THE ASTROPHYSICAL JOURNAL, 197:L9–L12, 1975 April 1

EVIDENCE FOR THE DETECTION OF GAMMA RAYS FROM CENTAURUS A AT $E_{\gamma} \geq 3 \times 10^{11}$ eV

J. E. GRINDLAY AND H. F. HELMKEN
Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory
AND
R. HANBURY BROWN, J. DAVIS, AND L. R. ALLEN
School of Physics, University of Sydney, Australia
Received 1974 November 27

ABSTRACT

Results of extended observations of the active galaxy NGC 5128 (Cen A) at energies $> 10^{11}$ eV are presented. Data were recorded from three observing periods (1972–1974) in Australia. The atmospheric Cerenkov technique was used, together with partial cosmic-ray rejection, to search for γ-ray–initiated extensive air showers from the direction of Cen A. A 4.5 σ (time-averaged) excess over background was detected. Some implications of this probable γ-ray flux are discussed.

Subject headings: cosmic rays—galactic nuclei—gamma rays

I. INTRODUCTION

Centaurus A (NGC 5128), the closest active galaxy, is particularly well suited for observational study. The linear and symmetrical alignment of the extended ($\sim 5°$) and inner ($\sim 4'$) radio lobes have long been recognized as indicative of violent activity in the central galaxy. The recent detection of X-rays from Cen A (Bowyer *et al.* 1970; Kellogg *et al.* 1971; Lampton *et al.* 1972) provides direct evidence that high-energy processes are occurring there. To extend our knowledge of these processes to the highest possible energies, we carried out a search for very high-energy ($\gtrsim 3 \times 10^{11}$ eV) γ-rays from Cen A. The energy range above 10^{11} eV can be studied by ground-based observations of Cerenkov light produced by extensive air showers (EAS) (e.g., Jelley 1967).

II. OBSERVATIONS

We have described (Grindlay *et al.* 1973) our first observations of southern sky objects as possible high-energy γ-ray sources. Employing the atmospheric Cerenkov technique, we conducted these observations in 1972 April–July with an optical intensity interferometer (operated in Narrabri, NSW, by the University of Sydney) converted to detect Cerenkov light from cosmic-ray EAS. Since Cen A yielded the most promising positive effect ($> 3\ \sigma$) of 11 objects in the 1972 survey, we continued observing it with highest priority in our 1973 April–June and 1974 March–April observing programs.[1] A double-beam technique (Grindlay 1971) was employed, whereby the two optical reflectors were positioned on a 120-m baseline and pointed so that EAS were initially detected at their electron maxima and simultaneously examined for Cerenkov emission from their penetrating muon cores. Detection of the muon core in ~ 50 percent of the observed EAS rate ($\sim 1\ \mathrm{s}^{-1}$) permits rejection of this fraction of the cosmic-ray background. A complete description of the technique and apparatus used is given by Grindlay *et al.* (1975).

The detection-system parameters at the zenith are estimated to be as follows: effective solid angle $\Omega \simeq 5 \times 10^{-5}$ sr (or "beam" FWHM $\sim 0\overset{\circ}{.}45$), effective collection area $A_c \approx 1.6 \times 10^8\ \mathrm{cm}^2$, and γ-ray energy threshold $E_0 \approx 2 \times 10^{11}$ eV. At the zenith angles $\sim 35° \pm 10°$ for our data, A_c and E_0 were increased by a factor ~ 1.5.

Several improvements were made to the apparatus after the 1972 observations. The cosmic-ray-rejection efficiency was increased by installing off-axis rejection photomultipliers on both reflectors instead of on only one. Also, both rejection tubes were provided with ultraviolet-transmitting, visible-blocking glass filters (Schott BG-24) to reduce night sky background and improve the detection of the ultraviolet-rich muon Cerenkov pulses. A 26-channel pulse-height analyzer (PHA) measured the sum of the two coincident Cerenkov pulses from the EAS maximum; this covered a range of 20–1 in pulse height and thus in the primary energy. Finally, an expanded data-recording system, including real-time digital recording of all data, was used.

