Evolution of a Powerful Radio Loud Quasar 3C 186 and its Impact on the Cluster Environment at z=1

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Abstract.
   X-ray cluster emission has been observed mainly in clusters with "inactive" cD galaxies ($L_{bol} \sim 10^{40} - 10^{43}$ erg sec^{-1}), which do not show signs of accretion onto a SMBH. Our recent *Chandra* discovery of >100 kpc scale diffuse X-ray emission revealed the presence of an X-ray cluster associated with the radio loud quasar 3C 186 at redshift z=1.1 and suggests interactions between the quasar and the cluster. In contrast to the majority of X-ray clusters the 3C 186 cluster contains a quasar in the center whose radiative power alone exceeds that which would be needed to quench the cluster cooling. We present the *Chandra* X-ray data and new deep radio and optical images of this cluster. The 3C 186 quasar is a powerful Compact Steep Spectrum radio source expanding into the cluster medium. The 2 arcsec radio jet is unresolved in the *Chandra* observation, but its direction is orthogonal to the elliptical surface brightness of the cluster. The radio data show the possible presence of old radio lobes on 10 arcsec scale in the direction of the radio jet. We discuss the nature of this source in the context of intermittent radio activity and the interaction of the young expanding radio source with the cluster medium.

1. Introduction

We present an X-ray cluster at redshift z=1.1 associated with the radio loud quasar 3C 186. Diffuse X-ray emission surrounding a luminous quasar has only

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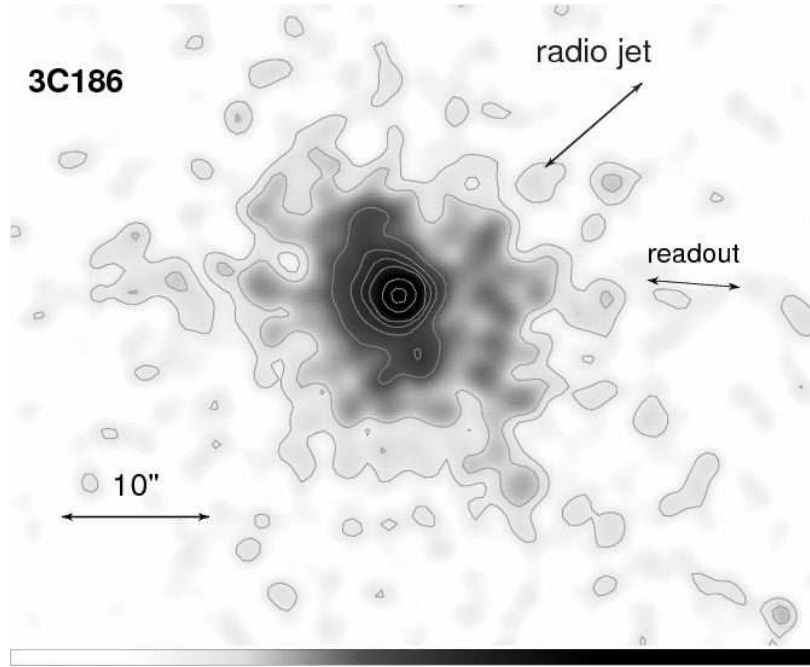[1]Jansky Postdoctoral Fellow of the National Radio Astronomy Observatory

Figure 1. Smoothed *Chandra* ACIS-S (0.3-7 keV) image of 3C 186 The diffuse cluster emission extends to ~120 kpc from the central quasar. The 10 arcsec (82 kpc) size is marked. The direction of an unresolved 2 arcsec radio jet is also marked; it is orthogonal to the elliptical distribution of the cluster X-ray emission.

been detected around a handful of low-redshift ($z < 0.4$) radio-loud quasars (Siemiginowska et al. (2005), Stockton et al. (2006)) and around a few $z > 0.5$ radio galaxies (Belsole et al. 2006). 3C 186 cluster is at high redshift. Its X-ray surface brightness is high enough to allow for measuring the cluster redshift and constraining the properties of the cluster at $z \sim 1$. This paper discusses the properties of the quasar, the cluster and their interactions.

