On the exclusion of intra-cluster plasma from AGN-blown bubbles

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ABSTRACT

Simple arguments suggest that magnetic fields should be aligned tangentially to the surface of an AGN-blown bubble. If this is the case, charged particles from the fully ionised intra-cluster medium (ICM) will be prevented, ordinarily, from crossing the boundary by the Lorentz force. However, recent observations indicate that thermal material may occupy up to 50% of the volume of some bubbles. Given the effect of the Lorentz force, the thermal content must then be attributed to one, or a combination, of the following processes: i) the entrainment of thermal gas into the AGN outflow that inflated the bubble; ii) rapid diffusion across the magnetic field lines at the ICM/bubble interface; iii) magnetic reconnection events which transfer thermal material across the ICM/bubble boundary. Unless the AGN outflow behaves as a magnetic tower jet, entrainment may be significant and could explain the observed thermal content of bubbles. Alternatively, the cross-field diffusion coefficient required for the ICM to fill a typical bubble is \( \sim 10^{16} \text{cm}^2 \text{s}^{-1} \), which is anomalously high compared to predictions from turbulent diffusion models. Finally, the mass transfer rate due to magnetic reconnection is uncertain, but significant for plausible reconnection rates. We conclude that entrainment into the outflow and mass transfer due to magnetic reconnection events are probably the most significant sources of thermal content in AGN-blown bubbles.

Key words:

1 INTRODUCTION

Observational studies indicate that powerful radio emission from Active Galactic Nuclei (AGN) at the centres of galaxy clusters is strongly related to the thermal state of the hot, X-ray emitting plasma that permeates the cluster. In particular, systems with short radiative cooling times at the cluster centre seem more likely to exhibit on-going star formation, optical line-emission and radio emission from AGN (e.g. Burns 1990; Crawford et al. 1999; Rafferty et al. 2008; Cavagnolo et al. 2008; Mittal et al. 2008). There is also a significant body of theoretical evidence indicating that outflows from AGN play an important role in the evolution of their surroundings (e.g. Binney & Tabor 1998; Benson et al. 2003; Croton et al. 2006; Bower et al. 2006; Short & Thomas 2009; Puchwein et al. 2003; Bower et al. 2003; Pope 2009). As a result, it is often assumed that AGN operate as thermostats which balance and regulate the radiative losses of the intra-cluster medium (ICM) (e.g. Kaiser 2007). In the standard paradigm, material cools out of the ICM and is accreted by a supermassive black hole located in the central galaxy. This releases vast amounts of energy, often in the form of outflows, which couple to and heat the ambient gas, thereby reducing the cooling rate of the ICM (e.g. Churazov et al. 2003).

To understand how the energy of the outflow is actually dissipated and heats the ICM, it is necessary to build an accurate model describing the interaction between the outflow and the ICM. In this article, we focus specifically on the interaction between the ICM and the bubble-like structures inflated by AGN outflows. Observations indicate that these bubbles are largely devoid of thermal material (e.g. McNamara & Nulsen 2007) and primarily consist of magnetic fields and high-energy particles (c.f. Dunn & Fabian 2004; Birzan et al. 2008). In order for the bubbles to appear as depressions in the X-ray surface brightness (e.g. McNamara & Nulsen 2007), we infer that the mass of thermal material entering from the ICM must be small compared to the mass initially displaced during the inflation. Therefore, the observations seem to indicate that the bubbles do not mix significantly with their surroundings. In addition, Sanders & Fabian (2007) argue, based on an analysis of the
bubbles in the Perseus cluster, that the volume fraction of thermal material in bubbles is no more than 50%.

It is generally supposed that mixing is mostly inhibited by the presence of magnetic fields at the interface between the bubble and the ICM. In particular, the work of Chandrasekhar (1961), De Young (2003), Kaiser et al. (2003), Dursi (2007) showed that a magnetic field oriented tangentially to the bubble surface may prevent the growth of Rayleigh-Taylor instabilities. This has also been shown numerically by Robinson et al. (2004), O'Neill et al. (2004). However, see also Pizzolato & Soker (2006); Scannapieco & Brüggen (2008) for other explanations of bubble stability.

