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THE GAMMA-RAY SPECTRUM OF CENTAURUS A: A HIGH-RESOLUTION OBSERVATION BETWEEN 70 keV AND 8 MeV

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ABSTRACT

The NASA/Goddard Space Flight Center Low-Energy Gamma-Ray Spectrometer (LEGS) observed the nearby active-nucleus galaxy Centaurus A (NGC 5128) during a balloon flight on 1981 November 19. The measured spectrum between 70 and 500 keV is well fitted by a power law of the form $(1.05 \pm 0.24) \times 10^{-4}(E/100\ \mathrm{keV})^{-(1.59 \pm 0.30)}$ photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{keV}^{-1}$. There is no evidence of a break in the spectrum or of any line features. The 2 σ flux upper limit for a narrow ($\lesssim 3$ keV) positron-annihilation line at 511 keV is 9.9×10^{-4} photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. The 2 σ narrow-line upper limits at 1.6 and 4.5 MeV (the energies at which the Rice University instrument observed lines in 1974) are 4.1×10^{-4} and 9.4×10^{-4} photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, respectively. The 1.6 MeV limit is a factor of 8 lower than the 1974 line flux, indicating that, if the 1974 feature was real, and, if it was narrow, then the line intensity decreased significantly between 1974 and 1981. The lack of observed annihilation-radiation from Cen A, combined with the temporal variations that are seen in the X-ray and γ-ray intensities, constrain the size of the emission region to be between 10^{13} and 5×10^{17} cm.

Subject headings: galaxies: individual — galaxies: nuclei — gamma rays: general

I. INTRODUCTION

Centaurus A (NGC 5128) is one of the nearest galaxies with an active nucleus, and one of the brightest extragalactic sources both at X-ray energies and in the radio band. The radio emission includes two sets of double-lobe structures that are approximately centered on the nucleus (Cooper, Price, and Cole 1965; Cameron 1969); the outer lobes are separated by ~5° (440 kpc for an assumed distance of 5 Mpc) and the inner lobes are separated by ~7′ (10 kpc). At the nucleus of the galaxy is a compact source, with structure that has been resolved with VLBI observations (Preston *et al.* 1983) and has been inferred from radio spectral observations (Kellermann 1974). Preston *et al.* (1983) propose a model based on the observations that has a two-component nucleus: one component is a 1 pc (~40 milli-arcsec) long jet which dominates the flux at 2.3 GHz, and the other component has a size of $\sim 3 \times 10^{16}$ cm (~0.4 milli-arcsec) and is visible at 8 GHz but self-absorbed at 2.3 GHz.

HEAO 2 observations (Feigelson *et al.* 1981) show that the X-ray emission from Cen A also has several components, including a compact nucleus, a jet connecting the nucleus with one of the inner radio lobes, and diffuse emission extending several arc minutes around the nucleus. The nucleus is unresolved, with an upper limit to its size of 0″.3 (7.3 pc). The nuclear X-ray emission is highly variable on a time scale of months to years with the most striking evidence for variability being a factor of 6 decrease in intensity between 1979 February and August observed by the *Einstein* Monitoring Proportional Counter (Feigelson *et al.* 1981), and several factor of >2 changes in intensity on 10-day time scales observed by *Vela 5B* (Terrell 1982). X-ray and low-energy γ-ray observations since 1968–1969 show long-term variability of a factor of ~5, with 1973–1975 being a period of particularly high flux (Baity *et al.* 1981 and references therein).

The *Einstein Observatory* data indicate that above ~3 keV the X-ray emission from Cen A is dominated by the nuclear source, whereas at lower energies the jet and the diffuse emission contribute most of the flux. The photon spectrum between ~7 and 100 keV is well represented by a power law of spectral index in the range −1.2 to −1.9 with most measurements near −1.7 (Baity *et al.* 1981 and references therein). Below ~4 keV the spectrum is cut off, with a shape indicating attenuation of the nuclear source by a column density of $\sim 10^{23}$ atoms cm^{-2} (Mushotzky *et al.* 1978). *SAS 2* upper limits between 35 and 200 MeV (Bignami *et al.* 1979), *COS B* upper limits between 50 MeV and 5 GeV (Pollock *et al.* 1981), and an atmospheric Cerenkov measurement at $\geq 3 \times 10^{11}$ eV (Grindlay *et al.* 1975) all fall below the extrapolation of the low-energy γ-ray spectrum, providing evidence for a spectral steepening somewhere in the 100 keV to 10 MeV range. Interestingly, it is found that for a wide range of quasars, Seyfert galaxies, and other active galactic nuclei, the hard X-ray spectrum is a power law with photon index in the range −1.6 to −1.7 (Mushotzky *et al.* 1980; Halpern 1982; Rothschild *et al.* 1983), and the flux measure-

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ments or upper limits above 10 MeV indicate a similar steepening of the spectrum (Bignami *et al.* 1979). The fact that the X-ray and γ-ray spectra of these different type objects have similar shapes hints at a common emission mechanism and environment in their nuclei. One of the objectives of the observation presented in this paper was to study the shape of the Cen A spectrum above 100 keV.

