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New Results on the AGN Content of Galaxy Clusters

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Abstract

We have analyzed deep, *Chandra* observations of several clusters of galaxies to identify Active Galactic Nuclei (AGN). Comparison of these X-ray observations with ground-based imaging reveals that some of these X-ray sources are associated with optically-bright counterparts. Our spectroscopy of these sources reveals that many are cluster members. These results imply the AGN fraction in clusters is higher than expected and has implications for the impact of the cluster environment on galaxy evolution, the fueling of AGN, the growth of supermassive black holes, and the role of AGN feedback in heating the intracluster medium.

1.1 Introduction

The environment and galaxy population in clusters of galaxies is quite different from the field population. Galaxies in clusters have much higher relative velocities than the field, which results in much less efficient galaxy-galaxy mergers, a difference that is more severe at lower redshift. Cluster galaxies are also dominated by early-type galaxies, especially in their central regions, and cluster galaxies on average have a lower cold gas content and star formation rate than field galaxies. These two physical differences in the environment and composition of galaxies between clusters and the field are commonly invoked to explain the differences in star formation rate between these two environments, a difference which grows progressively starker at lower redshift (e.g., Gunn & Gott 1972).

The same surveys that uncovered the differences in morphology (Dressler 1980) and star formation rate (Poggiati et al. 1999; Dressler et al. 1999) between the cluster and the field populations also noted a significant difference in the number of Active Galactic Nuclei (AGN) in clusters of galaxies relative to the field population (Dressler, Thompson, & Shectman 1985). Extensive spectroscopic surveys of many clusters, which also included some field galaxy 'contamination,' revealed that there were approximately a factor of five fewer AGN in clusters of galaxies relative to the field.

AGN are likely triggered by similar processes to those that fuel star formation. Both phenomena require the presence of a reservoir of cold gas and the removal of its angular momentum, although nuclear accretion and star formation are not necessarily triggered simultaneously or even always by the same event. Galaxy interactions are one of the best candidates for angular momentum loss and the fueling of significant star formation or nuclear activity. The inefficiency of mergers in clusters, combined with their smaller cold gas fractions, is one likely explanation for the relative difference in the AGN fraction in the cluster and field galaxy populations. However, even if galaxy interactions and cold gas content are not the fundamental parameters that determine the frequency of AGN in galaxies, the requirements for fueling star formation and AGN are sufficiently similar that the relative star formation and nuclear accretion rates in cluster and field galaxies are likely to have a similar origin.

These similarities make the study of AGN an additional probe of the interplay between cluster environment and galaxy evolution. The processes that drive accretion onto supermassive black holes occur much closer to the centers of galaxies where the gravitational potential can more effectively shield a reservoir of cold gas from the intracluster medium. The presence of AGN in clusters are therefore an indicator of how effectively galaxies can or can not retain cold gas in their circumnuclear region. The presence of AGN also indicate the growth of the central, supermassive black hole. The recently discovered correlation between supermassive black hole and host galaxy spheroid growth implies that galaxy spheroids may also increase in size in the cluster environment. Finally, while galaxy mergers are commonly invoked as the mechanism responsible for fueling AGN (e.g., Mihos & Hernquist; see also Mihos 2004), the observational evidence that they are in fact the main or only AGN trigger is based on a small number of examples. If the AGN fraction in clusters scales as the velocity dispersion or interaction rate, then this will provide strong evidence that mergers are responsible for fueling AGN.

1.2 Observations

The identification of a large AGN sample with well-defined selection criteria is a challenging task, due to both the small number of all galaxies that host AGN and the myriad effects of varying levels of obscuration, accretion power, and host galaxy luminosity on sample selection. At visible wavelengths these effects are particularly daunting. Large numbers of galaxies must be studied to find the few percent that host sufficiently luminous AGN that they can be detected out to moderate redshifts. Yet even then the sensitivity of a survey to AGN in galaxies depends strongly on distance and the amount of dilution due to significant host galaxy light in the spectroscopic aperture. These effects are difficult to quantify. To surmount these difficulties, we have begun a systematic study of clusters that have deep, archival *Chandra* observations. *Chandra*'s excellent point source sensitivity makes it possible to efficiently preselect galaxies with luminous X-ray emission. We then obtain spectroscopic observations to determine if the optical counterparts of these X-ray sources are cluster members.

