SIMULATIONS OF HOT BUBBLES IN THE ICM

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We review the general properties of the intracluster medium (ICM) in clusters that host a cooling flow, and in particular the effects on the ICM of the injection of hot plasma by a powerful active galactic nucleus (AGN). It is observed that, in some cases, the hot plasma produces cavities in the ICM that finally detach and rise, perhaps buoyantly. The gas dynamics induced by the rising bubbles can help explain the absence of a cooled gas component in clusters with a cooling flow. This scenario is explored using numerical simulations.

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1. Clusters of Galaxies and the ICM

Clusters of galaxies were first identified as regions in the universe containing overdensities of galaxies. For example, Abel defined a cluster as containing at least 50 bright galaxies within a circular area of sky of radius 1.5 Mpc/h. It was recognized as early as 1930 that clusters must contain more matter than is present in their component galaxies if they are to remain gravitationally bound. In fact, galaxies contribute only a few percent of the mass of a cluster, which ranges from about $10^{13} M_\odot$ for galaxy groups to about $10^{15} M_\odot$ for the richest clusters. About 15-20% of the mass exists in the form of a hot, diffuse plasma known as the intracluster medium (ICM), first detected in the early 1970s. Due to its high temperature ($\sim 10^7 - 10^8$ K), the ICM produces most of its radiation in the form of thermal X-rays whose surface brightness is strongly concentrated toward the center of a

$h$ is Hubble’s constant in units of 100 km s$^{-1}$ Mpc$^{-1}$. 
cluster. Measurements of the galaxy velocity dispersion, the temperature of the ICM, and more recently gravitational lensing show that at least 80% of the mass of clusters exists in some nonluminous form (dark matter) which is most likely nonbaryonic.

Galaxy clusters are the largest gravitationally bound objects in the universe. According to the hierarchical scenario of structure formation, they grow through infall and merging of smaller cluster and groups. This process appears to have continued to the present day. Morphologically we can classify clusters as being regular, having single brightness peaks and ellipsoidal or spherical shapes, or irregular, having multiple brightness peaks or irregular shapes. Irregular clusters appear to be undergoing or have recently undergone merger events. Regular clusters may have gone some time since their last mergers. However, since the timescale to re-establish equilibrium after a major merger event is of the order of several Gyr, and since projection effects can hide evidence for mergers, the fraction of clusters that appear regular most likely provides an underestimate of the fraction that have recently undergone mergers. Still, to first order hydrostatic and virial equilibrium is a reasonable approximation for many clusters; hence cluster properties are often computed under the assumption of spherical symmetry.

Typical X-ray luminosities of clusters range between about $10^{44}$ and $10^{45}$ erg s$^{-1}$. The X-ray emission of the ICM is due to thermal bremsstrahlung for $T > 3 \times 10^7$ K while line cooling becomes very important at lower temperatures. While to first approximation the ICM appears to be isothermal, there is evidence that the temperature profile decreases at large radii. Many clusters that host a cooling flow also show a temperature drop in the central region. Because of its high temperature, the ICM is almost completely ionized. The surface brightness follows the gas distribution: the gas density shows a central core and decreases at larger radii. The ICM is also rarefied; the electron density $n_e$ ranges from some $10^{-2}$ cm$^{-3}$ in the cores and then decreases below $10^{-4}$ cm$^{-3}$ at the limits of detectability. The gas metallicity is a fraction of solar ($\sim 0.3 Z_{\odot}$) and is in almost solar proportion. This implies that the gas is not completely primordial but rather has been partially processed in galaxies and then stripped by ram pressure or reinjected into the medium by supernova explosions. A metallicity excess is detected in the cores of cooling-flow clusters. Measurements of Faraday rotation in sources beyond clusters also show that the ICM hosts a magnetic field of about 0.1 to 10 $\mu G$.

2. The Cooling Flow Problem

Due to its X-ray emission the ICM loses energy over time. We can define the cooling timescale as $t_{cool} = -(d \ln T/dt)^{-1}$; for gas emitting via thermal bremsstrahlung this yields

$$t_{cool} = 8.5 \times 10^{10} \left( \frac{n_p}{10^{-3} \text{ cm}^{-3}} \right)^{-1} \left( \frac{T}{10^8 \text{ K}} \right)^{1/2} \text{ yr}$$
if the gas cools isobarically. Because of its low density, the ICM is thus expected to shine for billion of years without appreciable cooling, except in the very central regions of some clusters. Here the gas density is large enough that the cooling time becomes shorter than the Hubble time. For these clusters we can define a cooling radius $r_{\text{cool}}$ within which $t_{\text{cool}}$ is less than the age of the universe. The cooling radius can be larger than $\sim 100$ kpc.

