Do sound waves transport the AGN energy in the Perseus Cluster?

A.C. Fabian1*, S.A. Walker1, H.R. Russell1, C. Pinto1, J.S. Sanders2 and C.S. Reynolds3
1 Institute of Astronomy, Madingley Road, Cambridge CB3 0HA
2 Max-Planck-Institut für Extraterrestrische Physik, Giessenbackstrasse 1, D-85748 Garching, Germany
3 Dept. of Astronomy, University of Maryland, College Park, MD 20712-2421, USA

ABSTRACT

The level of random motions in the intrachannel gas lying between 20 and 60 kpc radius in the core of the Perseus cluster has been measured by the Hitomi Soft X-ray Spectrometer at 164 ± 10 km s$^{-1}$. The maximum energy density in turbulent motions on that scale is therefore low. If dissipated as heat the turbulent energy will be radiated away in less than 80 Myr and cannot spread across the core. A higher velocity is needed to prevent a cooling collapse. Gravity waves are shown to travel too slowly in a radial direction. Here we investigate propagation of energy by sound waves. The energy travels at ∼ 1000 km s$^{-1}$ and can cross the core in a cooling time. We show that the displacement velocity amplitude of the gas required to carry the power is consistent with the Hitomi result and that the inferred density and temperature variations are consistent with Chandra observations.

Key words: X-rays: galaxies, clusters

1 INTRODUCTION

The Soft X-ray Spectrometer on the Hitomi satellite has recently measured the level of gas motions in the X-ray bright IntraCluster Medium (ICM) in the core of the Perseus cluster to an unprecedented precision of 10 km s$^{-1}$ (Hitomi collaboration 2016). Small-scale motions (< 10 kpc) in a region 20 to 60 kpc from the central Active Galactic Nucleus (AGN) are 164 ± 10 km s$^{-1}$; larger scale shear across that region is also low, ∼150 ± 70 km s$^{-1}$. The energy density of turbulent motions is at most 4 per cent of the thermal energy density of the hot intrachannel gas.

In the absence of a heat source the hot gas in this region would cool radiatively, due to the emission of X-rays, on a timescale of 1 – 2 Gyr forming a massive cooling flow of several hundred $M_\odot$ yr$^{-1}$ (see e.g. Fabian 2012). Although the temperature of the hot gas does drop towards the centre, little gas is seen below 3 keV, ruling out such a cooling flow. If all the energy in random motions is ascribed to turbulence which is then dissipated as heat, then it will be used up in 4 per cent of the cooling time: it needs to be replenished on the same timescale, which is about 8 × 10$^7$ yr. However if the velocity at which energy flows is limited to 164 km s$^{-1}$ then the energy can only travel 13 kpc in that timescale, before being lost as radiation. Energy needs to be transported from the energy source – the AGN – at a much higher velocity of at least 700 km s$^{-1}$, close to the speed of sound in the region (∼1000 km s$^{-1}$). One energy transport mechanism that can do this is sound waves. The matter does not flow but the energy does. Here we explore further the case for the importance of sound waves in the Perseus and other cool core clusters. The observed velocity dispersion is consistent with that required to transport the energy required for heating the cluster core.

Many studies of cool-core clusters (Birzan et al (2004, 2012); Dunn & Fabian (2006, 2008); McNamara & Nulsen 2012; Fabian 2012) have shown that the bubbles produced by jets from the central black hole represent a considerable energy flow which is capable of balancing radiative cooling (e.g. Churazov et al 2002). What has remained unclear is the means by which the energy from the bubbles is transported throughout the core and distributed in a roughly isotropic manner. Ripples with a wavelength ∼ 15 kpc were seen in the first deep Chandra images of the Perseus cluster and interpreted as sound waves (Fabian et al 2003). Their amplitude was consistent with the required energy flux. Issues of dissipation were explored by Fabian et al (2005). Sound wave propagation and dissipation in intrachannel gas were simulated by Ruszkowski et al (2004a,b) and Sijacki et al (2005) and have been further discussed by Mathews, Faltenbacher & Brighenti (2006) and by Heinz & Churazov (2005).

The ripples became clearer in yet deeper Chandra ob-

* E-mail: acf@ast.cam.ac.uk
The core of the Perseus cluster filtered with an edge-detection algorithm (Sanders et al 2016b) and overlaid with the field of view of the Hitomi SXS (3x3 arcmin, or about 60x60 kpc).

Figure 1.

