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Deep Chandra Observations of the Centaurus A Jet

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Abstract. *Chandra* has observed the jet of Centaurus A for 560 ks in 2007, giving a total on-source observation time since the launch of *Chandra* of 720 ks. Combining these datasets gives us a uniquely detailed X-ray view of the jet in the nearest radio galaxy, while regular VLA monitoring provides complementary high-resolution radio data. We present some images and first results from the new data, including constraints on the variability of compact components of the jet and a discussion of the implications for particle acceleration of the spatial variation of jet X-ray spectral index.

1. Introduction

Centaurus A (NGC 5128), at a distance of 3.4 Mpc (Israel 1998), is the nearest radio galaxy to us, the nearest giant elliptical, the nearest major merger remnant and hosts one of the two nearest luminous active galactic nuclei (together with the Circinus galaxy, whose distance is consistent with the upper range of the distances adopted for NGC 5128). As a result, Cen A has been extensively studied for many years at all wavebands.

In 2007 the jet and environment of Cen A were the target of a *Chandra* Very Large Program (PI Ralph Kraft). The nominal 600 ks of observations (560 ks livetime) means that we now have a total of 720 ks of on-source *Chandra* time, making Cen A one of the most deeply observed extragalactic single objects. An image of the soft X-ray emission from the combined 720 ks of data is shown in Fig. 1. These deep X-ray observations will be important for studies of the active nucleus (heavily absorbed, and so not visible in the image of Fig. 1), the X-ray binary population (most of the point sources in the image are XRB in NGC 5128), the hot ISM of the elliptical galaxy (seen as diffuse emission in the image of Fig. 1), the dust lane (clearly visible as an absorption feature) and the interaction of the radio lobes with the hot gas (in addition to the well-known shock shell around the S lobe (Kraft et al. 2003), faint corresponding features around the N lobe are now visible). Analysis in all these areas is in

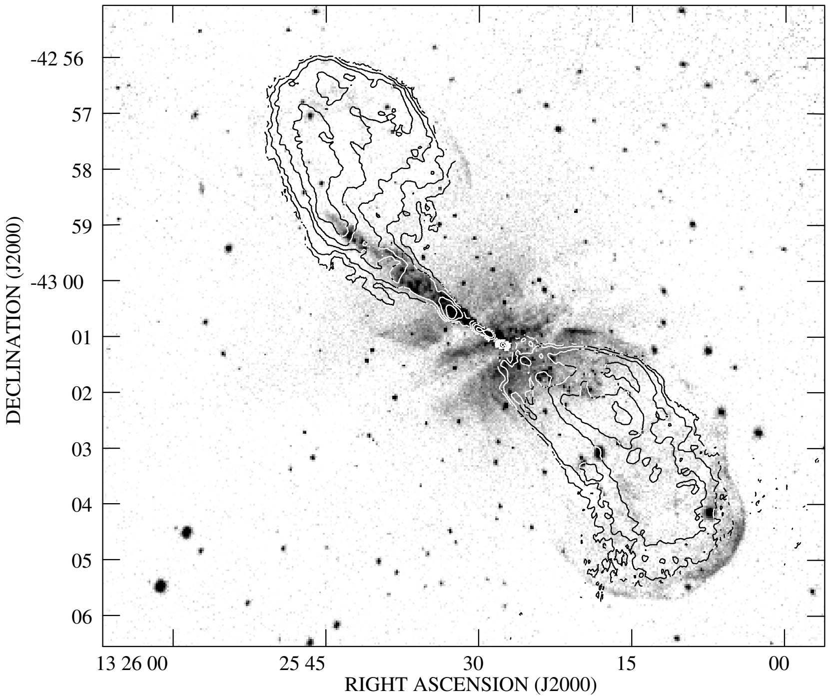

Figure 1. Exposure-corrected X-ray image of the center of the Centaurus A field combining all *Chandra* data taken to date (10 observations, 720 ks). Greyscale shows exposure-corrected 0.4–2.5 keV counts with a logarithmic transfer function in 1.97-arcsec pixels, while contours are from a 5-GHz VLA observation with 6-arcsec resolution corrected for the effects of the primary beam (Hardcastle et al. 2006).

progress. Here we present some new results related to the jet (Hardcastle et al., in preparation).

2. Jet Spectral Properties

We have previously only been able to look in detail at the X-ray spectral properties of the inner jet (e.g., Kraft et al. 2002; Hardcastle et al. 2003). The new data give us enough counts throughout the jet to fit spectra and make accurate maps of the jet photon index as a function of position. Fig. 2 shows such a map. The fits include all the available X-ray data and are carried out in ~ 90 regions derived from the 'contour binning' code of Sanders (2006), with photon index, normalization and $N_{\rm H}$ being free parameters. Clearly there is a systematic trend for the spectral index α to be steeper as a function of distance from the nucleus: there is also a clear trend for the compact 'knots' in the jet to have flatter spectra than their surrounding extended emission. In combination with the generally decreasing X-ray to radio ratio as a function of nuclear distance in the jet, the

