Aust. J. Phys., 1994, **47**, 615–18

Cygnus A—John Bolton's First Cosmic Source*

D. E. Harris

Smithsonian Astrophysical Observatory,
Cambridge, MA 02138, U.S.A.

Abstract

Using a sea interferometer, Bolton and Stanley isolated Cygnus A as a discrete source in 1948. It is a prime example of a powerful radio galaxy and, in the last decade, has also been studied extensively in X-rays. In this paper I summarise the results from a ROSAT X-ray image.

I first met Bolton at Caltech in 1955 when I was looking for a summer job. He said there was nothing then, but that I should 'come back next year when there would be plenty of work'. At the time I did not realise that, as his first graduate student, I would fulfil his prophecy by installing conduit, pulling cables by jeep, and wiring junction boards. However, there was also the excitement of discovery. Among the first results from the 90-ft antenna (operating at 960 MHz with a 50-arcmin beam) were the radio phases of the moon. Luckily we stumbled on the phenomenon of parallax before we published! But now, 35 years later, I muse on Bolton's discovery of the very first discrete cosmic source. Rereading sections from Pawsey and Bracewell (1955) provides a glimpse of the infancy of radio astronomy:

> In this period there were two further discoveries which play a basic role. The first was that of the discrete sources of cosmic radio waves, the 'radio stars'. The first clue to this discovery was the observation by Hey, Parsons, and Phillips (1946) of fluctuations in the intensity of cosmic radio waves from the constellation of Cygnus. A year later Bolton and Stanley (1948) showed that the fluctuations were associated with an intense radio source which they found in this region, though they were unable to identify it with any optical object.

The discovery of Cygnus A has become part of the Bolton legend, and the source itself continues to be a fascinating subject of study.

The Cygnus A radio galaxy is remarkable in many respects. It is the archetype of a Fanaroff–Riley type II radio galaxy (Fanaroff and Riley 1974), which has a double lobe with a hotspot at the outer edge, and high luminosity. Cygnus A is much closer to the Earth than the average distance between FRII sources, and it lies at the centre of a poor cluster of galaxies that has a hot, X-ray emitting,

* Refereed paper based on a contribution to the John G. Bolton Memorial Symposium held at the Parkes Observatory, 9–10 December 1993.

0004-9506/94/050615$05.00

intergalactic plasma. At a redshift of 0·0574, 1 arcsec corresponds to 1 kpc for $H_0 = 75\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$. Consequently, high-resolution radio studies have detailed unprecedented structure in the radio lobes, jets, and hotspots. Equally impressive maps have been made of the polarisation properties and rotation measure induced by the surrounding hot gas ascribed to the cluster and/or the optical galaxy (Dreher *et al.* 1987).

Results from the Einstein Observatory and other missions were used by Arnaud *et al.* (1984, 1987) to study the hot gas distribution and deduce the presence of a power-law spectral component. They found a gas temperature of 4 keV for the high-density region around Cygnus A, argued for the presence of a cooling flow, and noted a lower-density region extending up to a megaparsec from the central galaxy. They also derived a 2–10 keV luminosity of $10^{44}\ \mathrm{erg\,s^{-1}}$ for a power-law component with a spectral index of approximately 0·7 ($S \propto \nu^{-\alpha}$).

Cygnus A has now been observed with the high-resolution imager (HRI) of the ROSAT satellite. Analysis of this X-ray image (approximately 5-arcsec resolution) provides a new perspective of several radio features. The results of modelling the central gas distribution with a modified King model, using image-processing techniques of model building and subtracting (Harris *et al.* 1994*a*), are shown in Fig. 1. Residual features include the radio hotspots, a source identified with the radio core source of the galaxy, cavities (relative depressions in the brightness of the King distribution) coincident with the inner parts of the radio lobes, and two features embracing the eastern lobe, which may represent emission from cluster gas external to the radio lobes but inside the bow shock.

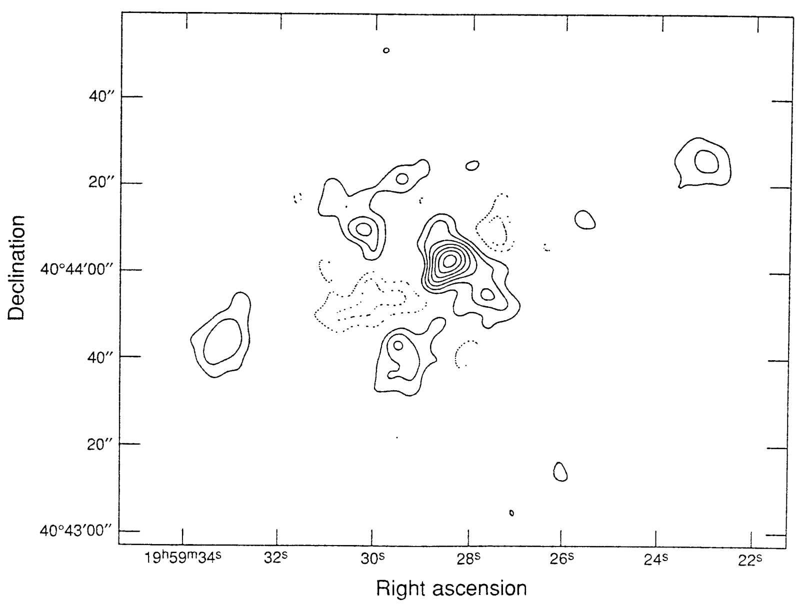

Fig. 1. Residual HRI image of Cygnus A after subtracting a modified King model with core radius = 35 arcsec and $\beta = \frac{3}{4}$. The data have been smoothed with a Gaussian of FWHM = 5 arcsec. Contour levels are linear at −0·132, −0·07, 0·07, 0·132, 0·194, ..., 1·0 cts pixel^{-1}. Note the core source, the cavities coincident with the inner parts of the radio lobes, the enhancements above and below the eastern cavity, and both hotspots (the outermost features).