To date we have studied four clusters: Abell 2550 ($z = 0.11$), Abell 2104 ($z = 0.154$), AC 114 ($z = 0.31$), and MS 0451.6-0305 ($z = 0.55$; hereafter MS 0451). These four clusters were the targets of long integrations with *Chandra* that are sufficiently sensitive to detect AGN with hard X-ray luminosities of $L_X[2-10\mathrm{keV}] \approx 10^{42-43}\mathrm{erg\,s^{-1}}$ at the redshifts of these clusters. We have obtained multicolor, ground-based images of these clusters with the 2.5m du Pont telescope at Las Campanas Observatory and registered the visible and X-ray data to identify counterparts to the X-ray sources. An *R*–band image of Abell 2104, along with X-ray contours from the *Chandra* observation, is shown in Figure 1. A number of the optically bright galaxies have significant X-ray flux, outside of the well-resolved, diffuse emission from the cluster. Spectra of the optically bright counterparts in Abell 2104 and the other three clusters were then obtained with the LDSS2 spectrograph on the 6.5-m Walter Baade telescope to determine if they are cluster members.

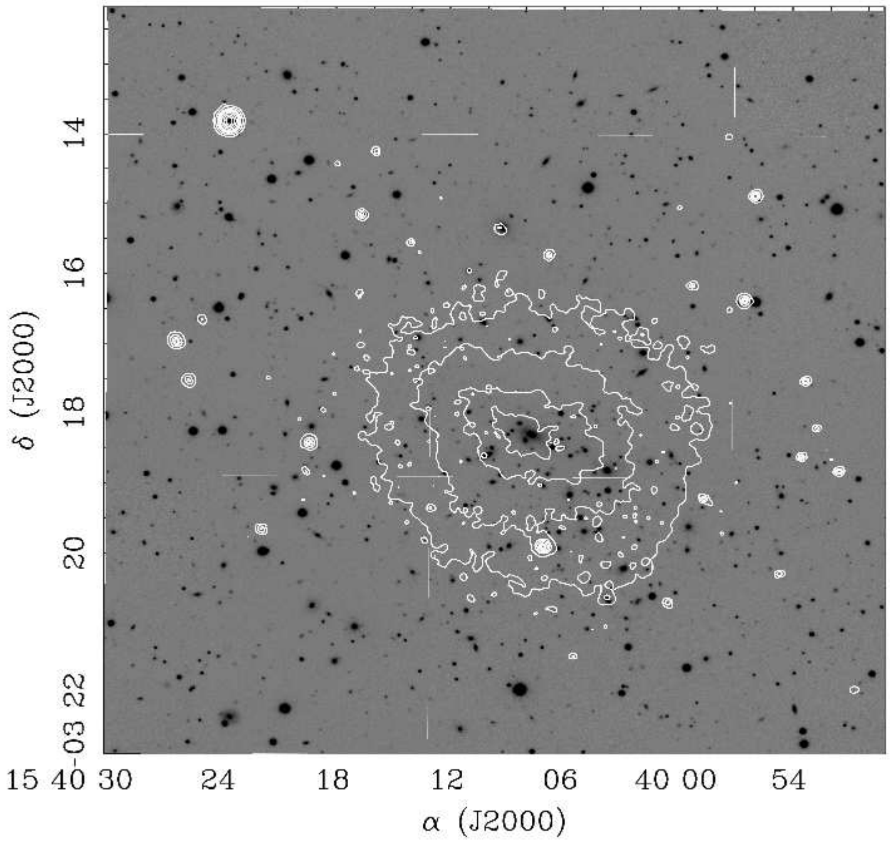

Fig. 1.1. An *R*–band image of the inner $10' \times 10'$ Abell 2104 along with X-ray contours from *Chandra*. In addition to the well-resolved X-ray emission from the intracluster medium, several of bright galaxies also have significant X-ray flux (from Martini et al. (2002), their Fig. 1).

