Particles and Fields in Radio Galaxies
ASP Conference Series, Vol. , 2001
Robert A. Laing and Katherine M. Blundell

Equipartition in the hotspots of 3C 123

Martin J. Hardcastle, Mark Birkinshaw & Diana M. Worrall

Department of Physics, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK

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 hotspot, with a 1-keV flux density of ~ 5 nJy. The X-ray flux and spectrum of the hotspot 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 hotspot are close to their equipartition values. 3C 123 is thus the third radio galaxy to show direct evidence for equipartition in hotspots.

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 hotspots, 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 hotspots 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 hotspots 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 hotspot of the radio galaxy 3C 123. 3C 123 ($z = 0.2177$) has a well-known peculiar radio structure (Hardcastle et al. 1997, H97 hereafter) but, for our purposes, its most important feature is its bright eastern double hotspot. With a flux density of ~ 6 Jy at 5 GHz, it is the second brightest hotspot complex known (after Cygnus A). The hotspots' structure and synchrotron spectrum are well known (H97; Meisenheimer et al. 1989; Meisenheimer, Yates & Röser 1997; Looney & Hardcastle, 2000) which allows a good prediction of the SSC emissivity as a function of magnetic field strength to be made.

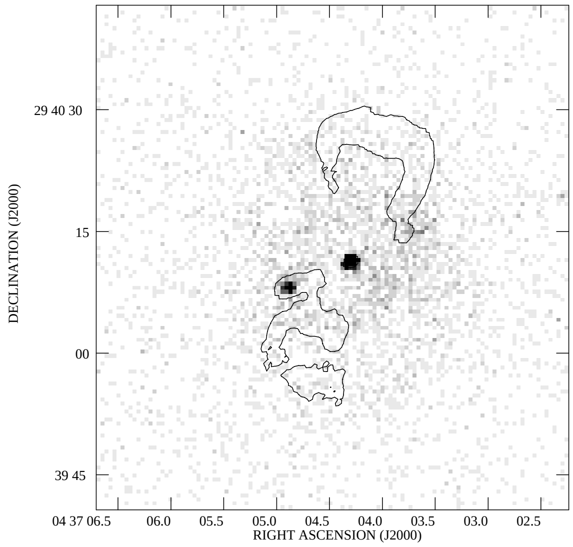

Figure 1. Exposure-corrected 0.5-7.0 keV *Chandra* image of the central region of 3C 123. Linear greyscale: black is 4×10^{-7} photons cm^{-2} s^{-1} per standard Chandra pixel (0.492 arcsec on a side). Superposed is the 3 mJy beam^{-1} contour from an 8.4-GHz VLA map with 0.6-arcsec resolution (H97), 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 hotspot are all detected in X-rays. Here we concentrate on the hotspot emission; the other components are discussed elsewhere (Hardcastle, Birkinshaw & Worrall 2000).

3. Results

The E hotspot 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 hotspot is positionally coincident with the larger, 'secondary' hotspot (E4, in the notation of H97) of the eastern hotspot 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 hotspot 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 hotspots. The basic model for the hotspots is described by Looney & Hardcastle (2000), who model their spectra as broken power laws. The secondary hotspot is 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 hotspot 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 hotspot. Reasonable changes in our assumptions about cosmological parameters (we use $H_0 = 50$ 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 hotspot 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 hotspot pair. The observed 1-keV flux density of the E hotspots 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 hotspot is 12 ± 2 nT (1σ statistical errors only) if we neglect the small SSC contribution from the primary hotspot, which is only 0.75 ± 0.125 of the equipartition value.

Other processes which might produce the X-ray emission (e.g. X-ray synchrotron emission, proton-induced cascade, inverse-Compton scattering of a second photon population) all require high magnetic field strengths in the hotspot (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 hotspots (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.

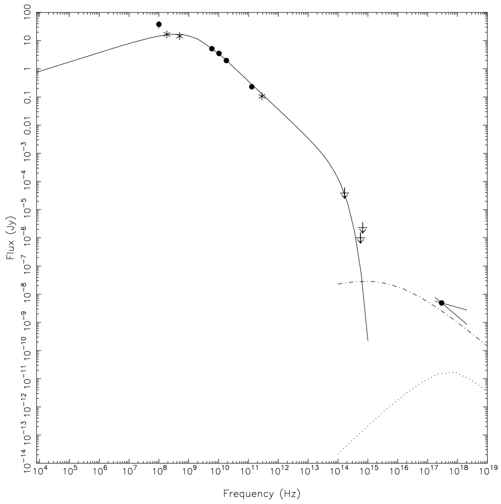

Figure 2. Data and models for the secondary hotspot (plotted in the rest frame of the source). The solid line is the model synchrotron spectrum. The dash-dotted line shows the predicted equipartition SSC spectrum (the dotted line shows CMB inverse-Compton emission). The two solid bars through the X-ray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

References

Hardcastle, M.J., Alexander, P., Pooley, G.G., & Riley J.M. 1997, 'High-resolution obser,vations at 3.6 cm of seventeen FR II radio galaxies with $0.15 < z < 0.30$' MNRAS, 288, 859–890

Hardcastle, M.J., Birkinshaw, M., & Worrall, D.M. 1998, 'Magnetic field strengths in the hotspots of 3C 33 and 111', MNRAS, 294, 615–621

Hardcastle, M.J., Birkinshaw, M., & Worrall, D.M. 2000, 'A *Chandra* detection of the radio hotspot of 3C 123', MNRAS, submitted

Harris, D.E., Carilli, C.L., & Perley, R.A. 1994, 'X-ray emission from the radio hotspots of Cygnus A', Nature, 367, 713–716

Harris, D.E., Hjorth, J., Sadun, A.C., Silverman, J.D., & Vestergaard M. 1999, 'X-ray emission from the radio jet in 3C 120', ApJ, 518, 213–218

Harris, D.E. et al., 2000, 'Chandra X-ray detection of the radio hot spots of 3C 295', ApJ, 530, L81–84

Meisenheimer, K., Röser, H.-.J., Hiltner, P.R., Yates, M.G., Longair, M.S., Chini, R., & Perley, R.A. 1989, 'The synchrotron spectra of radio hot spots', A&A, 219, 63–86

Meisenheimer, K., Yates, M.G., & Röser, H.-.J. 1997, 'The synchrotron spectra of radio hot spots. II. Infrared imaging', A&A, 325, 57–73

Looney, L.W. & Hardcastle, M.J. 2000, 'Subarcsecond imaging of 3C 123: 108 GHz continuum observations of the radio hot spots', ApJ, 534, 172–179

Stephens, P. 1987, 'Low frequency mapping with MERLIN', PhD thesis, University of Manchester