ABSTRACT

I derive the condition for narrow jets with varying axis, e.g., precessing jets, to inflate more or less spherical (fat) bubbles in planetary nebulae and clusters of galaxies. This work follows a previous work dealing with wide jets, i.e., having a wide opening angle. The expressions derive here are qualitatively and quantitatively similar to the conditions for inflating fat bubbles by non-precessing wide jets. This follows the similar physical cause of inflating fat bubbles, which is that the jet deposits energy inside the bubble. Fat bubbles in planetary nebulae (and similar stellar systems) and in clusters of galaxies, are likely to be formed by wide jets, precessing jets, or other jets whose axis is not constant relative to the medium they expand into.

Key words: galaxies: clusters: general — planetary nebulae: general — intergalactic medium — ISM: jets and outflows

1. INTRODUCTION

Chandra 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, e.g., Hydra A (McNamara et al. 2000), Perseus (Fabian et al. 2000, 2003), A 2597 (McNamara et al. 2001), RBS797 (Schindler et al. 2001), Abell 4059 (Heinz et al. 2002), MS 0735.6+7421 (McNamara et al. 2005), Abell 2052, (Blanton et al. 2003), HCG 62 (Vrtilek et al. 2002), and M84 (Finoguenov & Jones 2001). Radio emission inside these bubbles indicate that they were inflated by jets launched by the central active galactic nuclei (AGNs). The bubbles and jets play a key role in the energy and mass cycle of the intra-cluster medium (ICM) in these objects (e.g., Brüggen et al. 2002; Brüggen & Kaiser 2002; Heinz & Churazov 2005; see review by Peterson & Fabian 2006).

In a previous paper (Soker 2003; see astro-ph version of Soker & Bisker 2006 for more detail and images) I pointed out an interesting and not trivial similarity in the morphology
and some non-dimensional quantities between pairs of X-ray-deficient bubbles in clusters of galaxies and pairs of optical-deficient bubbles in planetary nebulae (PNs). Examples of PNs with nice pairs of bubbles are the Owl nebula (NGC 3587; PN G148.4+57.0: Guerrero et al. 2003), Cn 3-1 (VV 171; PN G038.2+12.0; Sahai 2000), and Hu 2-1 (PN G051.4+09.6; Miranda et al. 2001).

It is imperative to emphasize here that I try to explain the formation of a low density pair of bubbles with a narrow waist between them. These bubbles have more or less diffuse radio emission and are different from radio bubbles with strong radio hot-spots, e.g., e.g., 3C285 (Saslaw et al. 1978) and 3C219 (Perley et al. 1980), that Scheuer (1982) accounted for by precessing jets; the bubbles of 3C219 don’t coincide with X-ray cavities (Brunetti et al. 1999). The narrow waist between the bubbles I try to explain make them fundamentally different from cases where there is only one prolate spheroidal cavity, such as in Cygnus A (Wilson et al. 2006). For that, the cocoon dynamics studied by Begelman & Cioffi (1989) is not directly applicable to the present study.

The basic condition for a jet to inflate a fat, more or less spherical, bubble is that the bubble encloses the jet’s head. Namely, the jet’s head will reside inside the bubble during the inflation phase. In Soker (2004) I derived the condition for a jet having a constant propagation axis. In that case the condition for the jet’s head to be inside the bubble is that the expansion velocity of the bubble’s radius, $v_b$, be larger than the propagation of the jet’s head along its axis $v_h$. For PNs and other similar stellar systems, the approximate condition on the half opening angle of a non-precessing jet to inflate a fat bubble is

$$\alpha \gtrsim 40^\circ \left( \frac{v_j}{400 \text{ km s}^{-1}} \right)^{1/10} \left( \frac{\dot{M}_j}{0.01 \dot{M}_s} \right)^{3/10},$$

where $v_j$ is the velocity of material inside the jet, $\dot{M}_j$ is the mass flow rate inside the jet, and $\dot{M}_s$ is the mass loss rate into the spherically symmetric slow, $v_s \approx 10 \text{ km s}^{-1} \ll v_j$, wind into which the jet expands (for more detail see section 2 in Soker 2004).

