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HEAO 1 SCANNING MODULATION COLLIMATOR DISCOVERY OF AN EXTENDED X-RAY SOURCE AT CYGNUS A

G. FABBIANO,* R. E. DOXSEY,† M. JOHNSTON,† D. A. SCHWARTZ,* AND J. SCHWARZ*
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ABSTRACT

The *HEAO 1* modulation collimator data associate the X-ray emission from the Cygnus A region (4U 1957+40) with a small area including the radio galaxy. The source appears to be extended, with a size of $\sim 2'$; it may have a complex geometry. Any point source component must have a flux $S \leq 1.3$ UFU. We place a lower limit of 10^{-6} gauss on the magnetic field in the radio lobes, based on our upper limit on the X-ray flux due to inverse Compton scattering of radio electrons on the 2.7 K microwave background radiation. The X-ray emission is more likely due to driven accretion of the intercluster gas onto the giant cD radio galaxy. Therefore this source appears to be similar to the Virgo and Perseus clusters. The density we derive for the X-ray–emitting gas is too small for its thermal pressure to confine the radio source.

Subject headings: galaxies: clusters of — radio sources: extended — X-rays: sources

I. INTRODUCTION

Since the discovery of the X-ray source 4U 1957+40 in the vicinity of the radio galaxy Cygnus A (Giacconi *et al.* 1972), many attempts have been made to explain the nature of the X-ray emission. The problem arises from the complex morphology of the Cygnus A region: the radio source is a classical double of $\sim 2'$ separation and is centered on a giant cD galaxy. This galaxy also contains a compact radio source and is the brightest member of a cluster of galaxies (Baade and Minkowski 1954). The X-ray data have been alternatively interpreted as indicating either thermal emission from the cluster gas (Gursky *et al.* 1972; Brinkman *et al.* 1977) or nonthermal emission from the nucleus of the cD galaxy (see, for example, Kafatos 1978). Moreover, the presence of 4U 1957+40 in a very crowded region of the galactic plane introduces the possibility that the X-ray source might be galactic in nature.

In this *Letter* we report the results of the observations of 4U 1957+40 with the scanning modulation collimator experiment (MC) of the *HEAO 1* satellite. The *HEAO 1* MC position includes the radio galaxy. We find the X-ray source to be extended with a size of $\sim 2'$. Any point source component must have strength ≤ 1.3 UFU.[1] When we compare our data with the simultaneous *HEAO* A-2 detection (Mushotzky, private communication) and with the results of previous observations (Longair and Willmore 1974; Brinkman *et al.* 1977; Forman *et al.* 1978), we find that the Cygnus A X-ray source appears to have a complex extended structure, resembling that of other clusters of galaxies whose dominant member is an active cD galaxy (see Gorenstein *et al.* 1978; Schwarz *et al.* 1978).

* Harvard-Smithsonian Center for Astrophysics.

† Department of Physics and Center for Space Research, Massachusetts Institute of Technology.

[1] 1 UFU = 1.7×10^{-11} ergs cm^{-2} s^{-1}, 2–6 keV; $\approx 1.6\ \mu$Jy at 3.6 keV.

II. X-RAY OBSERVATIONS

a) Data Analysis

We have analyzed two sets of data for which Cygnus A is in the field of view of the scanning modulation collimator (MC) experiment. These are the data collected in the scanning mode in 1977 November and the data from a pointed observation on 1978 May 3.

The data were binned about the position of the center of the 4U error box and fitted to a point source response, using the method described by Gursky *et al.* (1978). We first binned the 1977 November and the 1978 May data separately, and then merged them to improve the statistical significance of our result. Table 1 summarizes the results of this analysis. The 1977 November and 1978 May observations give self-consistent values for the X-ray flux. The X-ray fluxes obtained from the merged data are obviously consistent with those obtained from the two separate observations but the merged flux is not the average of the unmerged fluxes, since no constraint was put on where to fit the centroid of the X-ray–emitting region. The X-ray flux detected in MC1 (the 30″ FWHM collimator) is less than detected in MC2 (the 2′ FWHM collimator) for a point source fit. This shows that the X-ray emission arises from an extended region, whose signal is demodulated by the narrow collimator. The actual merged and binned data are shown in Figure 1. The MC2 data alone allow a good fit to a point source response, but the MC1 data show a wider distribution of counts.