One possibility for the origin of such a favourable magnetic field orientation is that, during the expansion of the bubble, the ambient medium, along with its magnetic field, is excluded from the bubble. This results in a sheath around the bubble in which the field is primarily tangential to the bubble surface, and which has a higher value than the ambient value, due to the effects of compression (De Young 2003). Numerical simulations of moving bubbles (see Ruszkowski et al. 2007; Dursi & Pfrommer 2008) have also shown that that magnetic field from the ICM can become draped across the front of the bubble. This ensures that, whatever the initial configuration of the magnetic field on the bubble surface, there should always be layer of magnetic field that is oriented tangentially to the bubble surface.

However, suppressing the growth of fluid instabilities on the bubble surface is only one aspect of the interaction between the ICM and the bubble. That is, the magnetic field on the bubble surface might provide a stable framework which prevents the bubble from fragmenting into many smaller bubbles, but this does not necessarily prevent thermal material entering the bubble. An important and related effect arises from the fact that the ICM is a fully ionised plasma and therefore has a high electric conductivity, while the AGN-blown bubble contains a magnetic field. This scenario is extremely similar to the interaction between the solar wind and the Earth’s magnetosphere (see for example Chapman & Ferraro 1930; Kivelson & Russell 1995; Parks 2003). Therefore, in the idealised case, where the ICM carries no magnetic field, we expect a charge entering the bubble to experience a Lorentz force which is perpendicular to both its direction of motion and the magnetic field. Provided the bubble magnetic field is oriented tangentially to the bubble surface, the charge will be redirected out of the bubble and emerge back in the ICM. The combination of this exclusion and the stabilising effect of magnetic fields creates a relatively impermeable barrier between the bubble and the ICM. Furthermore, the ICM is not a perfect conductor and some of the electromagnetic energy, generated by the interaction, will be dissipated as heat in the region around the bubble. In principle, this could heat the ICM around the bubble, or help to power the optical emission from cool material observed behind some bubbles.

The plasma exclusion effect described above has significant implications for interpreting observations of bubbles. In particular, any thermal material could only have entered the bubble by the following processes: i) thermal material entrained into the outflow that originally inflated the bubble; ii) particle diffusion across the magnetic field on the bubble surface; iii) non-ideal processes such as magnetic reconnection, which occur as a result of non-zero resistivity in the ICM and the interaction between magnetic fields in the ICM and the bubble. With reference to the first process, mass-loading will decelerate the AGN outflow (Hartquist et al. 1994) and so may potentially explain the absence of strong shocks in the centres of galaxy clusters (e.g. Forman et al. 2007; Graham et al. 2008). The velocity of the outflow also plays a role in governing the morphology of the subsequent structure. For example, slower outflows are more likely to inflate bubble-like structures, rather than the elongated structures produced by faster jets (e.g. Sternberg & Soker 2006).

Therefore, determining the origin of a bubble’s thermal content is of importance in the wider context of AGN feedback.

The article is structured as follows: in section 2, we introduce the model which describes the interaction between the ICM and the bubble magnetic field. The main quantities derived from this model, such as the Ohmic heating rate and induced current are given in section 3. Section 4 provides a discussion of the mass transport rates associated with outflow entrainment, diffusion and magnetic reconnection. We summarise the findings in section 5.

2 MODEL

In this derivation, the ICM is taken to be an unmagnetised, fully ionised plasma consisting only of electrons and protons. The bubble’s magnetic field is taken to be aligned tangentially to the bubble surface, see figure 1. We also assume that both the ICM and bubble fluids can be described using the equations of ideal magnetohydrodynamics. This assumption is valid in the limit that the diffusion of magnetic fields is much less important than their advection. The relative importance of diffusion and advection for magnetic fields is often quantified using the magnetic Reynolds number, \(R_{\text{m}} = UL/\eta\), where \(U\) and \(L\) are the velocity and length scales of interest and \(\eta\) is the electric resistivity. For a fully ionised plasma \(\eta\) is given by (e.g. Bodenheimer et al. 2007)

\[
\eta \approx 260 \left( \frac{\ln \Lambda}{10} \right) \left( \frac{T}{10^8 \text{ K}} \right)^{-3/2} \text{ cm}^2 \text{ s}^{-1}
\]

where \(\ln \Lambda\) is the Coulomb logarithm. Therefore,

\[
R_{\text{m}} \approx 6 \times 10^{27} \left( \frac{U}{10^8 \text{ cm s}^{-1}} \right) \left( \frac{L}{5 \text{ kpc}} \right) \left( \frac{T}{10^8 \text{ K}} \right)^{3/2}
\]

Since \(R_{\text{m}} \gg 1\), the diffusion of magnetic fields is unimportant on the length scale of interest, \(L\). More specifically, we can say that a magnetic field initially residing in an AGN-blown bubble cannot diffuse far and so is effectively frozen to the bubble fluid. This is the so-called ‘frozen-in’ approximation, which corresponds to the flow regime known as ideal magnetohydrodynamics.

