Extended Inverse-Compton Emission From Distant, Powerful Radio Galaxies

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Full references and details are available in Erlund et al. 2006, MNRAS 371 29.

Introduction

Inverse-Compton scattering of the Cosmic Microwave Background (ICCMB, CMB) in high-redshift radio sources should be detectable, since the energy density of the CMB increases steeply with redshift, z, to counterbalance the surface brightness dimming (Schwartz 2002). Most high-redshift radio galaxies should therefore have extended X-ray emission produced by ICCMB, thus tracing an older relativistic electron population (with Lorentz factor $\gamma \sim 10^3$, see section on 3C 294) compared with the population producing the radio synchrotron emission. *Chandra* observations of two high-redshift radio galaxies (3C 432 and 3C 191) show extended X-ray emission along their radio axes which is most likely to be due to ICCMB. Assuming the X-ray emission is indeed produced by ICCMB, the minimum energy contained in the particles responsible for the up-scattering is calculated, giving a lower limit to the energy stored in relativistic particles in these jets.

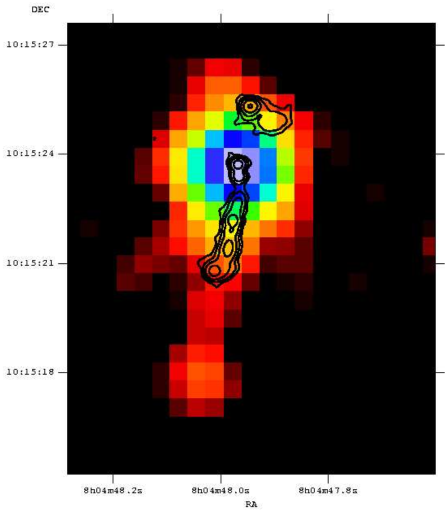

Fig. 1: Gaussian-smoothed $0.5 - 3$ keV X-ray image of 3C 191. The smoothing kernel was 0.49 arcsec. Overlaid are 8.46 GHz radio contours ($0.4, 1.3, 13$ and 40 Jy/beam).

3C 191 and 3C 432

The extended X-ray emission is preferentially aligned along the radio axis in 3C 191 and 3C 432 as shown in Figures 1 and 2. The X-ray emission extends far beyond sphere in which the nuclear radiation field could dominate over the CMB meaning that **the extended X-ray emission is likely to be due to inverse-Compton scattering of the CMB**.

The extended emission in 3C 191 continues beyond the end of the radio emission, both to the north and south, spanning 76 kpc compared with 40 kpc for the radio emission. This source may be a double-double radio galaxy, and we may be seeing ICCMB by old plasma which no longer emits at radio frequencies.

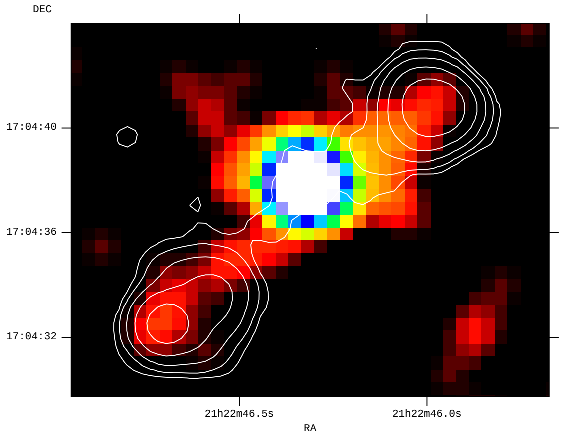

Fig. 2: Gaussian-smoothed $0.5 - 3$ keV X-ray image of 3C 432. The smoothing kernel was 1.5 pixels (0.74 arcsec). Overlaid with 1.54 GHz radio contours ($0.001, 0.0035, 0.012, 0.042, 0.144$ Jy/beam).