b) Location

The MC2 line of position is plotted in Figure 2 together with the 4U and *Copernicus* error boxes and the *HEAO* A-1 line of position for Cygnus A. The MC position includes the cD radio galaxy (Fig. 3). It is interesting to notice that the centroid of our position falls between the cD galaxy and the Sf lobe, which is the more powerful radio emitter of the two lobes (Hargrave and Ryle 1974).

c) Size

Comparing MC1 and MC2 results, we can put some constraints on the angular diameter of the X-ray source. While a point source will give rise to comparable detections in the two collimators, an extended source will be demodulated and appear fainter in the narrower collimator (MC1). On the assumption that the source has no pointlike component, we fit the data from the two collimators to a single Gaussian shape and find $0'.6 \leq \text{FWHM} \leq 2'.4$ (at the 90% confidence level). The upper limit to the X-ray flux that might arise from a pointlike component is less than 1.3 UFU (at 90% confidence level), based on the lack of a strong MC1 detection. The statistical significance of our data does not allow us to discriminate between a single Gaussian model and one composed by a Gaussian plus a point source. However, if the variability discussed below arises from Cyg A, there must of course be a pointlike component.

TABLE 1

CYGNUS A *HEAO 1* MODULATION COLLIMATOR OBSERVATIONS

Scanning Data (1977 Nov)		
MC1 = 0.80±0.64	UFU	(1.5σ)
MC2 = 2.10±0.80	UFU	(3.15σ)
Pointing Data (1978 May)		
MC1 = 0.65±0.38	UFU	(2.05σ)
MC2 = 1.84±0.41	UFU	(5.35σ)
Pointing Data plus Scanning Data		
MC1 = 0.58±0.33	UFU	(2.07σ)
MC2 = 2.08±0.37	UFU	(6.66σ)

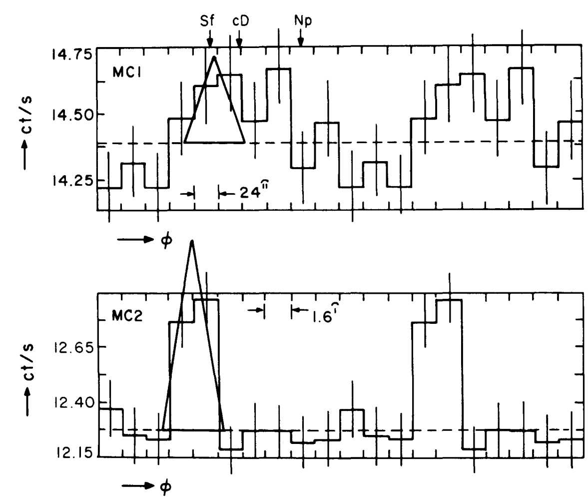

FIG. 1.—The merged and binned data (from MC1 and MC2) for 4U 1957+40 are plotted as a function of the phase angle (ϕ) between two maximum transmission bands of the collimators (Gursky *et al.* 1978). Each plot is repeated twice. Superposed on the data are the results of the fit to a background plus single point source model. The dashed lines identify the background level, and the triangles the point source response of the collimators for the fitted intensity (see Table 1). To convert MC1 (MC2) counts s^{-1} to Uhuru flux units (UFU), the following conversion factors (which include elevation and azimuth corrections) have been used: 1 (MC1) counts s^{-1} = 1.6 UFU; 1 (MC2) counts s^{-1} = 2.2 UFU. The projection of the cD galaxy and of the bright spots in the radio lobes (Sf, Np) on the MC1 scanning line are indicated by the arrows. These projections on the MC2 line all fall within a bin inside the MC2 triangle.

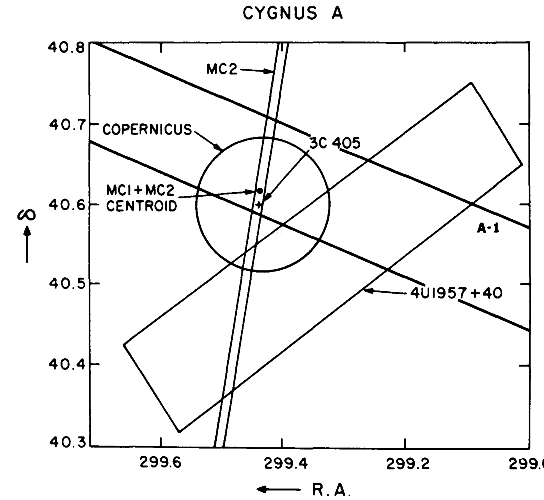

FIG. 2.—The 4U and *Copernicus* error boxes for 4U 1957+40 are plotted together with the MC2 position line and the A-1 line of position. The cross indicates the position of the radio galaxy Cygnus A and the dot the centroid of the MC1 and MC2 lines. The *ANS* error box (SXX) exceeds the scale of the figure.

d) Comparison with Previous X-Ray Observations

Table 2 summarizes the previous X-ray observations of Cygnus A.

