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THE LOCATION AND INTENSITY OF THE X-RAY SOURCE CENTAURUS A OBSERVED BY THE ASTRONOMICAL NETHERLANDS SATELLITE

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ABSTRACT

The HXX X-ray detectors on ANS have observed the source in NGC 5128, Cen A, with 10′ collimators and high time resolution during 1975 January 26–29. A source position is obtained that is consistent with the nucleus of NGC 5128. No rapid source variability was detected, and limits on pulsations are given. The source brightness was a factor of 5.1 ± 0.4 above the *Uhuru* value, although the spectral slope and low-energy cutoff were essentially unchanged. The source variability (1969–1975) is related to models for the nucleus of NGC 5128.
Subject headings: galactic nuclei, X-ray sources

I. INTRODUCTION

The X-ray source associated with Cen A has been the subject of recent interest both for its relation to the overall spectrum of the sources in the nucleus of Cen A (Perola and Tarenghi 1973; Grindlay 1975) and for its indications of variability not apparent in the early *Uhuru* observations (Tucker *et al.* 1973). The *Copernicus* experiment first reported (Davison *et al.* 1975) that on 1973 June 25, Cen A was detected with an intensity at ∼5 keV, a factor of ∼4 above the *Uhuru* flux of 1971 February. Winkler and White (1975) examined the MIT OSO-7 data for observations of Cen A in 1972 and 1973 and found an apparently constant flux at 2.2 times *Uhuru* during 1972 March–September. When the OSO-7 observations resumed in 1973 March, Cen A was a factor of 3.5 times *Uhuru* in X-ray luminosity, and this increased within a 6-day period in 1973 April to a factor of about 6.7 above the *Uhuru* flux. Such variation provided strong support for a model (Grindlay 1975) of a double Compton-synchrotron source structure in the nucleus of NGC 5128 and, of course, strengthened the original suggestion (Tucker *et al.* 1973) that the X-ray source was in the nucleus of the galaxy.

We report here the first observations of Cen A with detector spatial resolution sufficient to further refine the *Uhuru* position for the Cen A source. Our observations were also analyzed for variations of the source intensity on time scales from milliseconds to days. The data were acquired with the hard X-ray (HXX) detectors (∼1–30 keV) on board the Astronomical Netherlands Satellite (ANS). A complete description of these detectors and the ANS observing techniques is given in the preceding *Letter* by Gursky *et al.* (1975).

II. OBSERVATIONS AND RESULTS

Eleven observations of Cen A were recorded in regions of low and constant background from 1975 January 26 02:06 UT to 1975 January 29 03:49 UT. Most of these were ∼10 min observations alternating between the most probable position in the 3U error box (Giacconi *et al.* 1974) and background in 64 s intervals. We obtained several observations with offsets of −4 to +3′ from the nominal pointing position. The source position was then determined by examining the mean ratios of counts in the two HXX X-ray counters, since the two 10′ × 3° collimators are offset from the common pointing direction by +1′ and −2.7′ respectively (Gursky *et al.* 1975). Thus, for any offset angle from a pointing direction the ratio of the counts in the two detectors can give the actual offset of the source. The relation between the detector ratio and offset angle was calibrated on Cyg X-1 in 1974 November and again on the Crab in 1975 March by repeated observations in arc minute steps (−12′ to +7′) from the known source direction. The two sets of measurements agreed within counting statistics (∼5%), indicating there had been no change in relative detector sensitivities over the period including the Cen A observations. Typical errors in offset angle determined from a given ratio and the best-fit relation are ±0.5′.