In this paper we will refer to those clusters with an appreciable $r_{\text{cool}}$ as cooling-flow clusters, because in such clusters a cooling flow should be established in the absence of sources of heat. The classic picture of a cooling flow consists of a subsonic flow of cooling gas toward the cluster center. In a single-phase medium, the cooling gas should lose energy and be compressed by the pressure of the overlying gas, thus cooling still faster and eventually becoming invisible in X-rays altogether. Cooling flow clusters generally do have surface brightness distributions that are more concentrated than those of clusters without cooling flows, but homogeneous cooling models produce surface brightness profiles that are much steeper than observed. Inhomogeneous cooling can mitigate this problem; in this picture, cold clouds condense out of the flow over a wide range of radii, allowing some of the gas near the center to remain hot.

The temperature profiles of cooling-flow clusters often show a marked drop in the central regions, as expected. Because mergers increase the entropy of the ICM, the presence of a cool core is often taken to imply that a cluster is relaxed, even for those clusters that host a cooling flow together with substructures (e.g., Abell 85). A giant elliptical or a cD galaxy sits at the center of every cooling-flow cluster.

Recent observations have forced major revisions in our understanding of cooling flows. For the observed cores, we expect to see gas temperatures as low as $10^6$ K (0.1 keV) and mass deposition rates as high as $1000 M_\odot$ yr$^{-1}$. However, high-resolution XMM/Newton, ASCA, and Chandra spectra of cool cores do not show the expected signatures of cooling below 1-2 keV, namely the emission lines of metals that dominate cooling at such temperatures. Moreover, observations in the optical, radio, and infrared show much smaller amounts of cooled gas than predicted by earlier X-ray estimates of the mass accretion rate. The observed star formation rates are also smaller than expected from cooling flows. Some mechanisms have been suggested that could suppress the cooling flux at low energies and yet maintain the large cooling rates, but besides requiring some fine tuning, they do not address the question of the repository for most of the cold gas. So the other possible conclusion is that at most a small fraction of the ICM cools below 1-2 keV.

Maintaining gas at keV temperatures for a period several times longer than its cooling time requires one or more heating mechanisms. Any successful mechanism has to satisfy several requirements to match the observations consistently. First, it has to provide sufficient heating to balance the cooling losses. This heating must be properly tuned: too little heat will not impede cooling, while too much heat will...
produce an outflow from the core. This suggests that the heating process should be self-regulated. For example, the mass deposition may trigger the heating process and in turn be quenched by it. The heating mechanism must also affect (perhaps indirectly) the entire mass deposition region in order to prevent partial cooling in the less well-heated regions. The heating mechanism also must preserve the entropy profile of the ICM, which decreases toward the cluster center. This rules out a purely convective mechanism, which would act if the entropy were decreasing with radius. Finally, the heating should not destroy the metallicity profile, which shows a marked rise in the core.

Candidate heating mechanisms include thermal conduction by electrons in the ICM, reconnection of magnetic fields, turbulent mixing, and injection of hot plasma by the active galactic nuclei (AGN) hosted by the central galaxies of many clusters. In this paper we will focus on this last possibility.

3. The Interaction of Active Galaxies with the ICM

Recent observations show that almost all cooling-flow clusters host radio sources in their centers. Often these sources are rather faint, and it is not clear if a correlation exists between their radio power and the strength of the cooling flow. Anyway, about 71% of the cDs in cooling-flow clusters are radio loud compared to only 23% of non-cooling-flow cluster cD, and this suggests a connection between the AGN activity and the presence of the cooling flow, at least in clusters that host a cD.

In active radio sources, an AGN drives strong outflows in the form of jets which are highly collimated and composed of relativistic particles. The jet production process is not yet completely understood, but it is generally assumed to involve some magnetohydrodynamic mechanism which acts on the material falling onto a supermassive black hole. The plasma inside the jets produces radio synchrotron and synchrotron self-Compton emission and is sometimes observed in the optical and in X-rays. The jets lose energy by doing work against the surrounding medium, finally coming into pressure equilibrium with the ICM. At this point the jets inflate lobes which are filled with relativistic plasma and magnetic field. This plasma still emits synchrotron radiation, so the lobes are visible in radio waves.

The shapes of radio sources are determined by the interaction of the jets with their surroundings. For radio sources not connected with a cooling flow, the jets travel straight for tens or hundreds of kpc before ending in a hot spot or undergoing a sudden transition and continuing as broad tails. The central radio sources in cooling-flow clusters, on the other hand, show mostly a disturbed morphology: even when they host a radio-loud core, collimated jets exist only on kpc scales or below. After this the energy flow continues in a less collimated manner into the ICM, and the lobes take the shape of large bubbles.

