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X-ray Emission from a Proto-cluster at $z = 3.8$

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Abstract

We present X-ray imaging from *Chandra* of the high-redshift radio galaxy 4C 41.17 ($z = 3.8$). Our 150-ksec exposure detects strong X-ray emission from a point source coincident with the nucleus of the radio galaxy. In addition we identify extended X-ray emission with a luminosity $\sim 10^{46}$ erg s^{-1} covering a 100 kpc ($15''$) diameter region around the radio galaxy. The extended X-ray emission follows the distribution of radio emission in the radio lobes of this source, and the distribution of a giant Lyman-α emission line halo, while the spectrum of the X-ray emission is non-thermal and matches the power law index measured in the radio. We conclude that the most likely source is Inverse-Compton scattering of far-infrared photons from a relativstic electron population likely associated with past and current activity from the central object. Assuming equipartition in the radio plasma, the energy density in the CMB at $z = 3.8$ can account for the observed X-ray and radio luminosities. Published submillimeter maps of 4C 41.17 have detected an apparently extended and extremely luminous far-infrared emission around the radio galaxy, and this component may also contribute significantly to the pool of photons available for Inverse-Compton scattering into the X-ray. We suggest that photo-ionization by these Inverse-Compton X-ray photons may play a significant role in this system, and provides a new physical feedback mechanism to preferentially effect the gas within the most massive halos at high redshift. This is the highest redshift example of extended X-ray emission around a radio galaxy currently known and points towards an extraordinary halo around such systems, where cool dust, relativistic electrons, neutral and ionized gas, and intense infrared and X-ray radiation all appear to coexist.

1.1 Introduction

One of the major discoveries from *Chandra* observations of low and intermediate redshift clusters is the identification of bubble-like structures in the X-ray images (McNamara et al. 2000). These are apparently associated with energy injection due to nuclear activity from active galactic nuclei (AGN) in the brightest cluster galaxies. It appears that powerful radio jets are particularly effective mechanisms for inputting mechanical energy to the intracluster medium (ICM). This activity may influence the structure and energetics of gas in the highest density regions in the clusters. In particular, the redistribution of gas produced by this injection of energy may have profound consequences for the rate of cooling of gas in these regions. Such a conclusion would have an impact on a variety of fields, including theoretical modeling of galaxy formation – as large-scale cooling of gas is a critical route for building the baryonic mass of galaxies (Cole et al. 2000). Studying the influence of AGN on their surroundings is therefore important for determining the capacity of this form of feed-back to delay the on-set of gas accretion and star-formation in massive galaxies at high redshifts. The scaling properties of the ICM are also best explained by an absence of large amounts of very low entropy gas in cluster cores (Kaiser 1991, Evrard & Henry 1991, Mushotzky & Scharf 1997). Finding a workable mechanism for accomplishing this is at the forefront of cluster formation studies (e.g. Tozzi & Norman 2001, Voit et al. 2002), and likely candidates are heating and cooling of the ICM.

The possible role of radio sources in influencing the thermodynamics of dense gas in their environments is compounded by observations which demonstrate that individual, luminous, radio galaxies at high redshifts ($z > 2$) reside in apparently overdense regions: as traced through excesses of Lyman-break galaxies, Lyman-α emitters, Extremely Red Objects, X-ray detected AGN or luminous submillimeter galaxies (Steidel et al 1999; Pentericci et al. 2000; Kurk et al. 2000; Chapman et al 2000; Pentericci et al. 2002; Ivison et al. 2000). Thus the feedback from AGN (and star formation) in bright radio sources may have had ample opportunity to influence the formation and evolution of galaxies in regions which are believed to evolve into the cores of clusters at the present-day. Studying luminous radio galaxies in high-density environments at high redshifts therefore provides an important route to track the changing effects of feedback during the formation of a massive cluster of galaxies.

We present here a deep *Chandra* observation of one of the most distant and powerful high-redshift radio galaxies; 4C 41.17 at $z = 3.8$. Recent submillimeter observations of this galaxy using the SCUBA camera have detected intense, and apparently spatially-resolved, submm emission from the radio galaxy (Ivison et al 2000; Stevens et al. 2004). This emission is thermal radiation coming from dust grains within the galaxy which are heated by UV photons from young stars or an AGN. The far-infrared luminosity of the galaxy is in excess of $10^{13}\,L_\odot$ and the inferred mass of dust is around $6 \times 10^8\,M_\odot$ (Stevens et al 2004), both of which suggest intense star formation is occuring within 4C 41.17. Further evidence for extreme activity occuring in the vicinity of the radio galaxy includes the presence of an extended Lyman-α halo reaching to $>$100 kpc (Chambers et al. 1990; Reuland et al. 2003) as well as spatially-extended [O II] and [O III] emission on similar scales (van Breugel et al. 2002).