Another objective of the present measurement was to look for lines in the spectrum in the 100 keV to 8 MeV range. In 1974 two lines were seen during an observation of Cen A with the Rice University balloon-borne NaI instrument (Hall *et al.* 1976). The lines were at 1.6 and 4.5 MeV, and were both detected at the 3.3 σ level. The best fit to the 1.6 MeV line indicated a 400 keV broadening, although a width of less than 120 keV (the resolution of the instrument) could not be ruled out. The 4.5 MeV line was not resolved, giving an upper limit of ~150 keV to its width (Hall *et al.* 1976). The 1.6 MeV line was ascribed to nuclear deexcitation of the first excited state of ^{20}Ne, blended with lines from ^{24}Mg and ^{28}Si. The 4.5 MeV line was ascribed to excited ^{12}C. One advantage our germanium spectrometer offers over scintillator instruments is a much higher spectral resolution: for instance, a factor of ~40 at 1.6 MeV (~3 keV versus ~120 keV FWHM). In addition to being able to resolve narrower lines, the higher resolution also gives an improved sensitivity for narrow line detection, since a smaller bandwidth containing less background can be used in the line search.

Another spectral line of interest is the 511 keV line produced by positron annihilation in the source region. This line has never been detected from Cen A, but has been observed from the central region of our Galaxy (Leventhal, MacCallum, and Stang 1978). Preliminary results concerning the annihilation-radiation upper limits from the present observation are given by Gehrels *et al.* (1983).

II. INSTRUMENTATION AND OBSERVATIONS

The Goddard Low-Energy Gamma-Ray Spectrometer (LEGS) performs high-resolution spectroscopy between ~70 keV and 8 MeV using an array of three cooled high-purity germanium detectors surrounded by an active sodium iodide scintillation shield. The active volume of the detectors is 230 cm^3, which results in an effective area of 13.3 cm^2 at 511 keV and a peak effective area of 35.5 cm^2 at ~130 keV. The average in-flight energy resolution (FWHM) increases gradually from 1.8 keV at 70 keV to 3.5 keV at 2.6 MeV; the resolution at 511 keV is 2.2 keV. The active NaI shield is ~12 cm thick, and collimates the field of view of the detectors to ~16° FWHM.

The balloon-borne instrument is enclosed in an aluminum pressure vessel and mounted in a servo-controlled gondola which uses an altazimuth pointing system referenced to the Earth's magnetic field and the local vertical. Observations are normally performed by tracking a target in the sky under the control of an on-board microprocessor. Background is determined by rotating the elevation axis through the zenith to the same elevation angle as the target, but on the opposite side of zenith. These modes are alternated every 20 minutes over the observing period.

In-flight energy calibration is determined by monitoring the strong background lines at 54, 67, 140, and 198 keV produced by neutron activation of the Ge detectors, and the atmospheric 511 keV annihilation line. The weaker background line at 1461 keV, due to the radionuclide ^{40}K, is used for calibration at higher energies. A detailed description of LEGS is given by Paciesas *et al.* (1983).

The instrument was launched from Alice Springs, Australia, at 18:50 UT on 1981 November 19. Cen A was observed from 21:28 until 1:00 (November 20), at which time the galactic center was targeted. The flight was terminated at 9:01 (November 20). Results from the galactic center observation have been published (Paciesas *et al.* 1982).

The Cen A observation was divided into alternating source and background intervals as discussed above. For each interval, the start time, average pointing altitude angle of the telescope, and average atmospheric depth of the instrument are listed in Table 1. To determine the source flux for the spectrum and line upper limits described in the following section, we subtracted the background from each source interval, corrected for detector efficiency and atmospheric attentuation, and summed the residual fluxes. The background level used for each source interval was the average of the rate in the background half-intervals that immediately preceded and followed the source interval. Interval S1 was not included in the analysis (except where specifically noted) because it was not preceded by a background interval and because its atmospheric depth is significantly larger than that of the other

TABLE 1

OBSERVATION SEQUENCE AND INTEGRAL SOURCE FLUX

Interval[a]	Start Time[b] (UT)	Altitude Angle (degrees)	Instrument Atmospheric Depth (g cm^{-2})	Source Flux 70–300 keV (10^{-2} ph cm^{-2} s^{-1})
S1	21:28	50.8	4.5	1.5 ± 0.4
B1	22:01	55.3	3.5	
S2	22:21	58.6	3.3	1.1 ± 0.3
B2	22:41	61.7	3.2	
S3	23:01	64.6	3.2	1.1 ± 0.3
B3	23:21	67.2	3.2	
S4	23:41	69.3	3.2	1.4 ± 0.3
B4	0:01	70.8	3.2	
S5	0:20	71.4	3.2	1.5 ± 0.3
B5	0:41	71.2	3.2	

[a] SN = on-source interval #N; BN = off-source (background) interval #N.
[b] 1981 November 19–20.

intervals. The calculated source flux between 70 and 300 keV is listed in Table 1 for each of the five source intervals.

