Carnegie Observatories Astrophysics Series, Vol. 3:
Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution, 2004
ed. J. S. Mulchaey, A. Dressler, and A. Oemler (Pasadena; Carnegie Observatories:
http://www.ociw.edu/ociw/symposia/series/symposium3/proceedings.html)

Magnetic Bubbles in Galaxy Clusters

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Abstract
I discuss *Chandra* X-ray Observatory measurements of cavities in galaxy clusters and their implications for heating the intracluster gas. The emerging paradigm for cooling flows has important implications for understanding self-regulated galaxy formation.

1.1 Introduction

Chandra X-ray images of galaxy cluster cores have revealed a wealth of structure. Once thought to be relatively smooth, quiescent environments, cluster cores are now known to be dynamically complex regions of the universe. Examples of commonly observed structures include sharp surface brightness edges associated with mergers (Markevitch et al. 2000), filaments associated with cooling or dynamical wakes (Fabian et al. 2001), and the topic of this discussion: cavities or bubbles created by interactions between radio sources and the hot gas surrounding them (McNamara et al. 2000).

1.2 Properties of Cavities in Clusters

Cavities have been identified in at least a dozen clusters over the past three years (Bîrzan et al. 2004). The archetypes, Hydra A (McNamara et al. 2000) and Perseus (Böhringer et al. 1993, Fabian et al. 2000), are typical of most systems: twin surface brightness depressions $10-20$ kpc in diameter lying at distances of $10-30$ kpc from the nucleus of the cD. The cavities are devoid of thermal gas at the characteristic temperature of their surroundings. They are filled, however, with radio-synchrotron emitting particles and their accompanying magnetic field. The equipartition pressures within the cavities are generally between $5-10$ times lower than their surroundings (Nulsen et al. 2002, Blanton et al. 2001), which implies that they are short lived. Their ubiquity and and apparently advanced ages suggest otherwise.

Cavity pairs harboring faint radio emission located well beyond their brighter central radio sources, dubbed "ghost cavities" have been discovered in several clusters (eg., Fabian et al. 2000, McNamara et al. 2001). Propelled by buoyant forces, the time required for these cavities to rise to their current locations can approach $\sim 10^8$ yr, or several dynamical timescales. The cavities can survive against collapse to such an advanced age only if they are supported by internal pressure and if they are hydrodynamically stable. The source of this internal pressure is unknown. Candidates include a hot, dilute thermal plasma, a relativistic gas, or magnetic field. The temperature a thermal gas must have in order to support the cavities against collapse, and at the same time, elude detection in existing *Chandra* images is > 15 keV (Blanton et al. 2001, Nulsen et al. 2002). Synchrotron emission limits seem to preclude magnetic field as the sole source of internal pressure in the Perseus cavities (Fabian et al. 2002), so they probably contain very hot, possibly relativistic, gas. Their relatively stable configurations must be aided by surface tension in the bubble rims. Otherwise, the bubbles would quickly disintegrate by Rayleigh-Taylor forces (Soker, Blanton & Sarazin 2002). Magnetic fields are a likely source of surface tension (De Young 2003).

That the temperatures of the rims are as cool or cooler than the ambient gas was perhaps Chandra's most surprising discovery (McNamara et al. 2000, Nulsen et al. 2002). Early theoretical models incorrectly predicted hot rims associated with shock fronts (Heinz, Reynolds, & Begelman 1998). The cool rims imply that the cavities behave like bubbles (Churazov et al. 2001), rising buoyantly at or below the sound speed. The cool gas along the rims was probably lifted by the bubbles from the cooler central regions of the clusters (Nulsen et al. 2002, Blanton et al. 2001). This general picture has been bolstered by the recent discovery of sound "ripples" emanating from the two inner cavities in the Perseus cluster (Fabian et al. 2003).

1.3 Cavity Demographics & Energetics

Cavities have been observed in giant elliptical galaxies, such as M84 (Finoguenov & Jones 2001), groups, such as HGG 62, and clusters (Bîrzan et al. 2004). Their energy content ranges between $pV \sim 10^{55}$ erg s^{-1} in isolated galaxies and groups to $\sim 10^{59}$ erg s^{-1} in rich clusters; their ages range between $\sim 10^7$ yr-10^8 yr. The total energy associated with the cavities can be four times this number if they are filled with a relativistic gas.

1.4 Can Magnetic Bubbles Quench Cooling Flows?

The persistent symptom of the so-called cooling flow problem has been that the cooling rates exceed the star formation rates by at least an order of magnitude. This situation has changed dramatically in recent years. New XMM-Newton and *Chandra* observations (Peterson et al. 2001) have placed limits on cooling to low temperatures that are factors of $5-10$ below the old *Einstein* and *Rosat* rates. This reduction implies that the gas is being maintained at keV temperatures by a persistent energy source. Magnetic bubbles are a plausible source of this energy.