Observations of Cen A were restricted to nights of uniformly high atmospheric transparency in order to obtain reliable statistical comparisons between the EAS rates from Cen A and those from comparison directions. Uniform sky conditions were ensured by accepting an observation only if the EAS rates from the two comparison areas were within 3 σ of each other and if a χ^2 test of the distribution of fluctuations each minute of all the EAS rates were random about constant mean values with probability $P(> \chi^2) > 1$ percent. Fewer than 5 percent of all the data recorded were rejected by these criteria. As in our 1972 experiments, the neighboring sky "comparison areas" had the same declination as Cen A but were displaced 10 m in right ascension on either side of Cen A, so that they could be tracked over the identical azimuth and elevation ranges. The com-

---

[1] A complete description of our (other) observations is given in Grindlay *et al.* (1975).

parison areas were also chosen to have sky brightness identical to that of Cen A, and chart recordings of the phototube pulse rates were constant on and off source. When observing Cen A, the beam ($\sim 0^{\circ}.45$) was centered on the nucleus (Wade *et al.* 1971) of the optical galaxy ($\alpha_{1950} = 13^{h}22^{m}31^{s}.6$, $\delta_{1950} = -42^{\circ}45'30''.0$) and did not include the extended radio lobes. The two comparison regions (off source) were tracked for a total of 15 min, bracketing a period of 15 min on Cen A (on source) to complete a cycle. Unfortunately, the weather conditions in 1973 and 1974 were worse than in 1972. Consequently, although a total of 84 cycles was recorded in 1972, only 55 were measured in 1973 and 65 in 1974.

III. RESULTS

Table 1 lists our 1972 Cen A results (Grindlay *et al.* 1973) as well as those from 1973 and 1974. Total counts both on-source and off-source (sum of two comparison areas) are given, together with the exposure times, the corresponding ON minus OFF rates, and the number of standard deviation σ for the total number of EAS detected and also for the total number of EAS not rejected ("gamma events").

The data show a $\sim 4.5\,\sigma$ excess of time-averaged, nonrejected gamma events from the direction of Cen A. The sigma values in table 1 were computed assuming that Poisson statistics describe the EAS detection rate both on and off the source. This assumption was checked experimentally by computing the standard deviations of the three EAS detection rates (nonrejected gamma events, rejected EAS, and total detected) each minute for both of the two off-source comparison areas (separately and combined) and for the on-source data. These observed standard deviations were then divided by their corresponding Poisson values, and the distributions of resulting ratios examined. The means of the distributions were all within 3 percent of unity, with standard deviations of about 4 percent. Thus, our data seem to be well described by Poisson statistics.

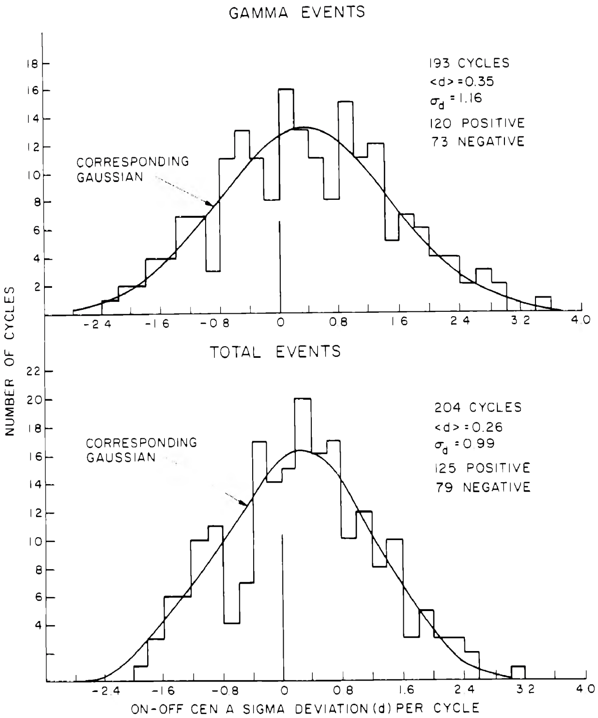


FIG. 1.—Distributions of observed σ for each observation cycle both on and off Cen A. All data (1972–1974) are included. The mean number of standard deviations (per cycle) and the standard deviations of the histograms are shown. The corresponding Gaussian curves fit the histograms with $\chi^2 \sim 0.9$ per degree of freedom.