In Figure 1 (Plate L5) we show the 90 percent confidence limit 3U error box for 3U 1322−42 (Giacconi *et al.* 1974), the most probable *Uhuru* position in this box (a cross), and the position of the galaxy NGC 5128 and its nucleus. The diagonal solid line marks the ANS best-fit position from analysis of the detector ratios described above; the dashed lines at ±1′.6 are the ±1σ limits. This

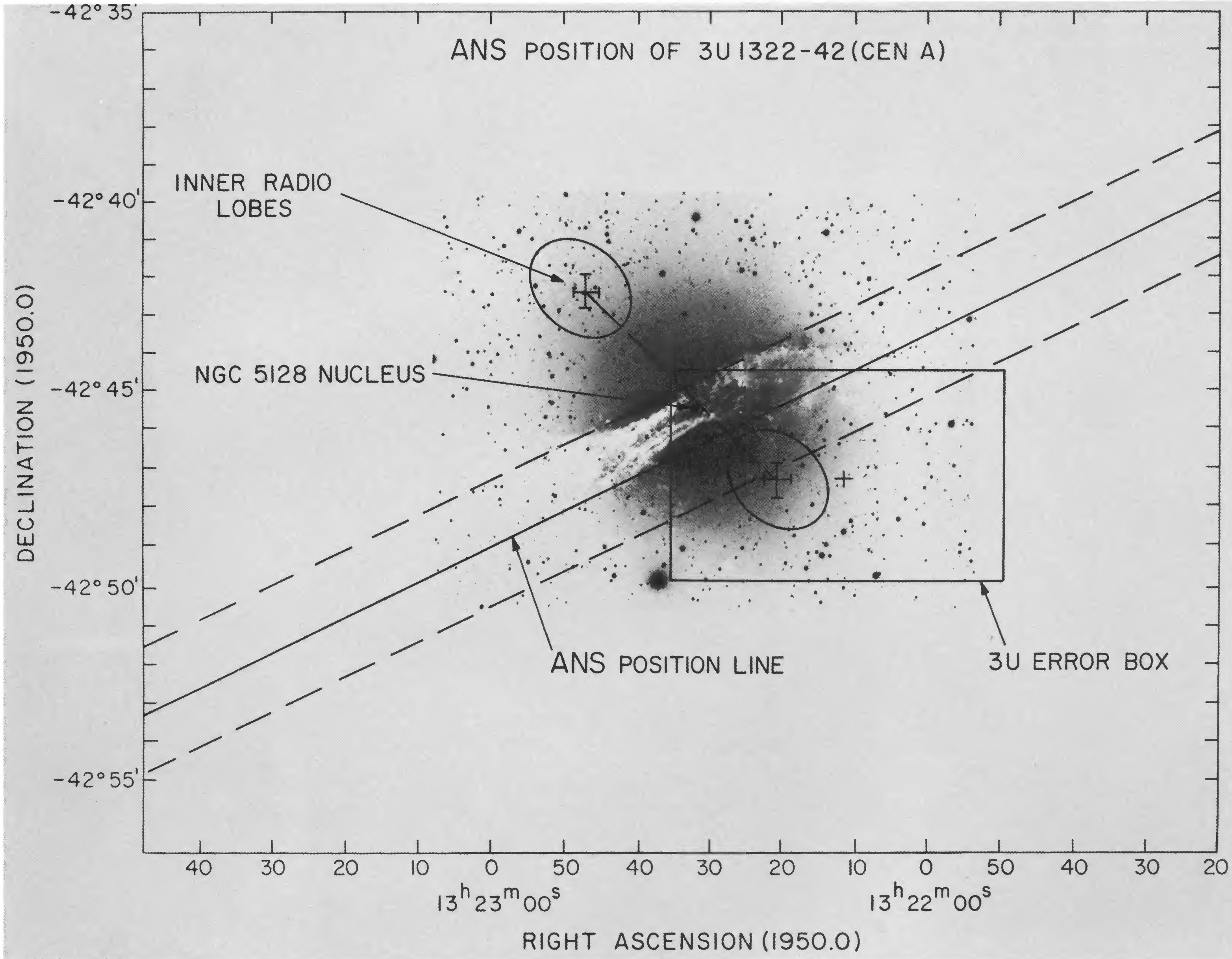

FIG. 1.—ANS position determined for the X-ray source Cen A (NGC 5128). The solid line shows the essentially one-dimensional position, and the dashed lines are the $\pm 1\ \sigma$ limits. The $\times$ marks the maximum of the 3° collimator response; the limits are off the scale of the figure. The intersection of the ANS position band and *Uhuru* error box includes the nucleus of NGC 5128 and excludes at least one of the inner radio lobes.