Each radio hotspot has an X-ray luminosity of $\sim 10^{42}$ erg s^{-1} (Harris *et al.* 1994). We argue that a thermal emission process is extremely unlikely because the required electron density ($0 \cdot 2$ cm^{-3}) is precluded by the absence of anomalous polarisation effects. The most reasonable interpretation of the observed X-ray intensity and morphology is synchrotron-self-Compton (SSC) emission. Since the photon energy density in the hotspots can be calculated rather well (given the high-resolution radio maps at many frequencies), the SSC emission can be translated into knowledge about the amplitude of the spectrum of relativistic electrons. Adding to this the knowledge of the observed synchrotron spectrum, a new estimate of the average magnetic field strength can be obtained which does not rely on the assumption of equipartition between field and particles, the classical assumption for non-thermal radio sources. The resulting field strengths of about 200 μG are consistent with minimum energy fields for the case of little or no contribution to the internal energy from relativistic protons.

In a preliminary report on the core source (Harris *et al.* 1994*b*) we provide the first direct detection (spatially) of the X-ray nuclear source, and show that either the line-of-sight column density in Cygnus A is somewhat less than previously proposed (Arnaud *et al.* 1987; Djorgovski *et al.* 1991) or that the inferred X-ray luminosity in the 2–10 keV range is some seven times greater than it was 10 years ago.

A study of the interaction of the radio source and the hot gas is presented in Carilli *et al.* (1994) and D. Clarke has made a preliminary numerical simulation of a hydrodynamic jet propagating into a gas with decreasing density. By integrating thermal emission along the line of sight with a functional relationship that mimics the HRI bandpass with the Galactic value for absorption, the simulation shows a remarkable similarity of position and morphology between enhanced emission regions in the bow-shocked gas and the two HRI features embracing the eastern radio lobe (see Fig. 1).

The legacy of Bolton's Cygnus A discovery continues to provide us with rewards and additional challenges. Bolton and Stanley (1948) remarked: 'Taking the size of the source as less than 8 arcmin, the constant component represents an effective temperature of more than 4×10^6 K at 100 Mc/s, which makes a thermal origin of the noise doubtful.' This brightest of all extragalactic non-thermal sources can now be studied across the electromagnetic spectrum, exhibits several types of emission processes, and provides us with the opportunity to study the interaction between the non-thermal features (jets, hotspots and lobes) and the ambient gas.

Acknowledgments

Analysis of the ROSAT HRI image of Cygnus A is being performed in collaboration with C. L. Carilli and R. A. Perley. The Cygnus A work at the SAO was supported by NASA grant NAG5–1536.

References

Arnaud, K. A., Fabian, A. C., Eales, S. A., Jones, C., and Forman, W. (1984). *Mon. Not. R. Astron. Soc.* **211**, 981.

Arnaud, K. A., Johnstone, R. M., Fabian, A. C., Crawford, C. S., Nulsen, P. E. J., Shafer, R. A., and Mushotzky, R. F. (1987). *Mon. Not. R. Astron. Soc.* **227**, 241.

Bolton, J. G., and Stanley, G. J. (1948). *Nature* **161**, 312.
Carilli, C. L., Perley, R. A., and Harris, D. E. (1994). *Mon. Not. R. Astron. Soc.* (in press).
Djorgovski, S., Weir, N., Matthews, K., and Graham, J. R. (1991). *Astrophys. J.* **372**, L67.
Dreher, J. W., Carilli, C. L., and Perley, R. A. (1987). *Astrophys. J.* **316**, 611.
Fanaroff, B. L., and Riley, J. M. (1974). *Mon. Not. R. Astron. Soc.* **167**, 31.
Harris, D. E., Carilli, C. L., and Perley, R. A. (1994). *Nature* **367**, 713.
Harris, D. E., Perley, R. A., and Carilli, C. L. (1994*a*). Proc. Astronomical Data Analysis and Software Systems—III (Eds D. R. Crabtree *et al.*), ASP Conf. Series, Vol. 61, in press.
Harris, D. E., Perley, R. A., and Carilli, C. L. (1994*b*). *In* 'Multi-wavelength continuum emission of AGN', IAU Symp. 159 (Eds A. Blecha and T. Courvoisier), p. 375 (Kluwer: Dordrecht).
Pawsey, J. L., and Bracewell, R. N. (1955). 'Radio Astronomy' (Oxford University Press: London).

Manuscript received 19 January, accepted 1 July 1994