As an additional check on the statistics of the Cen A results, we have plotted in figure 1 the histograms of all the numbers of standard deviations observed for the ON minus OFF rates for both total EAS and gamma events. A true source should displace the normal Gaussian distribution of detected deviations (d) from a zero mean to a positive value. Each σ deviation is the result obtained in one cycle of 15 min on source and 15 min off source. A few of the cycles were only 14 min both on and off source. Both distributions are well described by the Gaussians fitted to them. The σ distribution of the gamma events has a mean of $\pm$ 0.35 σ cycle^{-1} and a standard deviation of 1.16 σ cycle^{-1}. A fit to the corresponding Gaussian over the 17 bins with ≥ 5 cycles per bin yields $\chi^2 = 12.1$, or 0.86 per degree of freedom [$P(>\chi^2) \approx 60\%$]. The distribution is also consistent with the 4.6 σ total (gamma events) effect in table 1, since $0.35\,\sigma(193)^{0.5} \approx 4.8\,\sigma$. Similarly, the distribution of total events in figure 1 has a mean of $\pm 0.26\,\sigma$ cycle^{-1}, a standard deviation of 0.99 σ cycle^{-1}, and $\chi^2 = 0.93$ per degree of freedom [$P(>\chi^2) \approx 55\%$], for a fit to the corresponding Gaussian. Again, the pre-

TABLE 1

SUMMARY OF CENTAURUS A RESULTS

	TOTAL EAS					NONREJECTED EAS				
YEAR	On	Off	Time (min)	On minus Off Rate (min^{-1})	No. of σ	On	Off	Time (min)	On minus Off Rate (min^{-1})	No. of σ
1972...	76660	75601	1289	0.82±0.30	2.7	56471	55167	1240	1.05±0.27	3.9
1973...	35773	35726	782	0.06±0.34	0.2	15463	15297	662	0.25±0.26	1.0
1974...	64759	63757	975	1.03±0.37	2.8	39853	39139	975	0.73±0.29	2.5
Sum	177192	175084	3046	0.69±0.19	3.6	111787	109603	2877	0.76±0.16	4.6
Mean of rates weighted by σ^{-2}				0.63±0.19	3.3				0.66±0.16	4.2

dicted total effect is ~ 3.7 σ, as compared with 3.6 σ in table 1.

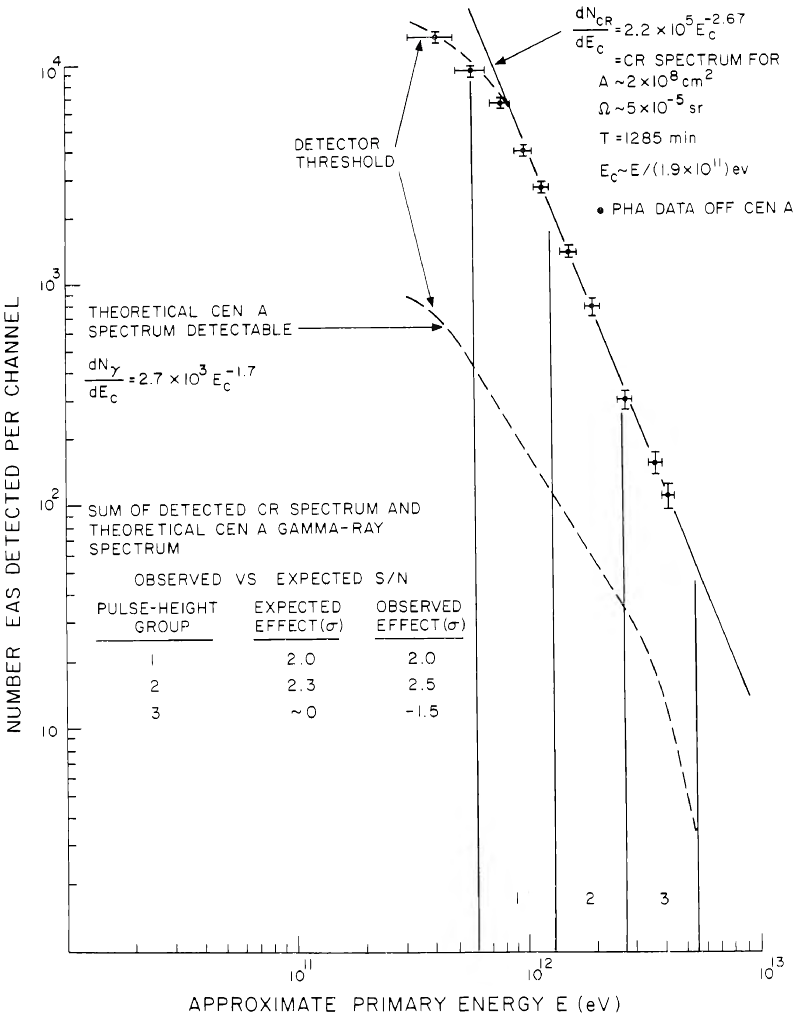
The results in table 1 suggest that the 1973 ON minus OFF source rates are a ~ 2 σ negative fluctuation from the mean of the 1972 and 1974 data. Although this does not necessarily require source variability, we shall cite below independent evidence for corresponding changes in the Cen A microwave source.