2. 3C186: Quasar

3C 186 is a very luminous quasar ($L_{bol} \sim 10^{47}$ erg sec^{-1}). It has a strong big blue bump (BBB) in the optical-UV band and broad optical emission lines. The quasar SED is shown in Fig. 2. The strong big-blue bump emission is generally interpreted as thermal emission from an accretion disk surrounding the SMBH. The total luminosity of the 3C 186 BBB is equal to 5.7×10^{46} erg s^{-1}. Assuming accretion at the Eddington limit we obtain a black hole mass of $4.5 \times 10^8 M_\odot$. Using the measurement of CIV FWHM from Kuraszkiewicz et al. (2002) and the scaling from reverberation mapping (Vestergaard 2002) the estimated mass of black hole is larger and equal to $3.2 \times 10^9 M_\odot$. Thus the central SMBH is large and given the required accretion rate of $\sim 10 M_\odot$ yr^{-1} to power this system it is still growing.
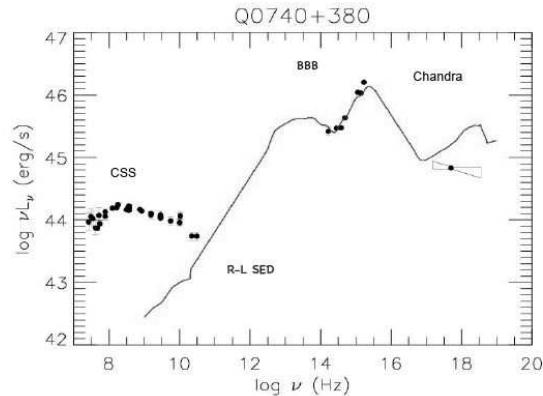
Figure 2.   Spectral energy distribution of the 3C 186 quasar. The *Chandra* data are plotted with the 1σ bow-tie regions. The radio and optical photometric data points are taken from NED. The solid line represents the average radio-loud quasar SED from Elvis et al. (1994) normalized at $\log \nu = 14.5$.

The quasar is extremely radio loud (radio loudness equal to $\mathrm{Log}(F_{5\mathrm{GHz}}/M_B) = 4.3$) as shown in Fig.2. where the average radio-loud quasars SED from Elvis et al. (1994) is drawn for a comparison. The radio morphology in Fig. 3 shows two components separated by $2''$ and a jet connecting the core and NW component. Murgia et al. (1999) estimated the age of the source to be of the order of $\sim 10^5$ years based on the spectral age of the radio source.

3.   3C186: Cluster

3.1.   X-ray Cluster

Chandra detected $\sim$740 source counts in a diffuse emission surrounding the quasar. We fitted the X-ray spectrum and determined a cluster redshift of $z = 1.1 \pm 0.1$ and estimated the X-ray cluster parameters (see Siemiginowska et al. (2005)). The temperature of $5.2^{+1.3}_{-0.9}$ keV and gas mass fraction of $\sim 10\%$ are typical of other clusters at this high redshift (Vikhlinin et al. 2002). Modeling of the cluster surface brightness gives a normal value of $\beta{=}0.64^{+0.11}_{-0.07}$, but a relatively small core radius of $\sim$45$\pm$12 kpc. The cluster luminosity, $L_{(0.5-2keV)} = 6 \times 10^{44}$ erg sec^{-1} is typical for the measured cluster temperature.

Diffuse X-ray cluster emission is detected out to $\sim$ 15 arcsec ($\sim$ 120 kpc, Fig. 1.). The X-ray cluster emission is non-symmetric and elongated in the NE-SW direction. This structure is orthogonal to the 2 arcsec radio jet unresolved in the *Chandra* observation. The hardness ratios indicate possible spectral differences within the NE-SW sectors with the harder emission towards the NE. Fitting a thermal model shows temperature variations between 3.7 keV and 4.9 keV, but with large errors $\pm$1.5-2 keV.
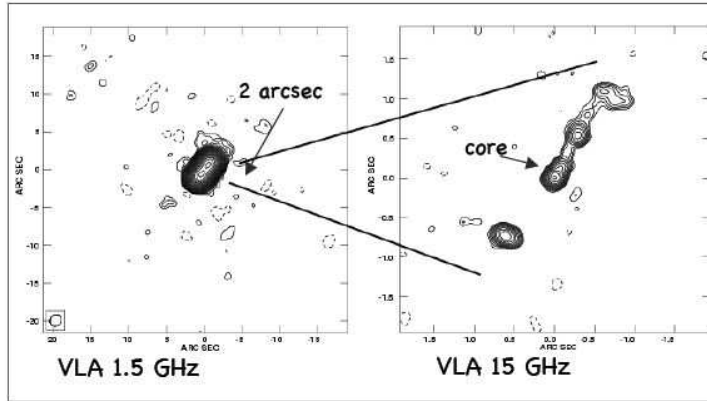
Figure 3.   **Left:** VLA 1.5 GHz image of 3C 186 from reprocessing of the archival datasets published in van Breugel et al. (1992). The restoring beam is 1.62" × 1.44" at position angle –42.7 degrees shown at bottom left. The image peak is 565 mJy/bm and contour levels begin at 0.5 mJy/beam (2σ) and increase by factors of $\sqrt{2}$. Some extended radio emission is apparent, though not at the angular scale of the observed extended X-rays. North is up East is left. **Right:** High resolution (0.15″) VLA 15 GHz image of 3C 186 showing two lobes and a jet connecting the core with the Northern Lobe. This structure is entirely located within a 2 arcsec (∼16 kpc) region. The image peak is 21.6 mJy/beam, and contours begin at 0.65 mJy/beam increasing by factors of $\sqrt{2}$.

