Search for point sources of ultrahigh energy γ rays in the southern hemisphere with the South Pole Air Shower Experiment

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We report on the results of a search for point sources of ultrahigh energy γ radiation in data collected in 1988, 1990, and 1991 by the South Pole Air Shower Experiment. Nine predefined point sources were investigated: the x-ray binaries SMC X-1, LMC X-4, Cen X-3, Vela X-1, 4U1626-67, 4U1145-61, the supernova 1987A, the globular cluster 47 Tucanae, and the unconfirmed source BL-1. No conclusive evidence was found for dc emission from any of the nine candidates. An all sky search for a time-averaged signal was performed, but no significant excess was found. We find a 95% C.L. flux limit of 2.0×10^{-13} cm^{-2}s^{-1} above 50 TeV for all sources, with the exception of Vela X-1 where we have set the limit at 0.6×10^{-13} cm^{-2}s^{-1} above 200 TeV. The four x-ray binaries SMC X-1, LMC X-4, Cen X-3, and Vela X-1 were investigated for γ-ray emission modulated with the orbital period. No evidence for a modulated γ-ray signal was found. A search for sporadic emission from the nine sources was conducted on time scales of one hour, one day, and one week. The hourly and weekly burst searches were unsuccessful, but a statistically significant excess from SMC X-1 (99.6% C.L.) was detected during one day in 1991: 178 events on-source versus 120 background events. If this excess is attributed to a γ-ray signal, the associated flux above 50 TeV is $(1.3 \pm 0.2) \times 10^{-11}$ cm^{-2} s^{-1}.

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I. INTRODUCTION

Several experiments located in the Southern hemisphere have reported the detection of TeV or PeV γ rays from objects such as Large Magellanic Cloud (LMC) X-4 [1], Vela X-1 [2], and Centaurus (Cen) X-3 [3].

Since the austral summer of 1987 the South Pole Air Shower Experiment (SPASE array), which is described in detail elsewhere [4], has operated nearly continuously, with interruptions only during austral summer periods for hardware and software maintenance. Located at the geographical South Pole near the U.S. Amundsen-Scott station in Antarctica, the SPASE array enjoys a unique position and very high altitude (695 g cm^{-2}) which are ideal for cosmic-ray source searches above 50 TeV. The circumpolarity of numerous x-ray binary systems allows virtually uninterrupted observation during the austral winter. The performance of the array is discussed in an accompanying paper [5]. In this paper we present the results of a search for ultrahigh energy γ rays using data collected in 1988, 1990, and 1991 for seven reported x-ray binaries, SN 1987A, the globular cluster 47 Tucanae (TUC), and a suspected source that was found by the SPASE group in an earlier all-sky survey [6]. A dc analysis was conducted for each candidate, as well as a search for sporadic emission on time scales ranging from 1 h to 1 week. A search for orbitally modulated emission was performed where appropriate.

II. SPASE ARRAY

The South Pole Air Shower Experiment was established jointly by scientists at the Bartol Research Institute of the University of Delaware and at the University of Leeds during the 1987–1988 austral summer. The original array consisted of 16×1 m^2 scintillator detectors on a 30 m grid, each viewed from below by a 3 in. EMI 9281B photomultiplier tube (PMT) with a typical rise time of 2.1 ns. Two pairs of side-by-side detectors are used to measure the fluctuations in pulse height and in shower front arrival time as a function of particle density and distance to the shower axis. Thus there are up to 14 times available for shower reconstruction, depending on the size of the shower. The original 16-module array encloses an area of 6235 m^2. The telescope began operating on 21 December 1987.

One radiation length of lead was put on top of the 16 timing modules during the summer of 1989/1990, which improves the definition of arrival times of the shower front and enhances the scintillator response [7].

In December of 1989 eight new detectors were deployed surrounding the original array. These so-called guard-ring detectors provide only pulse height information. Their purpose is to improve shower core location.

III. ANALYSIS METHODS

A detailed description of the analysis techniques used is given in an accompanying paper [5] and in van Stekelenborg [8]. Briefly, an event is recorded if at least six timing modules trigger at the one-particle level within a time window of 1 μs. The first step in the analysis consists of determining whether or not the shower core has landed inside the central array of 16 timing detectors. For a small array such as SPASE it is essential that the core position be known accurately. Since there are few detectors, the shower front curvature, which depends on the distance to the shower axis, needs to be accounted for. Therefore, if the core falls outside the central array, the shower is rejected. This will minimize systematic errors in the assignment of the arrival direction. A neural network [9] decides whether or not the core is inside. If so, then the core is obtained by a center-of-gravity calculation. Subsequently, the direction is determined by fitting the measured arrival times to the curved shower front.