1.3 Results

Many of the X-ray sources in the fields of these clusters are associated with optically luminous galaxies, several of which have very similar colors to cluster members. Figure 1.2 shows color–magnitude diagrams for the fields of the four clusters we have studied to date, including the optically luminous X-ray sources. Each panel of the figure shows the color–magnitude diagram for a different cluster field, where each galaxy is defined by a small point. Known cluster members, either from the literature or from our own spectroscopy (described below) are marked by red, filled circles, while counterparts to the X-ray sources are marked with blue, open circles. For each cluster there are one or more optically luminous X-ray counterparts on the cluster color-magnitude relation (Sandage & Visvanathan 1978), which traces the old, red cluster galaxy population. The X-ray sources that we have confirmed to lie in each cluster are described in the next subsections.

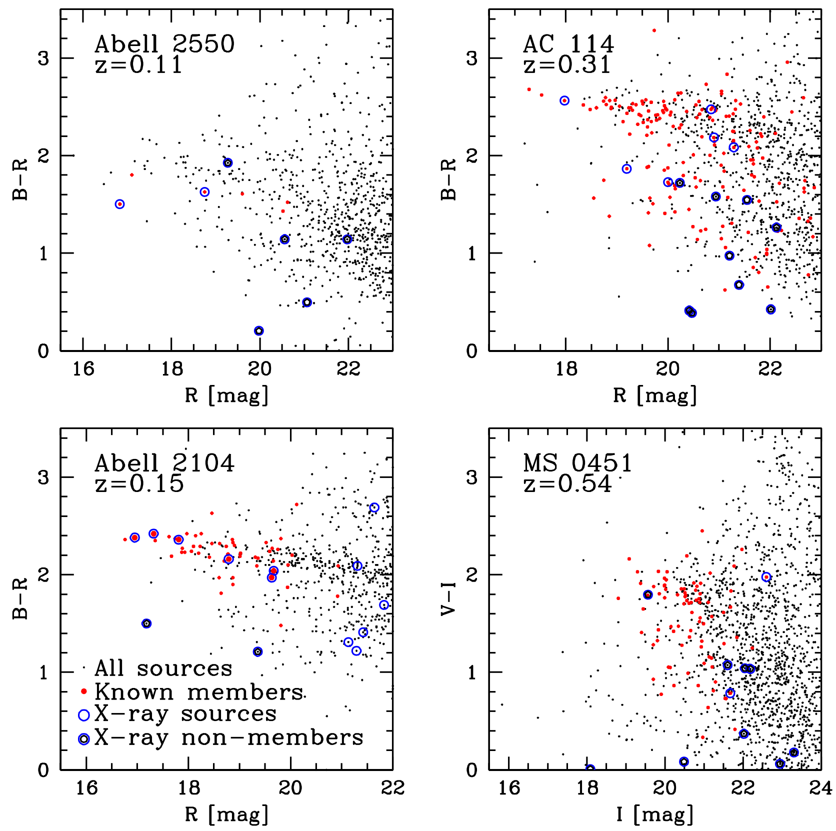

Fig. 1.2. $(B-R)-R$ Color–Magnitude diagrams for the four clusters we observed in 2002: Abell 2550, Abell 2104, AC 114, and MS 0451. Each panel shows all of the photometric data for the cluster field (*points*) along with X-ray sources (*blue circles*), confirmed cluster members (*red dots*), and confirmed X-ray nonmembers (*stars*).

1.3.1 Abell 2104

The field of Abell 2104 ($z = 0.154$) has X-ray sources in eight bright ($R < 20$ mag) galaxies, a much higher fraction than the two expected from the surface density found in blank field surveys (e.g., Mushotsky et al. 2000). We obtained spectra of these X-ray counterparts in April 2002 and determined that six of these X-ray sources were associated with cluster members, while the remaining two were a foreground Seyfert and a background QSO (Martini et al. 2002). All six of the X-ray sources in the cluster fall on the cluster color-magnitude relation (Fig. 1.2), which indicates their host galaxies are red and therefore likely to be dominated by an old stellar population. However, only one of the six shows the optical emission-line signatures characteristic of AGN (see Figure 1.3). The remaining five would not be classified as AGN based on their optical spectra.

Although five of these six X-ray sources do not shown AGN emission-line signatures, the most likely interpretation is that they are nevertheless AGN. This is because these sources have quite high X-ray luminosities, particularly at hard X-rays. There are essentially no other physical mechanisms that can produce comparable hard X-ray luminosities. The only exception is very massive star formation, which has both a lower space density than these low-luminosity AGN and would also be associated with blue galaxies, rather than the red host galaxies we observe in Abell 2104. The red host galaxies for these AGN also appear to be either smooth, early-type disks or ellipticals, which is also more consistent with the AGN interpretation than with massive starbursts.