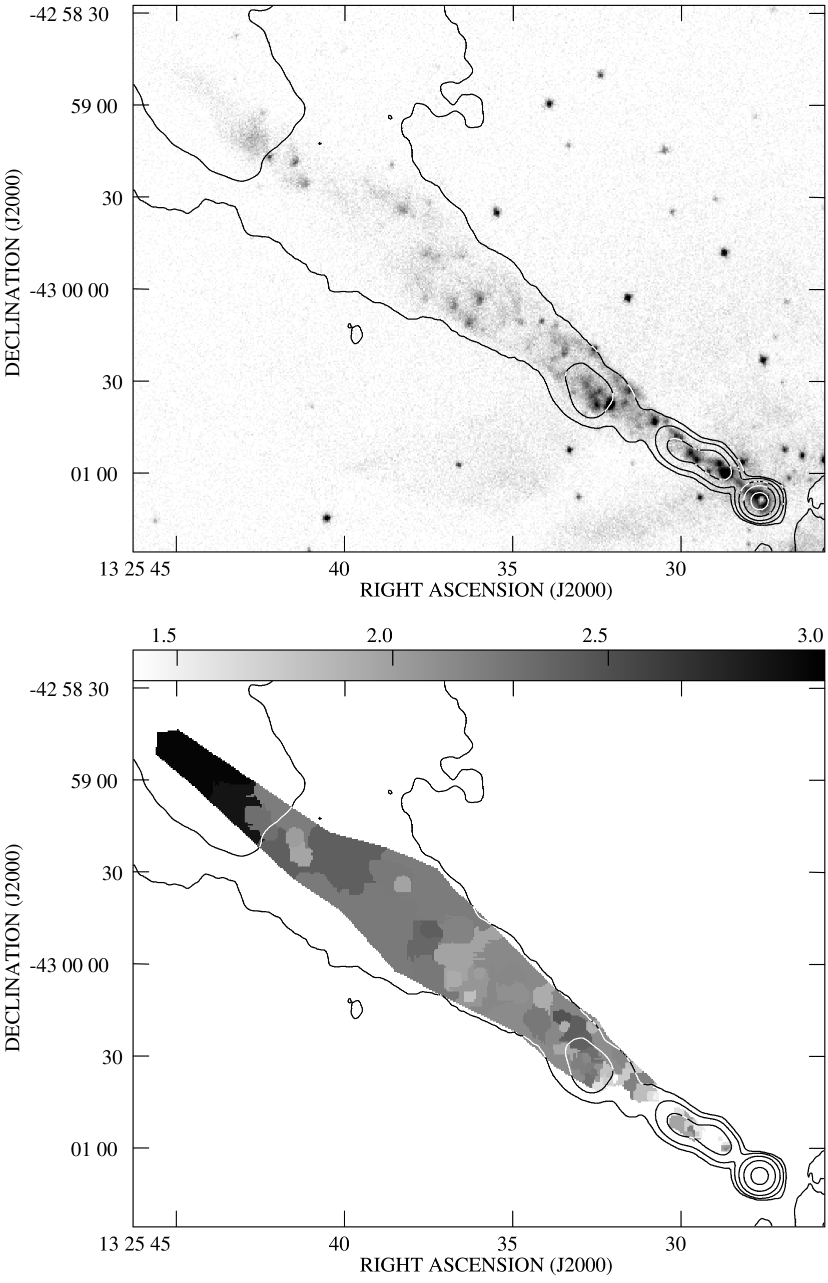

Figure 2. The structure and spectrum of the inner jet of Centaurus A. Top: exposure-corrected 0.4–2.5 keV counts with a logarithmic transfer function in 0.492-arcsec pixels. Bottom: greyscale of X-ray spectral indices between 0.4 and 2.0 (photon indices between 1.4 and 3.0). Contours as in Fig. 1.

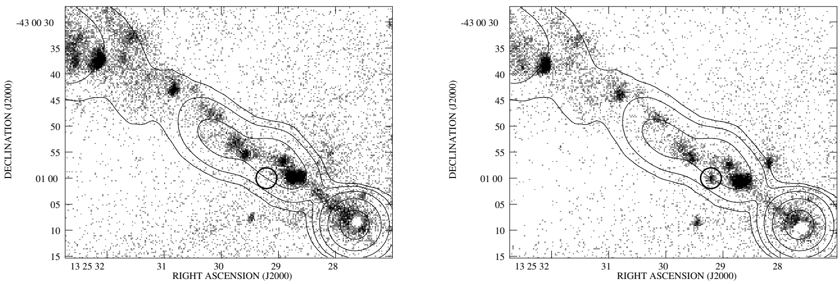

Figure 3. Variability of an X-ray feature close to the jet. The greyscales show (left) 100 ks of *Chandra* data taken in 2003/4 and (right) 90 ks taken in May 2007. The solid circle shows the significantly variable knot. Contours are from the 6-arcsec VLA map

steepening of spectral index with distance from the nucleus strongly suggests a decreasing efficiency of particle acceleration in Cen A (as has previously been suggested for the M87 jet: Perlman & Wilson 2005). However, we already know that some compact knots in the very inner part of the jet have steep spectra, so this cannot be the whole story: possibly more efficient loss processes are present there (see below).

3. Jet Variability

Perhaps disappointingly, no compact component of the jet has shown the bright flaring behaviour of the HST-1 knot of M87 (see Harris et al. 2006; Harris, these proceedings). One feature that we would have normally have classed as a jet knot has appeared in the 2007 observations: its flux density has increased by a factor > 5 since 2003 but is constant within the errors in 2007 (see Fig. 3). However, this may just be an X-ray binary — its position is right on the edge of the jet. Radio observations taken in early June (a continuation of the VLA monitoring program we have been running for the past few years) will show whether this feature has a radio counterpart, in which case we will almost certainly be able to confirm it as a jet knot flare. There is some evidence for a small but significant decrease in flux density (at the $\sim 20\%$ level), and/or an increase in spectral index, in the twin bright knots at the base of the jet (Ax1a and Ax1c in the notation of Hardcastle et al. 2003). As the brightest knots, these might be expected to have the highest magnetic field strengths, so the observation of possible variability is consistent with the possibility that these knots are being affected by synchrotron losses on timescales of years. Again, radio observations will be critical to the interpretation of these results (Goodger et al, in prep.).

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