A deep ROSAT PSPC observation towards the CMB decrement close to PC1643+4631 A & B: no cluster X-ray emission

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ABSTRACT
We report on a 16 ks observation with the ROSAT PSPC centred on the CMB decrement which Jones et al. (1997) report in the direction of the quasar pair PC1643+4631. We do not detect the X-ray emission which would be expected if the decrement were caused by Compton up-scattering of CMB photons by hot gas. Our upper limit on the bolometric X-ray flux within a circle of radius 1.5′ is $1.9 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ at 99.7% significance. This is based on data in the energy range 0.5-2.0 keV and assumes bremsstrahlung with an observed temperature of 2.5 keV. We investigate the requirements for a spherical body of hot gas to produce the decrement while remaining consistent with our data. With conservative assumptions we establish a lower redshift limit of 2.8 at 95% confidence for a 10 keV isothermal object of any size. Even higher limits obtain for objects with temperatures between 0.2 and 10 keV. We discuss alternatives to a single, spherical cluster, such as a double or elongated cluster, a supercluster/filament, or scattering by a moving cluster. None of these appears attractive, especially since another candidate for a decrement near a QSO pair and without an obvious associated cluster has been found. An explanation other than Comptonization by hot gas within a virialised object appears needed.

Key words: X-ray – cosmic microwave background – quasars:individual: PC1643+4631 A & B – galaxies:clusters

1 INTRODUCTION
In an intriguing paper Jones et al. (1997) report the discovery of a decrement in the cosmic microwave background (CMB) in the direction of the quasar pair PC1643+4631 A & B. They suggest this may be due to a distant galaxy cluster which might also produce the quasar pair through gravitational lensing of a single source. The lack of detected X-ray emission in this field enabled Jones et al to establish that any such cluster must be at a redshift of 1 or greater. In this paper we report results from a pointed ROSAT observation which improves this X-ray constraint by a factor of about 20.

The interferometric data of Jones et al were taken with the Ryle Telescope (RT) at 15 GHz and give a flux decrement of $-380 \pm 64 \mu$Jy averaged over the $110'' \times 175''$ beam. For a circularly symmetric signal, this corresponds to a true decrement of at least 560 μK, this minimum value implying a core radius of about 60″, or roughly 250h$^{-1}$ kpc at high redshift. (Here $h = H_0/(100 \text{km/s/Mpc})$.) Since intrinsic fluctuations in the CMB are not expected on arc-minute scales, the most plausible origin for this decrement is inverse Compton scattering of CMB photons by hot intracluster gas (Sunyaev & Zel’dovich 1972). Decrements of this size have been detected in the direction of a number of massive galaxy clusters (Birkinshaw, Gull, Hardebeck 1984; Birkinshaw, Hughes, Arnaud 1991; Jones et al. 1993; Grainge et al. 1993; Birkinshaw, Hughes 1994; Wilbanks et al. 1994; Herbig et al. 1995; Grainge et al. 1996; Carlstrom, Joy, Grego 1997; Holzapfel et al. 1997; Myers et al. 1997). As Jones et al. discuss, such intracluster gas should be detectable in X-rays. They were able to put an upper limit on the X-ray flux using a 11.4 ks observation with the ROSAT PSPC in which the quasar pair serendipitously lies just within the field of view. Unfortunately vignetting and smearing by the point spread function greatly reduce the sensitivity of this observation, and we were able to establish a comparable (but independent) upper limit using data from ROSAT All-Sky Survey, which has a local exposure time of only 801 sec. Both observations limit the flux to be below $2 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (0.1-2.4 keV) at 99.7% confidence. Jones et al show that this constrains any cluster to be at $z > 1$. An extensive
search has so far identified no optical or infrared counterpart (Saunders et al. 1997). An HST observation has been scheduled (7342 by Saunders et al.) which should probe to even deeper limits.

If the observed decrement is indeed due to Compton scattering from hot gas, then X-ray observations offer the only way to detect this gas directly. The ROSAT detectors, with an energy range of 0.1–2.4 keV, are ideally suited to observe high redshift clusters which are expected to have temperatures in the range 1–10 keV. We therefore proposed and obtained a long pointed PSPC observation of this field.