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error includes the uncertainty ($\sim\pm 0'.6$) in the offset angle due to both pointing and the calibration of the detector ratios as a function of offset angle. The $\times$ marks the maximum of the 3° response direction ($1950\alpha = 13:22:30$, $1950\delta = -42°46'12''$). However, the limits in the 3° direction are off the scale of the figure, and so the position determination is essentially one-dimensional. The intersection of the ANS best-fit position band ($\pm 1.6\ \sigma$ for 90% confidence) and the 3U error box limits the source location to about half the 3U error box and also includes the nucleus of NGC 5128. The combined ANS-*Uhuru* position excludes at least one of the inner radio lobes from being the X-ray source on positional grounds alone as well as the considerations of Tucker *et al.* (1973).

Assuming the source is at the nucleus position, we have plotted in Figure 2*a* the source minus background intensities with appropriate aspect corrections. These are plotted as total counts per 64 s in the window ~1.3–7 keV. The mean shown by the dashed line is 175 ± 13 counts $(64\ \text{s})^{-1} = 2.7 \pm 0.2$ counts s^{-1}. Since the conversion factor between ANS and *Uhuru* counts is 15.2 ± 0.4 *Uhuru* counts (ANS counts)$^{-1}$, our mean Cen A intensity corresponds to 41 ± 3.2 *Uhuru* counts s^{-1}. This is a factor of 5.1 ± 0.4 above the value given in the *Uhuru* catalog. The χ^2 value for these points is 7.6 for 9 degrees of freedom, and so there is no evidence for nonstatistical fluctuations of the source intensity. It should be noted that if the source were elsewhere along the best-fit line of position, i.e., not at the $\times$ in Figure 1, the true source intensity would be higher.

Most of these data were recorded with 1 s integration times. Since individual pointings lasted as long as 512 s, we have calculated the power spectra and autocorrelation functions of these data to search for fluctuations and periodicities in the range 2–512 s. The resulting flat power spectra indicate at the 95 percent confidence level that less than 30 percent of the source power are in fluctuations or periodic pulses in this range of time scales. Several of the observations were recorded in the pulsar timing mode where the arrival times of the first six photons each second were recorded to 4 ms accuracy. Analysis of these arrival times again revealed that less than 50 percent of the source power could be in fluctuations or periodicities in the time scale range ~10 ms–1 s.

Finally, we have summed all the data in Figure 2 and obtained a fit to the source spectrum using a standard minimum χ^2 spectrum fitting program procedure. We cannot distinguish ($\chi^2 \approx 10$ for 12 degrees of freedom) between power law (with energy index $\alpha = 0.4 \pm 0.6$, and cutoff energy $E_a = 3.2 \pm 0.9$ keV) and exponential spectra ($T \geq 10^8$ K, $E_a = 3.5 \pm 0.7$ keV) fits to the data. The spectrum thus appears similar to that observed by Winkler and White (1975) and is marginally flatter than the *Uhuru* spectrum of Tucker *et al.* (1973). Using the abundances of Brown and Gould (1970), our cutoff values require $N_{\text{H}} = 8(+8, -4) \times 10^{22}$ H atoms per cm^2.