Shortly, the radio galaxies should evolve through three stages. At the beginning the radio plasma is driven by the momentum of the jets and inflates cigar-
shape cocoons which are overpressured with the respect to the ambient medium. Hence the cocoons expand laterally meanwhile the jets are lengthening their channels, and the supersonic lateral expansion become rapidly comparable to the lengthening. However, the cocoon expansion relents then by the way, and after the expansion velocity has became subsonic the evolution of the cocoon is governed by buoyancy.

A rather different scenario suggests that the observed ultrarelativistic jets are instead embedded in an unobserved subrelativistic flow. In this case the outflow from the AGN would carry a significant amount of momentum, and the cocoons would rise supersonically pushed by the jets.

High angular resolution X-ray images obtained by Chandra show in some cases depressions of the X-ray flux, suggestively referred to as cavities, that are coincident with AGN radio lobes. Cavities are observed, for example, in Perseus, Hydra A, Abell 2052, and Centaurus. They are usually some tens of kpc across and a similar distance away from the cluster center. They are often surrounded by bright rims of denser and cooler gas which presumably has been displaced, uplifted or entrained by the hot plasma during the formation of the cavity or its subsequent motion.

In some cases weak shocks are observed but no strong shocks, thus is assumed that the radio-emitting plasma in these cavities is almost in pressure equilibrium with the surrounding ICM. As stated above, it is then easy to show that the lobes filled by relativistic particles and magnetic field should have a smaller specific weight than the ICM and act as bubbles that finally detach and rise buoyantly. In simulations the cavities rise at about 1/3 the sound speed in the ICM.

Chandra X-ray images also show cavities that are not coincident with bright radio lobes, for example in Abell 259, Perseus, and Abell 405. These structures are referred as ghost cavities. The relativistic electrons in the radio lobes are expected to lose enough energy via synchrotron emission to become invisible in the radio after 50 to 100 Myr. If this interpretation is correct, the ghost cavities are buoyantly rising relics of a radio outburst that ended at least 50 to 100 Myr ago.

Cavities, both filled and ghost, have been clearly detected in 15 clusters that host an AGN in a cool core. A correlation has been shown to exist between the mechanical luminosity of the cavities $L_{\text{mech}}$ and the power of the radio source. Here $L_{\text{mech}}$ is defined as $pV/t$, where $p$ is the pressure inside the cavity, $V$ is the volume of the cavity, and $t_c$ is its age. A correlation also exists between $L_{\text{mech}}$ and the X-ray luminosity due to the cooling ICM gas. These correlations suggest that the cavities are indeed powered by AGN and that the AGN activity level is related to the accretion of cooling gas. However, the mechanical luminosity is not large enough for rising bubbles to balance radiative cooling by themselves except in a few cases.

The commonly observed cold fronts discovered by Chandra also provide hints regarding the effect of AGN on the intracluster medium. Cold fronts are sharp discontinuities in X-ray surface brightness marking boundaries between hotter and colder masses of gas in the ICM. The density and temperature jumps inferred for
cold fronts through deprojection analysis are consistent with continuous pressure changes across the fronts, showing that the discontinuities are not shocks. While cold fronts are usually explained as remnants of past merger events, they have been observed also in apparently regular clusters such as RXJ 1720.1+2638, Abell 1795, 2A 0335+09, and MS 1455.0+223. The gas sloshing induced by the motion of a pre-existing cavity may explain these observations.

Finally, radio-emitting regions as large as 1 Mpc are sometimes found in the outskirts of clusters far from radio sources that might power them. Some of these ‘radio relics’ are quite far from cluster centers. These relics may trace the shock waves generated by merger events. Alternatively, they may represent very late-stage ghost cavities that have been re-energized at some point.

4. AGN as a Source of Heat

As shown above, recent X-ray observations show that the cores of cooling-flow clusters are often far from being settled down; rather, central radio sources drive gas motions that should heat the intracluster medium. It is tempting to argue that this heating addresses the problems with the cooling flow model described in Section 2. However, this cannot be the whole story, and in any case many details remain to be worked out.

Bubbles might heat the ICM in any of several different ways. Part of the jet plasma energy is transferred to the ICM during the process of bubble formation, and also work can be done on the ICM by the adiabatic expansion of the bubbles as they rise. If the bubbles expand subsonically (on average), both of these processes transfer energy into the ICM as weak shocks and sound waves, thus affecting the ICM at a distance from the bubbles themselves and possibly outside the cool core.

The rising of a bubble by buoyancy is a process driven by the potential energy released as the surrounding medium falls in around the bubble to fill the space it occupied. It is easy to show that the potential energy dissipated as the bubble rises is given by the variation of the enthalpy $H = \gamma pV / (\gamma - 1)$ of the bubble. This energy is mostly deposed in the wake of the bubble as kinetic and potential energy of the entrained gas, as turbulence and possibly as gravity waves, and finally converted to heat by damping and/or mixing. This process is called sometimes effervescent heating.