Uhuru did not observe any variability in the X-ray flux. We calculated χ^2 for the hypothesis of no variability in the 32 *Uhuru* observations and we obtained χ^2 = 38.8. *ANS* observed 4U 1957+40 on three different occasions (Brinkman *et al.* 1977). We have averaged the second and third *ANS* fluxes together, because they are entirely consistent with each other and also with the *Uhuru* PST flux. The first *ANS* observation did not show any positive signal in the narrow angle high energy detector (HXX), but did yield a stronger (~2 times the previous measurements) signal in the wider soft energy detector (SXX). The *ANS* observers averaged together all their observations and interpreted them either as an indication of emission from a region more extended than ~10′, thus identifying the X-ray source with the cluster, or else as the emission due to a point source other than the radio galaxy. This second hypothesis is the only one allowed by our data, unless the 1974 *ANS* observation detected a soft X-ray flare from the radio galaxy. The high flux detected by the *Copernicus* satellite might be indicative of variability or might reflect the fact that that experiment covers a different spectral range from *Uhuru*. Kafatos (1978) reports that variability was observed in the *OSO 8* experiment data by the GSFC group.

All these observations allow contradictory interpretations. In particular, variable X-ray emission would originate in the nucleus of the active galaxy or in a transient variable galactic source present in the field of view of the observing instrument. On the assumption that the luminosity of the "spurious" galactic transient source and/or the nuclear flares is not too high (else it would have appeared in the *Uhuru* data), and that the duty cycle is low, these transient events could give only a small contribution to the *Uhuru* PST flux, which we therefore interpret as the average flux of the extragalactic source.

The flux detected by the *HEAO 1* A-2 experiment from Cygnus A, simultaneous with the 1977 November MC measurement, is ~3 UFU (±20%) (Mushotzky, private communication), indicating that no transient activity, either galactic or in the radio galaxy, was likely to be present.

The MC2 flux is compatible with the A-2 flux and the *Uhuru* PST flux, indicating that the X-ray emission is originated in regions of few arcminutes about the cD galaxy. Since the A-2 experiment has a field of view large enough to include all possible extended emission from the Cyg A cluster, we can compare this flux with the MC2 flux to see if there is any evidence of an extended component of size considerably larger than ~2′. Such a component, in fact, would be demodulated in MC2, giving a flux lower than the A-2 detection. If we compare the A-2 flux to that detected in MC2 (Table 1) and if we postulate a Gaussian shape for the surface brightness of the source, we obtain an upper limit for the size of such an additional emitting region of 6′.0 (90%). This suggests that the geometry for the Cygnus A X-ray source resembles that already detected in the Perseus and Virgo clusters (Gorenstein *et al.* 1978;