There is growing evidence that bubbles are produced periodically in cooling flow clusters. The older and radially distant ghost cavities in the Perseus cluster (Fabian et al. 2000) and the Abell 2597 cluster (McNamara et al. 2001) were probably created by an earlier generation of the central radio source. The ghost cavities are associated with radio lobes that have since detached from their jets and have traveled buoyantly to their current locations over the past $\sim 10^8$ yr. In the mean time, the rejuvenated central radio source has created a new set of radio-filled cavities near the nucleus. These and perhaps other systems launch cavities every several tens of Myr. Coupled with the fact that cD galaxies in cooling flows are radio audible $\sim 70\%$ of the time (Burns 1990), the rising bubbles may deposit up to $\sim 10^{61}$ erg of energy into the intracluster medium over their lives (McNamara et al. 2001). This would be enough energy to impede or quench a moderately sized cooling flow. The production rate required to prevent cooling in the Perseus cluster, for example, is one bubble pair every $\sim 10^7$ yr (Fabian et al. 2003).

Bubble production may be able to retard or quench cooling in many systems, but apparently not throughout the lives of all systems. For example, the Abell 1068 cluster harbors moderate cooling at a rate $\lesssim 140\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$ (Wise et al. 2004). The star formation rate in its cD galaxy is $\sim 70\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$. To within their uncertainties, the cooling and star formation rates are consistent with each other (McNamara et al. 2004), and there is no need to appeal to heating. Furthermore, Abell 1068 has no cavities, its radio source is weak, conduction is too inefficient to prevent cooling, and supernovae associated with the starburst are incapable of quenching the cooling flow. Abell 1068 has the qualities of a classical cooling flow, at least at this stage of its life. Therefore, all cooling flows do not achieve a steady balance between heating and cooling throughout their lives.

1.5 Conclusions & Speculations about a New Cooling Flow Paradigm

Cooling flows are usually messy systems. Even those in which bubble production is energetically sufficient to prevent cooling, cold gas and young stars abound. Cooling to low temperatures is probably occurring within cD galaxies along filaments of cool gas located near the sites of star formation (McNamara et. al. 2000, Blanton et al. 2003, McNamara et al. 2004). The star formation itself often occurs in bursts.

The emerging cooling flow paradigm no longer supports the notion of long-term, steady cooling. Instead, a cooling cycle that fuels repeated episodes of star formation is established, followed by accretion onto the central black hole. A radio outburst ensues, creating bubbles that reheat the cooling gas. This cycle repeats. Thermal conduction may play a critical role in maintaining the feedback loop (Ruszkowski & Begelman 2002). The existence of a trend between the central X-ray luminosity and cavity energy (Bîrzan et al. 2004) suggests that this process proceeds in a self-regulatory fashion.

This primitive sketch of a cooling flow must include the essential physics of self-regulated galaxy formation. In this picture, black holes regulate the rate at which bulges form. Similar processes may have been operating during the earliest phases of galaxy formation when the relationship between black hole mass and bulge velocity dispersion was established (Ferese & Merritt 2000, Gebhardt et al. 2000). In addition, bubble production is a potential source of preheating during the construction phases of groups and clusters.

1.6 Acknowledgements

I thank my collaborators Michael Wise, Paul Nulsen, Liz Blanton, and Craig Sarazin, and my students Laura Bîrzan and David Rafferty. This research was supported by NASA Long Term Space Astrophysics Grant NAG5-11025, Chandra Archival Research Grant AR2-3007X, and a grant from the Department of Energy through the Los Alamos National Laboratory.

References

Bîrzan, L., Rafferty, D., McNamara, B. R., Wise, M. W., Nulsen, P. E. J. 2004, in preparation
Blanton, E. L., Sarazin, C. L. McNamara, B. R., Wise, M. W. 2001, ApJ, 558, L15
Blanton, E. L., Sarazin, C. L. McNamara, B. R. 2003, ApJ, 585, 227
Böhringer et al. 1993, MNRAS, 264, L25
Burns, J. O. 1990, AJ, 99, 14
Churazov, E., Brüggen, M., Kaiser, C. R., Böhringer, H., & Forman, W. 2001, ApJ, 554, 261
De Young, D.S. 2003, MNRAS, 343, 719
Gebhardt, K., et al. 2000, ApJ, 539, L13
Fabian, A. C. et al. 2000, MNRAS, 318, L65
Fabian, A. C. et al. 2001, MNRAS, 321, L33
Fabian, A. C., Celotti, A., Blundell, K. M., Kassim, N. E., Perley, R. A. 2002, MNRAS, 331,369

Fabian, A. C. et al. 2003, MNRAS, 344, L43
Ferrarese, L., Merritt, D. 2000, ApJ, 539, L9
Finoguenov, A., Jones, C. 2001, ApJ, 547, L107
Heinz, S., Reynolds, C. S., & Begelman, M. C. 1998, ApJ, 501, 126
Markevitch, M. et al. 2000, ApJ, 541, 542
McNamara, B. R., Wise, M., 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
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
McNamara, B. R., Wise, M. W., Murray, S. S. 2004, ApJ, in press
Nulsen, P. E. J., David, L. P., McNamara, B. R., Jones, C., Forman, W.R., & Wise, M. 2002, ApJ, 568, 163
Peterson, J. R., Paerels, F. B. S., Kaastra, J. S., Arnaud, M., Reiprich, T. H., Fabian, A. C., Mushotzky, R. F., Jernigan, J. G., Sakelliou, I. 2001, A&A, 365, L324
Ruszkowski, M. & Begelman, M. C. 2002, ApJ, 573, 485
Soker, N., Blanton, E. L., & Sarazin, C. L. 2002, ApJ, 573, 533
Wise, M. W., McNamara, B. R., Murray, S. S. 2004, ApJ, in press