1.2 Results

As illustrated in Figure 1 our *Chandra* ACIS-S observation (135 ksec usable time) detects both a central point source and extended emission. The central point source has a hardness-ratio of 0.0 ± 0.55, consistent with a Type-II AGN of luminosity $L_X = 4 \times 10^{45}$ erg s^{-1}. The extended emission is well fit with a power-law spectrum of index 1.29 ± 0.18 (in close agreement with the radio spectrum), implying a bolometric luminosity of $1.22 \pm 0.12 \times 10^{46}$ erg s^{-1}. In Scharf et al. (2003) we determine that IC scattering of CMB photons and most likely some amount of locally produced far-infrared photons provides an excellent match to the observations. No evidence for thermal emission is found, with an upper limit of 10^{44} erg s^{-1} on any such component. IC emission has been extensively discussed in the context of radio galaxies (e.g. Brunetti 2002) and in a few high-z radio galaxy/cluster environments has been discussed, but not confirmed, as the mechanism behind extended X-ray emission in these systems (Fabian et al. 2001, 2003, Carilli et al. 2002). As pointed out most recently by Schwartz (2002a,b), since the energy density of the CMB increases as

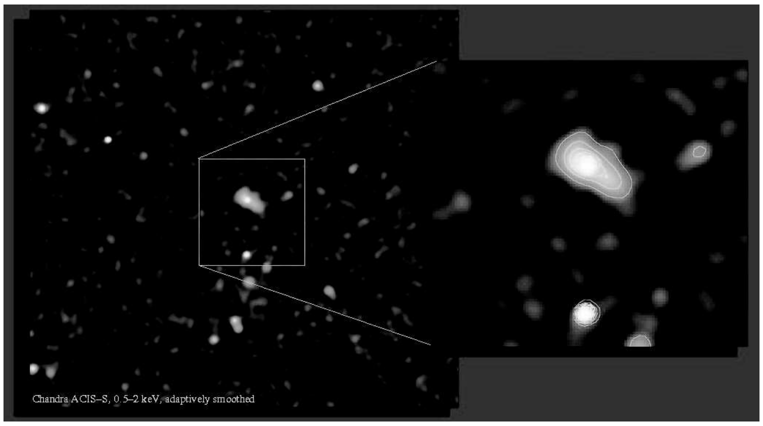

Fig. 1.1. The adaptively smoothed Chandra image (0.5-2 keV) is shown. The left panel is a field approximately $2' \times 2'$, point sources are readily identifiable to the south of 4C41.17 in the center. Right panel is expanded view centered on 4C41.17, the extended halo of X-ray emission is clearly seen - across a region approximately $15''$ or ~ 100 kpc assuming the WMAP cosmology.

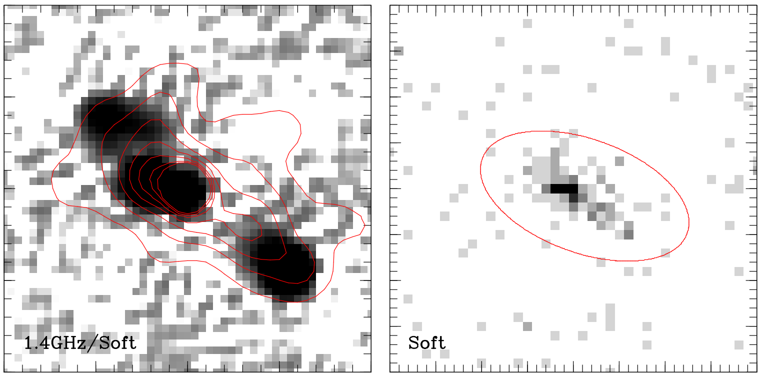

Fig. 1.2. Left panel is $20'' \times 20''$ region showing adaptively smoothed 0.5–2 keV *Chandra* data overlaid on 1.4GHz radio map grayscale (logarithmic intensity scaling). Right panel is $40'' \times 40''$ region showing 0.5–2 keV X-ray data binned to $1''$ pixels commensurate with the on-axis *Chandra* PSF. The region used to extract counts for the diffuse emission is shown as an ellipse in the right panel.

