Chandra Observations of Hybrid Morphology Radio Sources

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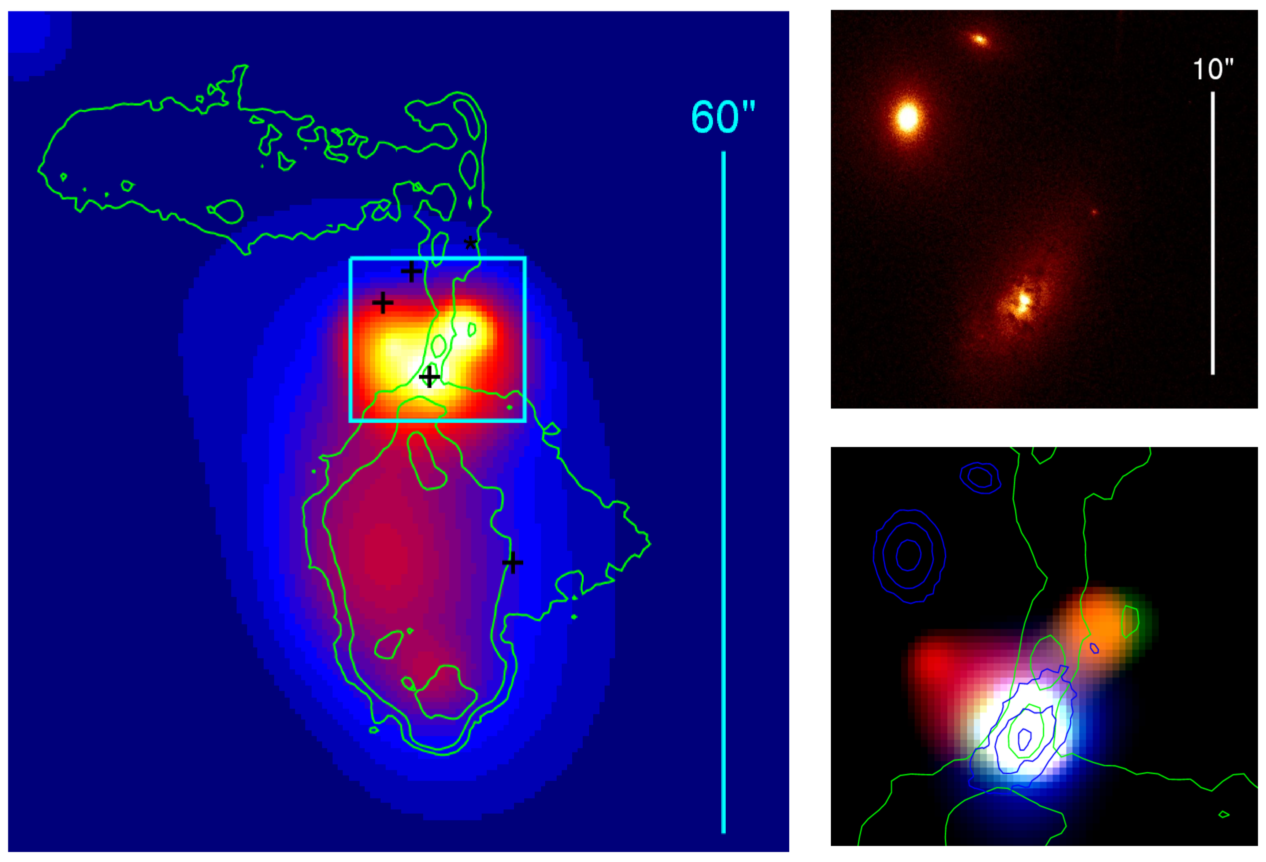
Overview

The classification scheme devised by Fanaroff & Riley (1974) identifies FR I sources as core brightened and the more luminous FR II sources as lobe dominated. A small number of radio sources possess both an FR I jet and an FR II lobe on opposite sides of their core; the structure of such hybrid morphology radio sources may arise from propagation of twin jets into an asymmetric medium (Gopal-Krishna & Wiita 2000). Our Chandra observation of the hybrid source PG 1004+130 revealed an X-ray jet slightly upstream of the FR I jet but with multiwavelength and X-ray spectral properties similar to those of other FR II jets, supporting the hypothesis that the FR I structure results from an intrinsically powerful jet encountering a relatively dense environment. We present results from recent ~40 ks *Chandra* observations of the hybrid sources 3C 433 and 4C 65.15; both objects display X-ray emission aligned with the FR I radio jet and nuclear properties consistent with those of comparable FR II sources.



