Interaction between the intergalactic medium and central radio source in the NGC 4261 group of galaxies

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ABSTRACT

Using observations from the Chandra and XMM–Newton X-ray observatories, we examine the interaction between the intra–group medium and central radio source in the nearby NGC 4261 galaxy group. We confirm the presence of cavities associated with the radio lobes and estimate their enthalpy to be \(\sim2.4 \times 10^{58}\) erg. The mechanical power output of the jets is \(\geq 10^{43}\) erg s\(^{-1}\), at least a factor of 60 greater than the cooling luminosity in the region the lobes inhabit. We identify rims of compressed gas enclosing the lobes, but find no statistically significant temperature difference between them and their surroundings, suggesting that the lobe expansion velocity is approximately sonic (\(M \leq 1.05\)). The apparent pressure of the radio lobes, based on the synchrotron minimum energy density argument, is a factor of 5 lower than that of the intra–group medium. Pressure balance could be achieved if entrainment of thermal gas provided additional non-radiating particles in the lobe plasma, but the energy required to heat these particles would be \(\sim 20\) per cent. of the mechanical energy output of the radio source. NGC 4261 has a relatively compact cool core, which should probably be categorised as a galactic corona. The corona is capable of fuelling the active nucleus for considerably longer than the inferred source lifetime, but can be only inefficiently heated by the AGN or conduction. The expansion of the radio lobes has affected the structure of the gas in the galaxy, compressing and moving the material of the corona without causing significant shock heating, and expelling gas from the immediate neighbourhood of the jets. We discuss the possible implications of this environment for the duration of the AGN outburst, and consider mechanisms which might lead to the cessation of nuclear activity.

Key words: galaxies: individual (3C 270, NGC 4261) — intergalactic medium — galaxies: active — cooling flows — X–rays: galaxies

1 INTRODUCTION

The importance of radio galaxies as sources of heating in groups and clusters of galaxies has become increasingly apparent in recent years. Active galactic nuclei (AGN) are now considered the most likely mechanism acting to balance radiative cooling of the hot intra–group medium (IGM, McNamara & Nulsen 2007; Peterson & Fabian 2006). Approximately 50 per cent. of galaxy clusters (e.g., Sanderson et al. 2006) and perhaps as many as 85 per cent. of galaxy groups (Dong et al. 2010) have a cooling region centred on a giant elliptical or cD galaxy, and the link between cool cores and nuclear activity in these galaxies is well established (e.g., Burns 1990; Mittal et al. 2009; Sun 2009).

X–ray and radio imaging has provided a means to examine the interaction between radio galaxies and their environment, and revealed that many nearby groups and clusters contain complex structures associated with the radio jets and lobes. Shock and sound waves driven by the expansion of radio jets may directly heat the gas (e.g., Nulsen et al. 2005; Fabian et al. 2006; Sanders & Fabian 2007; Forman et al. 2007) while cavities may inject energy by doing work on the gas, or reduce its ability to cool by lifting material out from the densest, most highly enriched regions (e.g., Fabian

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et al. 2005; Wise et al. 2007; Blanton et al. 2009). The enthalpy of cavities associated with radio lobes has been shown to be sufficient to balance radiative cooling in many systems (Birzan et al. 2008), and there is evidence that in some systems shocks may deposit similar amounts of energy into the gas (e.g., Million et al. 2010).

However, the mechanisms by which AGN are fuelled, and thus the processes involved in starting and stopping nuclear activity are not clear. Correlations between the AGN power output and the Bondi accretion rate suggest that Fanaroff-Riley class I (FR I) radio sources could be fuelled by hot gas (Allen et al. 2006; Hardcastle et al. 2007; Balmaverde et al. 2008). While actual Bondi accretion would require unrealistic efficiencies (McNamara et al. 2011), this at least suggests that fuelling by gas cooled from the hot phase is a possibility. Fuelling by large reservoirs of cold molecular gas or neutral hydrogen appears to be less likely, with poor correlation between cold gas mass and radio power (McNamara et al. 2011; Emonts et al. 2007). To form a feedback system, the AGN must be able to effectively heat its fuel supply, located in its immediate surroundings. Shocks originating in the nuclear region could be effective in this regard, while cavity heating would require conduction to distribute the energy azimuthally and perhaps radially.

While these mechanisms may be feasible in many systems, they appear difficult to achieve in those dominant ellipticals which host galactic coronae, cool cores with radii of only a few kiloparsecs. Coronae are thought to be largely unaffected by the radio jets of the AGN they host, and conduction into the cool gas from the surrounding IGM is suppressed (Sun et al. 2007). Owing to their small size, relatively small heating efficiencies (<1 per cent. in some cases) would raise the temperature of the corona gas to that of the ambient medium, suggesting that conduction is strongly suppressed by magnetic fields, and that the jets tunnel through the cool core with little or no interaction. Coronae are thought to consist of gas lost from stars within the cool region. Their cooling rate is often similar to the rate of stellar mass loss in the core (Sun et al. 2007), implying that if the AGN is fuelled by cooling gas, a corona can fuel its AGN over long periods without requiring inflowing gas from the IGM. Destruction of coronae by mergers or by ram-pressure stripping seems infeasible given the relatively large numbers of such systems observed (Sun et al. 2007). Coronae thus raise serious problems for the feedback model, since they can apparently provide enough gas to fuel an AGN for long periods, without being heated by the jets this activity produces. While this possibility is as yet speculative, there is at least one example of a corona fuelling an unusually old radio galaxy (O’Sullivan et al. 2010). AGN in corona systems are also known to have different radio properties; the radio power of radio galaxies in large cool cores scales with the luminosity of the cool core, whereas those in coronae show no such relationship (Sun 2009).

The question of how the supply of gas to the AGN can be stopped is important in all cluster and group–central AGN, and particularly so in coronae. Addressing this issue is difficult in that it requires examination of the AGN/gas interaction on very small scales. Many cavity systems studied to date are distant, making such an examination difficult, and this is particularly true of corona systems. It would therefore be useful to study nearby radio galaxies embedded in small-scale cool cores or coronae, to determine what effect the radio source has on the core, and how this might affect fueling of the AGN.

One such system is the NGC 4261 group, which has a well-established cool core and whose central elliptical hosts the well known FR I radio source 3C 270. Our aim in this paper is to use the available deep Chandra and XMM–Newton observations of the group to examine the interaction between the radio source, the cool core and the surrounding intra-group medium. We can thus determine the effects of the ongoing AGN outburst (or series of outbursts) on the gas, the energies and timescales involved, and the current physical structure of the gas. NGC 4261 is particularly suited to such a study, since the well–defined axis of its jets removes any question of large projection effects in determining the size of structures, and its radio properties and black hole mass are relatively well constrained. We describe the group, galaxy and radio source in more details in Section 1.1. In Section 2 we describe the Chandra and XMM–Newton observations and their reduction, and in Section 3 the results of imaging and spectral analysis of these data, including estimates of the age and expansion rate of the cavities. We further analyse these results in Section 4 to examine the energy output of the AGN, the properties and particle content of the radio lobes, and the state of the cool core. These results and their relationship with, and implications for, other group– and cluster–central radio galaxies are discussed in Section 5, and we summarise our conclusions in Section 6.

Throughout this paper we assume \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and a distance for NGC 4261 of 31.6 Mpc, in line with that adopted by Worrall et al. (2010). This gives an angular scale of \( 1'' \approx 9.2 \text{ kpc} \). We note that Humphrey et al. (2009) use a smaller distance (29.3 Mpc) based on surface brightness fluctuation measurements (Tonry et al. 2001). Our conclusions would not be altered were we to adopt this distance value. Worrall et al. (2010) also adopt the redshift of NGC 4261, 0.00746 (Trager et al. 2000), as appropriate for their goal of studying the AGN and jets. As our aims concern the IGM, we adopt the mean redshift of the group, 0.00706 (Nolthenius 2001). However, we note that adopting the galaxy redshift would not significantly alter the fit results.

1.1 NGC 4261

NGC 4261 and its surrounding group have been extensively studied, and it is useful to review what is known of the system before moving on to discuss our analysis. NGC 4261 is a boxy, cuspy–cored, slowly rotating E2 galaxy (Ravindranath et al. 2001), whose rotation axis is close to the major axis, leading to the conclusion that the galaxy is prolate (Davies & Birkinshaw 1986). The galaxy hosts a low-ionisation nuclear emission–line region (LINER, Ho et al. 1997) and the bright FR I radio source 3C 270 (~19 Jy at 1.4 GHz, Kühr et al. 1981), whose twin jets lie close to the plane of the sky. The galaxy has a kiloparsec–scale kinematically decoupled core (Cappellari et al. 2007) which contains a 100 pc–scale disk of dust and cool molecular and atomic gas (Jaffe et al. 1993; Jaffe & McNamara 1994) whose rotation axis is closely matched with the axis of the radio jets (Ferrarese et al. 1996). On large scales, deep optical imaging has revealed a faint tidal tail to the northwest and tidal fan extending southeast from the galaxy (Tal et al. 2009) and there is evidence of anisotropy in the globular cluster distribution (Giordano et al. 2005). These disturbed features suggest that NGC 4261 underwent tidal interactions or merger with another galaxy within the past 1–2 Gyrs.

Diffuse X–ray emission was first detected in the NGC 4261 group using the ROSAT PSPC, which revealed a gaseous halo extending to at least 40′ (>360 kpc) with a luminosity weighted mean temperature of ~0.85 keV (Davis et al. 1995; Worrall & Birkinshaw 1994). ASCA observations confirmed the presence of a central, spectrally hard X–ray source (Matsumoto et al. 2001). The poor spatial resolution of these data prevented any detailed examination of structure within the halo, but more recent observations by
Chandra and XMM–Newton have revealed X–ray features which are clearly related to the radio source and its interaction with its environment. On scales of a few arcminutes, XMM–Newton imaging showed arm-like features enclosing the inner edges of the radio lobes (Croston et al. 2005), and confirmed that at least in the western lobe, these correspond to the edges of a cavity (Croston et al. 2008).