The condition for a jet to inflate a fat bubble in a cluster can be also written as a condition on the half opening angle $\alpha$ (eq. 14 in Soker 2004). Narrower jets will have to propagate to larger distances in order to inflate a fat bubble. It is possible to write the condition on the distance from the center along the jet’s axis where the jet is capable to inflate a bubble

$$z_{\text{bub(wide)}} \gtrsim 10 \left( \frac{\alpha}{65^\circ} \right)^{-1} \left( \frac{\dot{E}_j}{10^{45} \text{ erg s}^{-1}} \right)^{3/10} \left( \frac{\dot{M}_j}{10^{-4} \text{ km s}^{-1}} \right)^{-1/2} \times \left( \frac{\rho_c}{10^{-25} \text{ g cm}^{-3}} \right)^{-3/10} \left( \frac{\tau}{10^7 \text{ yr}} \right)^{2/5} \text{kpc},$$
where $\rho_c$ is the density of the ICM at the location of the bubble, $\tau$ is the age of the bubble, and the jet is a non-relativistic jet, with a kinetic power of $\dot{E}_j = \dot{M}_j v_j^2 / 2$.

The results of Vernaleo & Reynolds (2006) agree with this estimate. For a jet power of $\dot{E}_j = 9.8 \times 10^{45}$ erg s$^{-1}$, a speed of 10,500 km s$^{-1}$, and a half opening angle of $\alpha = 15^\circ$, they find the jet to inflate a bubble at a distance of $z_{\text{bub}} \sim 400$ kpc and time of $\tau \sim 2 \times 10^8$ yr. In many cooling flow clusters the bubbles are much closer to the center, implying a larger opening angle (Soker 2004), or the destruction of the jet by a relative motion of the ICM (Loken et al. 1995; Soker & Bisker 2006), or other types of changes in the jet’s axis, such as precession (Soker 2004), or a random change (Heinz et al. 2006).

Motivated by the discussions and talks in a recent meeting on cooling flows in galaxies and clusters of galaxies (Pratt et al. 2007), I study in the present paper the condition for inflating fat bubbles by very narrow precessing jets. Namely, I consider the limit case where the axis returns to a previous direction over an average time much longer than the inflation time of the bubble. In Soker (2004) I considered the other extreme, where the jet’s axis does not change and the jet is wide. The cases in between narrow precessing jets studied here and wide jets studied in Soker (2004) should be explored by numerical simulations. Narrow jets that precess very fast will return to a previous direction several times during the inflation phase. They actually have the same physics as wide jets, and will inflate bubbles according to the conditions in (Soker 2004). In the present paper I derive the condition on slowly precessing jets that don’t return to a previous directions. Such jets can leave a signature on the bubble, e.g., one side is brighter than the other. This could be the case in MS 0735.6+7421 (McNamara et al. 2005). In Sec. 2 the general condition is derived. In Sec. 3 this condition is applied to PNs and similar stellar systems, and in Sec. 4 to clusters of galaxies. A short summary is in Sec. 5. As this paper is a continuation to the study conducted in Soker (2004), only essential background material is given here. More details and the motivation for studying inflation of fat bubbles both in PNs and clusters are in earlier papers (Soker 2003, 2004; Soker & Bisker 2006).

2. THE CONDITION FOR INFLATING A FAT BUBBLE BY A SLOWLY PRECESSING JET

By precession I refer also to other types of jet’s motion, e.g., due to the relative motion of the ICM and the cD galaxy, or a stochastic variation of the jet’s axis. I emphasize again that I take the limit case where the jet’s axis does not return to the same direction.

A narrow jet will expand through the medium (slow AGB wind in PNs and the ICM in
clusters) until the supply of jet’s material ends. Let us consider a conical narrow jet having a half opening angle $\alpha$, and let the direction of the jet’s axis change at a rate $\dot{\theta}$ (radians per second). Where ever the jet center passes, material were flowing for a time of $\alpha/\dot{\theta}$ before the jet axis was along that direction, and jet’s material will continue to flow along that direction for a time $\alpha/\dot{\theta}$ after that. During that time the jet’s head will propagate to a distance

$$z_{\text{bub}}(\text{precess}) = \int_{0}^{t_t} v_h(t) dt,$$

where $v_h$ is the jet’s head propagation speed through the medium and

$$t_t \equiv \frac{2\alpha}{\dot{\theta}}.$$  \hfill (4)

Therefore, the inflation distance of the bubble is determined by the opening angle and the precession rate, as well as the jet’s speed.