III. RESULTS

a) *The Spectrum*

Figure 1 shows the observed spectrum of Cen A and the best-fitting power law. The inset gives the 90% joint confidence contour ($\chi^2_{\rm min} + 4.6$; Lampton, Margon, and Bowyer 1976) for the parameters A and α of the spectral form $A(E/100 \text{ keV})^{-\alpha}$. The best-fitting values and 1 σ uncertainties ($\chi^2_{\rm min} + 2.3$) for the parameters are $A = (1.05 \pm 0.24) \times 10^{-4}$ and $\alpha = 1.59 \pm 0.30$. The measurements have been corrected for detector efficiency and atmospheric attenuation, and therefore represent the photon flux from Cen A incident on the top of the atmosphere. Although the LEGS field of view ($\sim 16°$ FWHM) includes the entire Cen A galaxy, the spectrum in Figure 1 is very likely that of the nuclear source since the *Einstein Observatory* X-ray images and spectral data indicate that the nuclear source dominates above ~3 keV (Feigelson *et al.* 1981).

The data are consistent over the entire measured energy range with a power law of photon index $-\alpha = -1.59$. This value for the index is similar to that of previous low-energy γ-ray observations of Cen A (Baity *et al.* 1981, and references therein) and is close to the range -1.6 to -1.7 found generally in active galactic nuclei. A previously published *HEAO* A-4 observation of Cen A (Baity *et al.* 1981) gave evidence for a spectral break at 140 keV, but a recently revised analysis[2] (W. A. Baity, private communication 1983) indicates that the break is no longer required by those data. We therefore conclude that there is not yet any direct observation of the break in the spectrum that is required for consistency with the *SAS 2* (Bignami *et al.* 1979) and *COS B* (Pollock *et al.* 1981) upper limits between 35 MeV and 5 GeV.

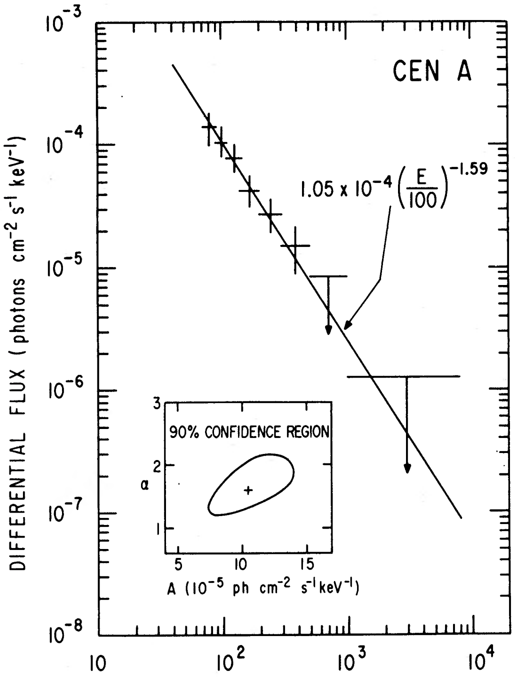

FIG. 1.—Cen A spectrum and best-fitting power law. The points between 70 and 500 keV are shown with 1 σ statistical error bars, while the upper limits between 500 keV and 8 MeV are 2 σ (98% confidence) upper limits. The inset shows a 90% confidence contour for parameters A and α. The contour was obtained by fitting the data to the spectral form $A(E/100 \text{ keV})^{-\alpha}$.

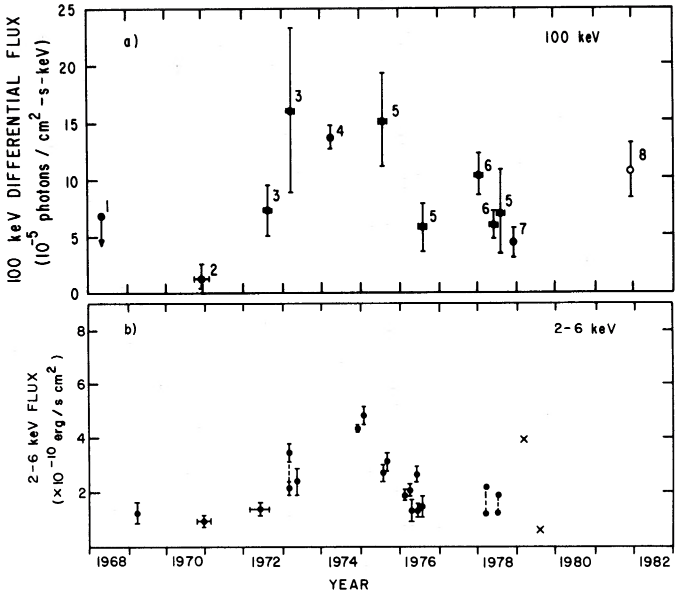

FIG. 2.—Historical summary of γ-ray and X-ray flux observations of Cen A. (*a*) Differential flux at 100 keV. Measurement 1 is a 95% upper limit, and measurements 2–8 are shown with ± 1 σ error bars. (1) Haymes *et al.* (1969), (2) Lampton *et al.* (1972), (3) Mushotzky *et al.* (1976), (4) Hall *et al.* (1976), (5) Beall *et al.* (1978) for the 1975 and 1976 points, J. F. Dolan (private communication 1983) for the 1978 point, (6) Baity *et al.* (1981), (7) Pietsch *et al.* (1981), and (8) LEGS (present observation). (*b*) Integral flux from 2 to 6 keV. From Feigelson *et al.* (1981).