On smaller scales, a short Chandra exposure revealed X–ray jets corresponding to the inner few kiloparsecs of the radio jets (Gliozzi et al. 2003; Zezas et al. 2005), strongly indicating that the jet axis is close to the plane of the sky. Analysis of a more recent, longer observation suggests a synchrotron origin for the jet X–ray emission, and finds wedge-like regions of reduced surface brightness along the jet axis (Worrall et al. 2010). These are interpreted as conical volumes in which the thermal gas has been displaced by relativistic plasma from the radio lobes, suggesting that up to 20 per cent. of the gas within ~10 kpc of the galaxy core has been moved by the action of the AGN jets and lobes. Radial spectral analysis confirms that the group temperature profile follows a typical form, with a central cool core (kT ~0.6 keV) of radius ~10 kpc, at the upper end of the range observed in other corona systems, and a temperature peak at ~200″ (kT ~1.6 keV), with a decline at larger radii (Helsdon & Ponman 2000; Humphrey et al. 2006). These profiles have been used to place limits on the total mass of the group (~6×10^12 M⊙, Humphrey et al. 2006), and on the central supermassive black hole (~4.4×10^8 M⊙) which are in good agreement with dynamical estimates (Humphrey et al. 2009; Ferrarese et al. 1996).

2 OBSERVATIONS AND DATA REDUCTION

2.1 Chandra

NGC 4261 has been observed twice by the Chandra ACIS instrument, first during Cycle 1 on 2001 May 26 (ObsId 894), for ~35 ks, using 1/2 subarray mode, and again in Cycle 9 on 2008 February 12 (ObsId 9569) for just over 100 ks. A summary of the Chandra mission and instrumentation can be found in Weisskopf et al. (2002). In both observations the S3 CCD was placed at the focus of the telescope and the instrument operated in faint mode for the first observation and very faint mode for the second. We have reduced the data from the pointings using CIAO 4.1.2 and CALDB 4.1.3 following techniques similar to those described in O’Sullivan et al. (2007) and the Chandra analysis threads. The level 1 events files were reprocessed, very faint mode filtering was applied to the second dataset, bad pixels and events with ASCA grades 1, 5 and 7 were removed, and the cosmic ray afterglow correction was applied. The data were corrected to the appropriate gain map, the standard time-dependent gain and charge-transfer inefficiency (CTI) corrections were made, and a background light curve was produced. The observations did not suffer from significant background flaring, and the final cleaned exposure times were 29.6 and 100.9 ks. While data from the entire detector were examined, for the purposes of this study we primarily use the S3 CCD, as the radio source and the galaxy fall on that chip.

Identification of point sources on S3 was performed using the WAVDETECT task, with a detection threshold of 10^-6, chosen to ensure that the task detects ≤1 false source in the field, working from a 0.3–7.0 keV image and exposure map from the combined observations. Source ellipses were generated with axes of length 4 times the standard deviation of each source distribution. These were then used to exclude sources from most spectral fits. An extended source was detected coincident with the peak of the diffuse X–ray emission; this was not excluded.

Spectra were extracted using the SPECEXTRACT task. Spectral fitting was performed in XSPEC 12.6.0. Abundances were measured relative to the abundance ratios of Grevesse & Sauval (1998). A galactic hydrogen column of 1.75×10^20 cm^-2, drawn from the [fTOOLS] task nh and based on the survey of Kalberla et al. (2005), was adopted in all fits. This differs slightly from the column of 1.58×10^20 cm^-2 adopted by Worrall et al. (2010), based on the survey of Dickey & Lockman (1990). The difference probably arises from the finer angular resolution of the Kalberla et al. survey (0.675° compared to 1°), but testing suggests it has no significant effect on our spectral fitting. 90 per cent errors are reported for all fitted values. Spectra were grouped to 20 counts per bin, and counts at energies above 7 keV and below 0.7 keV (see below) were ignored during fitting.

Background spectra were drawn from the standard set of CTI-corrected ACIS blank sky background events files in the Chandra CALDB. The exposure time of each background events file was altered to produce the same 9.5–12.0 keV count rate as that in the target observation. A region enclosing the AGN and jets was excluded from the estimation of the count rate of the target observation, to avoid any contamination from source photons. Very faint mode background screening was applied to the background data sets where appropriate. Comparison of source and background spectra suggested some mismatch between the source and background spectra, mainly below 0.5 keV. This is not unexpected, as the soft X–ray background arises largely from hot gas in our galaxy, and from coronal emission associated with solar wind interactions, and thus is both spatially and temporally variable (e.g., Kuntz & Snowden 2000; Snowden et al. 2004). There are also indications that the spectral shape of the background has changed since the creation of the blank-sky background files (c.f. the ACIS background cookbook2), which could contribute to the disagreement at low energies. NGC 4261 also lies on the outskirts of the Virgo cluster and close to the galactic north polar spur (Böhhringer et al. 1994). It is possible that emission from both these sources could contaminate our observations. We therefore ignored energies below 0.7 keV when performing spectral fitting, so as to avoid any biases arising from inaccuracies in estimating the soft X–ray background.

2.2 XMM–Newton

The NGC 4261 group was observed with XMM–Newton during Cycle 1 (2001 December 16) for just over 33 ks (ObsId 0056340101) and again in Cycle 6 (2007 December 16 and 18) for a total of 130 ks (ObsIds 0502120101 and 0502120201). We reduced all three observations, but as ObsId 0502120101 has by far the longest exposure (~127 ks before filtering) our analysis focussed on this dataset.

The EPIC instruments were operated in full frame mode, with the medium optical blocking filter. A detailed summary of the XMM–Newton mission and instrumentation can be found in Jansen et al. (2001, and references therein). Reduction and analysis were performed using techniques similar to those described in O’Sullivan et al. (2007). The raw data from the EPIC instruments

1 http://asc.harvard.edu/ciao/threads/index.html

2 http://asc.harvard.edu/contrb/maxim/acisbg/COOKBOOK
were processed with the XMM–Newton Science Analysis System (SAS v.9.0.0), using the EPCHAIN and EMCHAIN tasks. Bad pixels and columns were identified and removed, and the events lists filtered to include only those events with FLAG = 0 and patterns 0-12 (for the MOS cameras) or 0-4 (for the PN). The total count rate for the field revealed significant background flaring. Times when the total count rate deviated from the mean by more than 3σ were therefore excluded. The effective exposure times for the MOS and PN cameras were 72.9 and 46.8 ksec respectively for ObsId 0502120101.

Images and spectra were extracted from the cleaned events lists using the SAS task EVSELECT. Response files were generated using the SAS tasks RMFGEN and ARFGEN. The central AGN is relatively X-ray bright, and a significant number of out-of-time (OOT) events are found on the PN detector, visible in the PN data as a trail extending from the centre of the source toward the CCD read-out. An OOT events list was created using EPCHAIN, and scaled by 0.063 to allow statistical subtraction of the OOT events from spectra and images (c.f. the XMM–Newton users handbook\(^3\)). Point sources were identified using EDETECT\_CHAIN, and regions corresponding to the 85 per cent encircled energy radius of each source were excluded. A source corresponding to the active nucleus was not excluded.

Creation of background images and spectra for the system was hampered by the fact that the group X-ray halo extends beyond the field of view. Use of the “double-subtraction” technique (Arnaud et al. 2002; Pratt et al. 2001) involves correcting blank-sky exposures to match a source-free area of the observation; for NGC 4261 this is not feasible. We therefore adopt several approaches. For deprojected radial spectral profiles, we use a local background extracted at the extreme edge of the field of view and discard results from the outer annulus of the radial profile as potentially biased. The effect of the deprojection should act to reduce any bias in the successive inner annuli. Comparison with our deprojected Chandra profile and with that of Humphrey et al. (2009) shows good agreement, suggesting that our results are not seriously affected.

For spectral analysis of particular X-ray structures we use local background spectra extracted close to the region of interest, so as to subtract off any overlying group and background emission.

### 2.3 Very Large Array

We analysed 1.5 GHz data in C-array configuration retrieved from the Very Large Array (VLA) public archive (project AL693). The observations were made in two 25-MHz bands centred on 1365 MHz and 1646 MHz, in May 2008 for a total integration time on source of approximately 38 minutes. We used the NRAO Astronomical Image Processing System (AIPS) package for the data reduction and analysis. Data calibration and imaging were carried out following the standard procedure (Fourier Transform, Clean and Restore). Phase-only self-calibration was applied to remove residual phase variations and improve the quality of the image. The final image has an angular resolution of 16arcsec × 15arcsec and a rms noise level (1σ) of 0.3 mJy beam\(^{-1}\).

### 3 RESULTS

#### 3.1 IGM structures associated with the radio source

We initially examined images extracted from both Chandra and XMM–Newton, smoothed at a range of scales, to determine the distribution of diffuse emission. The AGN is the brightest source in the field, and the jets are clearly visible in the Chandra data. The diffuse emission is strongly centrally peaked, and fills both the Chandra and XMM–Newton fields of view.

On scales of a few arcminutes, similar to the size of the stellar component of the galaxy (see Figure 1a), it is clear that moderately luminous diffuse emission extends north and south of the central AGN, to a distance of at least 2 arcminutes (~18 kpc). This extension is perpendicular to the jet axis, and poorly aligned with the major axis of the galaxy. On larger scales, fairly uniform emission extends throughout the field of view of both instruments. However, comparing archival VLA 1.5 GHz radio maps to the X-ray images, there are hints of structures associated with the radio lobes. In particular, after subtraction of point sources from the Chandra image and refilling of the resulting holes using the CIAO dmfilth task, heavy smoothing reveals an apparent arc of X-ray emission extending along the southern edge of the eastern radio lobe, and hints of a similar structure south of the western lobe (see Figure 1a). These could be parts of a shell of compressed gas surrounding cavities excavated by the expanding radio lobes, but the limited field of view of the S3 CCD prevents us from determining whether the structures completely enclose the lobes.