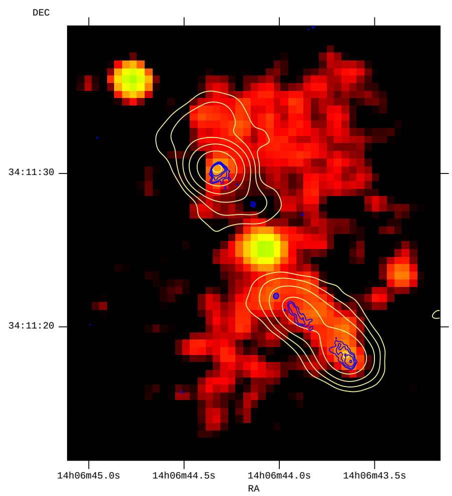

Fig. 3: Gaussian-smoothed $0.5 - 3$ keV X-ray image of all three observations of 3C 294. The smoothing kernel was 1 pixel. Overlaid with 8.46 GHz radio contours in blue ($0.24, 1.1, 5.2, 24$ mJy/beam) and yellow 1.425 GHz radio contours ($0.002, 0.006, 0.02, 0.06, 0.2, 0.6$ Jy/beam)

3C 294

The diffuse hour-glass emission from 3C 294 (see Figure 3) is most likely to be due to ICCMB following the detailed modelling by Fabian et al. (2003).

The radio morphology shows that both jets are bent but lie parallel to each other; this change in jet direction could be due to precession or shearing by an external medium. There is no radio emission associated with the NW-SE axis of the X-ray emission.

The X-ray emission along the radio axis (NE-SW) is particularly bright and there is a significant offset between the X-ray and radio jet (as shown in Figure 4). **ICCMB preferentially takes place in old plasma and indicates that 3C 294 is precessing: the X-ray emission traces where the jet used to be and not where it is now.**

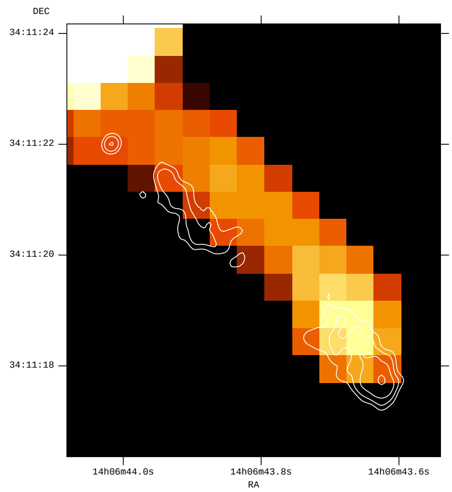

Fig. 4: Gaussian-smoothed $0.5 - 3$ keV X-ray image. The smoothing kernel was 2 pixels. Overlaid with 8.46 GHz ($0.24, 0.40, 0.67, 1.1$ mJy/beam). The contrast has been adjusted to highlight the significant offset between the X-ray and radio jet emission.

Minimum Energy in Relativistic Particles

A lower limit for the energy stored in relativistic particles can be calculated by assuming that the extended X-ray emission is produced purely by ICCMB and that a δ-function of the electrons with a Lorentz factor of $\sim 10^3$ are responsible. The X-ray luminosity of the extended region has been used to calculate the energy in these particles (see Table 1), which gives a minimum energy stored in relativistic particles in the jet. This method probes lower Lorentz factor electrons than the radio synchrotron emission and does not require the use of equipartition. **The minimum energy in relativistic particles in these jets is $\sim 10^{59}$ erg**. The energy estimate increases by a factor ~ 1.5 when a power-law distribution of electrons is considered and possibly by up to 10^3 when a possible proton component is included.

Source	RA	Dec	z	*Chandra* ObsID	time [ks]	L_{X} [10^{44} erg s^{-1}]	$\mathcal{E}_{\mathrm{e}}$ [10^{59} erg]
3C 191	08h04m47.9s	+10d15m23s	1.956	2134, 5626	25	2.40 ± 0.54	2.50 ± 1.08
3C 294	14h06m44.0s	+34d11m25s	1.779	1588, 3445, 3207	206	2.93 ± 0.17	3.91 ± 1.42
3C 432	21h22m46.2s	+17d04m38s	1.785	5624	20	1.85 ± 0.57	2.44 ± 1.14

Table 1. Source information. The co-ordinates are in J2000. L_{X} is the $2 - 10$ keV rest frame luminosity of the extended emission and $\mathcal{E}_{\mathrm{e}}$ is the lower limit to the energy stored in relativistic particles in these sources.