The expected temperature changes associated with sound waves were observed (Fabian et al 2006; Sanders & Fabian 2007). The temperature and density profiles in Perseus (Fig. 2) imply scale-heights of ∼ 15 kpc radial extent. Measurements of the temperature and density profiles in Perseus (Fig. 2) imply scale-heights of ∼ 15 kpc radial extent. For AGN feedback, confirming that the level of turbulent heating is very inefficient with less than 1 per cent of the energy injected by the AGN activity ending up as turbulence in the ICM. Yang & Reynolds (2016) have then used further hydrodynamical simulations to explore momentum-driven jet flow driven by AGN, with the energy propagating at the group velocity, v = ∇kω.

Figure 2. Profiles of the intrachannel temperature, density, radiative cooling time and sound speed in the Perseus cluster.

2 THE GENERATION AND PROPAGATION OF TURBULENT MOTIONS

Reynolds, Balbus & Schekochihin (2015) have examined the generation of subsonic turbulence through 3D hydrodynamical simulation of AGN-like events. Gravity waves (g-modes) are launched by these events into the ICM and decay to volume-filling turbulence. They find however that the process is very inefficient with less than 1 per cent of the energy injected by the AGN activity ending up as turbulence in the ICM. Yang & Reynolds (2016) have then used further hydrodynamical simulations to explore momentum-driven jet feedback, confirming that the level of turbulent heating is low, accounting for only about one per cent of the energy. Turbulence is not necessarily an essential ingredient of cluster AGN feedback.

Still, it is possible that processes not captured by these simple hydrodynamic models might lead to significantly stronger AGN-driving of g-modes (see Section 6 of Reynolds et al. 2015) and so it is interesting to examine the subsequent propagation speed of g-modes. Working within a local/WKB approximation, the dispersion relation for a particular g-mode with (angular) frequency ω and wavevector k is ω² = N²k²/|k|², where k_h is the horizontal component of the wavevector and N is the Brunt-Väisälä frequency given by

\[ N² = \frac{c_s²}{\gamma} \frac{\partial (\ln P)}{\partial z} \frac{\partial (\ln ρ^{−\gamma})}{\partial z}. \]  

(1)

(\(c_s\) is the adiabatic sound speed, \(ρ\) is density, \(P\) is pressure, and \(γ\) is the adiabatic index which we take to be \(γ = 5/3\)). Energy propagates at the group velocity, \(v_g = \nabla kω\), and so the outwards/radial speed of propagation is

\[ v_{g,r} = \frac{\partial ω}{\partial k_r} = \sin θ \cos² θ \frac{N}{k_r}. \]  

(2)

Here, \(θ\) is the angle that the propagation direction makes with the outward pointing direction and \(k_r\) is the radial component of the wavevector. Since |\(\sin θ \cos² θ| \ll 2/3\sqrt{3} \approx 0.38\), we see that \(v_{g,r} < 0.38(N/2π)(2π/k_r)\) — this has the simple interpretation that, with each buoyant cycle, the g-mode propagates upwards by (at most) half of a radial wavelength \(λ_r = 2π/k_r\).

If \(H_p\) and \(H_S\) are the density and entropy scale-heights, equation (1) becomes \(N = c_s/\sqrt{H_pH_S}\) and we find that

\[ v_{g,z} < 0.047c_s \frac{λ_r}{\sqrt{H_pH_S}}. \]  

(3)

so we immediately see that g-modes propagate very subsonically provided that \(λ_r < H_pH_S\) (note that, if this condition were violated, the local approximation used here would break down). Measurements of the temperature and density profiles in Perseus (Fig. 2) imply scale-heights of \(H_p, H_S \sim 30 - 50\) kpc which, when compared with the \(~ 15\) kpc radial wavelength of the observed ripples, yields radial propagation...
speeds for the $g$-modes of $v_{g,s} < 0.02 c_s \approx 20 - 30 \text{ km s}^{-1}$. Even taking the maximum wavelength possible ($\lambda_r \sim H_\rho$) yields $v_{g,s} < 0.05 c_s \approx 50 - 70 \text{ km s}^{-1}$. These $g$-mode propagation velocities are at least an order of magnitude too small to replenish the decaying turbulence, if the turbulence is indeed responsible for offsetting the radiative cooling.

The sharp high-energy edge to the Fe He resonance line observed from the Perseus cluster by the Hitomi SXS leaves no room for any significant component with larger velocity motions.