Another possibly effective heating mechanism consists of the mixing of the cold gas uplifted and/or entrained from the cluster center with the hot gas from more external regions that slides off the bubbles during their rise. This mechanism would be as more effective in heating the cool core as more material is radially displaced without disrupting the metallicity profile.

It can be observed that the cold gas uplifted by the bubbles could expand adiabatically into the surrounding warmer ICM due to its higher pressure, thus cooling further before it mixes. This would explain the X-ray observation that the shells of material surrounding cavities appear sometimes colder than the ICM in...
the center of the cluster. If the bubbles survive long enough, they reach a hydrostatic equilibrium position where they expand only laterally, again helping to distribute energy globally in the cooling-flow region. However, the final fate of the bubbles is unclear. While the bubble plasma should finally mix with the ICM, the persistence of ghost cavities suggests that it does not mix significantly on timescales comparable to the bubble rise time. This is a rather difficult behaviour to reproduce even in numerical simulations unless we invoke the presence of a confining magnetic field. It has also been observed in simulations, that bubbles driven by subrelativistic flows tend to resist disruption longer.

Two major points that AGN heating models must address are the lack of correlation between the power of the central radio source and the strength of the cooling flow and the fact that the cavities are not a universal phenomenon. Radio sources are not even detected in some cooling-flow clusters, and cavities are reported only in a fraction of those clusters that host a radio source. A possible solution is then to assume a duty cycle: the cooling of the gas triggers the AGN activity, and the resulting ejected plasma inflates the radio lobes that in turn reheat the ICM and stop cooling. The timescale of the radio lobes’ evolution should then be a few times shorter than the cooling timescale.

Even though it is often observed that the bolometric luminosity of the AGN does not account for the mechanical power needed to balance the cooling, the details of the bubble heating mechanism can be important in determining the AGN duty cycle.

Indeed, simulations have been performed to explore the effect of recurrent bursts of activity from the AGN, but these have shown that the mixing of the ICM that follows the rising of a bubble can endure even for 1 Gyr, thus effectively reducing the cooling that led to the activity in the first place.

While it appears that the rising of the bubbles and related phenomena do not alter the entropy profiles, the observed metallicity gradients place constraints on the efficiency with which bubble can mix the ICM.

Other questions that deserve a better understanding include the possibility that other heating mechanisms cooperate with AGN to prevent cooling, the role of AGN in generating cold fronts, the interaction of bubbles with pre-existing bubbles or with galaxies, and the revitalization of ghost cavities by mergers.

5. The Numerical Approach
Exploring the dynamics of the hot plasma in the cluster environment is a very complex problem, owing to its intrinsic three-dimensionality, and to the chaotic interaction of the hot plasma with the ICM. The main tool consists of hydrodynamic simulations, although some analytic and semi-analytic models exist. We review here some of the most recent results.

Brüggen & Kaiser (2002) perform a pair of very high resolution simulations...
adopting a plane-parallel configuration and a twodimensional system of coordinates. They use the adaptive mesh FLASH code to simulate a region of size 50 kpc × 100 kpc with a resolution of 25 pc. They do not impose a jet or a bubble, but rather they inject energy locally into the ICM: this injection mimics the effect of the jet on the ICM and generates a buoyant cavity. Although this is a rough approximation, this model is able to show that the bubble motion has a significant effect on the ICM: after the passage of the rising bubble, the average cooling time in a gas layer increases by up to a factor 1.4 with respect than the value set in the initial conditions.

Brüggen (2003) extends the previous work adopting a more realistic density distribution; he assumes a modified Navarro, Frenk, & White (NFW) profile for both gas and dark matter and a bipolar distribution for the energy injection. Radiative cooling is also included and the ICM and the hot plasma respectively obey perfect-gas equations of state with γ = 5/3 and γ = 4/3. The simulation is performed again using FLASH and spans a region of size 140 kpc × 140 kpc centered on the cluster center, with a resolution of 68 pc; the energy is injected at some distance from the center in two opposite spherical regions of radius 0.5 kpc at the rate of $L = 6 \times 10^{44}$ erg/s for 208 Myr. The simulation lasts ∼380 Myr. This more realistic simulation confirms the previous results and also shows that cold gas from the cluster core is effectively uplifted by the rising bubbles and appears as bright rims in surface brightness maps.

Brüggen et al. (2002) describe a set of three three-dimensional simulations using the ZEUS-MP code. In the first two cases, they simulate a region of size 10 kpc × 10 kpc × 30 kpc with a resolution of 67 pc. The assumed initial distributions of mass, electron density, temperature and pressure are those of the Virgo Cluster. Cooling is not included and γ = 5/3 is used for both the gas phases. Energy is injected in a sphere of radius $r = 0.7$ kpc at a distance of 9 kpc from the cluster center. Two different values of the energy injection rates are considered: $L = 4.4 \times 10^{41}$ erg/s and $L = 3.8 \times 10^{42}$ erg/s. In a third case, the simulated region spans 16 kpc × 16 kpc × 20 kpc while the source luminosity is $L = 10^{44}$ erg/s. The most relevant result of these simulations consists in the observation that cavities are quite difficult to detect, both in radio and in X-rays. Thus it is suggested that a significant amount of energy can be hidden in bubbles in clusters.