A condition for the inflation of a more or less spherical (fat) bubble is that the energy be injected inside the already existing bubble; the pressure of the hot bubble’s interior will act then to make the bubble spherical. If during the bubble age $\tau$ the jet’s head moves a transverse distance $D_b$, the condition reads

$$D_b(\tau) \lesssim R_b(\tau),$$

where $R_b(\tau)$ is the bubble’s radius at age $\tau$, taken according to Castor et al. (1975). Again, I consider slowly precessing jets, and not fast precessing jets, that have physics similar to wide jets. Let us consider a precessing jet with the jet’s axis angle to the precession axis being $\beta$, and the precession period $T_p$, implying that $\dot{\theta} = 2\pi \sin \beta / T_p$. The maximum distance between two points along the jet’s head is the diameter of the precessing jet’s head $D_b \simeq 2z_{\text{bub}} \sin \beta$, reached after a time $T_p/2$. For $\tau = T_p/2$ condition (5) can be written as $z_{\text{bub}} \dot{\theta} T_p / \pi \lesssim R_b(T_p/2)$. Under the assumptions made here (Soker 2004) the speed of the bubble surface is $v_b = \dot{R}_b = (3/5)R_b/\tau$, which allows us to approximate condition (5) in a general way

$$\dot{\theta} z_{\text{bub}} \eta \lesssim v_b(\tau).$$

For a precessing jet and for $\tau = T_p/2$ we found above $\eta = 6/5\pi = 0.38$. For randomly moving jet axis (as discussed by Heinz et al. 2006), the jet’s head moves less from its original position, and $\eta$ is smaller.

To inflate a fat bubble by a jet with a moving axis, e.g. precessing jet, close to the center the rate of change in axis’ angle, $\dot{\theta}$, is constraint from below by condition (3). For the bubble to be spherical more or less (a ‘fat’ bubble) $\dot{\theta}$ is constraint from above by condition (6), or more precisely by condition (5). In Sec. (3) we derived this condition for PNs and related stellar binary systems, and in Sec. (4) for cooling flow clusters of galaxies.
3. JETS IN STELLAR SYSTEMS

The flow structure is of a jet flowing into the dense circumstellar material, which is the expanding AGB (or a similar giant star) wind. For a narrow jet, $\alpha \ll 1$, the distance the jet reaches after a time $t$ is (Soker 2004)

$$z_{\text{bub}} = v_h t = \left( \frac{\dot{M}_j v_j}{M_s v_s} \right)^{1/2} \frac{2}{\alpha} v_s t,$$

(7)

where $v_s$ is the velocity of the slow wind, assumed to be spherically symmetric, into which the jet material expands with a speed $v_j$, and $v_h$ is the speed of the jet’s head. $\dot{M}_s$ and $\dot{M}_j$ are the mass loss rates into the slow wind and one jet, respectively; both are constant, and defined positively. Substituting typical values for PNs, and $t = t_t = 2\alpha/\dot{\theta}$ from equation (4), yields

$$z_{\text{bub}} = 8 \times 10^{16} \left( \frac{\dot{M}_j}{0.01 \dot{M}_s} \right)^{1/2} \left( \frac{v_j}{400 \text{ km s}^{-1}} \right)^{1/2} \left( \frac{v_s}{10 \text{ km s}^{-1}} \right)^{1/2} \left( \frac{\dot{\theta}}{\text{rad/1000 yr}} \right)^{-1} \text{ cm.} \quad (8)$$

This is the inflation region of the bubble, which under the assumptions used here does not depend on the opening angle of the jet.

