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An upper limit to 300 GeV gamma ray emission from Centaurus A

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Abstract. The nearby active galaxy Centaurus A (NGC 5128) which has been previously identified as a source of very high energy gamma rays has been observed with the Narrabri very high energy (VHE) gamma ray telescope. A total of 44 h of data collected between 1987 March 29 and 1988 April 20 place an upper limit on the gamma ray emission of 7.8 10^{-11} photons $cm^{-2} s^{-1}$ at a threshold energy of 300 GeV. A corresponding 3 σ upper limit of 2.5 10^{41} erg s^{-1} is found for the luminosity of $>$250 GeV gamma rays, a result which is compared with an earlier result at $E>300$ GeV.

Key words: gamma rays – galaxies: Centaurus A – galaxies: active

1. Introduction

Centaurus A is the closest "active" galaxy, at a distance of 5 Mpc. It is known to show inner and outer radio lobes, which suggest that at least two violent explosions have occurred within this galaxy, the earliest of which having taken place about 2.5×10^7 yr ago (Moffet, 1966). The object has long been identified as a strong source of both radio emission and X-rays. The early X-ray observations are described by Bowyer et al. (1970). Kellogg et al. (1971) and Lampton et al. (1972), and the existence of an X-ray jet emanating from the centre of the galaxy is reported by Feigelson et al. (1981). The central X-ray source is highly variable, both on timescales of years and days. High energy gamma ray data collected with the SAS 2 telescope were employed by Hall et al. (1976) and Mushotzky et al. (1978) to establish an upper limit of 2.0 10^{-6} photons $cm^{-2} s^{-1}$ to the flux of gamma rays at $E>100$ MeV (95% confidence); at a distance of 5 Mpc, this implies a luminosity limit of 2.9 10^{42} erg s^{-1}. At ultra high energies, Clay et al. (1984) report a 2.7 σ excess in cosmic ray showers (energy threshold 10^{15} eV) in a direction coincident with that of Centaurus A. However, the strongest evidence for a previous detection at high energies is that of Grindlay et al. (1975). Data were recorded during 1972 to 1974 using a stellar interferometer as a VHE gamma ray telescope employing the atmospheric Cerenkov technique. A 4.6 σ time-averaged excess of events was detected from Cen A, corresponding to 0.66 ± 0.16 photons per minute in the telescope, with a derived flux of (4.4 ± 1) $10^{-11} cm^{-2} s^{-1}$.

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The observations described here were made using the University of Durham Mark III VHE gamma ray telescope. We find no evidence for any gamma rays from the direction of Cen A, and we calculate an upper limit to the flux of 250 GeV gamma rays. The question of the compatibility of this result with that of Grindlay et al. (1975) is considered.

2. The gamma ray telescope

The observations were made with the University of Durham Mk III gamma ray telescope situated at Narrabri, NSW, Australia (30° 29′ S, 149° 39′ E, altitude 210 m a.s.l.) (Chadwick, 1987; Brazier et al., 1989a). The telescope has a threshold energy of 250 GeV near the zenith and is of conventional design. It comprises three light collectors made of high reflectivity aluminium, each of area 11.4 m^2, on a single alt-azimuth mount. The geometrical aperture of each channel of the system is 1°.0 full width. Each light collector is viewed by a cluster of 7 fast 40 mm dia photocathode PMTs (type RCA 8575). The 21 PMTs are arranged to provide 7 light-detecting channels, each one comprising a triple mirror-PMT combination for 3-fold coincidence selection. The typical count rate of each channel when the telescope is near to the zenith is about 100 min^{-1}. One of the channels views the object and the others monitor the surrounding regions of sky at equal angular offsets of 2°, providing comprehensive monitoring of the background.

The mode of operation of the Mk III telescope employed during all the observations of Cen A involved the mechanical chopping of the signal by movement of the whole telescope through 2° in azimuth every 2 min so that the central PMT system and another located in the same horizontal plane alternately observed the source candidate and a background sky region. The chopping technique, and its data analysis, have been developed to minimise any systematic effects which might mask a source signal or generate spurious signals. Since the two observing channels are at the same zenith angle at all times, and the telescope alters only its azimuth, there is no involvement of the strong zenith-angle dependence of counting rate in the differences between the channels or in the on-source/off-source rate comparison of each detector's counts. Each channel therefore follows a track on the sky which is continuous in zenith but which contains the source for only half the viewing time. There are two possible sources of error which remain. The first arises from a change in energy threshold which is possible if the PMT gain changes when the telescope axis is pointed at a part of the sky of different brightness (this gain