These six AGN comprise approximately 5% of the brightest hundred cluster members, a factor of five increase over expectations from previous surveys. As only one of these six is optically identifiable as an AGN, this result is perfectly consistent with previous spectroscopic work on the statistics of emission-line galaxies in clusters (Dressler et al. 1985). However, this high AGN fraction is counter to the expectation that cluster galaxies should have less gas and fewer mergers that could create AGN. One explanation for this difference may lie in the kinematics of the host galaxies. The average velocity of these six AGN is offset by nearly $1000 \mathrm{km\,s^{-1}}$ from the cluster, which indicates that some fraction of these AGN may have recently entered the cluster potential. In addition, observations of local ellipticals in clusters show that they can effectively maintain a cold, neutral interstellar medium in their cores, as revealed by *HST* observations of circumnuclear dust lanes (Jaffe et al. 1994; Martel et al. 1999).

1.3.2 Abell 2550

Abell 2550 ($z = 0.11$) was classified as a richness class 2 cluster, although no spectroscopic survey of cluster membership has been published to date. Our spectroscopic work reveals that Abell 2550 is in fact not a cluster at all, but instead a superposition of several groups along the line of sight, including two at $z = 0.11$ and $z = 0.12$. The nearer of these two contains two optically bright X-ray counterparts. As our spectroscopy of the other bright galaxies in the field identified only a total of six galaxies in this group, its AGN fraction appears to be extremely high.

Unlike five of the six AGN in Abell 2104, both of the X-ray sources in Abell 2550 have the optical emission-line signatures of AGN. These two galaxies would be classified as low-luminosity Seyfert 2 galaxies as they have narrow Hα and Hβ permitted lines (see Figure 1.4). The presence of AGN spectral features in both of these X-ray sources, in contrast to only one in six in Abell 2104, may be a reflection of the lower redshift (and therefore smaller dilution) of the Abell 2550 group, or a difference between the low-density group environment and the higher-density cluster.

1.3.3 AC 114

AC 114 ($z = 0.31$) is a well-studied, “Butcher-Oemler” cluster known for its high blue galaxy fraction (Butcher-Oemler galaxies; Butcher & Oemler 1978). It is therefore a very different cluster that Abell 2104, which has essentially no blue, starforming galaxies. This cluster has already been studied extensively (Couch & Newell 1984; Couch et al. 2001) and thus a great deal of membership information already exists. With our new spectroscopy of optically bright X-ray sources (four galaxies), along with the existing membership information for this cluster (two), we have identified a total of six AGN in this cluster (Kelson et al. 2004).