The XMM–Newton images are large enough to cover the whole radio source, but are more severely affected by the bright AGN emission, owing to the broader XMM–Newton point spread function. Other point sources in the galaxy, and sources associated with other galaxies in the field of view, are also problematic, and unresolved sources increase the level of noise in the area of interest. We therefore adopted two approaches aimed at clearly determining whether there are cavities corresponding to the radio lobes, and the overall form of any structures in the IGM. As a simple test, we applied the wvdecomp wavelet decomposition and smoothing algorithm (Vikhlinin et al. 1998) to examine the amount of structure on different spatial scales. Removal of features with small smoothing scales (≤3 pixels or 13.2arcsec) allowed us to effectively subtract point sources, small noise features and much of the AGN emission. Adopting a 5σ detection threshold, we obtained the image shown in Figure 1b. This clearly shows the north-south bar of emission across the galaxy core, but also shows a looped structure to the east, and corresponding arms of emission extending west from the northern and southern ends of the bar. These correspond to the western cavity and small eastern surface brightness decrement identified by Croston et al. (2008).

An alternate method for revealing any X-ray structures associated with the radio lobes is to model the AGN and large scale group halo, subtract these models from the image and examine any residual features. Such models need not be physically meaningful, so long as they provide a good approximation to the emission components we wish to remove. We fitted 2-dimensional surface brightness models using the CIAO SHERPA package (Freeman et al. 2001). Point sources were removed from the image (as described in section 2.2), and a larger region was used to exclude the bright X-ray point source RX J1219.8+0545. Models were convolved with the monoenergetic exposure map and PSF, determined for an energy of 1 keV, approximating the mean photon energy of the data. A background image consisting of the scaled particle–only image and scaled pn OOT events image was used, and convolved and un-

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\(^3\) http://xmm.esac.esa.int/external/xmm_user_support/documentation/
Figure 1. a) Chandra 0.3-3 keV image, binned by a factor of 2 and smoothed with a Gaussian of sigma 16 pixels (15.8″). VLA 1.5 GHz contours are overlaid, starting 3σ above the r.m.s. noise level of 0.3 mJy beam$^{-1}$ and increasing by factors of 2. The restoring beam size is 16″ × 15.1″ (HPBW). Annular regions used to examine surface brightness across the cavity rim are marked in white. b) XMM–Newton 0.3-3 keV wavelet smoothed MOS+pn image, with scales chosen to exclude point sources and emphasise diffuse emission. Dark linear features show chip gaps and bad columns, and should be ignored. c) XMM–Newton residual map, showing the image after removal and filling of point sources, and subtraction of the best fitting surface brightness model for the galaxy and larger group halo, smoothed with a Gaussian of sigma 4 pixels (17.6″). Solid ellipses indicate the optical D$_{25}$ contours of NGC 4261 and several smaller galaxies in the field. Dashed ellipses indicate the regions used to define cavity size and position. d) XMM–Newton residual map, as in the lower left panel, overlaid with VLA contours and the partial annuli used to extract surface brightness profiles across the cavity rims.

Experimentation showed that modelling the AGN as a point source (a delta function or narrow gaussian convolved with the PSF) was not effective, probably because of emission from the jets and dense gas in the centre of the galaxy. We therefore modelled the core with a β–model. The model was fixed to be circular, since the extended emission to north and south tended to drive the model to extreme ellipticities. The best fitting parameters for this model were $r_{\text{core}} = 1.0^{+1.2}_{-1.0}$ and $\beta = 0.55^{+0.01}_{-0.02}$, but we again emphasize that this model is not intended to be physically meaningful, but simply to provide an approximation to the core emission, to allow it to be subtracted. A second β–model was added to model large–scale group emission, with slope and core radius fixed at the values determined from ROSAT ($r_{\text{core}} = 1.68^{+0.01}_{-0.01}$, $\beta = 0.31$ Davis et al. 1995), but a low normalisation was found for this component, suggesting that the central β–model accounted for most of the emission in the field. Figure 2 shows the XMM–Newton radial surface brightness profile, with fitted model components for comparison.

To examine any residual structure, we subtracted the best fitting model from an image in which the point sources had been removed and replaced (using the dmfilth task) and the OOT readout streak subtracted. The resulting residual map is shown in Figures 1c and d. The emission north and south of the core produces the strongest residuals, but structures associated with the radio lobes are clearly visible. In the west, arcs of emission extend along the south side of the radio lobe, and along part of the north side. There is an apparent gap, or weakening of this emission in the northwest quadrant. On the east, emission corresponding to the lobe boundary is more diffuse, but extends approximately to the far
end of the radio lobe, and encloses it to north and south. Agreement with the wavelet smoothed image is generally good, though the eastern cavity rim is less clearly defined and appears to extend further east. Immediately outside these structures is a band of negative structure. Although a five component model was fitted, it is clear that the data are primarily described by a central point source, a fairly compact β-model and a flat background.

To test the significance of these structures we extracted 0.3-3 keV surface brightness profiles across the eastern and western ends of the lobes. We used partial circular annuli of width 5 pixels (22″) with limiting angles chosen to avoid regions which seem to be affected by unsubtracted point sources. The annuli were centred at R.A. 12h19m14s, Dec. +05°49′53″ (J2000) for the western and R.A. 12h19m30s, Dec. +05°49′24″ for the eastern lobe. The regions, overlaid on the surface brightness residual image to make their relationship to the rims clear, are shown in Figure 1d and the resulting profiles in Figure 3. The difference between the east and west regions is clear; the western profiles have much lower central surface brightness than the eastern profiles. However, both the southeastern and southwestern profiles show a strong peak at ∼100″, followed by a decline to ∼200″, after which the outer points rise again. The peak at ∼100″ corresponds to the structures at the edge of the radio lobes, which are likely cavity rims. The outer rise appears to be caused by point sources or small clumps of emission with no clear large-scale structure, or by a large residual to the southeast surrounding RX J1219.8+0545. We therefore consider the difference in surface brightness between the highest and lowest values, and find that the cavity rims are significant at 7σ (SW) and 5.7σ (SE) confidence.

The northwestern quadrant shows no significant change in surface brightness across the edge of the radio lobe, confirming the presence of the break in the rim seen in this area in the residual image. The northeast profile shows a slow decline from high values inside the lobe, with no clear rim. This is probably due to the diffuseness of the emission in this region; the residual image also shows no clear rim, but a broad area of emission coincident with the radio and declining towards the end of the lobe. We therefore conclude that the lobes of 3C 270 have formed cavities in the IGM, and that they are surrounded by rims of gas swept up by the lobe expansion. However, the western rim is either weak or incomplete in its northwest quadrant, and the complexity of the emission around the eastern lobe suggests that either the cavity has a complex morphology or that there are additional emission components present, such as unresolved point sources.

### 3.2 Structure in the galaxy core

On smaller scales, we can examine the structure of the diffuse emission immediately surrounding the AGN and jets. Figure 4 shows a...
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Kim & Fabbiano (2004) and taking a total $K$-band luminosity of $2.2 \times 10^{13} L_{\odot}$ (Ellis & O’Sullivan 2006, scaled to our chosen distance). We note that this is likely to be an overestimate, since we have already excluded all resolved point sources but we expect the profile to be largely unchanged. The luminosity is converted to an expected number of counts in our band using a powerlaw model with $\Gamma=1.8$. A similar scaling is used to determine the expected contribution from coronally active binaries and cataclysmic variables, based on the relation of Sazonov et al. (2006) and scaling using a 0.5 keV, solar abundance APEC model. Surface brightness profiles were determined using elliptical regions chosen to match the optical light distribution, with axis ratio 1.24 and position angle 68.3° (where the position angle is defined as the angle between the major axis and axis west). Regions corresponding to the X-ray jets were excluded, but testing shows that these make only a minor contribution in the central bins of the profile. It is clear that the observed surface brightness profile is steeper than that expected for emission from the stellar population, but more extended than the Chandra 1 keV point spread function, confirming that much of the emission in this band arises from hot gas.

3.3 Spectral properties of the cavity rims

Given the ongoing jet activity in the system, it is possible that the radio lobes are still expanding. If they are expanding subsonically, their X-ray bright rims must consist of compressed gas which may be expected to be cooling more rapidly than its surroundings. If they are expanding at or above the sound speed, the lobes will cause shock heating of the surrounding gas. Using XMM–Newton, we found no significant temperature differences between the cavity rims, and regions immediately inside and outside the cavities. This is unsurprising, since the regions used are necessarily large and include unresolved point sources and gas at a range of temperatures.

While the field of view of the ACIS S3 CCD limits our ability to examine the edges of the radio lobes with Chandra, we can examine the southern parts. Figure 1a shows a series of partial elliptical annuli which were used to search for a surface brightness jump across the southeast lobe edge. These regions were chosen to match the shape of the apparent surface brightness feature, with large widths to increase the signal-to-noise ratio in each bin. Figure 5 shows the exposure corrected surface brightness in each bin. A peak is found at the position of the lobe rim, where the surface brightness exceeds that immediately outside the rim at $>3\sigma$ significance (a 3.4σ difference between bins 3 and 4). This corresponds reasonably well with the feature observed in the XMM–Newton images.

If this surface brightness increase is the result of a shock, the standard Rankine-Hugoniot jump conditions (e.g., Landau & Lifshitz 1959) can be used to estimate the shock velocity. The change in surface brightness of a factor $\sim 1.15$ indicates a shock with Mach number $M = 1.05 \pm 0.02$, suggesting that if a shock is present, the lobe is expanding only marginally supersonically. The presence of a shock can only be confirmed by the detection of a temperature increase. Spectra were extracted across the rim, using larger regions inside and outside to maximise the signal-to-noise ratio. The spectra contained $\sim 1900-5400$ counts, with the background contributing 24-35 per cent. Figure 5 shows the temperatures measured from an absorbed APEC model fitted to these spectra, and the fit parameters are shown in Table 1. The uncertainties are large, as expected for relatively small regions with extensive foreground and background group emission, and while the best fitting temperature of the rim is higher than that of its surroundings, the temperature

Figure 4. 0.3-2 keV Chandra image of the core of NGC 4261, with 0.493″ pixels smoothed with a Gaussian of sigma 2 pixels (upper panel) and adaptively smoothed Chandra temperature map (lower panel). The colour bar indicates the approximate gas temperature in keV. The two panels have the same alignment and angular scale.