Basson & Alexander (2003) perform a set of two three-dimensional simulations using the ZEUS-MP code adopting a spherical system of coordinates; the grid spans 194 × 64 × 64 cells in $r \times \theta \times \phi$ and is arranged so as to increase resolution along the polar axis, where the jets are placed. The ICM is modeled by an isothermal $\beta$-profile and the dark matter potential is derived accordingly. The computational domain is bounded by two spherical surfaces, and the external radius appears to be ∼2800 kpc as derived from their pictures. Cooling of the gas is accounted for, and the cooling function is created composing expressions from the literature. Instead of injecting energy in spherical regions, two jets of plasma are modeled in these simulations. These simulations show that a long-lived buoyancy-driven convective flow is established by the rising of the cavities. Even if the cluster reverts to
having a cooling flow, the convective motions are able to remove the cold gas accumu-
lating in the cluster core. Indeed there is a net outflow persisting for timescales
of about one order of magnitude longer than the time for which the source is active.

Dalla Vecchia et al. (2004) perform a set of three-dimensional simulations using
the FLASH code in Cartesian coordinates. They consider an isothermal cluster
of mass \( M = 3 \times 10^{14} M_{\odot} \) and temperature \( k_B T = 3.1 \) keV. The dark matter density
follows an NFW profile, so the gas density is derived accordingly. The computa-
tional domain covers a cubic region of 1.9 Mpc on side with a resolution of 7.4
kpc. Radiative cooling is considered. The energy is injected in spheres distributed
in random directions in the cluster halo with a different energy in each simulation
run. A duty cycle in the energy injection is imposed and a new sphere is injected
every 100 Myr, while the simulation lasts for 1.5 Gyr. It is shown that a value of the
injected energy exists which effectively balances the energy loss due to cooling and
preserves the ICM temperature. It is also shown that the cooling rate is reduced not
by the direct heating of the cooling gas, but by its convective transport to regions
of lower pressure.

Omma et al. (2004) perform a set of two three-dimensional simulations using
the ENZO code, with an adaptive grid. They simulate a computational box
635 kpc on side with a resolution of 620 pc. Cooling is neglected, but the AGN
outflow is modeled as a subrelativistic flow starting from the cluster center. The
cavities generated by this flow rise supersonically as long as the source is active,
driving a vortex of uplifted gas in their wake. As the AGN is switched off, the vortex
region finally overtakes the cavity, filling it with cool plasma, which is overdense
with respect to the surrounding ICM. This overdensity is heated by the dissipation
of the \( g \) modes of the cluster and is strongly excited by them before it falls back
inwards.

Omma and Binney (2004) explore the structural stability of cooling flows
adopting a set of five simulations similar to those described above and varying the
jets’ parameters. They raise the possibility that the feedback mechanisms between
cooling gas and radio source breaks down in FRII systems, because they will deposit
the majority of the ejected energy outside the core.

Robinson et al. (2004) perform a set of two-dimensional simulations using the
FLASH code with plane-parallel configuration. The simulated region covers 120 kpc
\times 150 kpc with a resolution of 29 pc. They compare the evolution of bubbles with
and without the presence of conduction and of magnetic field. It is shown that the
magnetic field is indeed necessary to preserve the bubble’s integrity for a time long
enough to observe it as ghost cavity or for a few bubble rise times.

6. Conclusions
The new observations of the cores of cooling-flow clusters show clearly the inter-
action between the central radio source and the ICM. However, the details of this
interaction and its relationship with the cooling flow problem are still uncertain.
The field needs new insights, both from the observational side and the theoretical side.

Deep X-ray observations will detect faint features due to shocks and sound waves and perhaps discriminate between the various models of the outflow from the AGN. Deep radio observations could probably detect faint central radio sources or cavities, while observations at different wavelengths could better determine the power of the sources and test the correlation with the luminosity of the cooling flow.

Future simulations should consider several physical phenomena affecting the ICM and the ejected plasma that have not yet been considered or properly modeled. The role of magnetic fields deserves further examination, particularly considering their effect on the thermal conductivity of the ICM. The modeling of the AGN duty cycle and initial bubble injection are still overly simplified. The equation of state of the relativistic bubble plasma must be treated more carefully. Finally, while the studies to date have considered bubbles in idealized cluster atmospheres, clusters are known to undergo mergers which dramatically affect their structure. The turbulent mixing produced by these mergers and by the motion of galaxies through the ICM should strongly affect the development of AGN-blown bubbles, so it is important that the next generation of bubble simulations consider clusters within their cosmological context.

