equatorial plane
near the center we find in some runs (e.g., Figures 10, see also Paper I) is real and not a
numerical artifact.

Point 5 has far reaching implications. Are such a high mass outflow rates as we find
here and in Paper I where we simulated wide jets, $\dot{M}_{\text{back}} \approx 1 - 50 M_{\odot} \text{ yr}^{-1}$, compatible
with observations? Are wide jets simulated in Paper I (or wide precession angle simulated
here) compatible with observations? The answer to both questions seems to be positive. In
Paper I we have already discussed indications for AGNs that blow slow jets, some of them
with wide angles (Crenshaw & Kraemer 2007; Behar et al. 2003; Kaspi & Behar 2006).
These recent observational results (see also de Kool et al. 2001), and our numerical results
support the model where the feedback in both cooling flow clusters and in the process of
galaxy formation occurs mainly (but not solely, as relativistic narrow jets also exist) by slow
massive jets, as suggested and discussed by Soker & Pizzolato (2005). The massive jets
imply that not only energy, but mass as well is part of the feedback cycle (Soker & Pizzolato
2005; Pizzolato & Soker 2005). Massive jets were also considered before by, e.g., Begelman
& Celotti (2004) and Binney (2004), and were simulated by Omma et al. (2004), who took
the jet speed and mass outflow rate to be $v_j = 10^4 \text{ km s}^{-1}$ and $2M_\odot \text{ yr}^{-1}$, respectively. In the simulation of Heinz et al. (2006) one jet has a mass loss rate of $35M_\odot \text{ yr}^{-1}$. This implies that the two jets inject $70M_\odot \text{ yr}^{-1}$ into the ICM. Without stating it, Heinz et al. (2006) followed the suggestion of Soker & Pizzolato (2005), that a large fraction or even most of the gas that cools to low temperatures in cooling flow clusters gains energy directly from the central black hole, and is injected back to the ICM.

The main effect discussed in the present paper is a dynamical effect with supersonic velocities. Therefore, the temperature (and entropy) profile of the ICM has little effect on the conclusions. In a forthcoming paper we will follow the bubbles as they buoy to larger distances ($\sim 100 \text{ kpc}$). There the entropy will have a crucial role, and a more realistic temperature profile will be used.

There are some discrepancies between our results and observations.

(1) In many of the simulated cases, but not in all of them, a non negligible low density matter flows to the equatorial plane and stays there. This is generally not observed. It is quite possible that magnetic tension will suppress this low density backflow. This is because the backflow is expected to stretch magnetic field lines. In addition, gravity might cause this low density equatorial gas to buoy outward. Gravity and magnetic fields are not included in our simulations. We will include gravity in future simulations. However, neither gravity nor magnetic fields are expected to prevent the presence of hot low density gas in the equatorial plane in cases of very fast jets where the backflow toward the equator is strong.

(2) In some cases a torus shaped cavity is inflated at the beginning of the simulation, achieving a spherical shaped cavity only at later times. We remind the reader that we assumed a very short-period precession about the symmetry axis, in effect reducing the simulations dimensions to two. A full three dimensional simulation of a randomly precessing jets (and even a pulsed jet, whose activity is turned on and off), might result in the inflation of low density small bubbles and not a torus as in the 2D simulations. These small bubbles merge on a short time to form a larger bubble. We leave the investigation of this process to a full 3D simulations in the future.

Concerning these discrepancies and the observations discussed above, we suggest that in most, but probably not in all, cases fat bubbles are inflated by wide jets or rapidly and randomly precessing jets.

We thank John Blondin for his immense help with the numerical code. We thank Ehud
Behar and Nahum Arav for helpful discussions regarding the use of wide massive slow jets. This research was supported by the Asher Fund for Space Research at the Technion.