Our results in table 1 are thus consistent with having detected at the $> 4\ \sigma$ confidence level a flux of $F_\gamma \simeq 0.66 + 0.16$ gamma events min^{-1}, or given the detector parameters,

$$F_\gamma(\gtrsim 300 \text{ GeV}) \simeq (4.4 \pm 1) \times 10^{-11} \text{ photons cm}^{-2}\text{ s}^{-1} \qquad (1)$$

averaged over the 3 years of observations.

The Cen A data in 1973 and 1974 were recorded with a 26-channel PHA system. We have thus attempted to investigate the spectral distribution in the range ~ 300–3000 GeV of the apparent flux given in equation (1) by combining the pulse-height channels in three groups. Each group has a gain increase by an additional factor ~ 2 above the detector threshold. In figure 2, we have plotted the pulse-height spectrum detected off source for 1285 min of 1973 + 1974 Cen A PHA data. Some representative points of the individual PHA channel counts above threshold are plotted, and they follow closely a straight-line power law ($\alpha = -2.67$). This close agreement in slope with the expected cosmic-ray spectrum confirms the linear relationship over this range between detected Cerenkov pulse heights and cosmic-ray primary energy E_0. We have therefore fixed the energy scale on the x-axis in figure 2 by using the known cosmic-ray flux and the previously mentioned Narrabri detector parameters. The flatter spectrum with $\alpha = -1.7$ shown in figure 2 (*dashed line*) is a theoretical γ-ray spectrum (Grindlay 1975) for a Compton-syn-



OBSERVED VS EXPECTED S/N

PULSE-HEIGHT GROUP	EXPECTED EFFECT(σ)	OBSERVED EFFECT(σ)
1	2.0	2.0
2	2.3	2.5
3	~0	-1.5

FIG. 2.—Observed off-source pulse-height spectrum of gamma events plotted on the corresponding cosmic-ray primary energy scale. All the PHA data (about 70 percent of the 1973 and 1974 data only) are included. The steep solid-line spectrum is the known cosmic-ray flux for the Narrabri detector parameters given. A Compton-synchrotron model spectrum for the γ-ray flux that could be detected from Cen A is also shown (*dashed line*) for comparison with the cosmic-ray spectrum. The predicted on-source spectrum is then the sum of the dashed- and solid-line spectra. The resulting predicted signal-to-noise ratios for the pulse-height groups (1–3) are given and compared with the observed values.

chrotron model of the Cen A nucleus. In plotting this curve, we have taken into account the difference (approximately a factor of 2) between the primary energies of γ-ray– and cosmic-ray–initiated EAS yielding the same detected Cerenkov pulse height. The expected total on-source spectrum is the sum of the predicted γ-ray and the observed cosmic-ray spectra. The statistical significance of the difference in the number of counts (expressed in σ) between this combined spectrum and the detected off-source spectrum is listed in figure 2 for pulse-height groups 1–3. The number of sigma actually observed in the three groups is also given. The approximate agreement suggests that the observed Cen A flux is consistent with a flat source spectrum ($\alpha = -1.7$) with a high-energy break at $\sim 10^{12}$ eV, as assumed in the model.

