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Equipartition in the hot-spots of 3C 123

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Abstract. *Chandra* X-ray Observatory observations of the powerful, peculiar radio galaxy 3C 123 have resulted in an X-ray detection of the bright eastern hot-spot, with a 1-keV flux density of ~ 5 nJy. The X-ray flux and spectrum of the hot-spot are consistent with the X-rays being inverse-Compton emission from the population of electrons responsible for the radio emission, if the magnetic fields in the hot-spot are close to their equipartition values. 3C 123 is thus the third radio galaxy to show direct evidence for equipartition in hot-spots.

1. Introduction

In recent years it has become possible to use X-ray observations to measure the magnetic field strengths in components of radio sources. In hot-spots, the emission mechanism that allows this is the 'synchrotron self-Compton' (SSC) process, in which the synchrotron-emitting electrons inverse-Compton scatter synchrotron photons up to X-ray energies. Because the emissivity from this process depends on the photon number density (which is known from radio observations) and the electron number density as a function of energy, observations of SSC emission allow the electron number density to be inferred, and so determine the magnetic field strength. Harris, Carilli & Perley (1994) detected the hot-spots of Cygnus A with *ROSAT* and showed that the X-ray emission could be interpreted as being due to the SSC process, with a magnetic field strength consistent with the equipartition model (see also Wilson, these proceedings). More recently, *Chandra* observations have detected the hot-spots of 3C 295, another powerful radio galaxy, at a level which implies field strengths fairly close to the equipartition values if the emission process is SSC (Harris et al. 2000, and these proceedings). Here we report a new *Chandra* detection of the E hot-spot of the radio galaxy 3C 123. 3C 123 ($z = 0.2177$) has a well-known peculiar radio structure (Hardcastle et al. 1997, hereafter H97) but, for our purposes, its most important feature is its bright eastern double hot-spot. With a flux density of ~ 6 Jy at 5 GHz, it is the second brightest hot-spot complex known (after Cygnus A). The hot-spot's structure and synchrotron spectrum are well known (H97; Meisenheimer et al. 1989; Meisenheimer, Yates & Röser 1997; Looney & Hardcastle 2000) allowing a good prediction of the SSC emissivity as a function of magnetic field strength to be made.

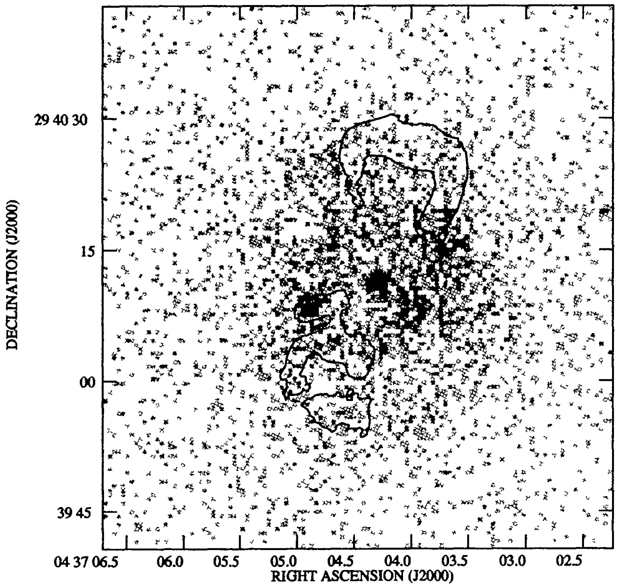

Figure 1. Exposure-corrected 0.5-7.0 keV *Chandra* image of the central region of 3C 123. Linear greyscale: black is 4×10^{-7} photons cm^{-2} s^{-1} per standard Chandra pixel (0.492 arcsec on a side). Superposed is the 3 mJy beam^{-1} contour from an 8.4-GHz VLA map with 0.6-arcsec resolution (H97), showing the position of the radio lobes.

2. Observations

We observed 3C 123 with *Chandra* for 46.7 ks on 2000 March 21. The source was near the aim point for the S3 ACIS chip. After filtering for intervals of high background, the usable exposure time was 38.5 ks. We considered events in the energy range 0.5 - 7.0 keV, as the response of the instrument is uncertain outside this range. Fig. 1 shows the exposure-corrected *Chandra* image of 3C 123 in this band. Diffuse cluster emission, an X-ray nucleus and the eastern hot-spot are all detected in X-rays. Here we concentrate on the hot-spot emission; the other components are discussed elsewhere (Hardcastle, Birkinshaw & Worrall 2000).

3. Results

The E hot-spot complex is detected with 145 ± 32 0.5-7.0 keV counts, using a 2.5-arcsec source circle and concentric 3–5 arcsec background annulus. This X-ray hot-spot is positionally coincident with the larger, 'secondary' hot-spot (E4, in the notation of H97) of the eastern hot-spot pair in the radio. The X-ray emission is slightly elongated in an east-west direction, matching the radio. The X-ray spectrum of the hot-spot is well fitted with a power law with photon index $\Gamma = 1.6 \pm 0.3$, with the absorbing hydrogen column fixed at the Galactic value of 4.3×10^{21} cm^{-2}. The corresponding unabsorbed 1-keV flux density is 4.6 ± 0.9 nJy.