b) *Source Intensity*

Cen A has been observed numerous times by X-ray and γ-ray instruments since the first measurements in 1968–1969. In Figure 2*a* we include our determination of the differential flux at 100 keV in a historical summary of measurements at that energy. The LEGS observation is represented by the open circle in 1981 at a value of $(10.5 \pm 2.4) \times 10^{-5}$ photons cm^{-2} s^{-1} keV^{-1}. The 1978 point number 5 in the figure is also a new result that has not been previously published. The data are from the High-Energy Celestial X-Ray Instrument on *OSO 8* (Dennis *et al.* 1977) during an observation of Cen A from 1978 July 31 to August 9. The measured 100 keV flux is $(7.1 \pm 3.7) \times 10^{-5}$ photons cm^{-2} s^{-1} keV^{-1} and the best-fitting photon spectral index is -1.64 ± 0.55 (J. F. Dolan, private communication 1983). In Figure 2*b* we show, for comparison, a similar summary of measurements of the X-ray integral flux between 2 and 6 keV, taken from Feigelson *et al.* (1981). In addition to the data in Figure 2*b*, there is a continuous record of the 3–12 keV X-ray flux from Cen A between 1973 and 1975 obtained by *Vela 5B* (Terrell 1982). The source intensity at X-ray and γ-ray energies is seen in

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[2] The 2 σ flux upper limit between 1.0 and 2.24 MeV in Fig. 3 of Baity *et al.* (1981) is now 4×10^{-6} ph cm^{-2} s^{-1} keV^{-1} instead of 4.5×10^{-7} ph cm^{-2} s^{-1} keV^{-1}. Other points in the figure are unchanged.

Figure 2 to have long-term variations of a factor of ~5, with 1973–1975 being a period of generally high flux.

Our measured flux in 1981 November is a factor of ~2 higher than the last three observations in 1978, and may indicate a return to a "high state" emission period. However, *HEAO 1* and *2* observations in 1978 and 1979, respectively, both give evidence of significant flux variations on a time scale of months (Baity *et al.* 1981; Feigelson *et al.* 1981). Also, the *Vela 5B* data (Terrell 1982) show that during the 1973–1975 period of high flux there were frequent fluctuations in the flux by factors of more than 2 over periods as short as 10 days. Variations on these short time scales may be in addition to a continuing long-term modulation, or they may be the only variations occurring at present. Our single measurement of a relatively high flux may therefore represent a transient increase instead of a return to a high state.

The temporal characteristics of the Cen A nuclear flux on time scales less than 10 days have not yet been definitely established. At X-ray energies there are several reports of short-term variations: a factor of 1.8 increase in 6 days (Winkler and White 1975), a factor of 1.8 increase in ~2 days (Lawrence, Pye, and Elvis 1977), a 25% increase in several hours (Delvaille, Epstein, and Schnopper 1978), and others (Mushotzky *et al.* 1976; Mushotzky *et al.* 1978). However, there are also some null results, the most constraining of which are the *Einstein Observatory* 3 σ upper limits of 3% variation on ~3 hour time scales (Feigelson *et al.* 1981) and the *HEAO* A-2 90% confidence upper limits of 2% variation on 20 minute time scales (Tennant and Mushotzky 1983).

No short-term variations have yet been observed at γ-ray energies (Baity *et al.* 1981; Pietsch *et al.* 1981); the *HEAO* A-4 upper limit is 35% variation on a time scale of days. We searched the LEGS data for short-term variations by dividing the measured 70–300 keV flux into 5 periods—one for each source interval in the observation. These periods and fluxes are listed in Table 1. The five points are consistent with a constant flux, and give an upper limit of 25% (95% confidence) for variations on a ~1 hour time scale.

c) Spectral Line Flux Upper Limits

The LEGS data were searched for features in the spectrum, with the result that no statistically significant narrow or broad lines were seen. The 3 σ flux upper limits for narrow lines (line width less than the instrument resolution: $\lesssim 3$ keV FWHM) are shown, as a function of line energy, by the solid line in Figure 3. The upper limits range from 6×10^{-4} to 2×10^{-3} photons cm^{-2} s^{-1}, with much of the interesting energy range $\gtrsim 500$ keV having a limit less than 10^{-3} photons cm^{-2} s^{-1}.

In order to obtain the lowest possible upper limits in Figure 3, different analysis techniques were used in different energy regions. At energies less than 500 keV, the flux of a particular line candidate was calculated as the source flux in a 4 keV bin centered on the line, minus the average source continuum flux in 40 keV bins on either side of the center bin. A 4 keV line bin was chosen because it is close to the optimum size for our ~3 keV FWHM resolution (Jacobson *et al.* 1975). The average residual fluxes resulting from this procedure are statistically consistent with zero, so that the upper limits in the figure are the combined statistical uncertainties in the fluxes of the center and continuum bins. At energies greater than 500 keV there is no significant source flux in our data, and therefore it was not necessary to subtract the average continuum flux on either side of the line bin; statistics are slightly improved by not performing the subtraction. Between 500 keV and 3.2 MeV, the plotted upper limits are the combined statistical uncertainties in the on-source and off-source rates in 4 keV intervals centered on the candidate-line energies. At energies greater than 3.2 MeV, even the number of background counts in 4 keV bins is small, so that the upper limits are based on the on-source data only. The limits were calculated using Poisson statistics and a 99.9% confidence level, which corresponds to 3 σ for a Gaussian distribution. In this energy range all five on-source intervals listed in Table 1 were used. The energy ranges of the different techniques are labeled in Figure 3, and the dashed lines show the upper limits of a given technique in adjacent energy ranges.