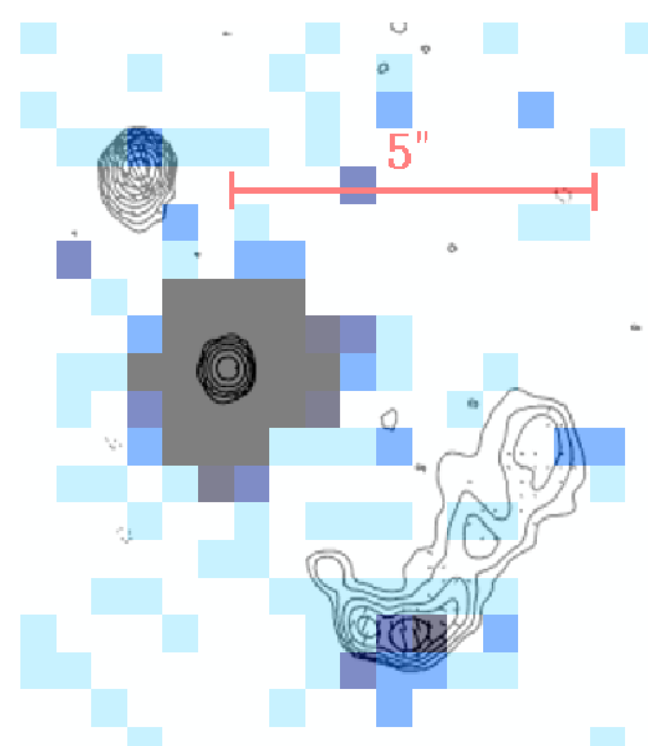
3C 433

This low-redshift (z=0.102) narrow-line radio galaxy has a fading jet to the north that tails off to the east, and a bright southern lobe with multiple hotspots. *Einstein* X-ray observations were presented by van Breugel et al. (1983) and there is *ASCA* coverage, but only the *Chandra* data resolve the X-ray structure and provide a high S/N spectrum.

Left: Adaptively smoothed 0.5-2 keV *Chandra* X-ray image of 3C 433 overlaid with 8.3 GHz radio contours at 0.2, 1, 5 mJy/beam. Galaxies are marked with crosses. *Top*: HST WFPC2 image cropped to match box region. Note the dust in 3C 433 (de Koff et al. 1996). *Bottom*: Smoothed X-ray image colored by energy (red is 0.3-1 keV, green 1-2 keV, and blue 2-8 keV) with radio and optical contours.

4C 65.15

This z=1.625 broad line quasar was identified as a hybrid object by Gopal-Krishna & Wiita (2000) and displays a bright lobe opposing a jet that decreases in intensity as it bends away from the core.



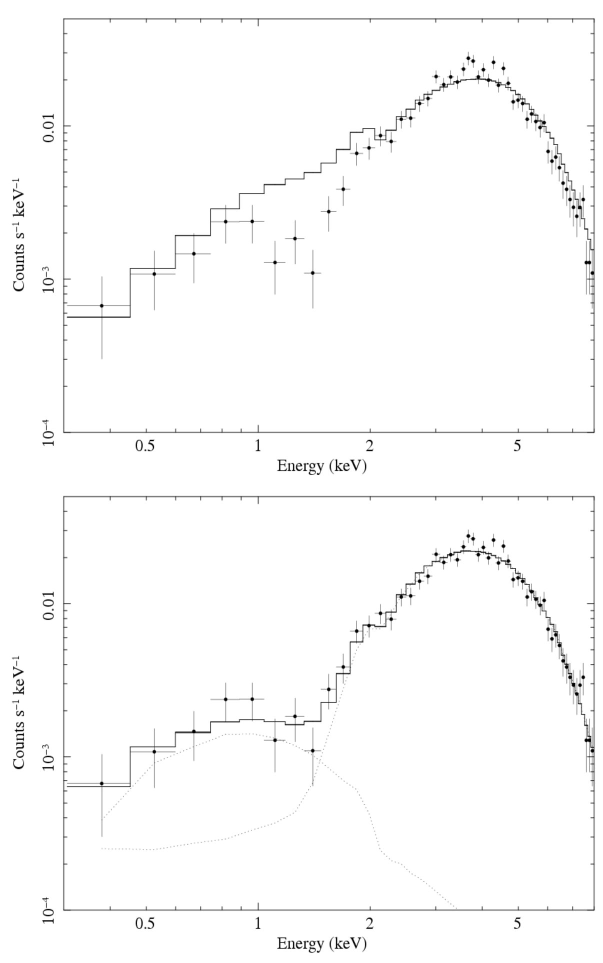
Right: *Chandra* X-ray image of 4C 65.15 overlaid with 5 GHz radio contours taken from Lonsdale et al. (1993). The image saturates at 5 counts/pixel and the radio contour levels are 0.45 X (-1, 1, 2, 4, 8, …) mJy/beam. An X-ray jet is detected.