3 SOUND PROPAGATION

The energy in a sound wave is carried at the speed of sound, as the particles oscillate about their mean position at a much lower (displacement) velocity. If the energy density due to random motions is $\frac{\rho v^2}{2}$, where $v$ is the gas velocity then the maximum rate at which energy flows from a central source is

$$P_v = 2\pi r^2 \rho v^3.$$ (4)

The energy flux due to sound waves which have a displacement velocity $v_s$ is

$$P_s = 4\pi r^2 c_s \rho v_s^2.$$ (5)

Sound waves can therefore transport $2c_s/v_s$ times more power than random motions alone, for a given measured velocity. This is over an order of magnitude increase in the case of the Perseus cluster considered here, where $c_s \sim 1000 \text{ km s}^{-1}$ and $v_s \sim 164 \text{ km s}^{-1}$.

In order to determine the displacement velocity from the observed broadening of emission lines we need to correct for projection effects. We achieve that by simulating a cluster as many cubic cells, of size matching the SXS 10 kpc pixels, each containing gas of the appropriate density and temperature to match observed profiles (Fig. 2). Assigning a radial velocity to the gas in each cell according to a radial sine wave enables us to assemble the emission-weighted line profile as a function of projected radius (Fig. 3: the intrinsic profile is shown in the upper panel and the profile which would be observed, after convolution with the instrumental and thermal broadening, is shown in the lower panel).

The sharp peak is due to the brightest gas along any line of sight lying in the plane of the Sky where the apparent radial displacement velocity of the gas is zero. We measure one standard deviation of that profile (68 per cent of the total emission from the line centre) and use that value. It varies with radius and is between about one third to one half of the amplitude of the true displacement velocity. This yields another factor of at least four in favour of sound wave propagation. (The 200 km s$^{-1}$ used for Fig. 3 is a fiducial value.)

If all the measured dispersion is attributed to radial sound waves then their intrinsic velocity amplitude would be about 300 km s$^{-1}$. It is possible, of course, that the observed dispersion is a combination of sound waves of lesser amplitude with other random motions and turbulence.

Future microcalorimeters with higher spectral resolution, such as the planned X-ray Integral Field Unit (X-IFU: Barret et al 2016) on ESA’s Athena X-ray Observatory may be able to measure the non-gaussian nature of the perturbations caused by sound waves.

We note that the recent simulations of Yang & Reynolds (2016) provide strong support for the idea that sound waves are a major contributor to the ICM velocities. They use a Helmholtz decomposition to separate compressible motions (sound waves and shocks) from incompressible motions (turbulence and large scale circulation) in their simulations of a Perseus-like cluster with self-regulation by a jetted AGN. Throughout most of the volume of the cluster core (i.e. the region away from the “jet cones”) at a typical snapshot in time, the compressible motions dominate with a magnitude $v_s \sim 150 \text{ km s}^{-1}$; turbulent velocities are somewhat less ($v_{\text{turb}} \sim 100 \text{ km s}^{-1}$) with bulk flow and circulatory motions being smaller yet (H.-Y. Karen Yang, private communication). Since the Yang & Reynolds simulations adopt an ideal hydrodynamic framework, there are no mechanisms that can efficiently dissipate the sound waves, and thus the heating actually occurs via bubble mixing and weak shocks in the jet-cone, with a gentle circulation that cycles a large part of the ICM through this region on Gyr timescales. The expectation is that, given the inclusion of a suitable dissipation mechanism, sound wave heating will be important in future developments of these models.

4 TEMPERATURE FLUCTUATIONS IN SOUND WAVES

Adiabatic sound waves are accompanied by temperature fluctuations

$$\frac{\Delta T}{T} = \frac{2}{3} \frac{\Delta n}{n} \approx \frac{1}{3} \frac{\Delta I}{I},$$ (6)

where $I$ is the soft X-ray surface emissivity.

Projection effects reduce the apparent amplitude of sound waves as observed in X-rays in intracluster gas (Graham et al 2008), such that waves with a density amplitude of 5 per cent, which leads to an emissivity fluctuation of about 10 per cent (ie $\propto n^2$) can appears as a surface brightness fluctuation of only 3-5 per cent. (The observed fluctuations are about $\pm 3$ per cent at radii of 20-60 kpc in the Perseus cluster; Sanders & Fabian 2007).