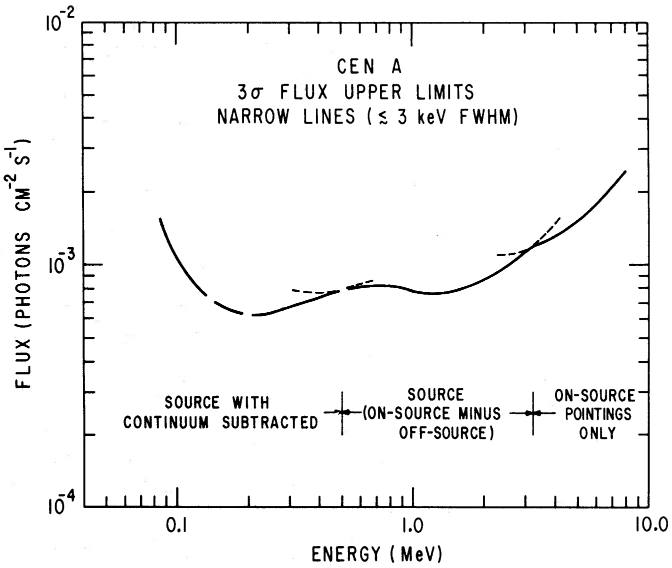

FIG. 3.—Cen A 3 σ (99.9% confidence) flux upper limits for narrow ($\lesssim 3$ keV FWHM) spectral lines. Three different computational techniques were used in different energy ranges to give the lowest possible upper limits, as described in the text. The curve is broken at 140, 198, and 511 keV due to the strong instrumental background lines at these energies.

The narrow-line flux upper limits in the regions of the strong instrumental background lines at 140, 198, and 511 keV are not plotted in Figure 3, but would be larger than the limits at nearby energies. The LEGS 2 σ upper limit for the astrophysically interesting positron-annihilation line at 511 keV is 9.9×10^{-4} photons cm^{-2} s^{-1} (3 σ limit = 1.5×10^{-3} photons cm^{-2} s^{-1}). In Table 2 we compare our 511 keV limit and upper limits for lines at 1.6 and 4.5 MeV with upper limits and measured flux values from the Rice University instrument (Hall *et al.* 1976) and with upper limits from *HEAO* A-4 (Baity *et al.* 1981). The lines listed as unresolved in the table are defined as having widths that are less than the instrument resolutions; for LEGS this means less than ~3 keV FWHM, and for the Rice University instrument and *HEAO* A-4, less than 50–150 keV FWHM depending on the line energy (see Table 2 footnote for specific widths). The other widths listed are bin widths from the previous analyses and

TABLE 2

SPECTRAL LINE FLUXES AND UPPER LIMITS

Energy (MeV)	Line Width[a] (keV)	Line Flux[c] Rice University (1974)[b] (ph cm^{-2} s^{-1})	*HEAO* A-4 (1978)[d] (ph cm^{-2} s^{-1})	LEGS (1981) (ph cm^{-2} s^{-1})
0.511	unresolved	$<8 \times 10^{-4}$	$<6.5 \times 10^{-4}$	$<9.9 \times 10^{-4}$
	50	$<8 \times 10^{-4}$	$<6.5 \times 10^{-4}$	$<2.1 \times 10^{-3}$
1.6	unresolved	$(3.4 \pm 1.0) \times 10^{-3}$	...	$<4.1 \times 10^{-4}$
	680	$(3.4 \pm 1.0) \times 10^{-3}$	$<4.1 \times 10^{-3}$[e]	$<6.7 \times 10^{-3}$
4.5	unresolved	$(9.9 \pm 3.0) \times 10^{-4}$	...	$<9.4 \times 10^{-4}$
	230	$(9.9 \pm 3.0) \times 10^{-4}$	...	$<4.1 \times 10^{-3}$

[a] "Unresolved" means line width less than the instrument resolution. For LEGS, 3 keV FWHM resolution (4 keV bin width) was used for all three energies. For the Rice Instrument, the resolutions at 0.511, 1.6, and 4.5 MeV are approximately 60, 120, and 150 keV FWHM. For the *HEAO* A-4 MEDs, the resolution at 0.511 MeV is 50 keV FWHM. Widths of 50, 680, and 230 keV were chosen to match bin widths of Rice and *HEAO* analyses.

[b] Hall *et al.* 1976.

[c] Upper limits are 2 σ (97.7% confidence). Flux measurements are quoted with 1 σ errors.

[d] Baity *et al.* 1981.

[e] This is a new, corrected upper limit (W. A. Baity, private communication, 1983); see also § III*a* and *n.* 2.

were used to allow direct comparison with the other reported values.