2 THE ROSAT PSPC OBSERVATION

The observation, carried out between the 25th of February and the 3rd of March, was centred on RA = 16h45m12s, DEC = +46°24′35″ (J 2000), and had a total accepted exposure time of 15889 s. This was among the very last observations with the PSPC before complete exhaustion of its gas supply. We were, nevertheless, able to check the absolute positioning of the ROSAT XRT by comparing several sources within the support structure with objects on the Palomar plates. This confirmed our estimated coordinates to be accurate to a few arcseconds. Our astrometry is thus much better than the width of the psf.

Fig. 1 shows an overlay of the CMB measurement on our X-ray observation; coordinates in this plot are B1950. The separation of the quasar pair (+) PC1643+4631 A (right) & B (left) is 198″. Positions of removed radio sources (x) are also marked. X-ray sources (see Tab. 1) are labelled 1–4.

Figure 1. Overlay of the CMB measurement (Jones et al. 1997) on our X-ray observation; coordinates in this plot are B1950. The separation of the quasar pair (+) PC1643+4631 A (right) & B (left) is 198″. Positions of removed radio sources (x) are also marked. X-ray sources (see Tab. 1) are labelled 1–4.

A small (∼10 %) drop in the gain occurred towards the end of our observation period and has been taken into account in the following analysis. Only few of the 61 X-ray sources detected in the observation have so far been identified, and all lie more than 37′ off-axis. We were, nevertheless, able to check the absolute positioning of the ROSAT XRT by comparing several sources within the support structure with objects on the Palomar plates. This confirmed our estimated coordinates to be accurate to a few arcseconds. Our astrometry is thus much better than the width of the psf.

has been chosen, followed by Gaussian smoothing with a third of the width of the psf. The faintest grey patches are individual photons. We have labelled four sources near the decrement with a detection likelihood ratio exceeding 5, and we give their properties in Table 1. This very low detection threshold was chosen to demonstrate that not even a marginally detected source lies close to the centre of the microwave decrement. Secure detections are commonly quoted for a likelihood ratio of at least 10 (∼4σ). Objects 2 and 4 are both significantly more extended than the psf. Visual inspection suggests that 2 could consist of two close point sources, while 4 might really be an extended object. There are too few counts to use spectral analysis to check the possibility of a galaxy cluster. Other data (Frunner et al. 1996) suggest that X-ray emission from the quasars might be detectable in our data. We find no secure detection at the quasar positions, but there are marginal detections close to both of them (source 1 and possibly one component (with roughly half the total count rate) of the extended source 2).

We use these to set 2σ upper limits of 7 and 20 × 10^{-14} cts s^{-1} on sources associated with A and B respectively. For typical X-ray energy indices of \(\alpha_x = 0.5–1.0\) the monochromatic luminosities are 7.5 and 21 × 10^{44} erg s^{-1} keV^{-1}, and with the optical magnitudes of \(M_B = -26.1\) and -25.8 (Schneider, Schmidt, Gunn 1991) we find limits on the optical to X-ray spectral indices of \(\alpha_{ox} > 1.4\) and 1.2.

The most stringent and robust upper limits on cluster X-ray emission associated with the decrement are obtained using the observed energy interval 0.5-2.0 keV, since the Galactic background is high at lower energies and the instrument has little sensitivity at higher energies. Results from including the 0.1-0.5 keV band, more stringent for intrinsic gas temperatures below 1 keV, are discussed later in the paper. We quote limits within a circular aperture of radius 1.5′ centred on RA = 251°29′58″, DEC = +46°40′56″, the centre of the decrement. This extends over the 3σ contours of the microwave observation. Within this area we have 13 counts compared to the expected background of 15 counts. (Consistent background estimates were obtained by a spline fit to the image after removal of detected sources, and by averaging random regions without obvious sources and more than 10′ from the decrement.) With a Gaussian approximation to the Poisson photon arrival distribution we find that a source with an expected count of 12.5 can be excluded with 99.7 % confidence. This corresponds to a limiting count rate of \(8.9 \times 10^{-14}\) cts s^{-1}. Deconvolving the effective area and response of the instrument, and correcting for Galactic absorption due to an HI column density of \(1.8 \times 10^{20}\) cm^{-2}, this corresponds to a bolometric flux limit of \(1.9 \times 10^{-14}\) erg cm^{-2} s^{-1} for an assumed bremsstrahlung spectrum with temperature 2.5 keV in the observer frame. This upper limit is almost twenty times lower than that found using the ROSAT Sky Survey data or the serendipitous observation analysed by Jones et al.