Chandra image of the core and jets. As noted by Worrall et al. (2010), there are wedge-like surface brightness decrements in the area immediately north and south of the western X-ray jet, and a suggestion of similar structure on the eastern side (see also Figs. 2 and 4 of Worrall et al. 2010). The emission bordering these decrements is somewhat brighter and extends to larger radius than the emission along the north–south axis, forming an X-shaped structure. The extension to the southwest is particularly notable, while that to the northwest appears weakest. Worrall et al. (2010) suggest that the decrements are caused by expulsion of the thermal gas by the expanding radio lobes. In this case the X–structure would likely be this expelled gas, compressed and driven north and south from the jet axis.

As a simple test of the importance of the different sources of emission in the core, we compared the 0.3-3 keV Chandra surface brightness profile with that expected from discrete sources in the stellar population of NGC 4261 (see Figure 2). We estimated the contribution from the low mass X-ray binary (LMXB) population using a $V$-band optical surface brightness profile (determined from observations described in Bonfini et al. 2011) scaled to the expected X-ray luminosity of the LMXB population, based on the relation of Sazonov et al. (2006) and taking a total $K$-band luminosity of $2.2 \times 10^{13} L_{\odot}$ (Ellis & O’Sullivan 2006, scaled to our chosen distance). We note that this is likely to be an overestimate, since we have already excluded all resolved point sources but we expect the profile to be largely unchanged. The luminosity is converted to an expected number of counts in our band using a powerlaw model with $\Gamma=1.8$. A similar scaling is used to determine the expected contribution from coronally active binaries and cataclysmic variables, based on the relation of Sazonov et al. (2006) and scaling using a 0.5 keV, solar abundance APEC model. Surface brightness profiles were determined using elliptical regions chosen to match the optical light distribution, with axis ratio 1.24 and position angle 68.3° (where the position angle is defined as the angle between the major axis and axis west). Regions corresponding to the X-ray jets were excluded, but testing shows that these make only a minor contribution in the central bins of the profile. It is clear that the observed surface brightness profile is steeper than that expected for emission from the stellar population, but more extended than the Chandra 1 keV point spread function, confirming that much of the emission in this band arises from hot gas.

3.3 Spectral properties of the cavity rims

Given the ongoing jet activity in the system, it is possible that the radio lobes are still expanding. If they are expanding subsonically, their X-ray bright rims must consist of compressed gas which may be expected to be cooling more rapidly than its surroundings. If they are expanding at or above the sound speed, the lobes will cause shock heating of the surrounding gas. Using XMM–Newton, we found no significant temperature differences between the cavity rims, and regions immediately inside and outside the cavities. This is unsurprising, since the regions used are necessarily large and include unresolved point sources and gas at a range of temperatures.

While the field of view of the ACIS S3 CCD limits our ability to examine the edges of the radio lobes with Chandra, we can examine the southern parts. Figure 1a shows a series of partial elliptical annuli which were used to search for a surface brightness jump across the southeast lobe edge. These regions were chosen to match the shape of the apparent surface brightness feature, with large widths to increase the signal-to-noise ratio in each bin. Figure 5 shows the exposure corrected surface brightness in each bin. A peak is found at the position of the lobe rim, where the surface brightness exceeds that immediately outside the rim at $>3\sigma$ significance (a 3.4σ difference between bins 3 and 4). This corresponds reasonably well with the feature observed in the XMM–Newton images.

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We are able to place a 90% upper limit on the temperature difference from Centaurus A, which is aligned roughly south. The rim of the lobe falls in bin 3 of the surface brightness profile. Surface brightness uncertainties are 1σ, temperature uncertainties 90%

difference is not statistically significant. However, the temperature increase expected for a $M = 1.05$ shock is only a factor 1.05, and the data are consistent with heating at this level.

*Chandra* observations of the southwest radio lobe of Centaurus A have shown that the X-ray emission at the boundary of the lobe is best characterised as a single component absorbed powerlaw model, and arises in large part from synchrotron emission (Croston et al. 2009). To test the possibility of a synchrotron component contributing to the emission around the lobes of NGC 4261, ‘powerlaw’ and ‘apec+powerlaw’ models were fitted to the spectra extracted across the lobe rim. Fitted model parameters are given in Table 1. An absorbed powerlaw model was a poor fit to all spectra. The addition of a powerlaw to the absorbed apec model did not significantly improve the quality of fits, and in all cases the photon index of the powerlaw was poorly constrained and the normalisation consistent with zero. Fixing the photon index at $\Gamma = 2$ (compatible with the data and similar to the values found for Centaurus A), we are able to place a 90% upper limit on the synchrotron flux from this portion of the lobe rim of $F_{\gamma, 0.3-7.0} \lesssim 3.18 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$. Scaling to the total area of the lobe rims, this is equivalent to an upper limit on luminosity of $L_{\gamma, 0.3-7.0} \lesssim 3.3 \times 10^{40}$ erg s$^{-1}$. The equivalent (detected) thermal luminosity of the rims is $L_{\text{X}, 0.3-7.0} \approx 4.15 \times 10^{40}$ erg s$^{-1}$. A similar analysis of the north-south bar also found no evidence of non-thermal emission.

The *Chandra* profiles extend across the cavity rim in a direction roughly perpendicular to the jet axis. We might expect a higher expansion rate, and therefore greater surface brightness differences (and potentially temperature differences), at the jet tips. The lack of a detected rim corresponding to the northwest quadrant of the western radio lobe (see Section 3.1) is informative in this regard, and we do not see strong surface brightness features corresponding to the east or west extremes of either lobe. However, if the expansion were very subsonic, gas swept up by the lobes would be able to flow out into regions of lower pressure, and a rim feature would be weak or nonexistent. It is therefore likely that the lobe expansion rate is comparable to the external sound speed. We conclude that the cavity rims consist of material swept up and compressed by the expansion of the lobes, and at most only weakly heated by shocks or compression.

### 3.4 Spectral map

To examine the spatial variation of temperature in the gas, we prepared a temperature map using the technique developed by David et al. (2009) which takes advantage of the close correlation between the strength of lines in the Fe-L complex and gas temperature in $\sim 1$ keV plasma. Most of the emission from such gas arises from the L-shell lines from Fe-XIX (Ne-like) to Fe-XXIV (He-like). For CCD resolution spectra, these lines are blended to form a single broad peak between approximately 0.7 and 1.2 keV. The centroid or mean photon energy of this peak increases with the temperature of the gas as the dominant ionisation state of Fe shifts from Fe XIX in 0.5 keV gas to Fe XXIV in 1.2 keV gas, with Fe XVII and Fe XVIII providing the strongest line emission at the temperatures seen in the core of NGC 4261. The mean photon energy of the blended L-shell lines is independent of energy above $\sim 1.2$ keV.

We can thus estimate the temperature distribution of the gas by mapping the mean photon energy in the 0.7-1.2 keV band. To determine the relation between $kT$ and mean photon energy we require information on the detector response and the typical properties of the gas. We therefore extracted a spectrum from a $\sim 1'$ region centred on the galaxy, excluding the central point source and jets, and fitted it using an absorbed apec model. Based on this fit, we chose a value of $0.5 \, Z\odot$ as representative of the abundance and temperature of the central part of the group, and simulated spectra based on this model, with redshift set to that of NGC 4261 and the hydrogen column set to the galactic value. These showed that for temperatures between $0.5$ and $1.1$ keV, the relationship is approximately linear ($kT = -4.43 + 5.68 < E >$). Prior testing in other systems suggests that the relationship is relatively insensitive to variations in abundance and hydrogen column (O’Sullivan et al. 2009).

Previous studies have shown the core temperature of NGC 4261 to be $0.6-0.7$ keV (e.g., Worrall et al. 2010) and the IGM temperature to be $\sim 1.6$ keV (e.g., Humphrey et al. 2009). The core is therefore suitable for mapping using this technique. The lower panel of Figure 4 shows the resulting map. The estimated temperatures are comparable with those derived from previous spectral fits (and our own radial temperature profile, see Section 3.5).

We do not expect to see the jet in the temperature map, since its powerlaw emission is spectrally flat compared to the strongly peaked plasma component, and indeed no features corresponding to the jet are observed in the map. The X-structure observed in surface brightness is clearly visible, which confirms that the core gas distribution is disturbed and that the arms of the X consist of cool gas with a temperature $\sim 0.65$ keV. The regions of low surface brightness along the west jet have a higher temperature (0.8-0.9 keV), in agreement with the temperature measured by Worrall et al. (2010). On slightly larger scales gas with temperatures $\lesssim 0.95$ keV appears most extended to the northeast and southwest. The cavity rims and the north-south bar are not observed in the temperature map, confirming that these do not contain significant quantities of cool gas. We conclude that NGC 4261 hosts a small cool core, whose structure has been disturbed by the expansion of the radio lobes and which is at present not spherically symmetric.

![Figure 5. 0.3-3 keV Surface brightness and temperature from elliptical annuli extending across the southern edge of the eastern radio lobe. Radii are measured along the minor axis of the ellipses, which is aligned roughly south. The rim of the lobe falls in bin 3 of the surface brightness profile. Surface brightness uncertainties are $1\sigma$, temperature uncertainties 90%](image)
Table 1. Fit parameters for the Chandra spectra extracted across the southern sector of the east lobe.

| Model                       | Parameter | Bin 1 | Bin 2 | Bin 3 | Bin 4 |
|-----------------------------|-----------|-------|-------|-------|-------|
| wabs*apec                   | $kT$ (keV) | 1.58±0.33 | 1.67±0.46 | 1.55±0.17 | 1.36±0.21 |
|                            | Abundance (Z⊙) | 0.67±0.95 | 0.85±1.06 | 0.57±0.56 | 0.50±0.35 |
|                            | $\chi^2$/d.o.f. | 68.56/84 | 79.9/74 | 172.54/156 | 175.23/189 |
| wabs*(apec+powerlaw) with $\Gamma$=2 | $kT$ (keV) | 1.65±0.39 | 1.70±0.46 | 1.54±0.16 | 1.35±0.19 |
|                            | Abundance (Z⊙) | 1.40±0.90 | 4.74±2.3 | 0.83±0.51 | 0.53±0.35 |
|                            | $\chi^2$/d.o.f. | 68.26/83 | 78.94/73 | 172.09/155 | 175.23/188 |
| wabs*powerlaw               | $\Gamma$ | 2.06±0.31 | 1.87±0.33 | 2.17±0.22 | 2.15±0.19 |
|                            | $\chi^2$/d.o.f. | 120.25/85 | 122.29/75 | 234.52/157 | 274.43/190 |

The powerlaw photon index was fixed at $\Gamma$=2 in the apec+powerlaw model, as it was poorly constrained when freely fitted.