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Fig. 4.— Density maps for a jet at a fixed precession angle of $\theta = 30^\circ$, with a half opening angle of $\alpha = 5^\circ$, $v_j = 7750 \text{ km s}^{-1}$ (Fix6, see Table 1), and $\dot{E}_j \simeq 2 \times 10^{44} \text{ erg s}^{-1}$. The jet inflates a more or less spherical cavity. The bubble is shown at $t = 40 \text{ Myr}$. There is a non-negligible flow of low density matter towards the equatorial plane, which is not in good agreement with observations. The arrows represent the velocity of the flow as in Figure 2.
Fig. 5.— Density maps for three different cases of jets at a fixed precession angles with a half opening angle of $\alpha = 5^\circ$. In the upper panel (case A: Fix4, see Table I) we show a high velocity jet ($v_j = 23250 \text{ km s}^{-1}$) with a small precession angle ($\theta = 15^\circ$), and jet luminosity of $\dot{E}_j \simeq 1.8 \times 10^{44} \text{ erg s}^{-1}$. In the middle panel (case B: Fix7, see Table I) we show high velocity jet ($v_j = 23250 \text{ km s}^{-1}$) with an intermediate precession angle ($\theta = 30^\circ$), and jet luminosity of $\dot{E}_j \simeq 1.2 \times 10^{44} \text{ erg s}^{-1}$. In the lower panel (case C: Fix10, see Table I) we show a low velocity jet ($v_j = 7750 \text{ km s}^{-1}$) with a large precession angle ($\theta = 60^\circ$) and jet luminosity of $\dot{E}_j \simeq 1.8 \times 10^{44} \text{ erg s}^{-1}$. In all three cases a fat bubble was not inflated.
Fig. 6.— Density maps for a jet with a uniformly changing precession angle, $5^\circ \leq \theta \leq 65^\circ$, with a precession period of $T_{\text{prec}} = 0.1$ Myr, half opening angle of $\alpha = 5^\circ$, $v_j = 7750$ km s$^{-1}$, and $\dot{E}_j \simeq 1.9 \times 10^{44}$ erg s$^{-1}$ (Con1, see Table 2). The arrows represent the velocity of the flow as in Figure 2.

Fig. 7.— A case of a wide jet ($\alpha = 70^\circ$) instead of a precessing jet, taken from Paper I. The parameters of this run are: $v_j = 7750$ km s$^{-1}$, and $\dot{E}_j \simeq 0.65 \times 10^{44}$ erg s$^{-1}$. This plot shows the bubble at $t = 5$ Myr. The arrows represent the velocity of the flow as in Figure 2.
Fig. 8.— Like figure 6 but for a faster jet with $v_j = 23250 \text{ km s}^{-1}$, i.e., $5^\circ \leq \theta \leq 65^\circ$, $T_{\text{prec}} = 0.1 \text{ Myr}$, $\alpha = 5^\circ$, and $\dot{E}_j \approx 1.2 \times 10^{44} \text{ erg s}^{-1}$ (Con2, see Table 2). The arrows represent the velocity of the flow, according to the five velocity ranges given in section 3.
Fig. 9.— Density maps for a jet with a constant rate of changing precession angle, $5^\circ \leq \theta \leq 65^\circ$, with a precession period of $T_{\text{prec}} = 5$ Myr, half opening angle of $\alpha = 5^\circ$, $v_j = 7750$ km s$^{-1}$, and $\dot{E}_j \simeq 1.6 \times 10^{44}$ erg s$^{-1}$ (Con7, see Table 2). The arrows represent the velocity of the flow as in Figure 2. The simulation was started with a precession angle of $\theta(0) = 5^\circ$. 
Fig. 10.— Density maps for a randomly precessing jet with $T_{\text{prec}} = 30$ Myr, $\alpha = 5^\circ$, $v_j = 7750$ km s$^{-1}$, and $\dot{E}_j \approx 1.8 \times 10^{44}$ erg s$^{-1}$ (Ran10, see Table 3). The jet’s axis precess between $\theta_{\text{min}} = 5^\circ$ and $\theta_{\text{max}} = 45^\circ$. The arrows represent the velocity of the flow as in Figure 2. The simulation was started with a precession angle of $\theta(0) = 45^\circ$.  


Fig. 11.— Density maps for a randomly precessing jet with precession period of $T_{\text{prec}} = 0.1$ Myr, jet’s opening angle of $\alpha = 5^\circ$, jet’s speed $v_j = 7750$ km s$^{-1}$, and one jet power of $\dot{E}_j \approx 1.4 \times 10^{44}$ erg s$^{-1}$ (Ran1, see Table 3). The jet’s interaction with the ICM is similar to that of a wide jet with half opening angle of $\alpha \sim 50^\circ$ (Paper I). The arrows represent the velocity of the flow as in Figure 2.