IV. DISCUSSION

The detection of the high-energy γ-ray flux from Cen A given by equation (1) is established at about the 4.5 σ level. A relative-likelihood analysis (O'Mongain 1973) also gives a probability of $< 2 \times 10^{-5}$ (or $> 4.5\ \sigma$) that the total gamma-event excess in table 1 is not due to a γ-ray source.

Since the extended ($\sim 5°$) radio lobes were well outside our beam, they can be excluded as the source. Indications of variability as well as theoretical considerations (Grindlay 1975) can also exclude the inner radio lobes from being the γ-ray source.

A model that assumes that the γ-ray flux originates in the compact nucleus of Cen A by inverse Compton scattering is in reasonable agreement with the observations, as shown in figure 2 and by Grindlay (1975). This model predicts that variations in the γ-ray flux would be associated with those in the microwave flux from the source. There is some evidence that the compact microwave source at the nucleus of Cen A is variable. The source was discovered by Wade *et al.* (1971) from observations at 2695 and 8085 MHz by the National Radio Astronomy Observatory (NRAO) in 1970 July and 1971 May, between which times a limit of ~ 10 percent was put on its variability. The Stanford group observed the source at 10.7 GHz in 1973 June–August (Price and Stull 1973) and again in 1974 May (Stull 1974). The flux in 1974 was ~ 75 percent higher than that for the previous year. The authors caution that much of this increase may be due to calibration uncertainties at the low elevations required, although they find the difference between their two results and those of NRAO rather striking and they plan future monitoring. Further evidence for a compact source of millimeter radiation in the nucleus of Cen A, possibly variable on a $\sim$ 1-day time scale, has recently been presented by Kellermann (1974).

We have presented our results of ground-based γ-ray observations of Cen A, which suggest that this active galaxy is the first extragalactic source of very high-energy γ-rays to be detected. When combined with observations of Cen A at lower energies, the results can be used to determine the angular size, the energy content, and the magnetic fields in the source (see, e.g., Grindlay 1975), and should lead to significant progress in our understanding of the origin of radiation from compact sources in galaxies.

This work was supported by the NSF (grant GP 38783), the Smithsonian Institution, the Australian Research Grants Committee, the Research Grants Committee of the University of Sydney, and the Science Foundation for Physics within the University of Sydney. We thank Professor Messel for his support and Dr. T. C. Weekes, G. Gifford, S. Owens, and E. Horine for their assistance with the program.

REFERENCES

Bowyer, C. S., Lampton, M., Mack, J., and De Mondonca, F. 1970, *Ap. J.* (*Letters*), **161**, L1.
Grindlay, J. E. 1971, *Smithsonian Ap. Obs. Spec. Rept.*, No. 334.
———. 1975, *Ap. J.*, **199** (in press).
Grindlay, J. E., Hanbury Brown, R., Davis, J., and Allen, L. R. 1973, *Proc. 13th Int. Cosmic Ray Conf.* (Denver), **1**, 439.
———. 1975, submitted to *Ap. J.*
Jelley, J. V. 1967, *Progress in Elementary Particle and Cosmic Ray Physics, 9* (Amsterdam: North-Holland), p. 39.
Kellermann, K. I. 1974, *Ap. J.* (*Letters*), **194**, L135.
Kellogg, E., Gursky, H., Leong, C., Schreier, E., Tananbaum, H., and Giacconi, R. 1971, *Ap. J.* (*Letters*), **165**, L49.
Lampton, M., Margon, B., Bowyer, S., Mahoney, W., and Anderson, K. 1972, *Ap. J.* (*Letters*), **171**, L45.
O'Mongain, E. 1973, *Nature*, **241**, 376.
Price, K. M., and Stull, M. A. 1973, *Nature Phys. Sci.*, **245**, 85.
Stull, M. A. 1974, private communication.
Wade, C. M., Hjellming, R. M., Kellermann, K. I., and Wardle, J. F. C. 1971, *Ap. J.* (*Letters*), **170**, L11.

L. R. ALLEN, R. HANBURY BROWN, AND J. DAVIS: School of Physics, University of Sydney, Sydney, Australia 2006

J. E. GRINDLAY and H. F. HELMKEN: Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138