3.5 Radial Spectral Analysis

In order to examine the underlying structure of the intra-group medium and estimate the energy required to form the cavities, we extract spectral profiles from the Chandra and XMM–Newton data. Regions corresponding to the cavities are excluded, and the core and jet are excluded from the Chandra spectra using a rectangular region of length 30′ and width 4′ centred on the nucleus. For the Chandra data, annular regions were selected to contain 3000 net counts, and for XMM–Newton a total of 10000 net counts across the three EPIC cameras. The only exception is the innermost bin of the XMM–Newton profile, whose radius was fixed at 35″ so as to simplify comparison with the Chandra profile. The spectra were fitted with a deprojected, absorbed APEC model. An additional powerlaw component was included to account for emission from the AGN in the innermost bin, and from unresolved point sources in the central three XMM–Newton bins. Abundances were tied between bins where necessary to stabilise the deprojection. Figure 6 shows the resulting temperature and density profiles, and the pressure profile derived from them. Pressure was calculated as $P = nkT$ where $n = 2\rho_e$.

The Chandra and XMM–Newton profiles agree reasonably well at large and small radii, but there is some disagreement in temperature in the ∼35-65″ bin, and in density between ∼35″ and 170″. The temperature disagreement is likely caused by the difference in the radii of the outermost bins of the two profiles, and the relatively low resolution of the profiles in comparison to the temperature gradient, particularly in the XMM–Newton profile, where the full range of temperatures across the gradient is represented by only a single model temperature in the deprojection. Scattering of low energy emission outward from the central bin is also a possibility, given the broad point spread function of XMM and the high surface brightness of the core. However, the large spectral extraction region of the central bin should reduce this effect. The density difference may be a product of the difference in extraction regions, since the XMM–Newton annuli cover a larger area north of the core than the ACIS spectra, which reach the edge of the S3 CCD. The outermost annuli of both profiles are excluded since they contain emission from the outer parts of the group halo (which extends beyond the field of view) and would thus give incorrect density estimates. However, the level of agreement is sufficient for our purposes. We note that the Chandra profiles also agree well with those of Humphrey et al. (2009).

The shapes of the temperature and density profiles are typical of cool-core galaxy groups. Defining the cooling region as that volume within which the temperature declines (∼10 kpc radius), the cool core is relatively small. The core has a relatively constant temperature of ∼0.6 keV, in agreement with the estimate in the temperature map. The temperature peaks at ∼1.6 keV, between 10 and 40 kpc from the AGN, and flattens or declines at larger radii. The pressure profile appears relatively smooth, though this may be misleading since the annular average conceals azimuthal variations (c.f., Figure 4).

4 ANALYSIS

4.1 Outburst energy budget and timescale

To estimate the mechanical energy output of the AGN, we approximate the area of the cavities with ellipses, and assume rotational symmetry about their major axis. The ellipses are shown in Figure 1c. Neither the shape of the radio lobes nor the shape of the cavities in the X-ray is straightforward, and therefore there is significant uncertainty in the following estimates. The east cavity in particular is poorly defined, and could be smaller than we have as-
sumed. The lobes may also be overpressured and still expanding, which would lead to an underestimate of the energy they contain.

Assuming the lobes to be completely filled by relativistic plasma, we can estimate their enthalpy to be $4PV$ where $V$ is the lobe volume and $P$ the external pressure. The two ellipses are defined as having semi-major and −minor axes of $18.3 \times 16.7$ kpc (West) and $20.7 \times 15.3$ kpc (East). Their size is such that the external thermal pressure of the IGM varies from $\sim 3.8 \times 10^{-12}$ erg cm$^{-3}$ along their length. We use pressure at the mid-point of the lobes, from the Chandra profile, $\sim 5 \times 10^{-12}$ erg cm$^{-3}$, but note that the XMM–Newton pressure estimate is a factor of 2 higher. We therefore estimate the enthalpy of the two cavities to be $\sim 2.4 \times 10^{58}$ erg.

The timescale over which cavities have formed, and therefore of the associated AGN outburst, is often estimated from dynamical arguments (e.g., Churazov et al. 2001; Dunn et al. 2005). In this system, the lobes appear still to be connected to the core, and their shape suggests that the jets are still the dominant factor determining the lobe size and location, rather than buoyant forces. We can estimate the timescale of formation based on the time taken for the lobes to expand to their current size at the external sound speed, but as it is likely that the lobes expanded more rapidly in the past, and are only now approaching pressure balance with the surrounding IGM, this should be considered as an upper limit on the timescale of formation. For $kT$=1.5 keV, the sound speed is $585$ km s$^{-1}$. The sound speed in the cool central region is considerably lower ($380$ km s$^{-1}$) but it seems likely that expansion through this region will have happened at the onset of the outburst, when the source is likely to have been strongly overpressured. The tips of the lobes are $\sim 38$ kpc (West) and $45$ kpc (East) from the central point source, suggesting that the lobes must be at most $75$ Myr old. The mechanical power output of the AGN (including both jets) is therefore $\gtrsim 10^{53}$ erg s$^{-1}$, with greater power output indicated if the radio lobes expanded supersonically over some portion of their history. This value is consistent with the energy output estimated for NGC 4261 by Croston et al. (2008). It exceeds the estimate of Cavagnolo et al. (2010) by an order of magnitude, but Cavagnolo et al. did not identify the main cavities, considering only the structure associated with the jets in the core region. Lower limits to the total radiative power output of the AGN can be taken from the intrinsic X-ray luminosity of the nucleus ($1.4 \times 10^{41}$ erg s$^{-1}$ Worrall et al. 2010), or the extended radio luminosity at 178 MHz ($\nu L_{\nu}=10^{40}$ erg s$^{-1}$ for $L_{\nu}=24.73$ W Hz$^{-1}$ Balmaverde et al. 2006; Chiaberge et al. 1999).

The longer eastern lobe extends to $\sim 5\circ$ ($\sim 45$ kpc) from the nucleus. The total X-ray luminosity of the gas within this radius is $\sim 1.6 \times 10^{41}$ erg s$^{-1}$ (0.3-7.0 keV), of which approximately two thirds arises in the central $10$ kpc. The mechanical power output of the AGN exceeds this value by at least a factor of 60. If the formation timescale of the cavities is longer than we have estimated, this would lead to an underestimate of the energy they contain. While a factor of $\sim 6$ less than the mechanical energy available from the jets, the conduction rate still exceeds the radiative cooling rate by a factor of $\sim 18$, suggesting that conduction must be strongly suppressed for the gas to have retained its cool temperature. Heating at this conduction rate would destroy the cool core in $16$ Myr, a shorter timescale than that required to form the cavities. Assuming a timescale equal to that of the AGN outburst, we find that conduction must be suppressed below the rate estimated from equation 1 by a factor of $>5$.

However, this timescale is almost certainly too short. There are several reasons to believe that the temperature structure of the IGM prior to the AGN outburst must have been similar to that currently observed. Firstly, most nearby galaxy groups have a temperature structure similar to that of NGC 4261, with a central cool core, peak in temperature at moderate radii and temperature decline at larger radii (Rasmussen & Pomman 2007; Sun et al. 2009), indicating that this is probably a moderately stable state. Secondly, the formation of the observed temperature gradient over a timescale comparable to that of the outburst would be difficult. If the AGN formed the temperature gradient by heating the ICM at $10-70$ kpc, the energy required would be $\sim 7.5 \times 10^{58}$ erg (assuming an initial temperature equal to that of the core, $\sim 0.6$ keV). This exceeds the enthalpy of the jets.
the cavities by a factor of 3, and would require strong additional heating of the gas, presumably by shocks, for which there is no evidence. Since the virial temperature of the group would be \( \sim 0.6 \) keV in this scenario, such strong heating would be likely to cause convective motions in the IGM, and might be sufficient to unbind gas from the group gravitational potential. The heated region also extends well outside the tips of the radio lobes (70 kpc compared to \( \sim 45 \) kpc), but the timescale over which heated gas could disperse outward is longer than the AGN outburst timescale. The sonic timescale for gas in the hot region corresponding to a distance of 60 kpc is \( \sim 100 \) Myr, and convective motions would take several times longer to transport the gas outward. It is therefore likely that the appropriate timescale over which to consider conduction into the cool core is much longer than that of the AGN outburst, and the suppression factor for conduction is correspondingly higher.

A suppressed conduction rate is not unexpected in the cool core of NGC 4261. The simplest assumption of a tangled magnetic field would lead to significant suppression. Magnetic field lines aligned radially along a temperature gradient, which would enhance conduction, are likely to be realigned by convective gas motions, taking on a tangential alignment which will strongly suppress conduction. This heat-flux-driven buoyancy instability (HBI, Parrish & Quataert 2008) can reduce the conduction rate by large factors. The timescale for saturation of the instability is long and dependent on the steepness of the temperature gradient (Parrish et al. 2009), and any field alignment can be disrupted if turbulent motions are introduced into the gas (Parrish et al. 2010). However, HBI provides a potential mechanism for suppressing conduction to the level required.