The determination of the shower front curvature and the uncertainties (weights) in arrival time are determined as a function of core distance and density (signal amplitude) by measurements with the side-by-side detector pairs.

For purposes of energy assignment some measure of the shower size or energy is required. At present we use a measure of the density at a fixed distance ($\sim$ 30 m) from the shower core. This $s(30)$ parameter is indicative of the primary energy. The relationship between average energy as a function of $s(30)$ at a zenith angle of 15° has been calculated by the use of a Monte Carlo procedure and is given by

$$E \sim 50 \times s(30)^{0.9} \text{ TeV}. \tag{1}$$

A traditional subarray comparison yields the angular resolution of the SPASE array, where we have used the definition [10]

$$\frac{dN}{d\Omega} = \frac{1}{2\pi\sigma_a^2} \exp(-\psi^2/2\sigma_a^2), \tag{2}$$

where ψ is the angle between the true and reconstructed directions, and σ_a is the angular resolution. In 1988 and 1989 the angular resolution was 1.6°, which improved to 0.9° in 1990/1991 because of the better timing capacity of the leaded array.

The absolute pointing accuracy was determined by using a Čerenkov detector pointing at a fixed azimuth and zenith angle. Showers coincident between the Čerenkov telescope and the air shower array were analyzed and the deduced arrival direction compared to the expected one. The pointing accuracy was found to be $0.2° \pm 0.5°$ [11]. The bin size used in the analysis is 3° in declination and $3°/\cos\delta$ in right ascension, which optimizes the signal-to-noise ratio.

IV. SOURCES

We report on the analysis of three seasons of data, some 58.8×10^6 triggers in 16 976 h of live time. The data from 1989 are problematic because 1 bit in the time word is contaminated. The results that we present here will therefore only reflect the events observed in 1988, 1990, and 1991. A general scan for excesses in any direction, the "all-sky survey," was made. We then concentrate on the nine potential sources listed in Table I. For each potential source dc and burst searches were performed. In the case where there is a known orbital period at other wavelengths a period analysis was performed.

All of these sources, except for SN 1987A, 47 Tuc, and BL-1, are x-ray binaries. The globular cluster 47 Tucanae contains a number of millisecond pulsars. The sky bin BL-1 is not a reported source at any wavelength, but a portion of the sky where, in a preliminary analysis, an excess of 4.9 standard deviations was reported [6]. All the potential sources, except Vela X-1, have zenith angles less than 30° and are therefore subject to minimal atmospheric attenuation.

Episodic emission from these sources was investigated on several different time scales. The four x-ray binaries Small Magellanic Cloud (SMC) X-1, LMC X-4, Cen X-3, and Vela X-1 were searched for a γ-ray signal modulated by the orbital period. The uncertainty in the orbital elements of the binary systems 4U1626-67 and 4U1145-61 prevents a search for a periodic signal.

TABLE I. List of potential sources. Right ascension and zenith ($\delta + 90°$) are referred to the 2000.0 equinox. Orbital period and pulsar period are indicated by P_0 and P_p, respectively. The ephemerides used in the period search of SMC X-1, LMC X-4, Cen X-3, and Vela X-1 are given in the references listed in the last column.

Source	RA	Zenith	d (kpc)	P_0	P_p (s)	Ephemeris
SMC X-1	19.28	16.55	65	3.89 d	0.71	[12]
LMC X-4	83.20	23.63	50	1.41 d	13.50	[13]
Cen X-3	170.33	29.38	10	2.09 d	4.83	[14]
Vela X-1	135.53	49.45	1.9	8.96 d	282.93	[15]
BL-1	174.5	27.5				
4U1626-67	248.08	22.53	3–6	$\sim$ 2485 s	7.66	
4U1145-61	177.00	27.80	1.5	$\sim$ 186.5 d	292	
SN 1987A	83.87	20.73	50			
47 Tuc	6.03	17.92	4.6			