$(1+z)^4$ the efficiency of IC cooling not only increases dramatically with redshift, but the surface brightness of the emission remains essentially constant with z.

1.3 Conclusions

We have detected extended X-ray emission in a high redshift structure, around the luminous radio galaxy 4C 41.17 at $z = 3.8$. The spectral properties of the diffuse X-ray emission are best described by a power-law model, with a spectral index which matches that seen in the radio waveband. Moreover, the general morphology of the X-ray emission correlates well with the distribution of radio emission. Both of these facts lead us to propose that IC scattering is the mostly likely origin of the X-ray emission and we limit any contribution from thermal emission by hot gas to less than 10^{44} erg s^{-1}.

We conclude that if the radio-emitting plasma is in equipartition, then the observed X-ray emission is in good agreement with that expected for IC scattering from CMB photons, albeit with significant uncertainties.

The detection of the galaxy as a bright submm source implies a local far-IR energy density which can readily exceed that of the CMB and therefore might play a significant role in the IC X-ray emission. We have compared simple geometrical models for the thermal dust emission around 4C 41.17 and conclude that estimates of the scale of this emission based on energy density equality with the CMB are consistent with direct measurements of the size of the galaxy in the submm waveband, which imply that the dust emission is extended over ~ 50 kpc scales within this galaxy. However, the wide variety of routes for injecting energy into the halo of this galaxy (e.g. jets, shocks, winds, etc) means that it is difficult to reliably constrain any single mechanism.

Further evidence for the properties of the extended halo around 4C 41.17 come from the detection of a strong and variable rotation measure across the radio source. This shows that the halo contains a large mass of ionized gas, through which runs a highly ordered magnetic field. 4C 41.17 thus exhibits three of the main features expected to regulate star formation in massive galaxies (Benson et al 2003): an ordered magnetic field to allow conduction of heat from the outskirts of the halo into the centre and so suppress the cooling of gas; AGN-driven feedback in the form of the mechanical input from the radio jets and lobes; and outflows associated with visible and obscured massive star formation. It is intriguing that even this combination of three mechanisms apparently hasn't been able to suppress the star formation in this massive galaxy (Dey et al. 1997; Ivison et al. 2001).

We propose that IC X-ray emission, enabled by the enhanced CMB and local IR luminosity at high redshift, can readily ionize the gas in this system. While, it is unlikely that this is the sole mechanism by which the Lyman-α halo is produced, it seems inevitable that it plays a significant role. It could also be very efficient at ionizing the less dense, outer halo, described above. Importantly if the observed Lyman-α emission is recombination following photo-ionization then this gas could also have a significantly lower temperature, shorter cooling time, and locally altered Jeans Mass. IC X-ray emission from high-z supernovae has been suggested as a useful reionization mechanism in the early universe (Oh 2001), with profound implications for the formation of stars and galaxies. On the basis of our results we are compelled to add that IC X-ray emission from early AGN activity should also be an important feedback mechanism – especially given that the diffuse IC emission from the CMB can easily exceed that directly due to the central black hole, and that its diffuse nature permeates the halo volume more thoroughly. Moreover, this form of feedback will operate preferentially in the most massive halos, those which are able to host powerful radio galaxies. This mechanism may therefore address fundamental problems in models of the formation of massive galaxies in the local universe (Benson et al. 2003).

Finally, we suggest that the combination of intense, but obscured, activity in 4C 41.17, coupled with its high redshift, and hence the strong increase in the energy density of the CMB, has substantially aided in our identification of the X-ray halo around this galaxy. If correct this would imply that large halos, containing large populations of low energy electrons (tracers of past radio activity), ordered magnetic fields and significant quantities of ionized gas, may be common around all massive galaxies at high redshifts, $z \geq 1$. If the IC X-ray emission plays an important photo-ionization role this would also provide an additional mechanism for switching on Lyman-α halos at high-z by radio activity and the CMB alone. Clearly the rapid decline in the energy density in the CMB, coupled with a similar strong decline in the typical far-IR luminosities of active galaxies at $z < 2$ (Archibald et al 2001; Page et al. 2001) mean that IC scattered X-ray halos rapidly decrease in intensity at lower redshifts.

As the construction site of a massive galaxy, and almost certainly what will become the core of a massive cluster of galaxies, this system directly illustrates the extent to which astrophysics helps mold the nature of the relatively quiet cluster environments we see today. Future X-ray observations of other high-z radio galaxies will lead to a more unified picture of energetics and feedback mechanisms in these systems.

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