The number of supernovae occurring within the core can be estimated based on the stellar population in the region. NGC 4261 was taken to be a prolate ellipsoid whose major axis lies in the plane of the sky, and which is described by a Sérsic (1968) model with effective radius 56.81\( \mu \)pc, axis ratio 0.80, and shape parameter \( n=5.44 \) (determined from observations described in Bonfini et al. 2011). These physical parameters are consistent with the limits determined from stellar velocity measurements, ignoring the probable small inclination of the galaxy away from the plane of the sky (Davies & Birkinshaw 1986). The Sérsic model was deprojected using the three dimensional luminosity density distribution described by Chakrabarty & Jackson (2009), normalising to the total optical luminosity \( L_{\text{opt}}=5\times10^{10}L_{\odot} \).

Assuming a supernova rate of 0.166 per 100 yr per \( 10^{10}L_{\odot} \) (Cappellaro et al. 1999), and an energy release of \( 10^{51} \) erg, we estimate the heating rate within the core to be \( 6.4\times10^{40} \) erg s\(^{-1} \), if the energy release is efficiently coupled to the gas. This agrees within a factor of 2 with the X-ray luminosity of the core. However, since the X-ray surface brightness profile is considerably more peaked than the optical light profile (see Fig. 2), it seems likely that supernova heating will be most effective in the outskirts of the cooling region, where it may balance radiative cooling, but that it will be unable to prevent cooling in the high density gas near the AGN.

To determine whether the cool core could potentially fuel the AGN, we estimate the isobaric cooling time and mass deposition rate in the innermost \( \textit{Chandra} \) spectral bin (radius \( \sim 0.3-0.8 \) kpc). We find a cooling time of \( \sim 60 \) Myr, and a mass deposition rate \( \dot{M}_{\text{cool}}=0.033\ M_{\odot} \ yr\^{-1} \). Comparing this with our estimate of the mechanical power output of the AGN, we find that the efficiency of the AGN in converting cooling gas into energy would be \( \epsilon_{\text{conv}} = \dot{P}_{\text{mech}}/\dot{M}_{\odot} c^{2} = 1.8\times10^{-3} \). Zezas et al. (2005) argued for an accretion rate much lower than this mass deposition rate (\( 4.3\times10^{-9} \) \( \dot{M}_{\odot} \ yr^{-1} \)), based on the Eddington ratio of the AGN) but it is unclear whether the core X-ray emission component used to make this estimate arises from radiatively inefficient accretion, or from the radio jets (Zezas et al. 2005; Worrall et al. 2010). Based on the rate of stellar mass loss from AGB stars (Athey et al. 2002), we estimate that \( \sim 0.095 \ M_{\odot} \ yr^{-1} \) of gas is injected into the core from stars. Supernovae will make only a minor mass contribution, based on the rate of \( 2\times10^{-10} \) SN yr\(^{-1} \), but will contribute to heating the gas to the observed temperature of \( \sim 0.6 \) keV. The total mass injection rate is similar (within the large uncertainties) to the rate of loss through cooling, suggesting that there is no need for a flow of cooling gas into the core to sustain its current size and gas content. It therefore seems possible for the cool core to provide cooling gas to fuel the AGN over long timescales, replenished only by gas lost from the stellar population within the core.

In summary, it seems likely that neither the AGN jets nor conduction from the surrounding IGM is effective in heating the cool core. Supernova heating may balance radiative cooling in the outer part of the core, but is unlikely to do so in the denser inner regions. However, stellar mass losses within the core should be sufficient to replenish any gas lost, allowing the core to maintain its current size and to continue to supply cooling gas to fuel AGN activity over timescales longer than that of the current AGN outburst.

4.3 Pressure balance in the lobes

As discussed in Section 3.3, while the lobes may be overpressured with respect to their environment, the difference in pressures is probably not large. Given approximate pressure equilibrium, a comparison of the apparent pressures of the thermal plasma of the IGM and the relativistic plasma of the radio lobes can provide insight into the particle content of the lobes (e.g., Hardcastle & Worrall 2000; Dunn et al. 2005; Birzan et al. 2008). The lobes of FR I radio sources are generally found to have apparent synchrotron pressures well below the IGM pressure (e.g., Feretti et al. 1992), and this is generally assumed to indicate either that the lobes contain a significant population of non-radiating particles, or that the assumption of equipartition is incorrect, with the magnetic field providing additional pressure support.

We estimate the physical properties of the radio lobes from the 1.5 GHz VLA archival data. The volume of the lobes is derived from the ellipse regions in Figure 1, as described in Section 4.1. We adopt an electron spectral index of \( p=2.2 \), equivalent to a radio spectral index of \( \alpha=0.6 \), which compares well with the flux density measurements compiled in NED\(^4\), and the value of \( \alpha=0.62\pm0.17 \) estimated by Kühr et al. (1981). We make the usual assumptions of minimum energy conditions, in which the total energy content of the relativistic particles and magnetic field are roughly equal, and a low energy cutoff in the electron energy distribution at a Lorentz factor \( \gamma_{\text{min}}=10 \). We can then estimate the strength of the minimum energy magnetic field \( B_{\text{min}} \) and the pressure of the relativistic plasma \( P_{\text{min, en.}} \), which is defined to be

\[
P_{\text{min, en.}} = \frac{B_{\text{min}}^{2}}{2\mu_{e}c} + \frac{(1 + k)E_{e}}{3V\phi},
\]

where \( V \) is the lobe volume, \( E_{e} \) is the energy of the electron population and \( \mu_{e} \) is the permeability of free space (\( 4\pi \times 10^{-7} \) in S.I. or \( 4\pi \) in cgs units). \( \phi \) is the filling factor of the lobes (assumed to be 1)

\(^4\) The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
and k the ratio of energy in non-radiating particles to the energy in relativistic electrons (assumed to be 0). The estimated parameters, assuming (1+k)/\epsilon=1, are shown in Table 2. The factor \epsilon is dependent on the ordering of the magnetic field, with \epsilon=3 for a tangled field, and \epsilon=1 for a uniform or stretched field (Leahy 1991). We have adopted \epsilon=3, but we note that \epsilon=1 is assumed in some commonly used formulae (e.g. Burns et al. 1979; Fabian et al. 2002). For comparison, adoption of \epsilon=1 would approximately double our estimate of lobe pressure.

Comparing with the IGM pressure at the lobe midpoint (\sim 5 \times 10^{-15} \text{ erg cm}^{-3}) the difference in IGM and lobe pressures of a factor 5 agrees closely with the estimate of Croston et al. (2008). Under the assumption that \epsilon=3 is an underestimate and the lobes and IGM are in fact in pressure equilibrium, we can rearrange Equation 2 to determine the changes in filling factor or non-radiating particle component necessary to explain the pressure imbalance. However, we must account for the dependence of \epsilon on k and \phi, and the dependence of \epsilon on \epsilon on B_{\text{min}}. In simplified form, \epsilon_{\text{min}} \propto \frac{1}{1+k} \phi_{\parallel}^{-1/2} B_{\text{min}}^{-1/2} (Worrall & Birkinshaw 2006). We find that pressure balance is achieved if (1+k)/\epsilon=5.1. If, as seems likely, the lobe is still mildly overpressured with respect to the IGM, this value can be considered to be a lower limit.

A reduced filling factor could occur in a number of ways; the lobes may contain a radio-quiet plasma component such as gas entrained by the radio jets, there may be variation in the relative density of magnetic field and relativistic particles leading to uneven radio emission, or the lobe volume could simply be overestimated, for example if their outer surfaces are more structured than a smooth ellipsoid and the lobes contain pockets or filaments of IGM plasma. In principle, it is possible to place a limit on the effects of the last of these possibilities from the X-ray data. If a fraction of the apparent lobe volume contains IGM gas, the expected X-ray surface brightness decrement will be reduced. Unfortunately the IGM surface brightness is low, only small decrements are expected, and the large uncertainties mean that we cannot determine a useful limit in this way. However, the presence of the cavity rims, probably consisting of material swept up by the expanding lobes, argues that the lobes have been effective in removing IGM gas from the volume they occupy. A detection of inverse Compton emission from the lobes (arising from CMB photons scattered up to X-ray energies by relativistic electrons) might allow us to place limits on the clumping of the relativistic plasma. Inverse Compton emission has been detected from the lobes of many FR II radio galaxies (Croston et al. 2005) and from the diffuse mini-halo in the core of the Perseus cluster (Sanders & Fabian 2007), but is not detected in the lobes of bright, cluster-central FR I radio sources such as Hydra A, Hercules A and M 87 (Hardcastle & Croston 2010; Simionescu et al. 2008). Unfortunately, the inverse Compton emission from the lobes of NGC 4261 is expected to have only a small flux if the minimum energy condition is correct, \sim 2 \text{nJy} at 1 \text{ keV} for each lobe. This compares with 2.6 \text{nJy} measured for the resolved X-ray jet (Worrall et al. 2010), but the expected 2 \text{nJy} would be spread over the whole area of the lobe and would be undetectable in our data. We are therefore unable to place limits on the filling factor, and must continue to assume \phi=1.

The additional pressure required could be provided by additional non-radiating particles in the relativistic plasma. Since we require k\sim 4, these would probably have to be introduced into the relativistic plasma via the entrainment and heating of thermal plasma by the radio jets. It has been suggested that some knots in the inner jets of Centaurus A may be caused by interactions between jet plasma and the winds of high mass stars (Hardcastle et al. 2003), and stellar mass loss from stars within the jets is an obvious source of entrained material. The well defined small–scale X–ray jets have a width of 4.7′′ (720 pc), and length 31.7′′ (4900 pc) for the longer western jet (Worrall et al. 2010), and we assume they are cylindrical. Using the mean stellar luminosity density within this radius (~0.11 L_{B,\odot} \text{ pc}^{-3}), based on optical modelling described in Section 4.2 and adopting the stellar mass loss rate from AGB stars \dot{M}=0.0788 (L_\odot/10^5 L_{B,\odot}) M_\odot \text{ yr}^{-1} (Athey et al. 2002), we estimate the rate of mass loss into each jet to be 1.67 \times 10^{-4} M_\odot \text{ yr}^{-1}. Assuming the timescale of the current AGN outburst to be our estimated upper limit (75 Myr), we would thus expect a minimum of \sim 125000 M_\odot of stellar material to be entrained by each jet.