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References

1. Abell, G. O., 1958, ApJS, 3, 211
2. Zwicky, F., 1933, Helv. Phys. Acta, 6, 110
3. Meekins, J. F., Fritz, G., Chubb, T. A., & Friedman, H., 1971, Nature 231, 107
4. Gursky, H., Kellogg, E., Murray, S., Leong, C., Tananbaum, H., & Giacconi, R., 1971, ApJ, 167, L81
5. Zwicky, F., 1937, ApJ, 86, 217
6. Mitchell, R.J., Ives, J.C., & Culhane, J.L., 1977, MNRAS, 181, 25P
7. Mushotzky, R.F., Serlemitsos, P.J., Smith, B.W., Boldt, E.A., & Holt, S.S., 1978, ApJ 225, 21
8. Fort, B., & Mellier, Y., 1994, AA Rev, 5, 239
9. Cavaliere, A., Menci, N., & Tozzi, P., 1998, ApJ, 501, 493
10. Gunn, J.E. & Gott III, J.R., 1972, ApJ 176, 1
11. Ricker, P. M., & Sarazin, C. L., 2001, ApJ, 561, 621
12. Ritchie, B. W., & Thomas, P. A., 2002, MNRAS, 329, 675
13. De Grandi, S., & Molendi, S., 2002, ApJ, 567, 163
14. De Grandi, S., & Molendi, S., 2001, ApJ, 551, 513
15.Govoni, F., Taylor, G. B., Dallacasa, D., Feretti, L., & Giovannini, G., 2001, A&A, 379, 807
16. Sarazin, C. L., 1988, "X-ray emission from clusters of galaxies", Cambridge University Press
17. Fabian, A. C., 1994, ARA&A, 32, 277
18. Fabian, A. C., Nulsen, P. J., & Canizares, C. R., 1984, Nature, 310, 733
19. Peres, C.B., Fabian, A. C., Edge, A. C., Allen, S. W., Johnstone, R. M., & White, D. A., 1998, MNRAS, 298, 416
20. Nulsen, P. E. J., 1986, MNRAS, 211, 377
21. Johnstone, R. M., Fabian, A. C., Edge, A. C., & Thomas, P. A., 1992, MNRAS, 255, 431
22. Eilek, J. A., proceedings of the conference "X-Ray and Radio Connections", Santa Fe, NM, USA, 3-6 February 2004. astro-ph/0405011
23. Mathews, W. G., Bright, F., Buit, D. A., & Lewis, A. D., 2003, ApJ, 596, 159
24. Peterson, J. R., Paerels, F. B., Kaastra, J. S., Arnaud, M., Reiprich, T. H., Fabian, A. C., Mushotzky, R. F., Jernigan, J. G., & Sakeliou, I., 2001, A&A, 365, L104
25. Tamura, T., Kaastra, J. S., Peterson, J. R., Paerels, F. B. S., Mittaz, J. P. D., Trudolyubov, S. P., Stewart, G., Fabian, A. C., Mushotzky, R. F., Lumb, D., & Ikebe, Y., 2001, A&A, 365, L87
26. Kaastra, J. S., Tamura, T., Peterson, J. R., Bleeker, J. A. M., Ferrigno, C., Kahn, S. M., Paerels, F. B. S., Piffaretti, R., Branduardi-Raymont, G., & Böringer, H., 2004, A&A, 413, 415
27. Makishima, K., Ezawa, H., Fukuzawa, Y., Honda, H., Ikebe, Y., Kamada, T., Kikuchi, K., Matsushita, K., Nakazawa, K., Ohashi, T., Takahashi, T., Tamura, T., & Xu, H., 2001, PASJ, 53, 401
28. David, L. P., Nulsen, P. E. J., McNamara, B. R., Forman, W., Jones, C., Ponman, T., Robertson, B., & Wise, M., MNRAS, 2001, ApJ, 557, 546
29. Kent, S. M., & Sargent, W. L. W., 1979, ApJ, 230, 667
30. Crawford, C. S., Allen, S. W., Ebeling, H., Edge, A. C., & Fabian, A. C., 1999, 306, 857
31. Edge, A. C., 2001, MNRAS, 328, 762
32. Edge, A. C., Wilman, R. J., Johnstone, R. M., Crawford, C. S., Fabian, A. C., & Allen, S. W., 2002, MNRAS, 337, 49
33. Mittaz, J. P. D., Kaastra, J. S., Tamura, T., Fabian, A. C., Mushotzky, R. F., Peterson, J. R., Ikebe, Y., Lumb, D. H., Paerels, F., Stewart, G., & Trudolyubov, S., 2001, A&A, 365, 93
34. Fabian, A. C., Mushotzky, R. F., Nulsen, P. J., & Peterson, J. R., 2001, MNRAS, 321, L20
35. Peterson, J. R., Kahn, S. M., Paerels, F. B., Kaastra, J. S., Tamura, T., Bleeker, J. A. M., Ferrigno, C., & Jernigan, J. G., 2003, ApJ, 590, 207
36. Molendi, S., & Pizzolato, F., 2001, ApJ, 560, 194
37. Böringer, H., Matsushita, K., Churazov, E., Ikebe, Y., & Chen, Y., 2002, A&A, 382, 804