Table 1. The observing log

Date	Observation length (min)
1987 Mar. 29	213
1987 Apr. 2	225
1987 Apr. 3	232
1987 Apr. 5	306
1988 Feb. 14	181
1988 Feb. 16	225
1988 Feb. 20	234
1988 Feb. 21	250
1988 Feb. 22	199
1988 Feb. 23	221
1988 Feb. 27	170
1988 Mar. 15	160
1988 Mar. 16	230
1988 Mar. 17	293
1988 Mar. 18	400
1988 Mar. 20	87
1988 Mar. 21	59
1988 Mar. 22	184
1988 Mar. 24	287
1988 Mar. 25	234
1988 Mar. 26	211
1988 Apr. 12	60
1988 Apr. 14	143
1988 Apr. 20	224

change with changing anode current is a known property of fast-focused PMTs). This potential source of systematic error is removed by having servo-controlled LEDs in the field of view of each PMT to maintain constant cathode illumination, independent of sky brightness. The second source of systematic error is also well understood: the slow change in zenith angle during an observation gives rise to a gradual change in counting rate. End effects (in the simplest case caused by starting and finishing an observation with different channels on source) can give rise to spurious signals if corrections are not applied. The corrections are exact for a linear variation of count rate with zenith angle. The actual variation is non-linear, but the effects of any deviation from linearity over a typical observation period are negligible.

All of these assumptions have been checked by simulations and by "chopped" observations of other sources, where any systematic effects < 1% would have been detected. Moreover, the technique has given good evidence for the existence of a DC excess from another source – Sco X-1 (Brazier et al., 1989b).

When the central PMT system was "on-source", its complete encirclement by 6 "guard ring" coincidence channels permitted maximum rejection of nucleon-induced events characterised by the simultaneous response of the central channel and another off-source channel. The non-central channel, used as an "on-source" channel, did not have the protection of a complete circle of "guard ring" detectors and so for the time that this channel is "on-source", the benefit from the background rejection technique (and hence the sensitivity) is less.

3. VHE gamma ray data

Observations of Centaurus A were made for a total of 89.6 h during 25 nights between 1987 March 29 and 1988 April 20. An observing log showing the length of each observation is given in Table 1. Only data on those nights with very good and stable sky conditions lasting for the whole observation have been selected for analysis, leaving a sub-total of 44 h. The mechanical chopping of the recorded signal was performed with reference to Coordinated Universal Time. The raw count totals have therefore been corrected for end effects and the number of observations on and off source have been equalised. Table 2 lists the nights chosen for analysis, together with the event totals for each observation after such adjustments.

4. Data analysis

The atmospheric Cerenkov technique was previously employed by Grindlay et al. (1973, 1975) to observe Centaurus A for a total

Table 2. The number of events in the on-source and off-source categories during each of the observations made under clear and stable conditions

Date	Events ON	Events OFF	ON-OFF	ON-OFF (min^{-1})
1988 Feb. 14	8380	8449	− 69	−0.38
1988 Feb. 16	12219	12082	137	0.61
1988 Feb. 20	12080	11949	131	0.56
1988 Feb. 21	12367	12425	− 58	−0.23
1988 Mar. 15	6915	6957	− 42	−0.26
1988 Mar. 17	13108	13352	−244	−0.83
1988 Mar. 18	16625	16504	121	0.30
1988 Mar. 24	10477	10458	− 11	−0.04
1988 Mar. 25	7951	8010	− 59	−0.25
1988 Apr. 14	16553	16356	188	1.31
1988 Apr. 20	10361	10430	− 69	−0.31
Total	127006	126981	25	$9.5\ 10^{-3}$

time of 51 h during 1972 April–July, 1973 April–June and 1974 March–April. From data collected in drift scans, each made up of two 7.5-min observations off-source spread about a 15-min observation on-source, they report a combined on-source count excess of 4.6σ (3.9σ from 1972, 1.0σ from 1973 and 2.5σ from 1974) and a time-averaged event rate of 0.66 ± 0.16 gamma rays min^{-1} of energy >300 GeV. A gamma ray flux (in $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) which is derived from an excess of events must include an estimate of the sensitive area of a telescope, which is rarely based on direct measurement, but rather on models. Any other experiment with which comparison is sought is faced with a similar unsatisfactory dependence on the assumed collecting area. In the special case of the Durham University Mark III telescope and the experiment of Grindlay et al., two telescopes of equal threshold energy and geographical locations, the comparison depends only on differences between the collecting areas. The collecting area of a VHE gamma ray telescope is only weakly dependent on most telescope parameters, being mainly dependent on the size of the Cerenkov light pool itself. So, a detailed derivation of the collecting areas of two such similar telescopes is unnecessary for comparing the results from them. If the predicted number of gamma ray counts in our data (based on the observation of Grindlay et al.) is P, the statistical test to be used is the relative likelihood of our data containing a background B_0 and no gamma rays ($P = 0$) to that for data containing a background B_1 plus signal P, i.e.:

$$\lambda = \frac{\mathrm{Max}\,B_1\,(\mathrm{Prob.}\ (N_{\mathrm{on}}/B_1,\ P = P))}{\mathrm{Max}\,B_0\,(\mathrm{Prob.}\ (N_{\mathrm{off}}/B_0,\ P = 0))}.$$

The present experiment secured a total of 2631 min of data under good sky conditions, all of which happened to be in 1988. For the duration of the observations specified in Table 2, if we assume the VHE gamma ray flux to be the same as observed by Grindlay et al. (1975), the expected on-source excess over the two observing periods is 1736 ± 421 gamma ray events in total. The central and the off-axis channels together recorded a total of 127006 events when pointing towards Cen A, and a total of 126981 events when they were monitoring the background. These figures correspond to only 25 ± 504 events observed "on-source", an average of 0.01 ± 0.19 events per minute. There is therefore no significant excess observed on-source for the total observation, and the corresponding time-averaged 3σ upper limit on detected gamma rays is $0.58 \pm 0.19\,\mathrm{min}^{-1}$, or 1518 gamma rays. The 3σ flux limit is $7.8\ 10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$: see Chadwick et al. (1988) for a description of the derivation of flux limits for the Narrabri telescope.