If the jet precess on a time scale of several thousand years the jet will reach a distance of $\lesssim 0.1$ pc, and can in principle inflate a bubble close to the center. However, there are two other conditions in PNs. First, the radiative cooling time of the post-shock jet’s material must be long compared to the inflation time. This in principle implies a jet’s speed of $v_j \gtrsim 200$ km s$^{-1}$ (Soker 2004), depending on the distance from the center where the bubble is formed.

Second, condition (6) should be met for a fat bubble to be formed. The expansion velocity if the jet’s head in stellar winds is constant, and using expression (7) for $z_{\text{bub}}$ in condition (6) with $t = t_t$ gives

$$2\alpha \eta v_h \lesssim v_b(\tau).$$

(9)

The constraint on a wide jet expanding along a constant axis to inflate a fat bubble is (Soker 2004) $v_h \lesssim v_b(\tau)$. It is clear that the condition for a slowly precessing jet is easier to meet since $2\alpha \eta < 1$ for narrow jets. Rapidly precessing jet’s (large $\dot{\theta}$) are more efficient to inflate fat bubbles near the center, but they will not reach a large distance from the center (eq. 8). In any case, the basic physics behind the condition for inflating fat bubbles in the two extremes (constant jet’s axis and slowly precessing very narrow jet) is similar, leading to similar expression.
Substituting the expression for \( v_b \) (eq. 4 of Soker 2004) and \( v_h \) as given in equation (7) above in condition (9) results in a condition for the inflation of a fat bubble by a slowly precessing jet

\[
z_{\text{bub}} \gtrsim 1 \times 10^{16} \left( \frac{\eta}{0.3} \right)^{5/2} \left( \frac{v_j}{400 \text{ km s}^{-1}} \right)^{1/4} \left( \frac{\dot{M}_j}{0.01 M_\odot} \right)^{3/4} \left( \frac{v_s}{10 \text{ km s}^{-1}} \right)^{3/4} \left( \frac{\tau}{1000 \text{ yr}} \right) \text{cm.} \tag{10}
\]

Under the assumption that the jet’s axis never repeats its direction and the jet is very narrow, this condition does not depend on the opening angle of the jet. It does depend on \( \dot{\theta} \) via the dependence of the inflation distance \( z_{\text{bub}} \) on \( \dot{\theta} \) (eq. 8).

The expression for a wide jet having a constant propagation axis (rearranged version of eq. 6 in Soker 2004) is similar, but a term \( (\alpha/37^\circ)^{-1} \) (written as \( (\beta/0.1)^{-1/2} \) in Soker 2004) replaces \( (\eta/0.3) \) here, and the coefficient is \( 8 \times 10^{16} \text{ cm} \) instead of \( 1 \times 10^{16} \text{ cm} \). Namely, the condition for inflating a fat bubble with a wide jet (or rapidly precessing narrow jet) is similar to that with a slowly precessing jet, both qualitatively and quantitatively (for a wide jet with \( \alpha \sim 1 \sim 60^\circ \)). For further elaboration on the properties of bubbles in PNs see Soker (2004).

The term \( z_{\text{bub}} \) can be eliminated from equations (8) and (10), yielding the following condition for inflating a fat bubble in stellar winds by slowly precessing narrow jets

\[
0.14 \lesssim \left( \frac{\eta}{0.3} \right)^{-5/2} \left( \frac{v_j}{40v_s} \right)^{1/4} \left( \frac{\dot{M}_j}{0.01 M_\odot} \right)^{-1/4} \left( \frac{\dot{\theta}}{\text{rad}/1000 \text{ yr}} \right)^{-1} \left( \frac{\tau}{1000 \text{ yr}} \right)^{-1} . \tag{11}
\]

4. JET PROPAGATION IN CLUSTERS OF GALAXIES

There are several significant differences between bubble inflation in PNs, or stellar systems in general, and in clusters (Soker 2004). (1) In clusters the thermal pressure of the ambient gas is non-negligible. However, following previous papers (Soker 2003, 2004) I neglect this pressure. (2) In clusters the ambient medium does not flow outward. (3) The ICM density profile in the inner regions of clusters, \( \rho_c(r) \), is much shallower than that of the slow wind from stars. I take it as a constant here. (4) The inflating jets in clusters may be relativistic, and the magnetic pressure inside the bubble can be large. (5) In clusters the bubbles can be observed as they form, unlike in PNs, where they are observed long after the jets have ceased (old bubbles may be observed in clusters—termed ghost-bubbles—as in the Perseus cluster; Fabian et al. 2000). However, as argued previously (Soker 2003, 2004), these don’t prevent a similar bubble-formation mechanism in PNs and clusters.
By neglecting the magnetic pressure inside the jet and relativistic effects, hence \( \dot{E}_j = \dot{M}_j v_j^2 / 2 \), the jet’s head speed through the ICM is (e.g., Krause 2003)