3 CLUSTER MODELS

We now study the constraints imposed on a possible high redshift cluster by the combined X-ray and radio data. We follow Jones et al. in modelling the intracluster medium as
an isothermal gas, temperature $T$, distributed spherically with density profile

$$n_e(r) = n_0 (1 + r^2 / r_c^2)^{-3/2}. \quad (1)$$

To determine the central value of the temperature decrement a detailed knowledge of the synthesised beam, including the scanning path, is required. In practice the response of the telescope to different profiles must be modelled and fit directly to the visibility data. Jones et al. fit various core radii for the model of equ. 1. These data (points) were kindly provided by the Cambridge MRAO group.

The results were kindly provided to us by Richard Saunders and are shown in Fig. 2. For this model an X-ray flux limit $F_{\text{lim}}$ within an aperture of radius $\Theta_c$ implies

$$(1 + z)^4 r_A(H_0, \Omega, z) \frac{(kT)^2}{f(T)} > \frac{1}{4\pi} \left( \frac{me^2}{\sigma_T} \right)^2 \frac{\gamma_0^2}{F_{\text{lim}}} \left(1 - \left[1 + \Theta_c^2 / \Theta_\xi^2 \right]^{-4} \right), \quad (3)$$

where $f(T) = L_x / n_e^2$ is the X-ray cooling function, $\gamma_0$ the central decrement, $\Theta_c$ the angular core radius of the cluster model, and $r_A(H_0, \Omega, z)$ the angular-size distance. All quantities on the right of this inequality are directly observable, although in practice the radio data only constrain a combination of $\gamma_0$ and $\Theta_c$ (Fig. 2). It turns out that a core radius near $1^\prime$ not only yields the minimum true central temperature decrement, but also the lowest value of the right-hand side of equation 2 (for given $F_{\text{lim}}$). It thus gives the most conservative lower limit on the redshift of the cluster. Given the parameter dependence of the left-hand side, we will clearly get the lowest possible limit on $(1 + z)$ if we take the largest plausible values for $T$ and $r_A$. We will quote limits mostly for $(1 + z) = 3$ which implies a temperature decrement with profile

$$\Delta T = \Delta T_0 (1 + \Theta^2 / \Theta_\xi^2)^{-4/5}. \quad (2)$$

Table 1. Source detections with likelihood $> 5$ near the centre of the decrement.

| Object | RA ($^\circ$+) | DEC ($^\circ$+) | ML | Dist | Cts | Ext | Ext ML | Rate |
|--------|----------------|----------------|----|------|-----|-----|--------|------|
| 1      | .25658         | .43541         | 6  | 132  | 4.9 ± 2.5 | 3.3 ± 1.7 |
| 2      | .34073         | .42180         | 73 | 122  | 43.8 ± 7.0 | 29.3 ± 4.7 |
| 3      | .29900         | .37534         | 18 | 152  | 10.6 ± 3.6 | 7.1 ± 2.4 |
| 4      | .32700         | .34584         | 78 | 263  | 64.1 ± 8.6 | 43.1 ± 5.8 |

ML: Likelihood ratio, Dist: distance to the centre of the CMB decrement in arcsec
Cts: counts, Ext: extent (FWHM in arcsec), Rate: count rate in $10^{-4}$ ct s$^{-1}$

To explore the limits imposed on redshift and gas temperature in a more systematic way, we combine the radio and the X-ray data and maximise the joint likelihood of the two