38. Narayan, R., & Medvedev, M. K., 2001, ApJ, 562, L129
39. Zakamska, N. L., & Narayan, R., 2003, ApJ, 582, 162
40. Voigt, L. M., & Fabian, A. C., 2004, MNRAS, 347, 1130
41. Soker, N., & Sarazin, C. L., 1990, ApJ, 348, 73
42. Kim, W.-T., & Narayan, R., 2003, ApJ, 596, L139
43. Birzan, L., Rafferty, D. A., McNamara, B. R., Wise, M. W., & Nulsen, P. E. J., 2004, ApJ in press
44. Burns, J. O., 1990, AJ, 99, 14
45. Ball, R., Burns, J. O., & Loken, C., 1993, AJ, 105, 53
46. Celotti, A., & Blandford, R. D., proceedings of the ESO Workshop "Black Holes in Binaries and Galactic Nuclei", Garching, Germany, 6-8 September 1999, astro-ph/0001056
47. Heinz, S., Reynolds, C. S., & Begelman, M. C., 1998, ApJ, 501, 126
48. Begelman, M. C., in "Carnegie Observatories Astrophysics Series, Vol. 1: Coevolution of Black Holes and Galaxies", ed. L. C. Ho. Cambridge: Cambridge Univ. Press.
49. Begelman, M. C., & Ruszkowski, M., proceedings of the Royal Society Discussion Meeting on the Impact of Active Galaxies on the Universe at Large, London, February 16-17, 2004, astro-ph/0403128
50. Blandford, R. D., & Begelman, M. C., 1999, MNRAS, 303, L1
51. Fabian, A. C., Sanders, J. S., Ettori, S., Taylor, G. B., Allen, S. W., Crawford, C. S., Iwasawa, K., Johnstone, R. M., & Ogle, P. M., 2000, MNRAS, 318, L65
52. McNamara, B. R., Wise, M. W., Nulsen, P. E. J., David, L. P., Sarazin, C. L., Bautz, M., Markevitch, M., Vikhlinin, A., Forman, W. R., Jones, C., & Harris, D. E., 2000, ApJ, 534, L135
53. Blanton, E., L., Sarazin, C. L., McNamara, B. R., & Wise, M. W., 2001, ApJ, 558, L15
54. Sanders, J. S., & Fabian, A. C., 2002, MNRAS, 331, 273
55. Nulsen, P. E. J., McNamara, B. R., Wise, M. W., & David, L. P., 2004, ApJ submitted, astro-ph/0408315
56. Churazov, E., Brüggen, M., Kaiser, C. R., Böhringer, H., & Forman, W., 2001, ApJ, 554, 261
57. McNamara, B. R., Wise, M. W., Nulsen, P. E. J., David, L. P., Carilli, C. L., Sarazin, C. L., O'Dea, C. P., Houck, J., Donahue, M., Baum, S., Voit, M., O'Connell, R. W., & Koekemoer, A., 2001, ApJ, 562, L149.
58. Heinz, S., Choi, Y., Reynolds, C. S., & Begelman, M. C., 2002, ApJ, 569, L79
59. Soker, N., Blanton, E. L., & Sarazin, C. L., 2002, ApJ, 573, 533
60. Markevitch, M., Ponman, T. J., Nulsen, P. E. J., Bautz, M. W., Burke, D. J., David, L. P., Davis, D., Donnelly, R. H., Forman, W. R., Jones, C., Kaastra, J., Kellogg, E., Kim, D.-W., Kolodziejczak, J., Mazzotta, P., Pagliaro, A., Patel, S., Van Speybroeck, L., Vikhlinin, A., Vrtilek, J., Wise, M., & Zhao, P., 2000, ApJ, 541, 542
61. Mazzotta, P., Markevitch, M., Vikhlinin, A., Forman, W. R., David, L. P., & VanSpeybroeck, L., 2001, ApJ, 555, 205
62. Markevitch, M., Vikhlinin, A., & Mazzotta, P., 2001, ApJ, 562, L153
63. Mazzotta, P., Edge, A. C., & Markevitch, M., 2003, ApJ, 596, 190
64. Mazzotta, P., Markevitch, M., Forman, W. R., Jones, C., Vikhlinin, A., & VanSpeybroeck, L., ApJ submitted, astro-ph/0108476
65. Röttgering, H. J. A., Wieringa, M. H., Hunstead, R. W., & Ekers, R. D., 1997, MNRAS, 290, 577
66. Giovannini, G. & Feretti, L., 2000, NewA, 5, 335
67. Roettiger, K., Burns, J. O., & Stone, J. M., 1999, ApJ, 518, 603
68. Miniati, F., Jones, T. W., Kang, H., & Ryu, D., 2001, ApJ, 562, 233
69. Enßlin, T. A., & Gopal-Krishna, 2001, A&A, 366, 26
70. Hoeft, M., Brüggen, M., & Yepes, G., 2004, MNRAS, 347, 389
71. Ruszkowski, M., Brüggen, M., & Begelman, M. C., 2004, ApJ, in press, astro-ph/0403690
Simulations of Hot Bubbles in the ICM