3C 433 X-ray spectra

There is significant X-ray absorption below 2 keV, such as is commonly observed in FR II NLRGs (Evans et al. 2006). A single-component power-law model (*top right*) with intrinsic partial-covering absorption (f_c = 0.95, N_H = 6.2 X 10^{22} cm^{-2}) requires an unusually flat photon index (Γ = 0.71) and has large residuals between 0.7-2 keV; this is not a satisfactory model.

The addition of a second power-law component (with no intrinsic absorption) significantly improves the fit (*bottom right*). The best-fit parameters are N_H = 8.3 ± 1.0 X 10^{22} cm^{-2} and Γ = 1.39 ± 0.22 with f_c = 1 for the absorbed component and Γ = 2.2 ± 0.9 for the unabsorbed component. The unabsorbed component may be fit equally well by a thermal model with kT = 1.2 keV; this temperature is poorly constrained.

There does not appear to be a detectable iron emission line in the X-ray spectrum of 3C 433. The upper limit equivalent width for unresolved neutral Fe Kα emission is 85 eV.



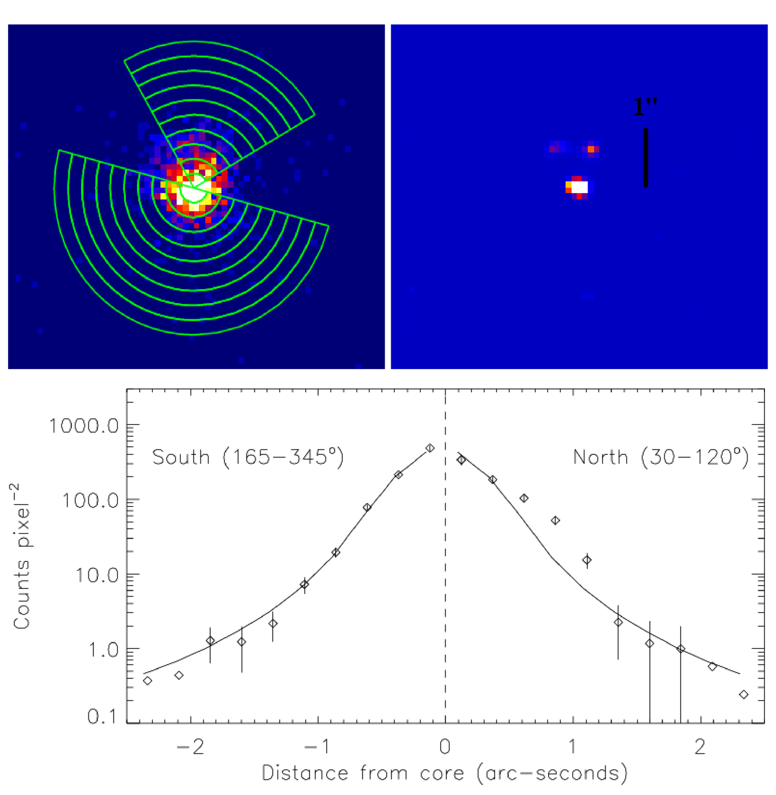
3C 433 core X-ray spectrum; see text for model details.

4C 65.15 X-ray spectra

A simple power-law model with no intrinsic absorption and Γ = 1.89 ± 0.07 provides an acceptable fit (χ^2 /dof = 56/82) to the nuclear X-ray spectrum of 4C 65.15. The addition of mild intrinsic absorption (N_H = 1.31 ± 1.25 X 10^{21} cm^{-2}) only slightly improves the fit (χ^2 /dof = 53/81; f-test probability 0.035; *bottom left*).

Adding an unresolved neutral iron emission line to the model does not improve the fit. Permitting the line energy to vary and fitting the ungrouped spectrum results in a best-fit rest-frame energy of 7.1 keV but the 90% confidence interval for the equivalent width includes zero.