\[
v_h \simeq \frac{1}{\alpha} \left( \frac{2\dot{E}_j}{\pi v_j \rho_c} \right)^{1/2} \frac{1}{z}.
\]

where, as before, \( z \) is the distance from the cluster center along the jet axis. Substituting equation (12) in equation (3) and solving gives

\[
z = 2v_h t.
\]

Using this relation in condition (6) with \( t = t_t = 2\alpha/\dot{\theta} \) for \( z = z_{\text{bub}} \) gives

\[
4\alpha\eta v_h \lesssim v_b(\tau).
\]

This is similar, up to a factor of 2, to equation (9). The condition for a wide jet expanding along a constant axis to inflate a fat bubble is (Soker 2004) \( v_h \lesssim v_b(\tau) \). As in PNs, it is clear that the condition for a precessing jet is easier to meet since \( 4\alpha\eta < 1 \) for narrow jets.

Again, the basic physics behind the condition for inflating fat bubbles in the two extremes, constant axis of a wide jet (or rapidly precessing jet) and slowly precessing very narrow jet, is similar, leading to similar expressions.

Substituting the expression for the expansion speed of the bubble front (eq. 11 from Soker 2004) and equation (12) above in equation (14) gives the condition for inflating a fat bubble by a slowly precessing jet close to the center in clusters of galaxies

\[
z_{\text{bub}} \gtrsim 13.6 \left( \frac{\eta}{0.3} \right) \left( \frac{\dot{E}_j}{10^{45} \text{ erg s}^{-1}} \right)^{3/10} \left( \frac{v_j}{10^4 \text{ km s}^{-1}} \right)^{-1/2} \times \left( \frac{\rho_c}{10^{-25} \text{ g cm}^{-3}} \right)^{-3/10} \left( \frac{\tau}{10^7 \text{ yr}} \right)^{2/5} \text{kpc},
\]

Comparing this condition with that for wide jets having a constant axis direction (Soker 2004; eq. 2 here) we find that the basic physics is the same, qualitatively and quantitatively. Similar to precessing jets in stellar systems, under the assumption that the jet’s axis never repeats its direction and the jet is very narrow, condition (15) does not depend on the opening angle of the jet. It does depend on \( \dot{\theta} \) via the dependence of the inflation distance \( z_{\text{bub}} = 2v_h(z_{\text{bub}})t_t \) on \( \dot{\theta} \). Explicitly this is

\[
z_{\text{bub}} = 2 \left( \frac{2\dot{E}_j}{\pi v_j \rho_c} \right)^{1/4} \dot{\theta}^{-1/2} = 5.8 \left( \frac{\dot{E}_j}{10^{45} \text{ erg s}^{-1}} \right)^{1/4} \left( \frac{v_j}{10^4 \text{ km s}^{-1}} \right)^{-1/4} \times \left( \frac{\rho_c}{10^{-25} \text{ g cm}^{-3}} \right)^{-1/4} \left( \frac{\dot{\theta}}{\text{rad} / 10^6 \text{ yr}} \right)^{-1/2}.
\]
Combining equations (16) and (15) the condition for inflating a bubble (at the distance $z_{\text{bub}}$) becomes

$$2.3 \lesssim \left( \frac{\eta}{0.3} \right)^{-1} \left( \frac{\dot{E}_j}{10^{45} \text{ erg s}^{-1}} \right)^{-1/20} \left( \frac{\nu_j}{10^1 \text{ km s}^{-1}} \right)^{1/4} \right.$$

$$\times \left( \frac{\rho_c}{10^{-25} \text{ g cm}^{-3}} \right)^{1/20} \left( \frac{\dot{\theta}}{\text{rad/}10^6 \text{ yr}} \right)^{-1/2} \left( \frac{\tau}{10^7 \text{ yr}} \right)^{-2/5}.$$ (17)

The qualitative difference between equation (17) and equation (11) is that in stellar wind the ambient density falls as $r^{-2}$, which is $z^{-2}$ along the jet axis, while in clusters of galaxies close to the center the density falls very slowly.