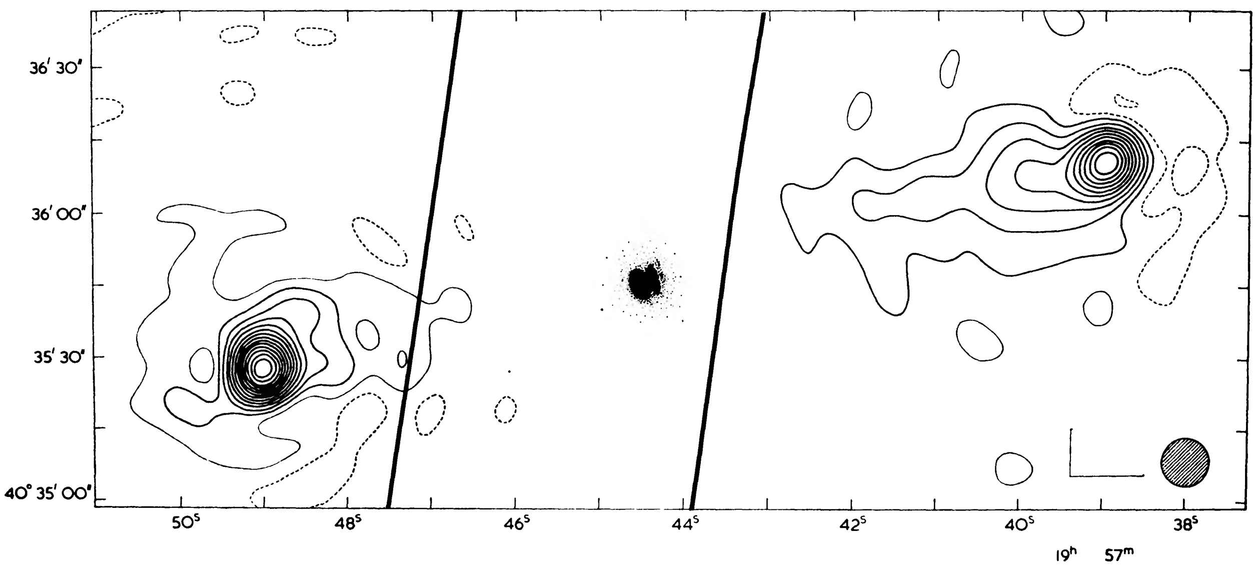

FIG. 3. The MC2 line is superposed to a radio map (Milton and Ryle 1969) of the Cygnus A region. The central object within the MC2 line is the active cD galaxy.

TABLE 2

CYGNUS A: SUMMARY OF X-RAY RESULTS

Experiment	Flux (2–6 keV) (UFU)	Dimension	Reference
Uhuru.................	+2.6 ±0.4 (PST)	...	Forman *et al.* 1978
Copernicus..............	+8.2 ±2.1	≲10′	Longair and Willmore 1974
ANS:			
1974 HXX...........	−0.29±1.58	≳12′ or point source not coincident with radio galaxy	Brinkman *et al.* 1977
1974 SXX............	+7.04±1.06		
1975 (av.) HXX......	+1.29±0.92		
1975 (av.) SXX.......	+3.34±0.56		
Average HXX.........	+0.86±0.80		
Average SXX.........	+4.4 ±0.4		
HEAO 1:			
MC1.................	+0.58±0.33	0′.6 to 2′.4 FWHM	
MC2.................	+2.08±0.37		
Point source..........	≲1.3	...	
A-2..................	≲3	...	Mushotzky, private communication

Schwarz *et al.* 1978). The source might consist of a small bright extended region of emission near the cD galaxy, superposed on a larger and fainter one. A pointlike component of nuclear emission (or the existence of a galactic source in the field of view) at an intensity ≤ 1.3 UFU cannot be excluded by the MC data.

III. DISCUSSION

As already discussed by Longair and Willmore (1974), the X-ray flux from Cygnus A is unlikely to originate in the radio lobes from inverse Compton scattering of the electrons that give rise to the radio synchrotron emission on the 2.7 K microwave background radiation. Using the value of the flux observed in MC2 as an upper limit to the X-ray emission from the radio lobes, we will attempt to calculate a lower limit on the magnetic field in the radio lobes. Using equations (5) and (6) of Gursky and Schwartz (1977), we can express the magnetic field H (assumed to be uniform in the radio lobes) as a function of the experimentally measured radio and X-ray fluxes:

$$H^{\alpha+1} = (2.47 \times 10^{-19})(4.99 \times 10^{+3})^{\alpha} T^{3+\alpha} \times \frac{F(m)}{a(m)}\left(\frac{h\nu}{E_x}\right)^{\alpha} \frac{dF_s(\nu)}{d\nu}\left[\frac{hdF_C(E_x)}{dE_x}\right]^{-1};$$

here α is the radiation spectral index, $m = 2\alpha + 1$ is the electron spectral index, $T = 2.7$ K is the temperature of the background radiation, $F(m)$ and $a(m)$ are tabulated functions (Blumenthal and Gould 1970), ν is the frequency of the synchrotron radio waves, E_x is the energy of the X-ray radiation, and F_s and F_C are the synchrotron (radio) and Compton (X-ray) flux densities, respectively. Using $\alpha = 1.2$ (Hargrave and Ryle 1974) and the radio flux at about $\sim$30 MHz (from Shklovsky 1960) which would be produced by the same electrons responsible for the inverse Compton X-ray radiation (Tucker *et al.* 1973), we obtain

$$H \gtrsim 1.6 \times 10^{-6} \text{ gauss}.$$

This is much smaller than the equipartition value $H_{eq} \sim 2 \times 10^{-4}$ gauss (Hargrave and Ryle 1974).