III. DISCUSSION

We have compared all of the Cen A X-ray observations reported thus far in Figure 2*b* where the source 2–6 keV luminosity derived from best-fit spectra quoted for each observation are plotted. The high energy balloon results of Lampton *et al.* (1972) and Haymes (1975) required an appreciable extrapolation of the respective best-fit spectra for 2–6 keV luminosities. The uncertainty in this extrapolation is included in the error bars. The calibration for each of the results plotted is based on mutually consistent observations of various reference sources (see, e.g., Davison *et al.* 1975). We thus believe the apparent changes in the Cen A X-ray luminosity are real. In general, the X-ray brightness appears to have increased by a factor of 2–5 since the 1969–1971 observations of Bowyer *et al.*

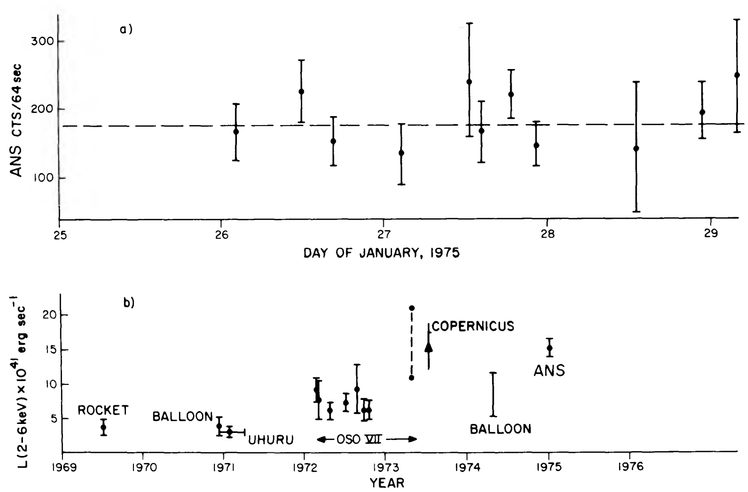

FIG. 2.—(*a*) Observed count rate on NGC 5128 by ANS in the range ~ 1.3–7 keV. The mean ot all the data is given by the dashed line. (*b*) Approximate X-ray luminosities of NGC 5128 in the range 2–6 keV obtained by integrating spectra reported for each published observation. The 1969 (discovery) rocket data are from Bowyer *et al.* (1970); the 1971 balloon data are from Lampton *et al.* (1972); the *Uhuru* data are from Tucker *et al.* (1973); the OSO-7 data from Winkler and White (1975); the *Copernicus* data from Davison *et al.* (1975); the balloon data from Haymes (1975); and the present ANS result. The implications of the both short- and long-term variability evident are discussed in the text.

(1970) and Lampton *et al.* (1972) and the 1971 *Uhuru* flux given by Tucker *et al.* (1973).

The nuclear region of Cen A has now been studied from 10^9 Hz to 10^{26} Hz, and significant variability is found in almost every part of this broad frequency range. Grindlay (1975) has interpreted this spectrum in terms of two distinct but unresolved sources, possibly the most recently ejected radio lobes and similar to the "knots" seen by VLBI in quasars or the inner and outer regions surrounding a supermassive "star." The principal argument for two sources is that radio emission found between 10^9 and 10^{10} Hz (component B) cannot originate in the same region as does the strong non-thermal (synchrotron) emission extending from 10^{10} to 10^{14} Hz (component A). Inverse Compton in the small (0.4 milli-arcsec) and variable component A then accounts in a natural way for a portion of the X-ray emission. However, the recently detected γ-rays at $\geq 3 \times 10^{11}$ eV (Grindlay *et al.* 1975) can only be accounted for as the inverse Compton effect from a larger (9 milli-arcsec) region (component B) which yields X-rays by the synchrotron process. Based on this model, it becomes possible to interpret (cf. Table 1) the variability that has been reported. For example, the relatively high X-ray flux (Winkler and White 1975) and $\sim 10^{11}$ eV γ-ray flux (Grindlay *et al.* 1975) in 1972 could be due to a sustained increase in component B. The relatively low γ-ray flux observed in 1973 April–June (Grindlay *et al.* 1975) suggests that the component B source was then low. However, the sudden X-ray increase observed over 6 days in 1973 April (Winkler and White 1973) and the high *Copernicus* flux observed in 1973 June (Davison *et al.* 1974) would be due to brightenings of component A. The relatively high γ-ray flux in 1974 March suggests that then component B was again bright only to be "replaced" by activity (March 28–April 1) in component A with the abrupt change in the millimeter flux reported by Kellermann (1974) and the high flux at ~ 1 MeV reported by Haymes (1975). The constant millimeter flux reported by Fogarty and Schuch (1975) and Price and Stull (1975) for 1974 April–1975 January indicates that then component A remained bright but relatively constant. The fact that the 10.4 GHz flux in this period was a factor ~ 1.8 times its value in 1973, whereas the X-ray luminosity observed by ANS is comparable to that seen by *Copernicus*, is further evidence that component B was indeed "replaced" by a sustained brightening of component A during this period. Thus, it is possible