The interaction between the ICM and the magnetised AGN-blown bubble can be understood by using a combination of fluid and particle approaches. The fluid model provides a description of the conditions at the ICM/bubble interface, showing that in order to prevent thermal ICM plasma entering the bubble there must be an electric current flowing in the boundary. The particle description shows that the ICM is excluded from the majority of the bubble due to the Lorentz force acting on the charges, but that the
partial penetration and deflection of these particles is sufficient to generate the current. These methods are described in detail below.

2.1 The fluid model

Observationally, AGN-blown bubbles appear as depressions in the X-ray surface brightness (e.g. McNamara & Nulsen 2007), meaning that they contain comparatively little material emitting at these energies. Recent evidence of bubbles in the Perseus cluster (Sanders & Fabian 2007) suggests that the volume fraction of thermal material is less than 50% meaning that the fluid pressure across the boundary must be discontinuous (e.g. Parks 2003). The conditions at the boundary must satisfy the fluid momentum equation. For a species, $i$, of charged fluid, the momentum equation is

$$\rho_i \frac{\partial v_i}{\partial t} + \rho_i (v_i \nabla) v_i = -\nabla P_i + \mathbf{J}_i \times \mathbf{B} + \rho_i \mathbf{F}_i,$$

where $\rho_i$ is the density of the fluid with pressure, $P_i$, $\mathbf{J}_i$ is the current density vector, $\mathbf{B}$ is the magnetic field vector and $\mathbf{F}$ is an external force per unit mass, such as gravity. The $\mathbf{J}_i \times \mathbf{B}$ term describes the reaction of the fluid to the magnetic field.

Therefore, assuming that the external force, $\mathbf{F}$, is locally unimportant, the equilibrium condition to be satisfied at the bubble surface is $\nabla P_i = \mathbf{J}_i \times \mathbf{B}$. The magnitude and direction of the induced current must then be (e.g. Parks 2003)

$$\mathbf{J}_i = \frac{\mathbf{B} \times \nabla P_i}{B^2},$$

(4)

Furthermore, the current calculated from equation (4) must also satisfy Ampère’s law

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t},$$

(5)

where $\mu_0$ is the vacuum permeability, and $\epsilon_0 \partial \mathbf{E}/\partial t$ is known as the displacement current, which can be neglected. This must produce the $\mathbf{J} \times \mathbf{B}$ force needed to balance the rate of change of ICM momentum. In the simplest case, where there is no coupling of energy or momentum across the boundary, these currents close on themselves.

An estimate of the induced current density, $\mathbf{J}$, requires a value for either $\nabla P_i$ or $\nabla \times \mathbf{B}$ which can be calculated using the particle model, described below.

2.2 Particle model

In the scenario depicted in figure 1, the incident ICM particles move in the negative $x$-direction with a velocity of magnitude $u$. The magnetic field points in the $z$-direction, with a magnitude $B$ so that the Lorentz force acting on an incident proton is in the $y$-direction, with a magnitude $|\mathbf{F}| = euB$. Once moving in the $y$-direction, the Lorentz force on the proton is then directed in the $x$-direction causing it to be excluded from the bubble. The transverse velocity component (in the $y$-direction) that arises during the half-orbit generates an electric current in the boundary which prevents the magnetic field from entering the ICM, and is usually referred to as the Chapman-Ferraro current (e.g. Chapman & Ferraro 1934; Funaki et al. 2007). Therefore, once back in the ICM, a charge experiences no further deflection.