None of the three instruments observed any feature in the Cen A spectrum associated with positron annihilation. The three flux upper limits for a narrow emission line at 511 keV are approximately the same, with the best value being the *HEAO* A-4 limit (2 σ) of 6.5×10^{-4} photons cm^{-2} s^{-1}. Neither the 1.6 nor the 4.5 MeV lines observed by the Rice University instrument in 1974 were seen by LEGS or *HEAO*. The LEGS narrow-line limit for the 1.6 MeV line is a factor of 8 lower than the measured flux, indicating one of the following possibilities: (1) the line had decreased in intensity between 1974 and 1981, (2) the line is not a narrow feature, (3) the 1974 feature was a 3.3 σ statistical fluctuation, or (4) some unknown systematic effect produced a line in the 1974 spectrum. The 1974 observation did provide evidence for a broadening of the line, although the statistical significance of the result was poor. For a broad 1.6 MeV line the LEGS and *HEAO* upper limits are both larger than the measured flux so that no conclusion can be reached. No conclusion can be reached also for the 4.5 MeV line, since even the narrow-line upper limit from LEGS is only slightly smaller than the measured flux in 1974.

IV. DISCUSSION

Upper limits for a positron annihilation line derived from the LEGS data can be used in combination with an estimate of the ≥ 511 keV luminosity to place lower limits on the size of the Cen A γ-ray source region. For a given ≥ 511 keV luminosity L, the diameter of the source region, d, is related to the positron production rate via γ-γ interactions, Q, by

$$d \sim 3 \times 10^{-25} L^2/Q \text{ cm} \tag{1}$$

(Lingenfelter and Ramaty 1982). This equation is derived by relating both L and Q to the photon density in the source region, and by using the measured pair-production cross section near 511 keV. The derivation assumes a spherically symmetric source region that is optically thin to energetic photons of $\geq$ 511 keV.

The Cen A luminosity at ≥ 511 keV is estimated to be $\sim 3 \times 10^{43}$ ergs s^{-1} (Gehrels *et al.* 1983). This estimate is based on an assumed spectral shape at energies ≥ 511 keV, of the form

$$\frac{dF}{dE} = \frac{0.159}{E^{1.59}[1 + (E/2000 \text{ keV})^{1.3}]} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} \tag{2}$$

in analogy to the observed spectrum for 3C 273 (Swanenburg *et al.* 1978; Bignami *et al.* 1979). The spectral form in equation (2) tends toward the measured spectrum below 1 MeV and is consistent with the *SAS 2* (Bignami *et al.* 1979) and *COS B* (Pollock *et al.* 1981) flux upper limits between 35 MeV and 5 GeV. We feel that equation (2) is, for the purposes of this analysis, a reasonable guess for the Cen A spectral form in the MeV energy range. It is possible, however, that the spectrum could have a lower break energy and/or a steeper break, and still be consistent with the low-energy γ-ray spectrum and with the *SAS 2* and *COS B* upper limits. If, for instance, the spectrum cuts off steeply at 1 MeV, L would be a factor of 3 smaller and the calculated value of d an order of magnitude smaller.

Upper limits to Q, and thereby lower limits to d, were calculated from LEGS annihilation-radiation line upper limits for different source region temperatures. The line upper limits were computed using a bin width equal to 1.2 times the expected FWHM of the line (Jacobson *et al.* 1975), where the expected FWHM and bin centers for a given source temperature were obtained from theoretical studies of e^+-e^- plasmas (Ramaty and Mészáros 1981). The conversion from annihilation-radiation line flux to positron production rate, Q, depends on the annihilation mode of the positron; for direct annihilation, two $\sim$511 keV photons are produced per annihilation, whereas for annihilation via positronium formation, an average of one $\sim$511 keV photon is produced for every two annihilations. For source temperatures greater than 10^6 K, direct annihilation is the dominant mode (Bussard, Ramaty, and Drachman 1979), and we therefore

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divided the upper limit to the annihilation-radiation line luminosity by 2 to obtain Q. For source temperatures less than 10^6 K, the fraction annihilating by each mode depends on whether or not the ultraviolet photon density in the source region is sufficient to break up the positronium atoms before they annihilate (binding energy = 6.8 eV). For these temperatures, we calculated limits on Q and d for two cases: (1) sufficient UV photons—100% direct annihilation, and (2) insufficient UV photons—ratio of positronium to direct annihilations at a given temperature determined from Figure 3 of Bussard, Ramaty, and Drachman (1979).