We used the synchrotron-self-Compton code described by Hardcastle et al. (1998) to predict the SSC flux density expected at this frequency from the hot-spots. The basic model for the hot-spots is described by Looney & Hardcastle (2000), who model their spectra as broken power laws. The secondary hot-spot is assumed to be a cylinder of 5.4×2.5 kpc. The apparent low-frequency turnover in the spectrum observed by Stephens (1987) requires a low-energy cutoff in the electron energy spectrum corresponding at equipartition to a minimum Lorentz factor $\gamma_{\rm min} \approx 1000$, and we adopt this value. We fix $\gamma_{\rm max}$ to equal the upper limit on the maximum Lorentz factor given by the non-detection in the IR, $\gamma_{\rm max} < 3.6 \times 10^5$; a lower limit is given by the detection at 231 GHz, $\gamma_{\rm max} > 8 \times 10^4$, and the SSC emissivity is relatively insensitive to $\gamma_{\rm max}$ within this range. With these parameters, the equipartition field strengths of the two eastern hot-spot components, assuming no non-radiating particles, are 24 nT (primary) and 16 nT (secondary), and the predicted SSC flux densities at 1 keV are respectively 0.44 and 2.6 nJy. The predicted photon index at this frequency is 1.55. Fig. 2 shows the synchrotron fluxes and SSC prediction for the secondary hot-spot. Reasonable changes in our assumptions about cosmological parameters (we use $H_0 = 50\,{\rm km\ s^{-1}\ Mpc^{-1}}$ and $q_0 = 0$), projection effects, and geometry change the predicted SSC flux by $< 10\%$.

4. Discussion

The magnitude of the observed flux density, its origin in the larger eastern hot-spot and its photon index are thus all in good agreement with the equipartition predictions of the SSC model, as is the non-detection of the western hot-spot pair. The observed 1-keV flux density of the E hot-spots is 1.5σ higher than the predicted value for an equipartition field. To increase the SSC flux density, we must reduce the magnetic field strength or find an additional (external) source of photons, but only a small change in field strength is required. The derived magnetic field strength in the secondary hot-spot is 12 ± 2 nT (1σ statistical errors only), or about 75 per cent of the equipartition value, if we neglect the small SSC contribution from the primary hot-spot.

Other processes which might produce the X-ray emission (e.g. X-ray synchrotron emission, proton-induced cascade or inverse-Compton scattering of a second photon population) all require high magnetic field strengths in the hot-spot (to suppress SSC emission), and all must 'coincidentally' produce an X-ray flux level similar to that predicted by the SSC model. Because of the element of cosmic conspiracy they require, we regard all such models as inherently less plausible descriptions of this source. However, some X-ray detections of hot-spots (e.g. 3C 120, Harris et al 1999; Pictor A, Wilson, these proceedings) are at a level much too bright to be consistent either with synchrotron emission (from the electron population responsible for the radio and optical synchrotron radiation) or with SSC at equipartition. For these sources no explanation yet presented seems entirely satisfactory. More observations are necessary to demonstrate that Cygnus A, 3C 295 and 3C 123, which do agree with the SSC/equipartition model, represent the 'typical' radio source.

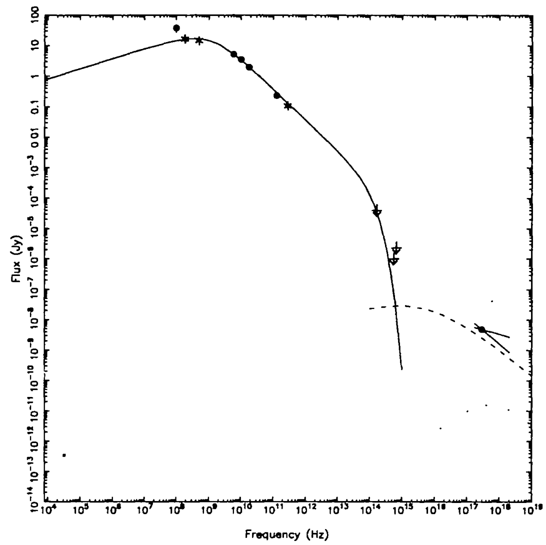

Figure 2. Data and models for the secondary hot-spot (plotted in the rest frame of the source). The solid line is the model synchrotron spectrum. The dash-dotted line shows the predicted equipartition SSC spectrum (the dotted line shows CMB inverse-Compton emission). The two solid bars through the X-ray data point (from 0.5 to 7.0 keV) show the 1σ range of photon indices permitted by the data.

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