For the idealised case, the thickness of the interaction boundary would be approximately the plasma skin depth, $\delta = c/\omega_p$, where $c$ is the speed of light and $\omega_p$ is the plasma frequency (Funaki et al. 2007). However, because of their heavier mass, protons tend to penetrate more deeply into the magnetic field than electrons. This leads to charge separation with a negative charge layer above the positive charge layer. Thus, the outwardly pointing electric field restrains the protons, while the electrons gain energy (e.g. Baumjohann & Treumann 1996).

The thickness of the boundary is therefore considered to be larger than $\delta$, being roughly the proton gyration radius

$$r_{g,p} = \frac{m_p v_{p}}{eB}$$

(6)

where $m_p$ is the proton mass, $v_{p}$ is the velocity perpendicular to the field line, $e$ is the electric charge, and $B$ is the magnetic field strength. Since the bubble ascends subsonically, the particle velocity is largely governed by its thermal motion. Then, for a thermal proton, the mean velocity is given by $v_{p} = (3k_B T/m_p)^{1/2}$, where $k_B$ is the Boltzmann constant and $T$ is the temperature. Therefore, assuming that the electrons and protons have the same temperature, the ratio of the thermal proton and electron gyration radii is $(m_p/m_e)^{1/2}$.

The total current density in the $y$-direction is the sum of the individual currents generated by the protons and electrons: $|\mathbf{J}| = \sum_{i=p,e} |J_i| = (n_pe v_p + n_e e v_e)$, where $n_p$ and $n_e$ are the number density of protons and electrons, respectively. $v_p$ and $v_e$ are the proton and electron velocities.

Then, using Ampère’s law, the magnitude of the induced current density is roughly

$$\sum_{i=p,e} |J_i| \approx \sum_{i=p,e} \frac{B}{\mu_0 r_{g,i}^2},$$

(7)

where $r_{g,i}$ is the gyration radius of the $i$th particle species and $P_i$ is the pressure of the $i$th species.

We also note that the current flows so as to exclude the bubble’s magnetic field from the ICM, which increases the field strength just inside the boundary region. The numerical value of the field inside the boundary is then twice the initial value. As a result, the current layer confines the bubble’s magnetic field to the region inside the boundary and so partly governs the size of the bubble.

3 RESULTS

Since the electric conductivity of the ICM is finite, some of the electromagnetic energy generated by the interaction will be dissipated as heat in the region around the bubble. In this section, we present a calculation of the expected heating rate. The magnitude of the induced current is also of interest, primarily for comparison with the values required in models of current-dominated jets (e.g. Nakamura et al. 2007). Accordingly, a calculation for the total current flowing across the surface of a bubble is also given in this section.

3.1 Heating rate

From equations (4) and (7), it is clear that particles with smaller gyration radii contribute a larger current density.
Because of this effect, the induced current density due to electrons is a factor of \((m_p/m_e)^{1/2}\) greater than for protons and has a magnitude
\[
|J_e| \approx 4 \times 10^{-5} \left( \frac{B}{10 \mu G} \right)^2 \left( \frac{T}{10^8 \text{ K}} \right)^{-1/2} \text{ A cm}^{-2}.
\] (8)

Although the electric conductivity of the ICM is extremely high, it is not infinite. Consequently, the induced current dissipates electromagnetic energy at a rate \(\dot{\varepsilon} = \eta|J|^2\), where \(\eta\) is the electric resistivity given by equation \(\Box\). This process is known as Joule or Ohmic dissipation. Due to the \(J^2\) term, the Ohmic dissipation rate is a factor \((m_p/m_e)\) higher for electrons than protons and can be written
\[
\dot{\varepsilon} \approx \eta|J_e|^2 \approx 3 \times 10^{-18} \left( \frac{B}{10 \mu G} \right)^4 \left( \frac{T}{10^8 \text{ K}} \right)^{-5/2} \text{ erg s}^{-1} \text{ cm}^{-3}.
\] (9)

A plasma with a temperature of \(T \sim 10^8 \text{ K}\) and a number density \(n \sim 0.01 \text{ cm}^{-3}\) primarily radiates energy by thermal bremsstrahlung at a rate \(n^2 \Lambda(T) \sim 10^{-27} \text{ erg s}^{-1} \text{ cm}^{-3}\). As can be seen, from equation \(\Box\) the Ohmic dissipation rate within the boundary region is a factor of \(\sim 10^9\) greater than the radiative losses due to thermal bremsstrahlung in the ICM surrounding the bubble. This is surprisingly large, suggesting that Ohmic dissipation might have an observable effect. To determine whether this is true it is necessary to calculate the total rate at which energy is dissipated.