If this entrained material takes the form of a thermal plasma mixed with the relativistic plasma of the radio lobes, the temperature required for it to balance the pressure of the surrounding IGM is >10 MeV. We note that Sanders & Fabian (2007) place an upper temperature limit of 100 keV on any thermal plasma in the radio lobes of Perseus A. For electrons, a temperature of 10 MeV is equivalent to a Lorentz factor \gamma \sim 20. The very low density of such a plasma component (n_e \sim 3 \times 10^{-3} \text{ cm}^{-3}) means that it is unlikely to produce any detectable emission either directly or via inverse-Compton scattering. Electrons of \gamma \sim 20 in the minimum energy magnetic field would be expected to radiate at \sim 1 \text{ kHz}, below observable frequency bands.

Limits can also be placed on the density of any thermal plasma component in the lobes, based on the degree of depolarization observed. The relationship between the observed degree of polarization \mathcal{P}_{\text{Obs}} and the intrinsic degree of polarization \mathcal{P}_{\text{Int}} can be approximated as

\[
\mathcal{P}_{\text{Obs}} = \mathcal{P}_{\text{Int}} \frac{\sin(RM \lambda^2)}{RM \lambda^2},
\]

where RM is the rotation measure and \lambda the wavelength (Govoni & Feretti 2004). The rotation measure of a thermal plasma intermingled with the relativistic plasma in the radio lobe is approximately

\[
RM = 4.05 \times 10^5 \int_0^L n_e B_\parallel dz \text{ rad m}^{-2},
\]

where \(n_e\) is the electron number density of the thermal material in cm\(^{-3}\), \(B_\parallel\) is the line–of–sight component of the magnetic field in Gauss, and the thickness of the region, \(L\), is in pc (Worrall & Birkinshaw 2006). A depolarization of \sim 8 per cent. at 21.2 cm is reported for the lobes of NGC 4261 (Bologna et al. 1969) and while the contribution from beam depolarization is unknown, we can limit the density of any thermal component to be \sim 2 \times 10^{-3} \text{ cm}^{-3}.

This is considerably greater than the density expected from entrained gas from stellar winds (3.6 \times 10^{-7} \text{ cm}^{-3} for the east lobe) but comparable to the IGM density. The limit thus argues only against the entrainment or envelopment of very large quantities of IGM gas into the radio lobes, but cannot rule out entrainment of gas from stellar winds.
The estimate of the mass of gas from stellar winds entrained by the jets ignores stars in the outskirts of the galaxy where the jets are broader, and the possibility of entrainment from the gas of the cool core or IGM. Increasing the mass entrained would lower the temperature of any thermal component within the lobes, but the energy required to heat such a component, \( \sim 5 \times 10^{57} \) erg summed over both lobes, would not be significantly altered. This is only \( \sim 20 \) per cent. of the estimated total mechanical power output of the jets, probably within the uncertainties on the available energy. Given the evidence of rims around the cavities, indicating that the lobes probably have a high filling factor and may be mildly overpressured, it seems likely that the true mechanical jet power is somewhat higher than our estimate, and this could easily provide the energy required to heat any entrained material.

5 DISCUSSION

5.1 The cool core and AGN

We can consider three sources of material which might fuel the AGN in NGC 4261: 1) a cold gas reservoir unrelated to the hot IGM, 2) hot gas produced within a cool corona, with no significant inflow of gas from the IGM to the corona, and 3) hot IGM gas via a cooling flow, with no separation between the cool core and the rest of the IGM. For AGN feedback to control cooling in the group, the AGN must be fuelled by material which it is capable of effectively heating, so that its power output directly affects the rate of fuel supply. This appears unlikely in case 1 and most likely in case 3, since we observe the interaction between the AGN and IGM. However, if the cool core is a galactic corona, magnetically separated from the surrounding IGM, then significant inflow from the IGM cannot occur and case 3 is ruled out. A feedback loop is possible in case 2 only if the AGN can effectively heat the gas of the corona or prevent its transport in to the central engine.

The evidence of past tidal interaction in NGC 4261 raises the question of whether the current nuclear activity could be related to a merger. This appears unlikely. Although a nuclear disk of gas and dust containing \( (5.4 \pm 1.8) \times 10^4 \) \( M_\odot \) of molecular and atomic hydrogen is observed (Ferrarese et al. 1996), cool gas has not been detected elsewhere in NGC 4261 (Serra & Oosterloo 2010; Combes et al. 2007). Stellar population modelling finds little evidence for a young stellar population in the galaxy core; the luminosity weighted age is estimated to be \( 12.6^{+0.7}_{-0.6} \) Gyr (Serra & Oosterloo 2010). It therefore seems likely that any merger was gas poor.

While a large injection of cool gas into NGC 4261 is unlikely, it seems probable that the cool gas disk is the immediate source of material fuelling the AGN. Direct accretion from the hot phase cannot be ruled out, but does not explain the presence of the cool gas. Assuming a conversion efficiency of 1 per cent., accretion of the material in the observed gas disk would release \( \sim 10^{57} \) erg, a factor of 20 less than the enthalpy of the cavities. Unless we are coincidentally observing NGC 4261 just as the AGN is about to consume the last of its fuel, the disk gas must be replenished by material cooling from the hot phase. Judging the likelihood of such a coincidence is difficult. The selection of NGC 4261 as a luminous radio galaxy with extended lobes could bias us toward observing the system during the period when the lobes have had time to expand and attain a high surface brightness, but before the jets shut down. Conversely, the lack of evidence of multiple AGN outbursts or star formation would require any gas introduced by a merger to be efficiently transported into the galaxy nucleus as a single unit. However, even if the current activity were fuelled by cold gas, the presence of the cool core strongly suggests that the AGN is ineffective in heating its immediate neighbourhood. The presence of the cool core argues that interaction between the jets and gas in the core regions is minimal, and shock heating is weak. The total energy released through shock heating need not be negligible, but it seems more likely that in this system any recent shocks have been driven by lobe/jet expansion rather than originating at the nucleus, and have occurred at radii >10 kpc.

The energetic conditions of the cool core (see Section 4.2) are similar to those described by Sun et al. (2007) for galactic coronae. Sun (2009) showed that for systems hosting relatively powerful radio galaxies, coronae fall into a region of \( L_X/L_{\text{radio}} \) space separate from systems with larger cool cores (see their Figure 1). From the deprojection analysis, we estimate the 0.5-2 keV luminosity of the gas in the core (radius \(<9.8 \) kpc) to be \( 5.9 \times 10^{40} \) erg s\(^{-1}\). The 1.4 GHz radio luminosity of 3C 270 is \( 2.4 \times 10^{24} \) W Hz\(^{-1}\) (Condon et al. 2002). This places NGC 4261 in the corona class. However, the cool core of NGC 4261 is relatively large compared to coronae in galaxy clusters and has a rather mild temperature difference with the surrounding IGM. This is expected, as corona size is dependent on the pressure of the surrounding IGM, which is lower in this group than in higher mass galaxy clusters. The limits on the suppression of condensation and efficiency of AGN heating are also comparatively weak. We conclude that the cool core of NGC 4261 is probably an example of a nearby, relatively large galactic corona, but that we cannot be sure of the classification in such a system.

The radio source has clearly affected the structure of the corona. Worrall et al. (2010) point out that the X-ray jets are surrounded by regions of low surface brightness, suggesting that thermal gas has been removed and the lobes now extend back to fill these regions, surrounding the jets. The X-structure observed in X-ray surface brightness and temperature maps, and the cool temperature of the structure, suggests that the gas of the cool core has been compressed and driven away from the jets by subsonic expansion of the lobes. Direct interaction with the jets appears unlikely, since there is no evidence of shock heating. The expansion of the lobes is also probably responsible for the general north-south extension of the X-ray emission within the stellar body of NGC 4261; the lobes have pushed the hot IGM gas originally occupying the outer part of the galaxy away from the jet axis to form an annular structure which we are viewing edge-on. It is worth noting that such an annulus would have a similar alignment to the disk of cool gas and dust which surrounds the AGN, though its scale would be \( \sim 200 \) times larger.

Since the corona shows no signs of having been heated by the current AGN outburst, it is unclear how nuclear activity can stop cooling in this region. If the AGN cannot effectively heat the core, it cannot form a feedback system with the IGM, and cooling and heating of the group gas need not be in balance. If the feedback relationship is to be sustained, we require a mechanism for ending nuclear activity. Several possibilities can be suggested:

(i) If the AGN is fuelled by a reservoir of cool gas left over from a gas–rich merger, activity will cease within the next few Myr, assuming a constant rate of consumption. This requires us to be observing NGC 4261 at an unusual period of its history, and suggests that FR I radio galaxies are fuelled from reservoirs of cool gas, and is thus unsatisfying.

(ii) A change in accretion or jet properties could alter the heating mechanism. For example, we could be observing NGC 4261
during a long period in which accretion drives jets without producing shocks in the nuclear region. At some future point, alteration of conditions could cause the amount of energy released in shocks to rise, heating the core and ending the outburst. This cannot be ruled out, but we note that there is evidence that the \( \leq 75 \) Myr period of activity which has formed the radio lobes has not been continuous, and that the jet properties have changed with time (Worrall et al. 2010).

(iii) The expansion of the lobes back along the line of the jets into the corona raises the possibility that they could reach the centre of NGC 4261 and envelop the nucleus. This could potentially reduce the amount of thermal plasma able to reach the central engine. Enclosure need not lead to an immediate cessation of nuclear activity, since the cool gas disk would still need to be consumed, and the enclosed region could also contain a high-pressure core of hot gas. However, it is unclear whether the pressure in the lobes will be sufficient to push aside the thermal gas at very small radii. As the lobes expand outward, moving down the IGM pressure gradient, we might expect their internal pressure to decline. In this case, they are unlikely to be able to move aside the high-pressure material in the inner part of the corona. It is also unknown whether flows of cooling material might be able to penetrate or push aside the enclosure formed by the radio lobes, transporting gas into the nucleus.