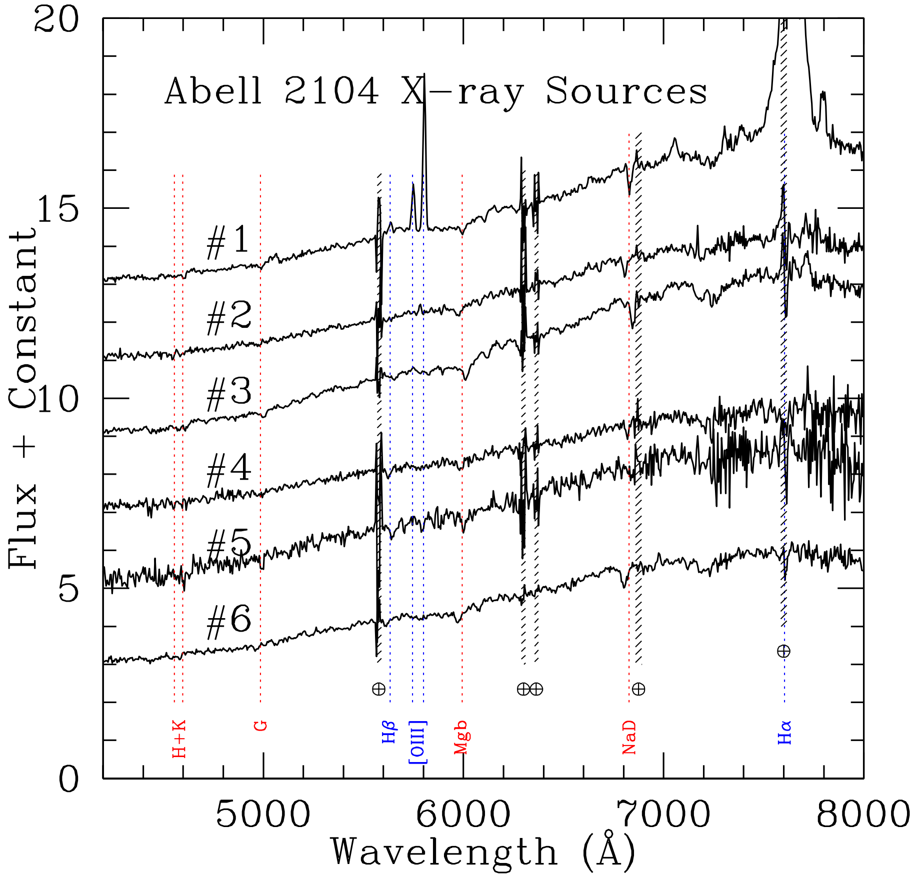

Fig. 1.3. Spectra of the six X-ray sources in Abell 2104. Only the first source has the characteristic spectral signatures of an AGN, the remaining five are classified as AGN based on their significant hard X-ray emission.

While none of our four spectra exhibit AGN spectral signatures (see Figure 1.5), several are in Butcher-Oemler host galaxies. This is in marked contrast to the host galaxies in Abell 2104, or even the group Abell 2550, which were only associated with the red and presumably old galaxies. One of these two galaxies has strong emission lines characteristic of star formation, while the other has an obvious poststarburst spectrum (e.g., Poggianti 2004).

In addition to this spectroscopic work, AC 114 has also been the target of an extensive *HST* imaging study by Couch et al. (1998) to investigate the morphology of the cluster members. The five AGN which fall within the field of view of their WFPC2 images are shown in Figure 1.6. All but the bottom left galaxy in the figure have very smooth surface brightness profiles, although the top left galaxy corresponds to the $k+a$ galaxy (#616) shown in Figure 1.5. The bottom left galaxy is a multiple merger system and corresponds to the emission-line galaxy #1172 shown in Figure 1.5.