Assuming that the bubble is spherical, the volume within which the electromagnetic energy is dissipated is \((4/3)\pi [(r_b + r_h)^3 - r_h^3] \approx 4\pi r_b^2 r_h\). Because of the extra factor of \(r_e\), the volume-integrated dissipation rate for electrons is a factor \((m_p/m_e)^{1/2}\) greater than for protons, so electron dissipation still dominates the total Ohmic dissipation rate
\[
\dot{E} \approx 4\pi r_b^2 r_{e,0} \dot{\varepsilon} \approx 2 \times 10^{37} \left( \frac{r_b}{5 \text{ kpc}} \right)^2 \left( \frac{B}{10 \mu G} \right)^3 \left( \frac{T}{10^8 \text{ K}} \right)^{-2} \text{ erg s}^{-1}.
\] (10)

It is also instructive to demonstrate how the heating rate may vary as the bubble evolves. In a stratified atmosphere, the rising, buoyant bubble expands to maintain pressure equilibrium with its surroundings. For the present case, pressure equilibrium requires that \(B^2/(2\mu_0) = P\), where \(P\) is the ambient pressure. Then, assuming the expansion is adiabatic, the bubble volume, \(V_b\), is related to the ambient pressure, \(P\), by \(PV_b^\Gamma = P_b V_b^{\Gamma,0}\), where \(P_b\) is the ambient pressure where the bubble was inflated, \(V_b^{0}\) the initial bubble volume and \(\Gamma\) is the adiabatic index of the bubble. A magnetically-dominated bubble can be described by a relativistic equation of state, for which \(\Gamma = 4/3\). Finally, the ICM pressure can be approximated by a \(\beta\)-model: \(P = P_0 [1 + (z/z_0)^2]^{-\beta}\), where \(P_0\) is the central pressure, \(z\) is the distance from the cluster centre, \(z_0\) is the scale height of the distribution, and typically \(\beta \approx 3/4\). Assuming the bubble was initially inflated at the cluster centre, and substituting for both \(r_b\) and \(B\), the heating rate can be re-written as
\[
\dot{E} \approx 2 \times 10^{37} \left( \frac{r_{b,0}}{5 \text{ kpc}} \right)^2 \left( \frac{P_0}{10^{10} \text{ erg cm}^{-3}} \right)^{3/2} \left( \frac{T}{10^8 \text{ K}} \right)^{-2} \left[ 1 + \left( \frac{z}{z_0} \right)^2 \right]^{-\beta} \text{ erg s}^{-1}.
\] (11)

The thickness of a shell around the bubble that will be heated by Ohmic dissipation can be estimated from \(\dot{E}_b = 4\pi r_b^2 \Delta r n^2 \Lambda(T)\), where \(n^2 \Lambda(T)\) are the radiative losses due to thermal bremsstrahlung. Using similar quantities to those above, it can be shown that \(\Delta r \sim 10^{-5} - 10^{-2} \text{ kpc}\), which will not be observable.
Therefore, Ohmic dissipation should be insignificant compared to the total radiative ICM cooling rate due to thermal bremsstrahlung and is unlikely to have a noticeable effect even in a thin shell around the bubble. Furthermore, even if the conductivity was drastically reduced, the small volume occupied by the induced current means that the total heating rate will always be negligible compared to the radiative losses of the ICM.

3.2 Total current

The current generated by the Lorentz force flows in a thin layer across the surface of the bubble. Assuming, again, that the bubble is spherical with a radius \( r_b \), the total available area over which the current can flow is \( 4\pi [(r_b + r_g)^2 - r_g^2] \approx 8\pi r_b r_g \). Then, using equation (3), the total current flowing around a typical bubble is

\[
I \approx 8\pi r_b \sum_{i=p, e} J_{g,i} = \frac{16\pi}{\mu_0} r_b B \approx 6 \times 10^{18} \left( \frac{r_b}{5 \text{kpc}} \right) \left( \frac{B}{10 \mu\text{G}} \right) \text{A},
\]

and is independent of the gyration radius.