Projection also affects the amplitude of the accompanying temperature fluctuations: all lines of sight contain variations, but some have more than others. In order to estimate these affects we have used the same simulation as mentioned above for the velocity only now we calculate the integrated spectrum along the line of sight. (The pixels and response files now match those of Chandra.) Such spectra are then converted to hardness ratios (Fig. 4). We employ the bands $0.5 - 4 \text{ keV}$ and $4 - 8 \text{ keV}$ as used by Zhuravleva et al (2016); the harder band is much more temperature dependent than the softer one. It is clear that it is very difficult to measure periodic variations in hardness ratio unless the exposure is significantly longer that the current one. We have also measured from the simulation the hardness ratio of the relative fluctuations in each band, which Zhuravleva et al (2016) and Churazov et al (2016) show is sensitive to the effective equation of state of the ICM. The resulting value is $1 \pm 0.2$ which is consistent with isolated isothermal perturbations. The adiabatic perturbations used in the simulation appear isothermal due to the large effect of projection.
Figure 3. Top: Simulated line profiles due to the effect of the displacement velocity of sound waves in the ICM of the Perseus cluster. The profiles shown are for three different lines of sight passing at increasing distances from the core, spanning the range covered by the Hitomi observation (20, 40 and 60 kpc), and using the same pixel size as the Hitomi SXS. The line of sight component of the displacement velocity was integrated through the cluster along these sight lines, weighted by the emission measure of the gas. The corresponding coloured dashed vertical lines show the width containing 68 percent of the line strength. There is only a small change if the phase of the sound waves is shifted by half a wavelength. Bottom: Appearance of line profile expected at 40 kpc offset, after convolution with both instrumental and thermal broadening.

Figure 4. Simulated hardness ratio profiles, using 4.0-8.0 keV for the hard band and 0.5-4.0 keV for the soft band. Top: The input model for the hardness profile, taking into account projection effects. Second: The residuals in the input hardness ratio model due to the input sound waves. Third: Hardness ratio residuals in a 1Ms simulated observation, compared to the input model (red). Fourth: Hardness ratio residuals in an 8Ms simulated observation.

5 GENERATION AND DISSIPATION OF SOUND

We are here considering the situation where the bubbling energy of the AGN is converted into mechanical motions in the gas which is transported throughout the cluster core and dissipated there. The above estimates and the observed limiting level on turbulent velocity preclude turbulence as the sole basis of the mechanical motions which heat the whole cluster core. Sound waves remain possible as the transport mechanism because they transport energy much faster.

Sound waves can be generated during the inflation stage of the bubbles, particularly if the jets are unsteady. Malzac (2014) has successfully modelled the jets of some X-ray binaries by relating the spectrum of variations in the accretion flow to the acceleration of matter in the jet. The AGN at the centre of the Perseus cluster, in the galaxy NGC1275, is known to vary by over a factor of 30 over the past 4 decades.
(Fabian et al 2015 and references therein). It may plausibly vary by even larger factors and many times over the much longer time taken to form the bubbles.

The bubbles may themselves oscillate especially as they detach and rise. The natural frequency of a bubble, the Minnaert frequency

\[ f_M = \frac{1}{2\pi r_b} \left( \frac{3\gamma P_A}{\rho} \right)^{1/2}. \]

This leads to a wavelength of about 4\( r_b \), where \( r_b \) is the bubble radius, \( P_A \) is the ambient pressure and \( \rho \) the density of the surrounding medium. Such a large wavelength (\( \sim 30 \) kpc) is probably too large to be relevant.

It is also likely that the \( 5 \times 10^{10} M_\odot \) of cold molecular gas in the core of the cluster (Salomé et al 2011) oscillates in response to the bubbling process and so generates further sound waves.

The power of the sound,

\[ P_s = 4\pi r^2 c_s \rho c_s^2 \]

\[ = 2.9 \times 10^{44} \left( \frac{r}{40 \text{kpc}} \right)^2 \left( \frac{v}{200 \text{ km s}^{-1}} \right)^2 \text{erg s}^{-1} \]

\[ = 4\pi r^2 \frac{\delta P^2}{\rho c_s}, \]

where \( P \) is the gas pressure and \( \delta P \) the pressure change associated with the sound wave. Note that

\[ \frac{\delta P}{P} = \frac{v}{c_s}. \]

The power scaling is close to that required to compensate for radiative energy losses in the cluster core (see Fig.5 of Sanders & Fabian 2007). The exact level required depends on the length of time since the present configuration of intracluster gas has lasted. Given the level of sloshing seen in the cluster this could be 4-5 Gyr, which agrees with the required power estimates of \( 2.5 - 5 \times 10^{44} \text{ erg s}^{-1} \) at 40 kpc radius. The power required at 10 kpc is \( 6 - 8 \times 10^{44} \text{ erg s}^{-1} \), with the difference having been dissipated at radii between 10 and 40 kpc.

The required dissipation length is 50–70 kpc. How the energy might be dissipated by sound waves has been considered by Ruszkowski et al (2004a) and Fabian et al (2005) and remains an open question. Simple hydrodynamic viscosity and conduction may be insufficient. Tangled magnetic fields may give a bulk viscosity as sound wave propagation changes the field configuration in a non-reversible manner.