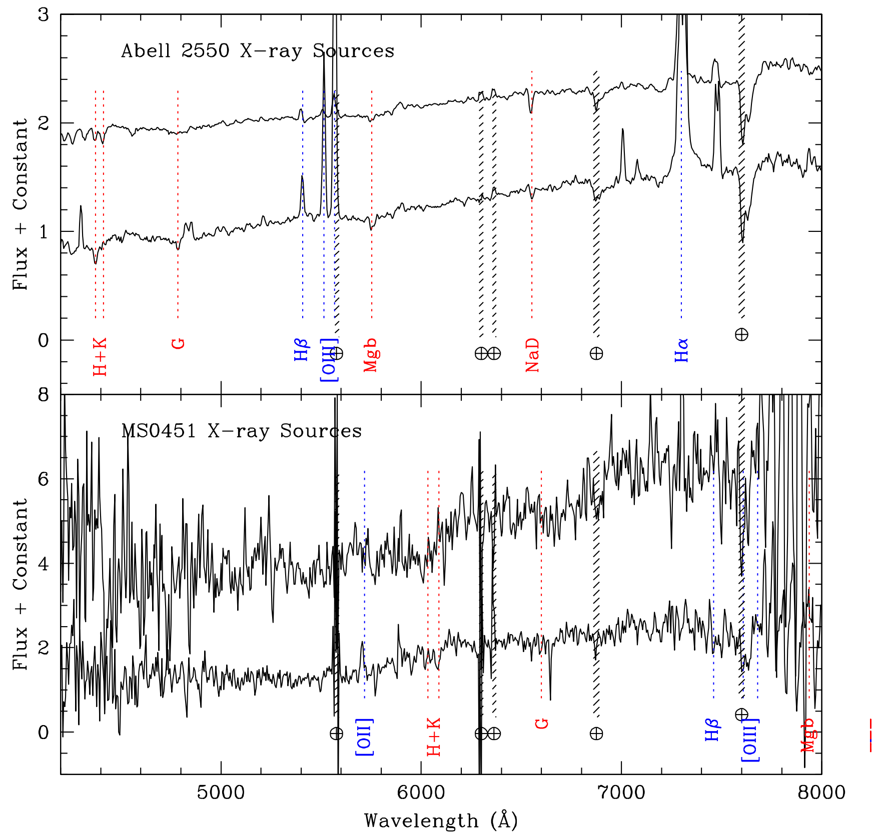

Fig. 1.4. Spectra of X-ray sources in Abell 2550 and MS 0451. Both sources in the Abell 2550 group at $z = 0.11$ show AGN emission features, while the two sources in MS 0451 only show weak emission lines that may be due to recent star formation. All of these sources are sufficiently X-ray luminous that it is likely that they are AGN. These four sources are also in red galaxies that fall on their group/cluster color-magnitude relation.

1.3.4 MS 0451

MS 0451 ($z = 0.55$) is the most distant cluster we have studied. While the *Chandra* observation is unfortunately not deep enough to detect X-ray sources at a comparable flux limit to the three, lower-redshift clusters described previously, we have nevertheless identified two X-ray sources in this cluster. Both AGN are in red cluster members (fig. 1.2), although both also have weak [OII] $\lambda 3727$ emission (fig. 1.4).

MS 0451 is one of several clusters have have been studied by other investigators to determine if the clusters have an excess point source population relative to blank *Chandra* fields. These studies have found that several clusters have an X-ray point source excess, which suggests that these clusters also have significant AGN populations (Cappi et al. 2001; Sun & Murray 2002). Interestingly, Molnar et al. (2002) studied this cluster (using the same

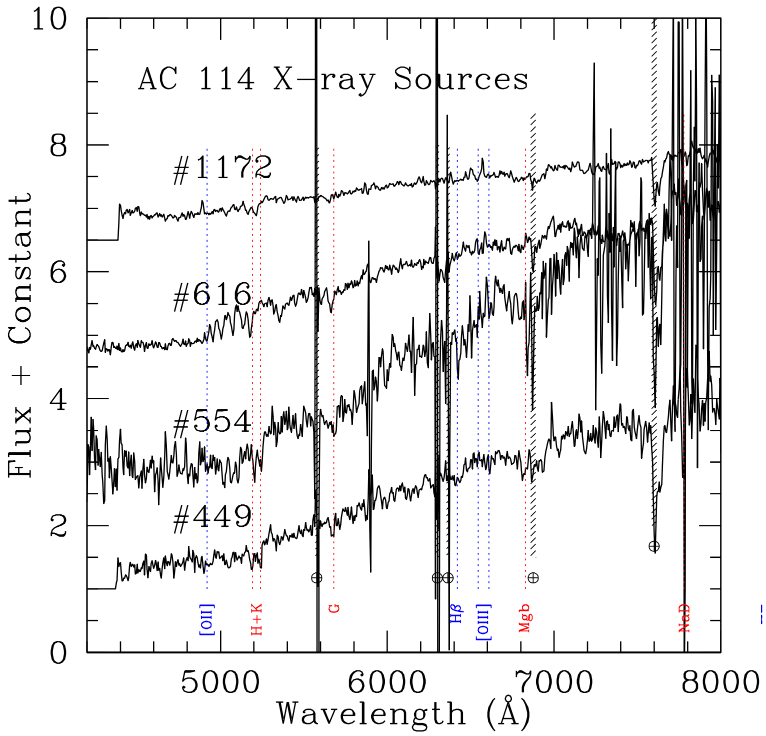

Fig. 1.5. Spectra of four of the six X-ray sources in AC 114. Only two of these sources are in red cluster members, the other two are in blue cluster galaxies. One of these two blue host galaxies is an emission-line galaxy, the other is a poststarburst galaxy.