The magnitude of the current given in equation (12) is somewhat uncertain because although the current loop probably closes somewhere at the rear of the bubble, it is impossible to say precisely where. Because of this uncertainty, the current may only flow over a fraction of the bubble surface, thereby reducing the total current. However, the reduction is unlikely to be more than an order of magnitude.

Nevertheless, the value of the current in equation (12) is almost identical to the values expected in current-dominated jets (e.g. Nakamura et al. 2006; Diehl et al. 2008). In fact, this is not a coincidence - the electric current and bubble radius associated with a magnetic field in pressure equilibrium with its surroundings are related by Ampere’s law. However, the values arise from different starting points. For the current-dominated jet, described by Nakamura et al. (2006), the constant current generates a magnetic field; the bubble radius can then be calculated assuming the field is in pressure equilibrium with the ICM. In contrast, we have calculated the induced current for an assumed magnetic field (in pressure equilibrium with its surroundings) and bubble radius. The main difference is that the current estimated in this way is not constant, and decreases as the bubble ascends through the ICM.

4 DISCUSSION

In the idealised model of the interaction between the ICM and the AGN-blown bubble, described above, there is no mass or energy transfer across the interaction boundary (as well no drag force exerted on the bubble). If this is true, then it is not clear there should be any thermal material in the bubble at all, while recent observations indicate that thermal material may occupy up to 50% of the volume of some bubbles in the Perseus cluster (Sanders & Fabian 2007). There are three main possibilities which can explain this discrepancy:

1) Thermal material from the ICM was entrained into the outflow that inflated the bubble. It may also be important to note that if a supersonic outflow entrains material, it will be decelerated so that its Mach number tends towards unity (Hartquist et al. 1986). This effect may explain prevalence of shocks in the ICM with Mach numbers close to unity (e.g. Forman et al. 2007; Graham et al. 2008), as well as the origin of thermal material in the bubble.

2) The second possibility is that charged particles diffuse into the bubble. Due to the initial expansion and the effect of magnetic draping, the magnetic fields will be primarily tangential to the bubble surface. Therefore, in order to enter the bubble, particles must diffuse across the field lines. Unlike diffusion parallel to the magnetic field lines, which can occur rapidly, diffusion across field lines is significantly reduced by many orders of magnitude (c.f. Enßlin 2003). In fact, the diffusion coefficients perpendicular to the field lines derived by Enßlin (2003) are more than 10 orders of magnitude less than those employed in numerical simulations by Ruszkowski et al. (2007); Mathews & Brighenti (2008). We also note that, since the bubble ascends at a velocity, \( w \), with respect to the material entering it, the transfer of mass is accompanied by a retarding force, \( -\dot{M}w \), where \( \dot{M} \) is the rate at which mass enters the bubble. Depending on the magnitude of the mass flux, the retarding force may play an important role in governing the terminal velocity of the bubble. The magnitude of the diffusive mass flux, therefore, has potentially important consequences for interpreting observations of bubbles.

3) Magnetic reconnection occurs in a medium with non-zero resistivity (e.g. the ICM) when oppositely directed magnetic fields are brought close together (Bodenheimer et al. 2007). Importantly, when the magnetic fields of the ICM and bubble become interconnected, the field attains a finite component, \( B_n \), normal to the bubble surface, allowing plasma to flow across the bubble/ICM boundary (e.g. Paschmann 1997). Transferring mass in this way would deliver a retardation to the bubble, and may also generate convective motions within the bubble that could affect its radio emission.

Regarding point 1), material may be entrained into an outflow due to the growth of Kelvin-Helmholtz (K-H) instabilities at the boundary between the outflow and ambient medium (e.g. De Young 2006). These instabilities form as a result of the velocity shear between the two fluids and have been shown to occur in magnetohydrodynamic (MHD) flows (Ryu et al. 2000) as well as purely hydrodynamic flows. If the masses entrained by hydrodynamic outflows, \( 10^7 - 10^8 M_\odot \) (e.g. De Young 1986; Reynolds et al. 2002), are applicable to real AGN outflows it is possible that this mechanism can explain the thermal content of AGN-blown bubbles. However, recent work (Nakamura et al. 2007) suggests that magnetic tower jets do not develop K-H instabilities. Thus, if AGN outflows follow this description, the thermal content of bubbles must arise from either cross-field diffusion or magnetic reconnection, discussed below.