3.2.   Optical Cluster

Quasars are usually observed to be offset from the optical peak emission in rich clusters at high redshift (Barr et al. 2003) suggesting loosely bound systems such as groups or proto-clusters, in the process of forming and undergoing mergers. The optical image (GEMINI, GN=2007A-Q-110) of the cluster taken in February 2007 is overlayed with the *Chandra* X-ray contours and is presented in Fig.4. There are many faint candidate cluster members in the field and their distribution will provide information about the structures formed in this cluster. We currently have a program to measure redshifts of the galaxies in the cluster field.

4.   Quasar-Cluster Interaction

The 3C 186 radio jet and two hot spots are not resolved in the *Chandra* X-ray image. The hot spots are separated by 16 kpc and located outside the host galaxy. Thus the jet is moving within the cluster medium. There are two aspects of the possible quasar cluster interaction: (1) cluster impact on the jet motion and (2) a transfer of the jet power to the cluster medium. The presence of the
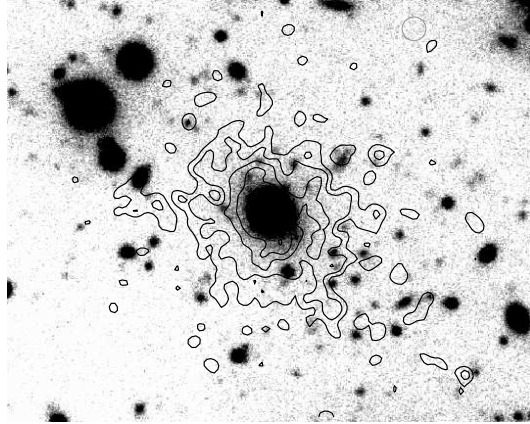
Figure 4. The *Chandra* contours of the X-ray cluster emission superimposed on the Gemini-GMOS r'-band image. The bright object in the center is the quasar, and numerous faint candidate cluster members are visible around it.

cluster allows us also to look for the signature of past quasar activity in the form of a relic radio source.

4.1. Jet Progress

Based on the cluster central density and temperature, we estimate a thermal pressure of $\sim 5 \times 10^{-11}$ dyn cm^{-2}. If this pressure is higher than the pressure within the expanding radio components then the cluster gas may be responsible for confining the radio source and its small size. Taking the radio spectral index to be 1, and approximating each component as a homogeneous spheroid, we estimate the minimum pressure in each radio component to be $\sim 10^{-8}$ dyn cm^{-2}. Thus the radio source is highly overpressured by about 2-3 orders of magnitude with respect to the thermal cluster medium and its expansion has not been affected by the medium.

The jet might also interact and be stopped by a clumpy cold medium of the host galaxy (Carvalho et al 1998, De Young 1991) and clouds with densities of 1-30 cm^{-3} are required to confine a jet. To estimate the total size of the clumpy medium we can use the limit to the total X-ray absorbing column density intrinsic to the quasar. The X-ray absorption limit of $N_H < 9 \times 10^{20}$ cm^{-2} gives the size of any clumpy medium along the line of sight of order 10-100 pc compared with the 16 kpc diameter of the radio source. Any such region cannot significantly limit the expansion of the radio source (see also discussion in Guainazzi et al. (2004)).