(iv) Disturbance of the structure of the corona by the radio source could affect the AGN in a number of ways. The lobes have already compressed the gas in the core, increasing its density and cooling rate. This could lead to an increase in the supply of gas to the AGN and potentially an increased heating rate. Disturbance of the corona structure may also affect the conduction rate. The surface of the corona has already increased above that of a sphere. If enough of this surface is in contact with the IGM (rather than the radio lobes) the increased surface area will lead to an increase in the conduction rate. Gas motions introduced as the lobes push the core gas aside may also alter the magnetic field structure, potentially increasing conduction if field lines are straightened by expansion, or reducing conduction if the motions cause further tangling of the field. If the suppression factor is significantly reduced, the corona could potentially be heated fairly rapidly, reducing the fuel supply to the AGN.

While we cannot determine whether any of these processes (or some other) will be effective in terminating the AGN outburst in NGC 4261, it is likely that physical changes in the structure of the core over a long timescale are an important factor. If this is true of other corona systems, it would suggest that whereas AGN in large cool cores may rapidly reheat the cooling gas which fuels them, AGN in coronae can remain active for longer periods without disrupting their fuel supply. Coronae therefore seem likely to fuel long-term nuclear activity, rather than short outbursts, and AGN in coronae may spend a larger fraction of their time active than AGN in large cool cores. This could explain why such systems lack large-scale cool cores; they inject more energy into the IGM, and heat it to a point where the cooling which occurs while the AGN is quiescent is insufficient for a cool core to develop before the jets restart. Studies of other nearby corona systems are clearly required to determine whether such important differences in duty cycle and energy output are real. Dunn et al. (2010) examined 18 nearby giant elliptical galaxies and found that 17 host nuclear radio sources, potentially lending weight to the idea that AGN in galactic coronae are able to remain active for long periods. However, a number of galaxies in the sample occupy the centres of groups or clusters, and have cool cores considerably larger than that of NGC 4261, so only a fraction of this sample are likely to be corona systems.

5.2 Structure of the radio source

The structure of the radio lobes, cavities and rims raises several questions. Considerably more X-ray emission is seen in the eastern lobe and its rim appears, at least in the XMM–Newton images, to be thicker. It is also complete, unlike the western rim, which is undetected in one quadrant. Possible explanations involve the data quality; the XMM–Newton data may simply be insufficiently deep to clearly detect the cavity rims and determine their shape, and our point source subtraction may also be ineffective. Prior studies of the X-ray point source population have shown a particular concentration of sources to the north and northeast of the AGN (Giordano et al. 2005), but also to the south and west. The poorer ability of XMM–Newton to resolve these sources compared to Chandra might produce increased noise in the northeast quadrant, leading us to overestimate the thickness of the rim in this area.

Other factors which could affect rim strength are the structure of the IGM into which the radio lobes have expanded, and the structure of the lobes themselves. Surface brightness modelling of the group with the ROSAT PSPC found the IGM to be centred to the east of NGC 4261, with the emission more extended to the south and east. Davis et al. (1995) found the centroid of diffuse emission to be R.A. 12\(^{\circ}\)19\(^{\prime}\)27\(^{\prime\prime}\), Dec. +05\(^{\circ}\)49\(^{\prime}\)58\(^{\prime\prime}\) (J2000), ~1\(^{\prime}\) (9.2 kpc) ENE of the nucleus (see also their fig. 1). If this extension is real, it suggests that NGC 4261 is slightly offset from the centre of the group X-ray halo. The eastern lobe would, in this scenario, have expanded into a denser environment than its western counterpart, and has therefore accumulated more gas in its rim.

The morphologies of the two radio lobes are also slightly different. The western lobe is broader but less extended, and has distinct bulges on its sides. If the extension of the lobe tip is driven by the jet, the shorter length of the western lobe could indicate that the western jet has encountered greater resistance to its expansion. However, we see no evidence of any feature which could be responsible for this resistance, such as a region of denser intra-group gas. The greater sideways expansion of the western lobe suggests that external pressure is lower on this side of the core, as expected if the galaxy is offset from the group centre. There is also some indication that the eastern radio jet bends inside the radio lobe (see the contour map in Figure 1a and fig. 1 of Worrall et al. 2010), while the western jet remains on approximately the same axis as the small-scale jets visible in the X-ray. This could perhaps affect the apparent structure of the eastern lobe, since we are viewing a projected image of a three dimensional structure. If the jet axis is no longer in the plane of the sky, the shell of gas around the expanding lobe tip might appear as a broader X-ray bright region rather than a relatively thin shell. This would probably require a fairly strong bend in the jet which, while quite possible, has yet to be confirmed from the available observational data.

6 CONCLUSIONS

We have analysed deep Chandra and XMM–Newton observations of the nearby group–central elliptical NGC 4261. The X–ray observations reveal a large degree of structure in the gas in which the galaxy is embedded. The AGN jets have inflated two large lobes, excavating cavities in the IGM and building up rims of compressed...
hot gas which almost entirely enclose the lobes. The western cavity has an apparent break in its rim, while the eastern lobe has a higher X-ray luminosity over most of its area. The enthalpy of the lobes is large, \( \sim 2.4 \times 10^{58} \text{ erg} \), and the likely timescale of the outburst, \( \lesssim 75 \text{ Myr} \), suggests that the mechanical power of the jets, \( \gtrsim 10^{43} \text{ erg s}^{-1} \), greatly exceeds their current radio power. The mechanical power of the AGN also exceeds the X-ray luminosity of the gas in the region the lobes inhabit, the central 45 kpc of the group. The available X-ray data are insufficient to determine conclusively whether the cavity rims contain shocks, but we can limit the maximum expansion velocity of the lobes to be \( M \lesssim 1.05 \), and their minimum expansion velocity to be a large fraction of the sound speed. These results suggest that the radio source may still be mildly overpressured relative to it environment, but that it is only inefficiently heating the IGM.

Spectral mapping and radial spectral analysis confirms that NGC 4261 has a cool core with radius \( \sim 9.8 \text{ kpc} \) and a typical temperature of \( \sim 0.6 \text{ keV} \), compared to a peak IGM temperature of \( \sim 1.6 \text{ keV} \). The core is not spherically symmetric, but contains an X-shaped structure, with the arms of the X extending to either side of the radio jets, the northeast and southwest arms being most extended. This structure was commented on by Worrall et al. (2010), who noted that the radio jets appear to have expelled gas in wedge-shaped regions to their north and south, probably corresponding to conical volumes. There is also a larger, bar-shaped structure extending north–south across the centre of NGC 4261, which is poorly correlated with the galaxy major axis but perpendicular to the jet axis. This is probably an annulus of gas viewed edge on, pushed into its current configuration by the expansion of the radio lobes. It is clear from these structures that the jets have played an important role in determining the structure and properties of the gas in and around NGC 4261.

The properties of the cool core suggest that it should be classified as a galactic corona. The relative radio power of the galaxy and luminosity of the cool core fall in the range occupied by corona systems. Heating of the corona by the AGN and conduction must have relatively low efficiencies. We limit the AGN heating efficiency to be \( < 3.5 \text{ per cent} \), and find that conduction into the cool core from the IGM is suppressed by a factor \( > 5 \). However these values probably overestimate the effectiveness of the heating mechanisms since they assume a timescale based on the length of the AGN outburst rather than the lifetime of the temperature gradient. Supernovae within the corona release \( \sim 6 \times 10^{50} \text{ erg s}^{-1} \) (compared to the 0.3–7.0 keV X-ray gas luminosity of \( \sim 10^{45} \text{ erg s}^{-1} \)), but since the stellar distribution is less centrally peaked than the gas density, they are unlikely to be able to prevent cooling in the inner core. Material lost from stars can balance the cooling rate of the corona, suggesting that cooling could fuel the AGN over timescales of several Gyr.

Since the AGN appears unable to effectively heat the corona, we have considered alternative mechanisms by which cooling could be disrupted or stopped. We conclude that changes in the corona structure, caused by the intrusion of the radio lobes into the cooling region, may be able to alter the cooling rate by compressing the gas, isolating the nucleus, or increasing the conduction rate. In any case, these results suggest that corona systems can potentially sustain longer periods of nuclear activity compared to their counterparts in large cool cores. Since the powers of radio galaxies with coronae and large cool cores are similar, it seems likely that sources in coronae will, on average, release more energy into the IGM over long timescales. Given the large numbers of coronae already detected in group– and cluster–central galaxies (e.g., Sun 2009), this may be an important consideration in determining the gas temperature structure of the population of galaxy systems.

Comparing the pressures of the IGM gas and the relativistic plasma of the lobes, we find the apparent lobe pressure to be a factor of 5 lower than that of the surrounding halo. This indicates that either additional non–radiating particles are present in the lobe plasma, that the filling factor of the lobes is low, or that the magnetic field departs from the minimum–energy solution. The currently available data are insufficient to place useful limits on the filling factor of the lobes. Thermal gas entrained from stars within the radio jets, or from the IGM, could potentially provide the additional pressure without radiating in a detectable waveband or producing excessive polarization effects. The energy required to heat this gas to its presumed temperature is \( \sim 20 \) per cent. of the total enthalpy of the radio lobes.

Acknowledgements

The authors thank the anonymous referee for several useful suggestions, and P. Bonfini for providing optical data for NGC 4261. EO’S thanks A. Sanderson for useful discussions of the X-ray analysis. Support for this work was provided by the National Aeronautics and Space Administration through Chandra Award Number GO8-9094X issued by the Chandra X-ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of the National Aeronautics Space Administration under contract NASA-03060. This work is partially based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA. This work has used data from the VLA. EO’S acknowledges the support of the European Community under the Marie Curie Research Training Network. Space Astrophysics in Crete is partly supported by EU FP7 Capacities GA No206469. GT and AW acknowledge support from the Agenzia Spaziale Italiana through grant ASI-INAF I/009/10/0. We acknowledge the usage of the HyperLeda database (http://leda.univ-lyon1.fr).

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