Table 2. Gas halo parameters at $z = 1$ and 3 for $T = 10$ keV and the model of equ. 1

| $z$   | Core radius | Central electron density | Emission integral | X-ray luminosity (bol.) | X-ray limit (2-$\sigma$, bol.) |
|-------|-------------|--------------------------|-------------------|------------------------|-----------------------------|
| 1.25  | 517 kpc     | 1.6 $\times 10^{-3}$ cm$^{-3}$ | 3.3 $\times 10^{-6}$ Mpc$^{-3}$ | 2.0 $\times 10^{45}$ erg s$^{-1}$ | 0.3 $\times 10^{45}$ erg s$^{-1}$ |
| 3     | 436 kpc     | 1.9 $\times 10^{-3}$ cm$^{-3}$ | 4.7 $\times 10^{-6}$ Mpc$^{-3}$ | 2.8 $\times 10^{45}$ erg s$^{-1}$ | 3.4 $\times 10^{45}$ erg s$^{-1}$ |

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Figure 3. The upper panel shows confidence contours for excluding the hot gas model of (equ. 1) based on the combined radio and X-ray data. The gas masses which yield the most consistent model at each redshift and temperature are shown in the lower panel (these are quoted in units of $10^{14} M_\odot$ and refer to the mass within a sphere of radius corresponding to 2'). The heavy lines in the upper plot give confidence levels for an $\Omega = 1$ universe, while the dotted line gives the 95.4% level for an open universe with $\Omega = 0.2$. The long and short dashed lines indicate the redshift of the quasar pair and of a damped Ly$\alpha$ absorption feature in the spectrum of quasar A. These plots are based on scalings derived from a thermal Bremsstrahlung model which assumes the standard helium abundance and no metals. We have checked the results against full spectral modelling including heavy elements, Galactic foreground absorption, and the response of the PSPC. Our results are little affected by these factors for emitted temperatures above 2 keV, but at lower temperatures they become sensitive to uncertainties in metallicity and absorption. Results from detailed spectral modelling for the allowed range of low gas temperatures are discussed in the text.

4 DISCUSSION

The X-ray flux predicted by our models could be reduced by a factor of 2 by assuming the cluster to be stretched along the line-of-sight to twice its apparent diameter or to be broken into two equal clusters which are superposed in projection. In fact, however, a factor of two is not a great help, since it only results in a $\sim 25\%$ reduction of our redshift limits. If the decrement is due to a virialised cluster, it seems that we need a cluster at least as massive as Coma at a redshift beyond 3. The existence of even one such cluster in the observable universe is quite unexpected in current structure formation models. When normalised to give the presently observed abundance of clusters, only open models with $\Omega_0 < 0.25$ predict more than one cluster on the whole sky with $3 < z < 4$ and with $M > 2 \times 10^{15} M_\odot$. (This calculation is based on a Press-Schechter model similar to those in White et al. (1993).) Such models overpredict the amplitude of fluctuations in the CMB.

Gravitationally confined gas which is considerably hotter than 10 keV has not been found observationally on the spatial scales of interest. At low temperature on the other hand large-scale gas properties are somewhat uncertain. The lower temperature window indicated by the drop in redshift below 2 keV in Fig. 3 might therefore be more promising for finding a plausible solution to the given data. Indeed the formal solution for a spherically symmetric object at redshift 3 and with temperature 0.2 keV could explain all observational data including the possible lensing for a gas mass fraction of 0.1. To derive this, the limit of $1.3 \times 10^{-3}$ ct s$^{-1}$ in the 0.1-2 keV energy interval was used, and very conservative assumptions about the plasma element abundances (zero metallicity, strongly suppressing line emission) and Galactic absorption ($N_H = 3.6 \times 10^{20}$ cm$^{-2}$, to account for local enhancements), which the limits in this temperature range depend sensitively upon, were made. The formation of such an object, however, would be hard to understand in the context of gravitational collapse. The implied gas mass of a few $\times 10^{15} M_\odot$ within a volume of $0.52 h^{-3}$ Mpc$^3$ has not been seen in any object and the assumed temperature is by two orders of magnitude lower then what would be expected for the virial temperature.