The diffusive mass flux, per unit area, can be written \( F = D \nabla \rho \), where \( D \) is the diffusion coefficient and \( \nabla \rho \) is the density gradient. The total mass flux into the bubble is then obtained by integrating \( F \) over the surface of the bubble, which, for a spherical bubble gives \( \dot{M}_{\text{diff}} = 4\pi r_g^2 F \). Furthermore, assuming that the bubble is initially devoid of thermal content and the bubble/ICM boundary has a thickness of roughly one proton gyration radius, the density gradient, \( \nabla \rho \), can be no greater than \( \rho / r_g \). As a result, the
rate at which mass diffuses into a spherical bubble cannot exceed \(4\pi \rho b / D \rho_b \).

A convenient way of expressing the importance of diffusion is the ‘refilling’ timescale over which the diffusive influx of material becomes comparable to the mass of ICM material displaced by the bubble, \(\tau_{\text{diff}} \equiv M_{\text{dis}} / M_{\text{diff}}\). Using \(M_{\text{dis}} = (4/3)\pi \rho_b b^3 \rho\) therefore, gives an upper limit on the refilling timescale due to diffusion

\[
\tau_{\text{diff}} \approx \frac{1}{3} \frac{r_b \rho_b \rho}{D} \approx 0.1 \left( \frac{D}{10^{16} \text{ cm}^2 \text{ s}^{-1}} \right)^{-1} \left( \frac{r_b}{5 \mu \text{pc}} \right) \times \left( \frac{B}{10 \mu \text{G}} \right)^{-1} \left( \frac{T}{10^6 \text{ K}} \right)^{1/2} \text{ Gyr}.
\]

Equation (13) shows that a typical cross-field diffusion coefficient of \(D \sim 10^{16} \text{ cm}^2 \text{ s}^{-1}\) is required to transfer a significant quantity of ICM material over a bubble lifetime of 100 Myr.

The diffusion coefficient must fall within the range \(D_{\text{clas}} \leq D \leq D_b\), where \(D_{\text{clas}}\) and \(D_b\) are the classical and Bohm diffusion coefficients, respectively (Ikhsanov 2001). Classically, the diffusion of charges across magnetic field lines arises from non-zero plasma resistivity (e.g. Spitzer 1962; Goldston & Rutherford 1995), that is, it scales with the collision rate of electrons with protons, \(v_{\text{e},p}\), and is roughly \(D_{\text{clas}} \approx v_{\text{e},p}/r_{g,e}\) (e.g. Goldston & Rutherford 1995), where \(r_{g,e}\) is the electron gyration radius. For typical cluster values, \(D_{\text{clas}} \sim 10^6 \text{ cm}^2 \text{ s}^{-1}\) and, therefore, will not lead to significant mass transfer from the ICM to the bubble on a realistic timescale.

The maximum diffusive mass transfer rate occurs if diffusion is governed by drift-dissipative instabilities - Bohm diffusion (e.g. Ikhsanov 2001; Enßlin 2003), for which \(D_b \approx k_B T/(16eB) \approx 5 \times 10^{15} (T/10^6 \text{ K})(B/10\mu \text{G})^{-1} \text{ cm}^2 \text{ s}^{-1}\). Therefore, mass transfer due to Bohm diffusion would be able fill a bubble on a timescale of 100 Myr. Despite being an extreme upper limit, the Bohm limit does, nevertheless, provide an estimate of the minimum possible timescale a bubble can survive before diffusion-driven mass transfer completely refills it.

Perhaps more realistically, Enßlin (2003) calculated diffusion coefficients for cosmic rays crossing a turbulent magnetic field to be \(\sim 10^{18} \text{ cm}^2 \text{ s}^{-1}\), using \(B = 10\mu \text{G}\). For thermal particles with an energy of \(\sim 10\text{ keV}\), the diffusion coefficient is reduced to \(D \sim 10^{11} \text{ cm}^2 \text{ s}^{-1}\). In this case, the time taken to completely refill the bubble would be \(10^{12} \text{ yr}\). Therefore, unless diffusion proceeds at the Bohm rate, it is unlikely to contribute a significant proportion of the thermal content of bubbles.

