X-RAY AND RADIO OBSERVATIONS OF INTERACTIONS IN COOLING CORE CLUSTERS

Tracy E. Clarke[1,2], Craig Sarazin[3], Elizabeth Blanton[4], and Namir Kassim[1]

[1]NRL, 4555 Overlook Drive SW, Washington, DC, 20375 USA
[2]Interferometrics Inc., 13454 Sunrise Valley Dr., Suite 240, Herndon, VA, 20171 USA
[3]Department of Astronomy, University of Virginia, P. O. Box 3818, Charlottesville, VA 22903-0818
[4]Astronomy Department, Boston University, 725 Commonwealth Ave., Boston, MA 02215, USA

ABSTRACT

We present a study of the radio and X-ray interactions in the cores of two dense cooling flow clusters. Our recent low frequency radio observations of these systems reveal low energy relativistic plasma which appears to connect the central radio source to the outer ghost cavities seen in Chandra images. We present details of the radio and X-ray observations of Abell 2597 which reveal several outburst episodes of the central AGN and provide the first suggestion of an X-ray tunnel which may be maintained over multiple outburst episodes. New radio observations of Abell 4059 reveal complex source morphology extending into the southeast ghost bubble. This synchrotron emission was not detected in previous higher frequency observations.

Key words: Galaxies: Cooling Flows, galaxies: clusters: individual (A2597, A4059); Radio Continuum: Galaxies.

1. INTRODUCTION

X-ray observations of the central regions of cooling core clusters such as Perseus (Böhringer et al. 1993; Fabian et al. 2000), Hydra A (McNamara et al. 2000), and Abell 2052 (Blanton et al. 2001) have revealed a wealth of detail in the thermal gas. One of the most spectacular results is the profound effect that the central radio sources in these systems have on the structure of the thermal gas. In most cases the active radio sources appear to expand subsonically or mildly transonically into the ICM and slowly displace the thermal gas (Fabian et al. 2000; McNamara et al. 2000). In a few clusters X-ray data reveal depressions or "ghost cavities" which are located well beyond the currently active radio galaxy. These cavities may delineate the location of old radio lobes which have detached and buoyantly risen in the cluster potential (Reynolds et al. 2005). The presence of numerous structures in cluster cores suggests that the central AGN may play a significant role in offsetting cooling in cores.

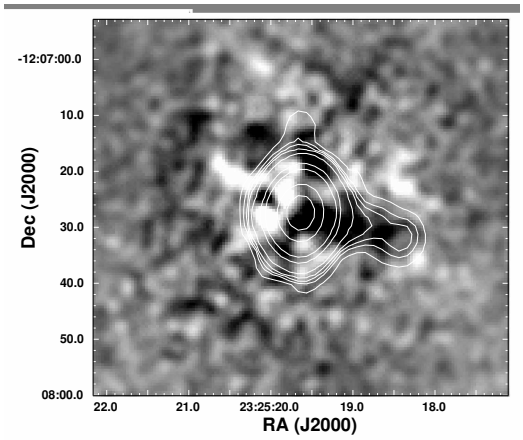

Figure 1. Greyscale shows X-ray residual image of $Chandra$ data for Abell 2597 obtained after subtracting a smooth elliptical model fit from the data. The residuals show significant structure and appear to reveal a tunnel connecting the AGN to the outer western ghost hole. Overlaid are the 330 MHz radio contours showing a low frequency extension running from the compact central galaxy to western hole.

2. ABELL 2597

Abell 2597 is a nearby cluster which contains a compact central radio galaxy (Sarazin et al. 1995) as well as optical and UV emission line filaments. The $Chandra$ X-ray observations of the system by McNamara et al. (2001) revealed the presence of X-ray depressions to the west and northeast located well beyond the active central radio galaxy. We investigated the cluster core structure in more detail by subtracting a smooth elliptical model fit to the $Chandra$ data (Clarke et al. 2005). In our residual map, the cavity to the west appears to be part of an X-ray tunnel running from the central AGN to the western cavity described by McNamara et al. We also see some evidence for a possible inner bubble located to the northeast.

We have analyzed archival VLA 1.4 GHz radio data of the central source and find a radio extension the fills the inner northeastern cavity. Further, a comparison of the 1.4 GHz radio data with the Ly_α filaments from O'Dea et al. (2004) shows that one of the filaments traces the outer edge of the radio extension. This 1.4 GHz data also shows some evidence (at a very low level) of emission extending along the X-ray cavity.