5. DISCUSSION AND SUMMARY

The main goal here was to derive approximate conditions to inflate more or less spherical (fat) bubbles by slowly precessing jets, or other jets with varying direction of propagation, close to their origin. I examined the condition for stellar winds, e.g., PNs, and for clusters of galaxies, emphasizing the similar physics between these two classes of objects. Narrow jets with changing axis’ direction reach a maximum distance given by equation (8) for stellar winds, and equation (16) for clusters.

To inflate a fat bubble the jet’s head should inject energy inside the bubble. The condition is given by equation (8), or in approximate form by equation (9). The conditions for inflating a fat bubbles in stellar wind is given by equation (10), or equation (11). The conditions for inflating a fat bubbles in clusters of galaxies is given by equation (15), or equation (17).

Rapidly precessing narrow jets have the same physics as than of wide opening angle jets with a constant axis. Narrow jets with precessing speed in between the slow jets studied here and rapidly precessing jets will inflate an azimuthally elongated structure, rather than one fat bubble, and no clear dense waist will exist between the two sides.

The expressions in stellar winds and clusters of galaxies have the same basic physics, with similar dependence on the rate of change of the jet’s axis direction $\dot{\theta}$, age of bubble $\tau$, and the jets parameters. Indeed, as was argued before (Soker 2003, 2004; Soker & Bisker 2006) there are similarities in morphology, some non-dimensional quantities, and formation mechanism, between X-ray-deficient bubbles in clusters of galaxies and the optical-deficient bubbles in PNs.
The expressions derive here are qualitatively similar to the condition for inflating fat bubbles by jets with wide opening angle (Soker 2004). The expression are quantitatively similar when the non-precessing wide jet has an opening angle of $\alpha \sim 1 \sim 60^\circ$. The similarity in the physics of inflating bubbles by wide jets (or rapidly precessing jets), slowly precessing jets, and motion of the ICM was discussed previously (Soker 2004).

In some cases where a fat bubble is inflated close to the origin, the jet’s axis changes direction on time scales short relative to the inflation time (but not very short), and it will be difficult to observe the precession itself (very fast precession will behave like a wide-opening angle jet). In cases of very slow precession (low value of $\dot{\theta}$) the jet will propagate to a large distance, and will change direction over a long time such that the precession can be observed; in some of these cases bubbles will be formed, in other not. An example of a bubble pair at a large distance from the origin where the precession is observed is the galaxy cluster MS 0735.6+7421 (McNamara et al. 2005), for which Pizzolato & Soker (2005) suggested that a binary black hole system, similar to binary stellar systems in PNs, is responsible for the precession. There are many PNs that show precession signatures, e.g., IPHAS PN-1 for a recent one (Mampaso et al. 2006). Bubbles formed by AGN jets with a long precession period are observed also in Seyfert galaxies (e.g., Markarian 6; Kharb et al. 2006). These cases, as well as cases where new jets have a different direction to that of old jets, e.g., the cluster RBS797 (Gitti et al. 2006), show that precession is quite common. However, in the present paper the main goal was to understand the formation of a pair of fat bubbles with a waist between them, where in most cases the precession is not expected to be observed directly.

Although the bulk motion of the ICM relative to the jet, e.g., shear and rotation, can also lead to the inflation of fat bubbles (Loken et al. 1995; Heinz et al. 2006), this is not a necessary ingredient, as in PNs in general such motions do not exist, but still fat bubbles are formed. Wide jets and precessing (or randomly moving) jets (Soker 2004) are more likely to be the cause in most cases. Bulk motion of the ICM in clusters, or of the wind in stellar system, will cause a large scale departure from axisymmetry (Soker & Bisker 2006).

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