Tracing Ghost Cavities with Low Frequency Radio Observations

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Summary. We present X-ray and multi-frequency radio observations of the central radio sources in several X-ray cavity systems. We show that targeted radio observations are key to determining if the lobes are being actively fed by the central AGN. Low frequency observations provide a unique way to study both the lifecycle of the central radio source as well as its energy input into the ICM over several outburst episodes.

1 Introduction

The radiative cooling time in the central regions of many dense clusters is less than the age of the cluster. Without any outside disturbance this gas should continue to cool to very low temperatures creating a “cooling flow” in the cluster center \cite{7}. The search for cool gas through X-ray spectroscopic observations has revealed the surprising fact that the temperature drop in cluster cores seems to halt at temperatures around one-third of the maximum cluster temperature \cite{16}. An obvious candidate for energy input to offset significant cooling is the cluster-center AGN, which is typically radio-loud in dense cooling core systems.

X-ray images of several cooling core clusters reveal the presence of significant interaction between the central radio source and the intracluster medium (ICM), thus supporting the idea that the AGN may be a source of energy input to the surrounding gas. The ICM shows evidence of cavities surrounded by (at least partial) rims in several systems. Associated radio observations at 1.4 GHz reveal that many of the cavities are filled with radio plasma from the lobes of the central AGN. In some systems, however, the X-ray cavities are not associated with emission at this frequency. These cavities are generally referred to as “ghost cavities” and are thought to be the result of buoyantly rising lobes from past radio outbursts. One such system, Perseus \cite{8}, shows low frequency radio spurs toward the ghost cavities which suggests that at
At least some ghost cavities are filled with old radio plasma. In order to understand the details of the AGN energy input into the ICM is it necessary to combine the X-ray observations with targeted radio observations over a range of different frequencies. Here we present a few examples of new results from multi-frequency radio observations of cavity systems.

2 Abell 4059

X-ray cavities in Abell 4059 were first detected with the High Resolution Imager on the ROSAT satellite [10]. Subsequent observations with Chandra revealed the presence of a central X-ray bar and showed that the two cavities (Figure 1 left) were not symmetric about the cluster center [9, 3]. Radio observations at 4.8 and 1.4 GHz showed that the emission associated with the central AGN was not aligned with the two cavities and did not extend as far as either cavity [3]. In this context the cavities in Abell 4059 were thought to be buoyant ghost cavities from a previous outburst.

New VLA observations of Abell 4059 at frequencies of 1400 and 330 MHz show that the X-ray cavities are filled with radio plasma (Figure 1 middle & right). The radio emission to the north extends beyond that seen by [3] and bends to the west to fill the cavity. Similarly the southern radio lobe bends to the east to fill the other X-ray cavity. In fact, radio emission within the cavities is seen at frequencies as high as 4.8 GHz, suggesting that the cavities are still being actively fed by the central AGN.

3 Abell 2597

Abell 2597 is well known to host a compact C-shaped radio source in the cluster core [17]. X-ray observations reveal the presence of ghost cavities [12]
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Fig. 2. Left: Unsharp masked Chandra image of the central $\sim 85 \times 125$ kpc region of Abell 2597. This deep (112 ks) image confirms the X-ray tunnel and cavities to the NE and shows evidence of a bright rim surrounding the tunnel. Right: VLA 1.4 GHz radio contours overlaid on the unsharp masked Chandra image.

as well as a tunnel in the ICM gas connecting the core to the western ghost cavity [5]. Evidence for cool gas is seen in HST FUV observations which show diffuse emission as well as filaments and knots [13], while further evidence from cool gas in the cluster core comes from FUSE OVI observations [14].

Radio observations of the cluster core at frequencies of 4.8 GHz and below reveal emission extended beyond the compact C-shaped source. Low frequency (330 MHz) observations show synchrotron emission filling the tunnel [5] while at 1.4 GHz (Figure 2 right) the emission appears to be clumpy and only fills a portion of the tunnel. The 1.4 GHz radio contours also trace emission extended to the NW, as well as an arc of emission to the NE which is associated with the inner NE cavity as well as a bright Ly$\alpha$ filament seen in the HST images.

4 Abell 262

Radio observations of the core of Abell 262 show that it is host to a weak double lobed source [15] which displays an S-shaped morphology. This radio source appears to be interacting with the surrounding thermal gas as seen from Chandra observations of the system which revealed an X-ray cavity associated with the eastern radio lobe [2]. An analysis of the energy required to create the X-ray cavity compared to the cooling luminosity in the system suggested that the current outburst in Abell 262 is too weak to provide sufficient energy to offset cooling [2].