Lower limits to d, calculated with equation (1) and the assumptions described above, are shown as a function of source temperature in Figure 4 (line labeled "Annihilation Radiation Limit"). At temperatures less than $\sim 10^6$ K, the solid line corresponds to 100% direct annihilation (case 1) and the dashed line to a mixture of positronium and direct annihilation (case 2). The upper limit of 5×10^{15} cm, shown as a long-dashed line in the figure, is a light travel time limit based on the reported factor of 1.8 increase in the X-ray intensity in ~ 2 days (Lawrence, Pye, and Elvis 1977). The more conservative limit of 5×10^{17} cm is based on the strong evidence for variations in the X-ray (Feigelson *et al.* 1981) and γ-ray (Baity *et al.* 1981) intensities on a time scale of 6 months. Also shown is a lower limit of 2.5×10^{12} cm, which is the Schwarzschild diameter of a 5×10^6 $M_\odot$ compact object. A central object of this mass accreting near its Eddington limit would produce the observed X-ray/γ-ray luminosity of $\sim 5 \times 10^{43}$ ergs s^{-1} assuming a 10% radiating efficiency. The line is represented as a lower limit since either a smaller accretion rate or a lower radiating efficiency would result in a more massive object, and therefore a larger source size. Fabian *et al.* (1976) place a similar lower limit ($\sim 10^7$ $M_\odot$) on the size of a compact object at the nucleus, based on the assumption that the nucleus supplied the energy content of the extended radio lobe structure.

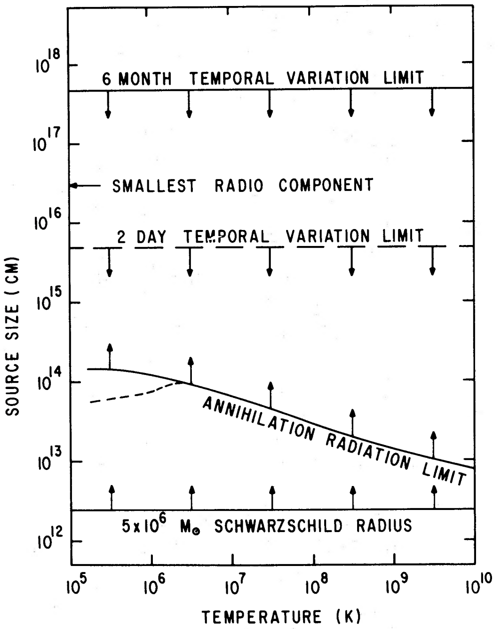

FIG. 4.—Limits to the size of the X-ray and γ-ray nuclear emission region in Cen A. The Schwarzschild radius lower limit is for a compact object of mass 5×10^6 $M_\odot$, which is the minimum mass required to produce the observed X-ray/γ-ray luminosity by accretion. The annihilation-radiation lower limit is based on eq. (1) and assumptions described in the text. Below $\sim 10^6$ K the solid line represents direct positron annihilation and the dashed line represents a combination of direct annihilation and annihilation via positronium. The temporal variation upper limits are based on light travel time arguments for source intensity variations, possibly on a time scale of 2 days (Lawrence, Pye, and Elvis 1977), and certainly on a time scale of 6 months (Baity *et al.* 1981; Feigelson *et al.* 1981). The smallest structure size implied by radio observations is shown for comparison.

The various limits constrain the source size to be between 10^{13} and 5×10^{17} cm, which is consistent with the size of the smallest structure implied by the radio observations of $\sim 3 \times 10^{16}$ cm (Kellermann 1974; Preston *et al.* 1983). The observed variations in the X-ray intensity on a time scale of days (Winkler and White 1975; Lawrence, Pye, and Elvis 1977) may indicate the presence of smaller X-ray emitting structures of size $\lesssim 10^{16}$ cm. If variations as short as the 25% increase in 2 hours observed by Delvaille, Epstein, and Schnopper (1978) are confirmed, then much smaller components yet, of size $\sim 2 \times 10^{14}$ cm, may also be present. It is interesting to note that, if the assumptions used in deriving the annihilation radiation limits in Figure 4 are correct, variations on this 2 hour time scale in the MeV γ-ray flux would predict the presence of an annihilation line near the detection threshold of present instruments.

V. CONCLUSIONS

Cen A was observed on 1981 November 19 with a high-resolution γ-ray spectrometer. The observed photon spectrum between 70 and 500 keV is well fitted by a power law of the form $A(E/100 \text{ keV})^{-\alpha}$ photons cm^{-2} s^{-1} keV^{-1} with $A = (1.05 \pm 0.24) \times 10^{-4}$ and $\alpha = 1.59 \pm 0.30$. There is no evidence of a break in the spectrum. Also, no lines or features were seen in the spectrum; the 2 σ (98% confidence) flux upper limits for narrow lines at 511 keV, 1.6 MeV, and 4.5 MeV are 9.9×10^{-4}, 4.1×10^{-4}, and 9.4×10^{-4} photons cm^{-2} s^{-1}, respectively. The 1.6 MeV limit is a factor of 8 lower than the line flux observed by the Rice University instrument in 1974 (Hall *et al.* 1976), indicating that, if the 1974 feature was real, and if it was narrow, then the line intensity decreased significantly between 1974 and 1981. The lack of narrow or broad annihilation-radiation emission from Cen A, and the observed temporal variations in the X-ray and γ-ray intensities, constrain the size of the emission region to be between 10^{13} and 5×10^{17} cm.