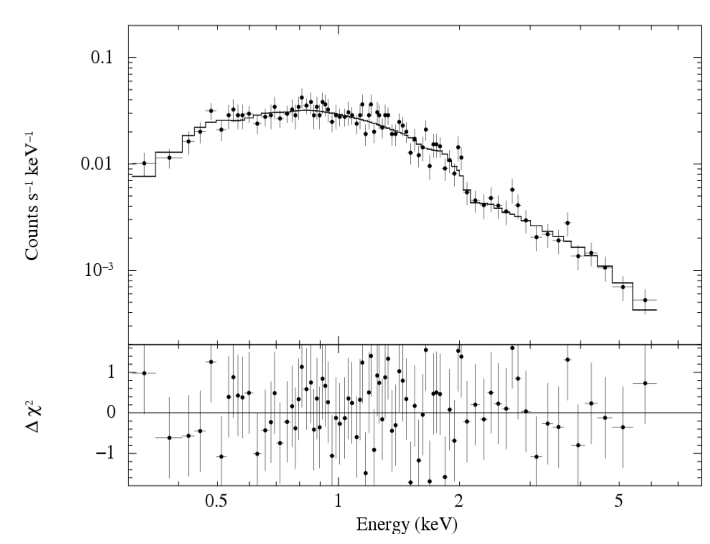
The jet contains sufficient photons for crude spectral modeling; a power-law model gives Γ = 1.2 ± 0.5 (*bottom right*). The jet photon index is consistent with the Γ ~ 1.5 found by Sambruna et al. (2004) for the brightest X-ray knots in FR II quasar jets, but does not match the Γ ~ 2.3 typical of FR I X-ray jets.



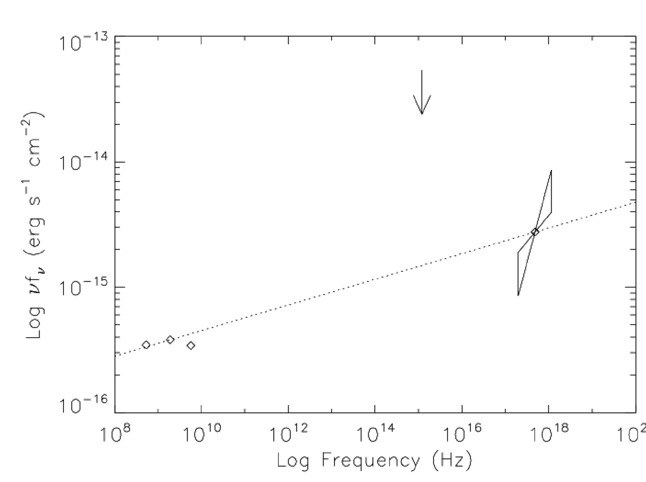
3C 433 core resolved by *Chandra*

There is evidence for extended *hard* X-ray emission <1'' to the north of the nucleus. A maximum likelihood reconstruction of the 4-8 keV image suggests an additional source may be present, possibly associated with the northern component of the double radio core noted by Black et al. (1992).

Top left: *Chandra* 4-8 keV image rebinned to 0.2 pixels after removal of pipeline pixel randomization. *Top right*: Maximum likelihood reconstruction of X-ray image. *Bottom*: Radial profile of 3C 433 core in the 4-8 keV band; the solid line shows a scaled 4 keV PSF generated with MARX. There is excess hard X-ray emission to the north.



Chandra 0.3-8 keV X-ray spectrum of 4C 65.15, fit with a power-law spectrum of Γ = 1.97 and mild intrinsic absorption of N_H = 1.3 X 10^{21} cm^{-2}



Spectral energy distribution for the jet in 4C 65.15. The radio fluxes are for the resolved feature at the bend of the jet, the optical limit is from the SDSS r-band image, and the X-ray flux and spectral index confidence range are from fitting the *Chandra* data.

Results

The *Chandra* observation of 3C 433 resolves the core and reveals diffuse X-ray emission to the north of the nucleus and throughout the southern lobe, while the *Chandra* observation of 4C 65.15 uncovers an X-ray jet. There is significant evidence that these are essentially FR II sources, in which case the hybrid morphology likely reflect environmental effects:

- Both 3C 433 and 4C 65.15 have X-ray spectra similar to comparable FR II sources.
- The absorbed and unabsorbed components in 3C 433 and the core and jet in 4C 65.15 lie along the radio core/X-ray luminosity correlation followed by other FR II sources (Evans et al. 2006).
- The X-ray jet in 4C 65.15 appears unlikely to be an extension of the radio synchrotron emission, such as is characteristic of FR I jets, and instead has properties similar to FR II jets.

Observations of core-dominated hybrids would complement and extend this work (see also Sambruna et al. 2008)

References

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We thank Leisa Townsley and Patrick Broos for assistance with maximum likelihood reconstruction.