Our unsharp masked analysis of the Chandra data of Abell 262 [1] reveals that the eastern cavity is surrounded by a complete X-ray rim. In addition, the cluster is also host to an X-ray tunnel running westward from the AGN (Figure 3 left). Multi-frequency radio observations at frequencies below 1.4 GHz reveal that the central radio source is more than three times larger than previous observations showed [4]. The 610 MHz emission (Figure 3 right)
fills the western tunnel, eastern X-ray cavity, and reveals three distinct radio features further eastward of the previously detected X-ray cavity. In fact the radio feature closest to the eastern X-ray cavity falls on top of a low significance X-ray deficit seen in the original *Chandra* images [2]. The other more eastern radio features are not detected as X-ray deficits but this may simply be a result of having insufficiently deep X-ray images to detect the depression. If the observed radio features all correspond to separate AGN outbursts (repetition timescale $\sim 3 \times 10^7$ yr) that have created X-ray cavities, then we find that the total energy input from those outbursts is within a factor of two of the X-ray cooling luminosity.

5 NGC 507

The galaxy group NGC 507 displays significant evidence of disturbance to the central X-ray emission [11]. The core shows two central X-ray clumps surrounded by an extended diffuse emission which displays a sharp surface brightness edge running from the northeast to the southeast (Figure 4 left). The sharp edge may be related to a metallicity gradient in the gas where the brighter emission is associated with cooler, higher abundance material [11]. A suggested origin for this material is gas which has been displaced from the central regions by the expanding radio lobe [11]. In the right panel of Figure 4 we show new high resolution VLA 1.4 GHz contours overlaid on the X-ray surface brightness image. The eastern radio lobe is seen to take a sharp bend to the south to trace the inner edge of the X-ray discontinuity, while the western radio lobe seems to be strongly interacting with the central ICM, creating a possible depression between the two central X-ray peaks.
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Fig. 4. **Left:** Gaussian smoothed *Chandra* X-ray image of the central $\sim 115 \times 90$ kpc region of NGC 507. The thermal gas is separated into two clumps in the core and a sharp-edged extension running from the NE to the SE. **Right:** VLA 1.4 GHz radio contours show that radio emission traces morphology of the X-ray surface brightness edge to the SE.

6 Discussion

There is no question that the observations obtained from *Chandra* and XMM have significantly advanced our understanding of the interactions between the central AGN and the thermal gas in galaxy groups and clusters. It is clear that over a wide range of system masses the central AGN has the ability to disrupt the thermal gas in the dense cores of these systems. A detailed understanding of these central interactions requires the addition of targeted multi-frequency radio data that is selected to probe both the relevant spatial scales for the system in question as well as a wide frequency range (including low frequencies) to track the radio outburst history of the central AGN.

In this paper we presented a few cases of sources where new radio observations have changed the view of the system under study. In the case of Abell 4059 it appears that the X-ray cavities are likely still undergoing active injection from the central AGN and thus are not buoyantly rising detached lobes. The radio observations of the central source in Abell 2597 reveal extended structures along several different position angles which are suggestive of multiple outbursts along possibly different initial directions.

In the case of Abell 262 the new radio observations reveal multiple structures along roughly the same position angle. These distinct structures may be signatures of different outburst episodes. Adding up the total energy input
into the ICM from all radio outbursts seen in Abell 262 suggests that the AGN is more powerful than previously thought and is within a factor of two of being powerful enough to offset cooling over several outburst episodes.

The presence of the extended radio emission toward the eastern region of Abell 262 suggests that the low frequency radio flux is originating from detached buoyant lobes from past AGN outbursts. Using the observed projected offset of the radio structures from the cluster cores in Abell 2597 and Abell 262 together with the buoyant velocity in the systems we estimate a repetition timescale for the central AGN of a few $\times 10^7$ yr. This is significantly shorter than the typical assumption of $10^8$ yr. Although there is some evidence of an X-ray deficit associated with one of the eastern emission regions in Abell 262 we note that it is relatively difficult to detect X-ray cavities once they are located beyond the densest parts of the cluster cores [6]. In these cases, low frequency radio observations provide an important tool for tracing the total energy input into the system to determine if it is sufficient to offset the radiative cooling.

Finally, in the case of NGC 507 we note that sensitive, high resolution radio images allow us to trace the interactions of the western radio lobe with the central X-ray structure. These observations also show the clear correspondence between the eastern radio lobe and the southern portion of the sharp surface-brightness discontinuity in the system.

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