Substantial reductions in X-ray flux are possible if we give up the assumption that we are seeing a collapsed and virialised system. The interferometer data require the extent of the object to be roughly $250 h^{-1}$ kpc in the directions transverse to the line-of-sight, but its depth could be much greater; it would then correspond to a supercluster “filament” seen end-on. Since such filaments are not fully virialised they can have temperatures which are substantially smaller than those of rich clusters, even though their masses are comparable or even larger. The gas in such filaments is heated by an accretion shock as it flows in from surrounding regions and by local virialisation shocks within subclumps along the filament. Typical velocities at these shocks are a few hundred km/s, so that post-shock temperatures of a few million degrees are expected. Thus at redshifts greater than 2 a prolate filament obeying equation (1) with $r_c = 50''$ but elongated by a factor of ten in depth (corresponding to a filament “length” of $\sim 5 h^{-1}$ Mpc) can be consistent with both X-ray and radio data for gas temperatures below 0.5 keV. The gas mass required is around $1 \times 10^{15} M_\odot$.
(for $h = 0.5$). This high gas mass and the a priori implausible aspect of a close alignment of the filament with the line-of-sight disfavour this model, but careful quantitative analysis of numerical simulations is needed to see whether sufficiently massive filaments are formed at high redshift in currently popular theories for structure formation.

Gas in an aligned filament could also produce the observed microwave decrement without significant X-ray emission if it happened to be flowing along the filament at high enough speed. The amplitude of the observed decrement could be reproduced by Compton scattering from $3 \times 10^{14} M_\odot$ of gas moving away from us at $850 \text{ km/s}$, regardless of the gas temperature. The speed required scales inversely with the mass of gas, and, as before, the gas needs to be projected onto a region with transverse diameter about $0.5 h^{-1} \text{Mpc}$. Again numerical simulations are required to estimate whether sufficiently large coherent velocities occur along massive enough filaments for this to be a quantitatively viable model. Notice that this mechanism should produce enhancements and decrements of the CMB with equal probability.

The decrement towards PC1643+4631 may not be a unique, or even a particularly rare object. Another rather similar decrement has now been reported. A decrement with a smaller amplitude and on a smaller angular scale has been mapped at the VLA by [Richards et al. 1997]. In this case also a deep ROSAT HRI observation found no X-ray emission. Furthermore, this decrement is also in the direction of an unusually close QSO pair at $z = 2.561$. We have applied our analysis to this case, for which $\Delta T_0 = -250 \mu \text{K}$, assuming $\Theta_c \sim 15''$ (comparable to the beam size), and the X-ray flux is less than $2 \times 10^{-14} \text{ erg cm}^{-2} \text{s}^{-1}$ at $99.7\%$ confidence in the $0.1-2.4 \text{ keV}$ band. For a $10 \text{ keV}$ cluster these data imply a redshift greater than about 0.7. The constraint is weaker than in the case of PC1643+4631 because the decrement has smaller amplitude and scale. Thus PC1643+4631 may be the first example of a class of objects which is somehow related to the background QSO’s. As Jones et al noted, the most obvious relationship might be through gravitational lensing, but to produce the observed $198''$ separation a filament at $z = 2$ would need to have a mass of $1 \times 10^{14} M_\odot$ projected between the two images. This seems very high, although again it cannot be excluded without detailed simulation of specific models.

5 CONCLUSION

Our X-ray limits make it seem unlikely that the decrement towards PC1643+4631 is due to a distant virialised galaxy cluster. We cannot definitively exclude the possibility of a hot, diffuse and massive cluster containing the two quasars at $z = 3.8$, but such a cluster is difficult to reconcile with present ideas about structure formation. A supercluster filament seen end-on at lower redshift may provide a more plausible solution, but then the association with the quasar pair is difficult to understand. It seems unlikely that this is pure chance since another similar decrement has been found also associated with a QSO pair. In view of these various problems it is undoubtedly important to constrain the microwave spectrum of the CMB decrement, to continue searching in other frequency ranges, as well as to explore other possible explanations, for example, topological defects such as textures or strings, exotic quasar phenomena, or foreground effects of various kinds.

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