72. Churazov, E., Sunyaev, R., Forman, W., & Böhringer, H., 2002, MNRAS, 332, 729
73. Begelman, M. C., Impact of Active Galactic Nuclei on the Surrounding Medium in "Gas and Galaxy Evolution", ASP Conference Proceedings, Vol. 240. Ed. J. E. Hibbard, M. Rupen, and J. H. van Gorkom. San Francisco: Astronomical Society of the Pacific, 2001, 363, astro-ph/0207656
74. Ruszkowski, M., & Begelman, M. C., 2002, ApJ, 581, 223
75. Quilis, V., Bower, R. G., & Balogh, M. L., 2001, MNRAS, 328, 1091
76. Dalla Vecchia, C., Bower, R. G., Theuns, T., Balogh, M. L., Mazzotta, P., & Frenk, C. S., 2004, MNRAS submitted, astro-ph/0402441
77. McCarthy, I. G., Babul, A., Katz, N., & Balogh, M. L., 2003, ApJ, 587, L75
78. Schmidt, R. W., Fabian, A. C., & Sanders, J. S., 2002, MNRAS, 337, 71
79. Blanton, E. L., Sarazin, C. L., & McNamara, B. R., 2003, ApJ, 585, 227
80. Robinson, K., Dursi, L. J., Ricker, P. M., Rosner, R., Calder, A. C., Zingale, M., Truran, J. W., Linde, T., Caceres, A., Fryxell, B., Olson, K., Riley, K., Siegel, A., & Vladimirova, N., 2004, ApJ, 601, 621
81. Omma, H., Binney, J., Bryan, G., & Slyz, A., 2004, MNRAS, 348, 1105
82. Voit, G. M., & Bryan, G. L., 2001, Nature, 414, 425
83. Basson, J. F., & Alexander, P., 2003, MNRAS, 339, 353
84. Böringer, H., Matsushita, K., Churazov, E., Finoguenov, A., & Ikebe, Y., 2004, A&A, 416, L21
85. Kaiser, C. R., & Binney, J., 2003, MNRAS, 338, 837
86. Brüggen, M., & Kaiser, C. R., 2002, Nature, 418, 301
87. Fryxell, B., Olson, K., Ricker, P., Timmes, F. X., Zingale, M., Lamb, D. Q., MacNeice, P., Rosner, R., Truran, J. W., & Tufo, H., 2000, ApJS, 131, 273
88. Brüggen, M., 2003, ApJ, 592, 893
89. Navarro, J. F., Frenk, C. S., & White, S. D. M., 1997, ApJ, 490, 493 (NFW)
90. Raymond, J. C., Cox, D.P., & Smith, B. W., 1976, ApJ, 204, 290
91. Brüggen, M., Kaiser, C. R., Churazov, E., & Enßlin T. A., 2002, MNRAS, 331, 545
92. Stone, J. M., & Norman, M. L., 1992, ApJS, 80, 753
93. Stone, J. M., & Norman, M. L., 1992, ApJS, 80, 791
94. Nulsen, P. E. J., & Böringer, H., 1995, MNRAS, 274, 1093
95. Sutherland, R.S., & Dopita, M. A., 1993, ApJS, 88, 253
96. Puy, D., Grenacher, L., & Jetzer P., 1999, A&A, 345, 723
97. Tegmark, M., Silk, J., Rees, M. J., Blanchard, A., Abel, T., & Palla, F., 1997, ApJ, 474, 1
98. Makino, N., Sasaki, S., & Suto, Y., 1998, ApJ, 497, 555
99. Theuns, T., Schaye, J., Zaroubi, S., Kim, T., Tzanavaris, P., & Carswell, B., 2002, ApJ, 567, L103
100. Bryan, G. L., & Norman, M. L., 1997, ASP Conf. Ser. Vol. 123, 363
101. Bryan, G. L., 1999, Comp. Sci. Eng., 1, 46
102. Omma, H., & Binney, J., 2004, MNRAS, 350, L13