To further study this system we have undertaken new low frequency observations of the central radio galaxy using the 330 MHz system on the VLA. Although we do not resolve the compact central radio source, we find that there is a clear radio extension from the inner source extending to the west giving a total source size of $\sim$ 68 kpc (compared to 8 kpc for the compact source). In Figure 1 we show an overlay of the 330 MHz contours on the $Chandra$ residual image showing that the radio emission is co-incident with the X-ray tunnel.

Using the observed separation between the inner radio source and edge of the 330 MHz extension we expect a buoyancy rise time of $\tau_{buoy} \sim 2 \times 10^8$ yr if the emission represents a detached buoyant lobe from a past outburst of radio activity. The current radio data do not have sufficient resolution to determine whether the radio extension is connected to the central radio source, or whether it represents a detached buoyant radio lobe.

3. ABELL 4059

ROSAT HRI images of the thermal gas in Abell 4059 by Huang & Sarazin (1998) revealed the presence of X-ray cavities roughly aligned with the central radio source. More recently, the analysis of the $Chandra$ images by Heniz et al. (2002) has revealed complex structure in the cluster core which appears to be the result of significant interactions between the ICM and the radio galaxy. Although they find a clear correspondence between the northwest cavity and the 8 GHz radio lobe, there is no evidence of radio emission toward the southeast cavity. Lower frequency radio observations at 1.4 GHz by Choi et al. (2004) also failed to find emission extending into the southeastern cavity leading to the suggestion that the cavity is a ghost cavity from a previous radio outburst.

We have continued our low frequency observations of cooling cores by taking deep 330 MHz observations of Abell 4059. We show these radio contours overlaid on the $Chandra$ X-ray emission in Figure 2 (Clarke et al., in prep.). At low frequencies, the radio source reveals significant extended emission filling the ghost cavity to the east of the southern 1.4 GHz radio lobe.

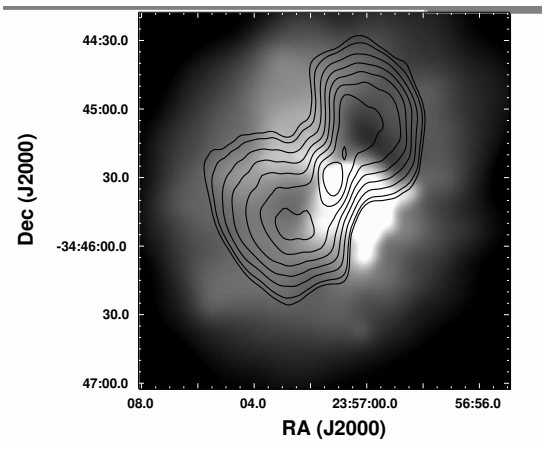

Figure 2. The adaptively smoothed $Chandra$ X-ray image of Abell 4059 is shown in greyscale with the VLA 330 MHz radio contours overlaid. The low frequency radio emission extends well beyond the higher frequency emission seen by Choi et al. (2004) and Heinz et al. (2002) and appears to fill both ghost cavities.

ACKNOWLEDGMENTS

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under a cooperative agreement by Associated Universities, Inc. Basic research in radio astronomy at NRL is supported by the office of Naval Research.

REFERENCES

Blanton, E. L., Sarazin, C. L., McNamara, B. R., & Wise, M. W. 2001, ApJ, 558, L15

Böhringer, H., Voges, W., Fabian, A. C., Edge, A. C., & Neumann, D. M. 1993, MNRAS, 264, L25

Choi, Y.-Y., Reynolds, C. S., Heinz, S., Rosenberg, J. L., Perlman, E. S., & Yang, J. 2004, ApJ, 606, 185

Clarke, T. E., Sarazin, C. L., Blanton, E. L., Neumann, D. M., & Kassim, N. E. 2005, ApJ, 625, 748

Fabian, A. C., et al. 2000, MNRAS, 318, L65

Heinz, S., Choi, Y.-Y., Reynolds, C. S., & Begelman, M. C. 2002, ApJ, 569, L79

Huang, Z., & Sarazin, C. L. 1998, ApJ, 496, 728

McNamara, B. R., et al. 2000, ApJ, 534, L135

McNamara, B. R. et al. 2001, ApJ, 562, L149

O'Dea, C. P., Baum, S. A., Mack, J., Koekemoer, A. M., & Laor, A. 2004, ApJ, 612, 131

Reynolds, C. S., McKernan, B., Fabian, A. C., Stone, J. M., & Vernaleo, J. C. 2005, MNRAS, 357, 242

Sarazin, C. L., Burns, J. O., Roettiger, K., & McNamara, B. R. 1995, ApJ, 447, 559