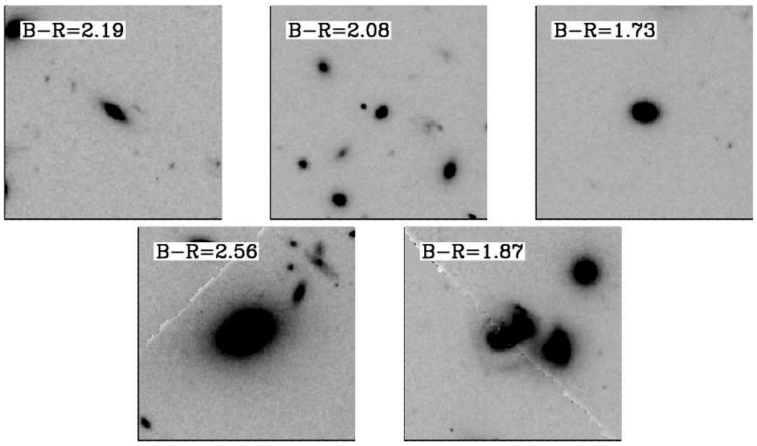

Fig. 1.6. Morphology of the five X-ray sources in AC 114 with archival *HST* observations. The poststarburst galaxy (#616) is shown in the top left, the emission-line galaxy (#1172) is the multiple merger in the bottom right panel. The remaining galaxies are red cluster members.

X-ray data) and determined that it does *not* have a point source excess. The presence of two relatively bright $L_X > 10^{42} \mathrm{erg\,s^{-1}}$ hard X-ray sources in this cluster suggests that even clusters without a point source excess may still have a significant AGN population. This is particularly likely in high-redshift clusters where the X-ray observations tend not be sensitive enough to detect low-luminosity AGN due to their relatively shorter integration times. Higher-luminosity AGN, such as these, have sufficiently lower space density that they may not be present in sufficient numbers to cause a point source overdensity.

1.4 Discussion

Our study of the AGN content of clusters of galaxies reveal that their AGN population may be significantly larger than expected. This new, more complete census of the cluster AGN population is possible due to the excellent point-source sensitivity of *Chandra*. X-ray selection is a much more efficient technique for identifying AGN, because essentially all luminous X-ray point sources are AGN, whereas they comprise only a fraction of galaxies that are luminous at visible wavelengths. X-ray selection is also more readily quantifiable.

The difference between optical and X-ray measurements of the AGN population in clusters, as well as in the field, could be due to two effects. The first is that the emission lines used to characterize AGN could be significantly diluted by host galaxy starlist. This effect is important even at low redshift, where for example the Palomar Seyfert Survey uncovered evidence for AGN in many bright, nearby galaxies that were previously considered to be inactive (Ho, Fillipenko, & Sargent 1997). This problem of dilution is compounded for higher redshift sources, where the typical spectroscopic aperture includes a greater fraction of the host galaxy light. Secondly, the AGN in these clusters, and perhaps in other "normal" high-redshift galaxies with X-ray emission, may be blocked from view at visible wavelengths by significant obscuration near the active nucleus. Even though *Chandra* has excellent hard X-ray sensitivity, a neutral Hydrogen column density of $N_H > 10^{23}$ cm^{-2} would obscure all but the most powerful of the AGN we have identified.

The presence of greater numbers of AGN in clusters bears on a number of current topics of research, including the effect of environment on galaxy evolution, the mechanisms for fueling AGN, and the role of AGN feedback in reheating the intracluster medium. Measurement of AGN fraction in clusters of galaxies as a function of redshift, and other cluster properties such as mass and dynamical state, will begin to significantly address these questions.

If the AGN fraction varies in different environments in a similar manner to the merger or interaction rate, then this will be strong evidence that mergers are indeed the dominant mechanism for fueling AGN. Two avenues that will pursue this issue further are the morphology of the AGN host galaxies and the radial distribution of AGN in clusters. Measurement of an enhanced frequency of mergers and tidal interactions in cluster AGN, relative to other cluster galaxies with similar colors, would provide strong evidence that interactions are responsible for the nuclear accretion (Kelson et al. 2004). In addition, most of the the mergers and interactions in clusters, particularly at low redshift, takes place in infalling groups of galaxies, where the local velocity dispersion is much lower than that of the cluster as a whole. An excess of AGN at large cluster radii, or on radial orbits, would further support this scenario.

Finally, AGN in clusters of galaxies may also have a significant impact on the evolution of the intracluster gas. AGN feedback, in the form of kinetic energy injected by jets, may be responsible for the absence of the extremely cool (< 1 keV) gas at the centers of clusters predicted by cooling flow models (e.g., Allen et al. 2001; Fabian et al. 2001). A census of the AGN population in clusters is one of the important measurements needed to quantify the potentially important role of AGN feedback in heating the intracluster medium.

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