Sound waves will refract and reflect from density changes and discontinuities, including cold fronts, meaning that the situation will not be simple but, at radii of a few wavelengths, approach that of a noisy room.

Weak shocks and possible sound waves have previously been reported from M87 (Forman et al 2007), the Centaurus cluster (Sanders et al 2009, 2016a) and A2052 (Blanton et al 2011). Difficulties in detecting sound waves, in part due to projection effects, have been explored by Graham et al (2008) and reveal that most current exposures are far too short. Walker et al (2016) have shown that edge-detection (Gaussian Gradient Magnitude GGM) techniques can increase the contrast of sound waves in X-ray images. That work and the GGM images of Sanders et al (2016b; see also Fig. 1 here) show that elongated, azimuthal structures are relatively common in cool core clusters.

The Hitomi SXS result demonstrates that cluster AGN feedback cannot just involve turbulence. We show here that sound waves, first observed with the necessary level of surface brightness fluctuations in 2003, have a velocity amplitude consistent with both the Hitomi spectrum and the propagation of AGN power through the cool core of the Perseus cluster. We anticipate that generation of powerful sound waves by AGN feedback is present in all cool core groups and clusters and is a major part of the feedback loop.

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REFERENCES

Arévalo P., Churazov E., Zhuravleva I., Forman W.R., Jones C., 2016, ApJ, 818:14
Barret D., et al. 2016, SPIE conference Proceedings, in press
Birzan L., Rafferty D.A., McNamara B.R., Wise M.W., Nulsen P.E.J., 2004, ApJ, 607, 800
Birzan L., Rafferty D.A., Nulsen P.E.J., McNamara B.R., Rottgering H.J.A., Wise M.W., Mittal R., 2012, MNRAS, 427, 3468
Blanton, E. et al., 2011, ApJ, 737, 99
Brüggen M., Ruszkowski M., Hallman E., 2005, ApJ, 630, 740
Churazov E., Sunyaev R., Forman W., Böhringer H., 2002, MNRAS, 332, 729
Churazov E., et al 2016, [arXiv:1605.08999]
Dunn R.J.H., Fabian A.C., 2006, MNRAS, 373, 959
Dunn R.J.H., Fabian A.C., 2008, MNRAS 385, 757
Ettori S., Fabian A.C., 2008, MNRAS, 389, L42
Fabian A.C., et al., 2003, MNRAS, 344, L43
Fabian A.C., Reynolds C.S., Taylor G.B., Dunn R.J.H., 2005, MNRAS 363, 891
Fabian A.C., Sanders J.S., Taylor G.B., Allen S.W., Crawford C.S., Johnstone R.M., Iwasawa K., 2006, 366, 417
Fabian A.C., 2012, ARAA, 50, 455
Fabian A.C., Walker S.A., Pinto C., Russell H.R., Edge A.C., 2015, MNRAS, 451, 3061
Forman W., et al, 2007, ApJ, 665, 1057
Graham J., Fabian A.C., Sanders J.S., 2008, MNRAS, 391, 1749
Heinz S., Churazov E., 2005, ApJ, 634, L141
Hitomi collaboration, 2016, Nature, 535, 117
Malzac J., 2014, MNRAS, 443, 299
Mathews W.G., Faltenbacher A., Brighenti F., 2006, ApJ, 638, 659
McNamara B.R., Nulsen P.E.J., 2012, New J.Phys., 14, 5
Reynolds C.S., Balbus S.A., Schekochihin A.A., 2015, ApJ, 815, 41
Ruszkowski M., Brüggen M., Begelman M.C., 2004, ApJ, 611a, 158
Ruszkowski M., Brüggen M., Begelman M.C., 2004b, ApJ, 615, 675
Salomé P., Combes F., Revaz Y., Downes D., Edge A.C., Fabian A.C., 2011, A&A, 531, 85
Sanders J.S., Fabian A.C., 2007, MNRAS, 381, 1381
Sanders J.S., Fabian A.C., 2009, MNRAS, 390, L93
Sanders J.S. et al., 2016a, MNRAS, 457, 82
Sanders J.S., Fabian A.C., Russell H.R., Walker S.A., Blundell K.M., 2016b, MNRAS, 460, 1898

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Sijacki D., Springel V., 2006, MNRAS, 366, 397
Walker S.A., Sanders J.S., Fabian A.C., 2016, MNRAS, 461, 684
Yang H.-Y.K., Reynolds C.S., 2016, arXiv 1605.01725
Zhuravleva I. et al., 2014, Nature, 515, 85
Zhuravleva I. et al., 2016, MNRAS, 458, 2902