The X-ray flux could then be produced by the interaction of the radio galaxy with the cluster (infall mechanism), as suggested for the Perseus cluster (Gorenstein *et al.* 1978; Fabian and Nulsen 1977) or M87 in the Virgo cluster (Mathews 1978).

The angular extent we measure for the Cygnus A X-ray source corresponds to a 50–200 kpc linear extent for the central source about the cD galaxy and to ≤ 500 kpc for a more extended less luminous component. If there is no pointlike, nonthermal component in the X-ray source, Mathews's isothermal hydrostatic model for the gas surrounding the cD galaxy would imply for Cygnus A a mass larger than the one of M87. In fact, using Mathews's (1978) approximate formula for the mass of the galaxy

$$M_* = 2\text{–}3 \times 10^{13}\left(\frac{T}{3 \times 10^7 \text{ K}}\right)\left(\frac{R}{100 \text{ kpc}}\right) M_\odot,$$

which gives a $M_* \sim 2\text{–}3 \times 10^{13}\ M_\odot$ for M87, and substituting the parameters for Cyg A (see Table 3), we obtain $M_* \sim 1 \times 10^{14}\ M_\odot$.

Table 3 shows the physical parameters for the $\sim 2'$ emission region detected by the MC experiment, on the assumption of an isothermal sphere model. The cooling time is less than the Hubble time, indicating that some kind of refueling of the X-ray source is needed. This could be connected to the mechanism that powers the radio source or could be due to pressure-driven accretion of the cluster gas onto the cD galaxy. If we calculate the value of the density near the radio lobes, we obtain $n \sim 4.7 \times 10^{-3}$, consistent with the upper limit of Hargrave and Ryle (1974). The value of the density we find for the Cygnus A cluster is larger than what was previously reported for larger clusters (Lee *et al.* 1973; Kellogg and Murray 1974). However, the *HEAO 1* scanning modulation collimator experiment has measured similar densities for many X-ray–emitting clusters containing a cD galaxy (Briel *et al.* 1978; Schwarz *et al.* 1979).

Gull and Northover (1973) have predicted that a hot, dense gas confines the radio lobes. In an ideal homogeneous case the condition for thermal confinement of an extended radio source can be expressed as (Pacholczyk 1977)

$$\frac{3}{2} nkT = \frac{\pi}{6}\frac{U}{d^3},$$

where n and T are the density and temperature of the surrounding gas, and U and d are the internal energy and the effective size of the radio source. In the case of Cygnus A, the density we derive, $n \sim 10^{-2.5}$ at the radio lobes, is of the order required (see Gull and Northover 1973; Pacholczyk 1977). However, a temperature $kT \gtrsim 86$ keV is required, much higher than that observed for the X-ray source (see Kafatos 1978). Since the value of U assumes equipartition, it might well be much larger, and we therefore rule out thermal pressure confinement of the radio source.

The above calculation disregards the complex morphology of the radio source. However, the argument is still valid: in particular, even if in certain regions of

TABLE 3

CYGNUS A ISOTHERMAL SPHERE PARAMETERS

A. MEASURED QUANTITIES

Distance........	$\sim$340 Mpc
kT.............	$\sim$6.5 keV
Flux...........	$\sim$2 UFU
FWHM........	$\sim 2'$

B. DERIVED QUANTITIES

Core radius	≈ 0.19 Mpc
L_x	$\approx 4.7 \times 10^{44}$ ergs s^{-1} (2–6 keV)
n_0	≈ 0.014 cm^{-3}
t_C	$\approx 3.4 \times 10^9$ yr

the radio source the condition for confinement could be achieved, in the regions where the density is higher than the average value U thermal confinement would be impossible. Since inertial and ram pressure confinement also raise substantial difficulties (see Hargrave and Ryle 1974), the existence of the extended radio source Cygnus A still remains an unresolved problem. Future X-ray observation with better spatial resolution, which will allow us to map the surface brightness of the X-ray emission, could be instrumental in the solution of this problem and in the more general understanding of the extended giant radio sources.

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R. E. Doxsey and M. Johnston: Center for Space Research, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139

G. Fabbiano, D. A. Schwartz, and J. Schwarz: Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138