The two telescope detector channels employed in the chopping technique are not of equal sensitivity. The principal channel is based on the central set of PMTs at the focal plane of each flux collector; the secondary channel uses one set of the outer ring of PMTs. Our routine method of enhancing any gamma ray signal depends on rejecting those events which involve responses from the "on-source" channel and a surrounding guard ring channel and are considered to be preferentially produced by cosmic ray nucleon primaries arriving from directions away from the source. (Brazier et al., 1989a). Clearly, the central detector channel is better protected by the complete "guard ring" of detectors, whereas the outer detector has only partial protection, and therefore is more sensitive. We have analysed those events which trigger the central channel alone when it is pointing towards the source. There were 52443 events observed when the central channel was pointing towards Cen A, and a total of 52469 events when it was monitoring the background. Evidently there is no "on-source" excess if the events from the more sensitive central channel only are considered.

5. Discussion

The 3σ flux limit derived from these observations is apparently compatible with the flux derived by Grindlay et al. (1975). However, as noted earlier there are fundamental problems with comparing derived fluxes from different experiments. Any flux calculation requires a knowledge of the telescope aperture, background cosmic ray proton rate and the size of the Cerenkov flash on the ground. Small differences or errors in any of these parameters, especially the latter, will produce large errors in the derived fluxes, making a meaningful comparison difficult. In addition to their flux measurement, Grindlay et al. (1975) noted an excess of 0.66 ± 0.16 events per minute from Centaurus A. Although the numerical flux quoted does not depend on any assumed parameters of Grindlay et al.'s telescope, a comparison of the counting rate of gamma rays does require a discussion of the effective collecting area of the two telescopes. The collecting area of a VHE gamma ray telescope depends on the lateral structure function of the Cerenkov light in the shower. This function is weakly dependent on primary energy, telescope aperture, altitude above sea level and zenith angle. Since the threshold energies of the two telescopes are approximately the same, and the altitude and geographical locations are the same, no significant difference due to collecting area arises when comparing gamma ray counting rates. The background counting rate of cosmic rays will depend directly on aperture, but the comparison depends only on taking into account the fluctuation in the background counts of the present telescope, since an error is quoted on the earlier flux which allows for background fluctuations in that telesocpe. We have therefore compared this result with our upper limit to the number of photons per minute from Cen A. If we apply a Z-test to determine if this result is consistent with our (non-significant) excess of 0.01 ± 0.19 events min^{-1}, we find that there is only a 0.93% chance that these two are compatible, a rejection at the 2.6σ level of significance. While this may seem a disappointingly weak rejection of the earlier result, it should be added that, since the effect of Grindlay et al. (1975) is significant at the 4.6σ level only and has a large standard error, the significance of any difference between results can never be greater than 4.1σ. An extremely long observation would be required to approach this level of significance.

Centaurus A is known to show long-term variability in X-rays. The longest observation of Cen A was made by the Vela 5 B satellite, which operated for 10 yr between 1969 and 1979 (Terrell, 1986). These data show that, beginning in 1973, Cen A was in an active phase for approximately 3 yr, the X-ray flux being about 3 times greater during this phase than previously. It then remained inactive for several years, becoming X-ray bright once more at the end of the life of the Vela 5 B satellite. Observations made with other satellites and with balloon-borne detectors confirm this history up to 1977 (Beall et al., 1978). Since that time only two measurements of X-ray emission from Cen A have been made; in 1984 the Tenma satellite observed Cen A in a quiet mode (Wang et al., 1986). More recently the continued low activity has been confirmed by preliminary results from the GINGA satellite (Inoue, 1989). In the radio region, the 10.7 GHz measurements show that the flux density from Cen A increased by a factor of approximately 1.5 between 1973 September and 1974 March. The flux then went through an apparent minimum in 1975 July, followed by a second increase later in that year and a subsequent decrease in mid 1976 (Price and Stull, 1973; Beall et al., 1978). It has been suggested that any VHE gamma ray flux from Cen A almost certainly arises in the same source volume as the X-radiation (Grindlay, 1975). If this is so, it may well be significant that the observations of Grindlay et al. (1975) were made when the X-ray source was in or closely approaching an active period. The X-ray data from Cen A for 1989 March show the object to have been in a low state and the applicability of this flux to the epoch of our observations lends weight to this theory. Further VHE gamma ray observations at times of known X-ray activity would be worthwhile.

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