4.2. Cluster Heating

The radio components are overpressured with respect to the thermal cluster gas. Thus the expansion of these components into the cluster medium could potentially heat the center of this cluster. The energy dissipated into the cluster by the expanding radio components has been widely discussed in the context of
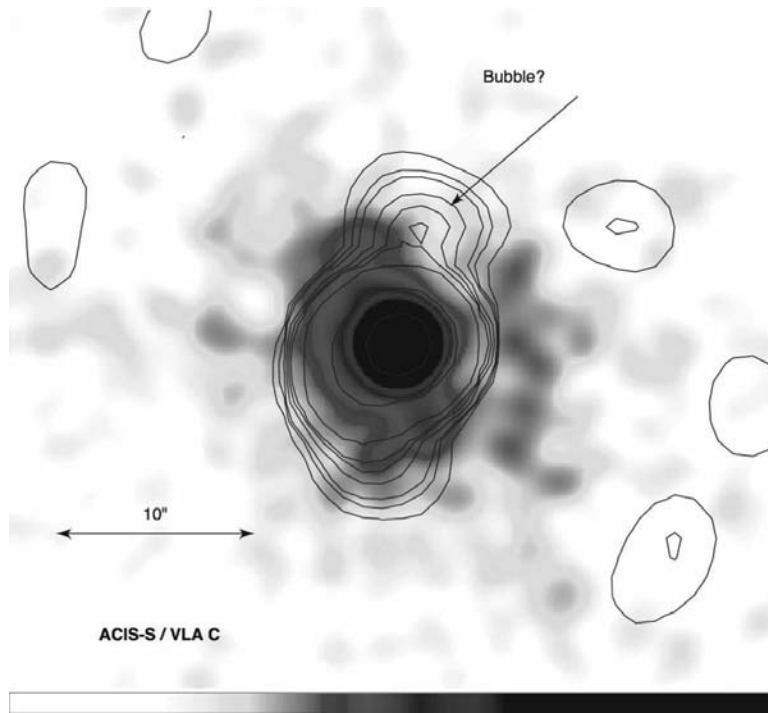
Figure 5.   VLA contours (1.4 GHz, C-configuration, July 2005) overlayed on the smoothed ACIS-S image of 3C 186. The radio image is "super-resolved" with a 3 arcse beam. The radio contours start at 0.35 (this is mJy/beam - corresponds to 3*rms) and continue at 0.7,1,2,3,4,10, 100, 500.

low redshift clusters, where there is evidence for repetitive outbursts of an AGN. However, the details of the dissipation process are undecided.

We estimate the energy content of the hot cluster gas assuming a total emitting volume of $2.3 \times 10^{71} \mathrm{cm}^3$ and $kT \sim 5$ keV, to be of the order of $\frac{3}{2} kTnV \sim 2 \times 10^{61}$ ergs. Using the 151 MHz flux density of 5.9×10^{-24} erg sec^{-1} cm^{-2} Hz^{-1} Hales et al. (1993)Willott et al. (1999) scaling which accounts for the total radio emission from the jet and hot spots, the jet kinetic power is of order $L_{jet} \sim 10^{46}$ erg sec^{-1}. If the expanding radio source dissipated this jet energy into the cluster's central 120 kpc region, then the heating time would be $\sim 10^8$ years. We can also estimate the amount of mechanical work done by the jet and radio components during the expansion to the current radio size ($2'' \times 0.3'' \sim 2.3 \times 10^{66} \mathrm{cm}^3$) as $pdV \sim 10^{56}$ ergs. If the expansion velocity is of the order of $0.1c$ then the radio source has been expanding for about 5×10^5 years with an average power of 6×10^{42} erg sec^{-1}. The estimated jet power is ~ 3 orders of magnitude higher.

4.3.   Relic?

Large scale radio emission can indicate quasar radio activity in the past. We obtained a deep VLA image of 3C 186 in July 2005 to look for any emission associated with the discovered X-ray cluster. In Fig. 5 we show the smoothed ACIS-S image overlayed with 1.4 GHz radio contours from our observation.

Extended emission is visible in N-S direction in the radio contours. Note that the elongation is slightly different than the elongation of X-ray emission, so the northern radio "lobe" points to a location of lower surface brightness in the cluster.

We estimated a negative signal ("bubble") in the X-ray data at the location of the northern radio lobe by comparing a number of counts in a circular region ($r=2.5$") centered on this lobe to the background counts in an annulus at the same distance from the quasar. We detect a deficit of -13.9 counts (1.5σ) at that location.

5.   Summary

- We detect a powerful radio loud quasar in an X-ray cluster at redshift $z = 1.1$.

- Based on radio and X-ray observations we conclude that the radio source has not been confined by the cluster gas.

- The source is at an early stage of expansion.

- Possible relic activity reflected in the X-ray and radio emission will be confirmed with the future *Chandra* and VLA observations.

- Optical spectroscopy is needed to determine redshifts of the galaxies and the cluster members.

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