TABLE 1

POSSIBLE ACTIVITY SEQUENCE (1969–1975) FOR COMPACT SOURCES A AND B IN NGC 5128

	APPROXIMATE DATES				
	6/69–1/72	1/72–10/72	4/73–6/73	>6/73–3/74	4/74–1/75
High	...	B	A	B	A
Low	A & B(?)	A	B	A	B
Evidence from	X-ray	γ-ray	X-ray	Radio, γ-ray	Radio, X-ray

to interpret the variations in the millimeter wavelength, X-ray (Fig. 2*b*), and γ-ray ranges as due to alternate activity in the source components A and B as if an outburst in A triggers one in B.

Sudden brightenings of component A might be expected to be detectable in the near-infrared if the spectrum was either not cut off at $\sim 10^{14}$ Hz as assumed (Grindlay 1975) or was not heavily absorbed. On 1975 February 4 and 16, M. Liller obtained red plates on NGC 5128 with the Cerro Tololo 60-inch (1.5 m) telescope. W. Liller (1975) has kindly examined these plates and found the relative brightness of the optical-infrared nuclear "hot spot" (Kunkel and Bradt 1971) to be within ~ 20 percent of its value in 1971 and (from HCO plates) constant back to at least 1934. Thus, although the underlying synchrotron sources have brightened by a factor of $\gtrsim 2$ and the X-ray luminosity by a factor of $\gtrsim 4$, the essential constancy in the optical suggests the component A and B sources are heavily obscured and the optical radiation seen is stellar.

Future observations of Cen A are needed both to further test the two-component model and to search for regularities and new instances of the source variability. Observations at ~ 600 MHz and $\gtrsim 30$ GHz as well as 10 μ would be very useful to correlate with future X-ray observations. With such data and especially a longer baseline of observations, it should be possible to search for periodicities or regularities in the outbursts and to significantly improve our understanding of the underlying sources of activity in the galactic nuclei. If, for example, the underlying source of energetic particles were a rotating massive collapsed object within component A surrounded by the larger component B source, fluctuations (possibly periodic) on time scales of hours to days might be expected. Winkler and White (1975) have observed one instance of X-ray variability with $\tau \approx$ days, and we have limited the source at a particular time to $\lesssim 50$ percent variations on time scales $\tau \approx$ 10ms–10 min and $\tau \approx$ 0.5–2 days. Clearly, more sensitive observations over this complete range of time scales are needed. As the closest member of its class, further study of Cen A may further clarify the probably general relationships between extragalactic X-ray sources and compact radio sources in galactic nuclei.

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Note added 1975 August 14. We have now analyzed quick-look data from a second series of ANS observations of Cen A during the period 1975 July 28–August 1. The mean source intensity was 103 $\pm$ 20 counts $(64\text{ s})^{-1}$ versus 175 $\pm$ 13 observed in January (cf. Fig. 2*a*). Observations of comparison sources (e.g., Cas A) indicate no measurable change in sensitivity, and so the ~ 50 percent reduction ($\sim 4\ \sigma$ level) in the Cen A intensity (~ 1.3–7 keV) is real. No significant variations are found within the new observations thus far available. The decrease in flux could be due to a decrease in component A in the sequence suggested in Table 1 and associated discussion, although more observations are clearly needed.

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