If magnetic reconnection occurs, the plasma transfer rate is determined by the dimensionless reconnection rate commonly defined as \(\zeta = B_0 / B\). However, even for the Earth’s magnetosphere it is difficult to accurately determine \(B_0\), though typical values indicate \(\zeta \sim 0.1\) (Elsner & Lamb 1984; Paschmann 1997). The mass flux entering the bubble is then given by \(M_{\text{rec}} = \pi r_b^2 \rho w \zeta\), where \(w\) is the ascent velocity of the bubble (Paschmann 1997). The timescale for refilling a bubble as a consequence of magnetic reconnection is then

\[
\tau_{\text{rec}} \equiv \frac{M_{\text{dis}}}{M_{\text{rec}}} = \frac{4 \pi}{3} \frac{r_b}{w} \approx 0.7 \left( \frac{r_b}{5 \mu \text{pc}} \right) \left( \frac{w}{10^7 \text{ cm} \text{ s}^{-1}} \right)^{-1} \left( \frac{T}{0.1} \right)^{-1} \text{ Gyr.}
\]

According to equation (14), it seems physically possible that magnetic reconnection could explain the observations of Sanders & Fabian (2002). Furthermore, the transfer of mass would also be accompanied by heating as the energy density of the magnetic field is transferred to the plasma. However, the significance of this channel of mass transfer depends crucially on the reconnection rate, \(\zeta\), which is highly uncertain.

## 5 SUMMARY

The aim of this article has been to describe one of the main processes which prevents thermal material from the ICM entering AGN-blown bubbles. As a direct consequence, it is possible to highlight the mechanisms which must occur if a bubble is to display thermal content. The main findings are summarised below:

i) The Lorentz force causes a charged particle entering the bubble to execute a half-orbit so that it is re-directed back into the ICM and excluded from the bubble. The transverse motions of the deflected charges generate electric currents along the bubble surface which prevent the magnetic field from entering the ICM (e.g. Chapman & Ferrara 1993; Funaki et al. 2007). Therefore, once back in the ICM, a charge experiences no further deflection. The charges penetrate roughly one proton gyration radius before being directed back into the ICM. This exclusion is different to the stabilising effect of magnetic fields (e.g. Chandrasekhar 1961; De Young 2003; Kaiser et al. 2003; Dursi 2007) which, strictly speaking, only explains why the bubbles do not fragment into smaller structures due to Rayleigh-Taylor instabilities. The combination of both effects provides an effective surface tension which, in the idealised model, prevents material from the ICM entering the bubble.

ii) Ohmic dissipation of the induced current heats the ICM adjacent to the bubble at a rate \(\sim 10^{35} - 10^{37} \text{ erg s}^{-1}\); this is insignificant compared to the radiative losses of the ICM. The total induced current on the bubble surface has a typical magnitude of \(I \sim 10^{28} \text{ A}\), which is similar to that required to produce bubbles from current-dominated jets (Diehl et al. 2008; Nakamura et al. 2008).

iii) Sanders & Fabian (2007) recently presented observations indicating that thermal material may occupy up to 50% of the volume of some bubbles in the Perseus cluster. Given the effect of the Lorentz force, the most likely explanations for the observed thermal content are that; mass is entrained into the outflow that inflated the bubble, charged particles diffuse rapidly across the bubble/ICM boundary, or magnetic reconnection on the bubble surface allows material to enter the bubble. We find that, unless the AGN outflow behaves as a magnetic tower jet, entrainment into the outflow can supply sufficient thermal material to explain the results of Sanders & Fabian (2007). However, for magnetic tower jets, the outflow entrainment rate is expected to be insignificant (Nakamura et al. 2007). The cross-field diffusion coefficient required for thermal material to fill a
typical bubble is $\sim 10^{16} \text{cm}^2 \text{s}^{-1}$. This value is anomalously high compared to predictions from turbulent diffusion models \citep{Enßlin2003}, but is comparable to the Bohm diffusion coefficient. Given that the Bohm limit is an extreme upper limit, it seems unlikely that cross-field diffusion contributes significantly to a bubble’s thermal content. Finally, the mass transfer rate due to magnetic reconnection is somewhat uncertain, but significant for plausible reconnection rates. We conclude, based on current models, that entrainment into the outflow and mass transfer due to magnetic reconnection are probably the most significant sources of thermal content in AGN-blown bubbles.

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