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REFERENCES

Baity, W. A., *et al.* 1981, *Ap. J.*, **244**, 429.
Beall, J. H., *et al.* 1978, *Ap. J.*, **219**, 836.
Bignami, G. F., Fichtel, C. E., Hartman, R. C., and Thompson, D. J. 1979, *Ap. J.*, **232**, 649.
Bussard, R. W., Ramaty, R., and Drachman, R. J. 1979, *Ap. J.*, **228**, 928.
Cameron, M. J. 1969, *Proc. Astr. Soc. Australia*, **1**, 229.
Cooper, B. F. C., Price, R. M., and Cole, D. J. 1965, *Australian J. Phys.*, **18**, 589.
Delvaille, J. P., Epstein, A., and Schnopper, H. W. 1978, *Ap. J.* (*Letters*), **219**, L81.
Dennis, B. R., Frost, K. J., Lencho, R. J., and Orwig, L. E. 1977, *Space Sci. Instr.*, **3**, 325.
Fabian, A. C., Maccagni, D., Rees, M. J., and Stoeger, W. R. 1976, *Nature*, **260**, 683.
Feigelson, E. D., Schreier, E. J., Delvaille, J. P., Giacconi, R., Grindlay, J. E., and Lightman, A. P. 1981, *Ap. J.*, **251**, 31.
Gehrels, N., Cline, T. L., Paciesas, W. S., Teegarden, B. J., Tueller, J., Durouchoux, P., and Hameury, J. M. 1983, in *Positron-Electron Pairs in Astrophysics*, ed. M. L. Burns, A. K. Harding, and R. Ramaty (New York: AIP), p. 309.
Grindlay, J. E., Helmken, H. F., Brown, R. H., Davis, J., and Allen, L. R. 1975, *Ap. J.* (*Letters*), **197**, L9.
Hall, R. D., Meegan, C. A., Walraven, G. D., Djuth, F. T., and Haymes, R. C. 1976, *Ap. J.*, **210**, 631.
Halpern, J. P. 1982, thesis, Department of Astronomy, Harvard University.
Haymes, R. C., Ellis, D. V., Fishman, G. J., Glenn, S. W., and Kurfess, J. D. 1969, *Ap. J.* (*Letters*), **155**, L31.
Jacobson, A. S., Bishop, R. J., Culp, G. W., Jung, L., Mahoney, W. A., and Willett, J. B. 1975, *Nucl. Instr. Methods*, **127**, 115.
Kellerman, K. I. 1974, *Ap. J.* (*Letters*), **194**, L135.
Lampton, M., Margon, B., and Bowyer, S. 1976, *Ap. J.*, **208**, 177.
Lampton, M., Margon, B., Bowyer, S., Mahoney, W., and Anderson, K. 1972, *Ap. J.* (*Letters*), **171**, L45.
Lawrence, A., Pye, J. P., and Elvis, M. 1977, *M.N.R.A.S.*, **181**, 93P.
Leventhal, M., MacCallum, C. J., and Stang, P. D. 1978, *Ap. J.* (*Letters*), **225**, L11.
Lingenfelter, R. E., and Ramaty, R. 1982, in *The Galactic Center*, ed. G. R. Riegler and R. D. Blandford (New York: Am. Inst. Phys.), p. 148.
Mushotzky, R. F., Baity, W. A., Wheaton, W. A., and Peterson, L. E. 1976, *Ap. J.* (*Letters*), **206**, L45.
Mushotzky, R. F., Marshall, F. E., Boldt, E. A., Holt, S. S., and Serlemitsos, P. J. 1980, *Ap. J.*, **235**, 377.
Mushotzky, R. F., Serlemitsos, P. J., Becker, R. H., Boldt, E. A., and Holt, S. S. 1978, *Ap. J.*, **220**, 790.
Paciesas, W., *et al.* 1983, *Nucl. Instr. Methods*, **215**, 261.
Paciesas, W. S., Cline, T. L., Teegarden, B. J., Tueller, J., Durouchoux, Ph., and Hameury, J. M. 1982, *Ap. J.* (*Letters*), **260**, L7.
Pietsch, W., Reppin, C., Trümper, J., Voges, W., Lewin, W., Kendziorra, E., and Staubert, R. 1981, *Astr. Ap.*, **94**, 234.
Pollock, A. M. T., Bignami, G. F., Hermsen, W., Kanbach, G., Lichti, G. G., Masnou, J. L., Swanenberg, B. N., and Wills, R. D. 1981, *Astr. Ap.*, **94**, 116.
Preston, R. A., Wehrle, A. E., Morabito, D. D., Jauncey, D. L., Batty, M. J., Haynes, R. F., Wright, A. E., and Nicolson, G. D. 1983, *Ap. J.* (*Letters*), **266**, L93.
Ramaty, R., and Mészáros, P. 1981, *Ap. J.*, **250**, 384.
Rothschild, R. E., Mushotzky, R. F., Baity, W. A., Gruber, D. E., Matteson, J. L., and Peterson, L. E. 1983, *Ap. J.*, **269**, 423.
Swanenburg, B. N., *et al.* 1978, *Nature*, **275**, 298.
Tennant, A. F., and Mushotzky, R. F. 1983, *Ap. J.*, **264**, 92.
Terrell, J. 1982, in *IAU Symposium 97, Extragalactic Radio Sources*, ed. D. S. Heeschen and C. M. Wade (Boston: Reidel), p. 117.
Winkler, P. F., Jr., and White A. E. 1975, *Ap. J.* (*Letters*), **199**, L139.

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