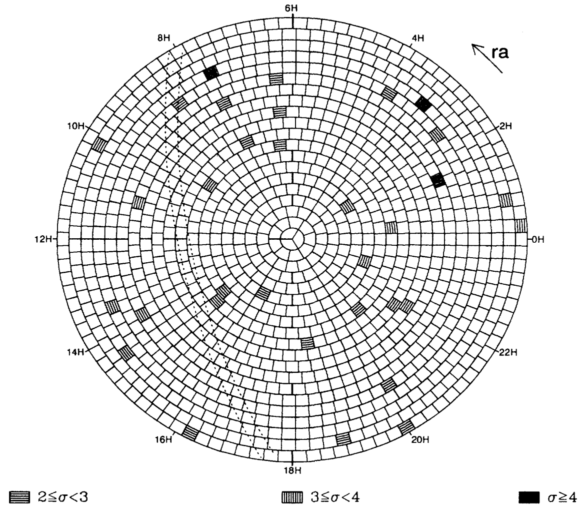

FIG. 1. All-sky plot for zenith angles up to 60°. The shading in the bins indicates the Li-Ma σ. Each circular band corresponds to a 3° declination band. The center of the figure corresponds to the zenith. The two dashed lines indicate the position of the galactic plane, i.e., $|b| < 1.5°$.

V. ALL-SKY SURVEY

The all-sky survey is very similar to the search for γ-ray emission from preselected candidates, the only difference being that every sky bin is considered a potential γ-ray emitter. In order to scan for unusual hot spots the entire sky down to a zenith angle of 60° is divided into 1100 $3° \times 3°$ bins. The total number of counts in each bin is compared to the average number of counts in the eight neighboring bins in the same declination band, which yields an excess or deficit in terms of the Li-Ma σ [16] for each sky bin. To avoid a situation in which an active sky region would be divided into two bins, the sky search is repeated with all bins shifted by 1° in declination and $1°/\cos\delta$ in right ascension (RA). Finally, a third search is conducted with a 2° shift in declination and $2°/\cos\delta$ in RA. Figure 1 represents the sky as seen by the SPASE telescope down to a zenith angle of 60° and divided into $3° \times 3°$ bins. The associated Li-Ma σ in each bin is calculated and shown graphically in the figure if its value exceeds 2.0. Inspection of the sky plot shows that only three bins (out of ~ 1100) exhibit an excess between 3σ and 4σ, while no region has an excess greater than 4σ. Repeating the sky search with all bins shifted as outlined above also fails to show a region with an excess greater than four standard deviations. The integral distribution of excesses and deficits in terms of σ, resulting from the 3305 sky bins, is plotted in Fig. 2. The observations are consistent with random fluctuations, i.e., a normal distribution with mean 0.0 and standard deviation equal to 1.0.

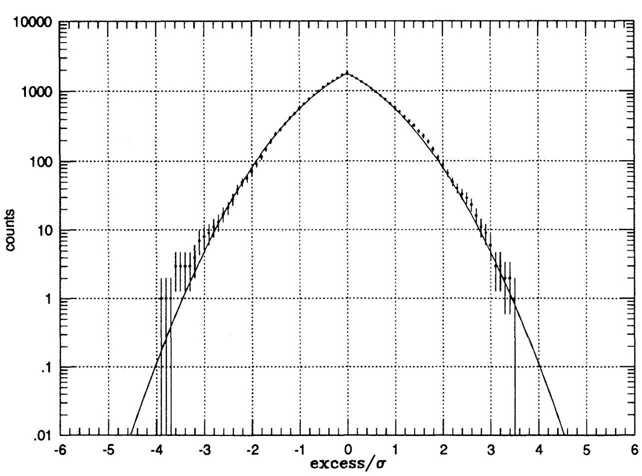

FIG. 2. Integral excess (≥ 0) and deficit (< 0) distribution for all-sky search. The solid line is the integral Gaussian distribution function with $\mu = 0$ and $\sigma^2 = 1$.

VI. RESULTS OF THE dc SEARCH

A. Calculation of upper limits on γ-ray emission

Upper limits at 95% confidence level on the flux and the luminosity were calculated as follows. The photon flux is assumed to follow a power law with integral spectral index γ:

$$\frac{dN}{dE} = C\,E^{-(\gamma+1)} \quad \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\ . \tag{3}$$

For the purposes of this paper we have assumed a value of 1 for γ. If T denotes the total observing time and B is the number of background counts as determined from the eight bins adjacent to the source bin, then the 95% C.L. upper limit on the counting rate is $1.64\sqrt{B}/0.71T$, where the factor 0.71 is included to correct for the fact that approximately 71% of the signal will be contained in the search bin. The expected counting rate, from Eq. (3), is given by

$$\int \frac{dN}{dE}\,A(E)\,f(E,d)\,dE$$

$$= C\int E^{-(\gamma+1)}\,A(E)\,f(E,d)\,dE\ , \tag{4}$$

where

$$f(E,d) = \exp[-d/l(E)]. \tag{5}$$

The function $f(E,d)$, where d is the distance to the source, accounts for the attenuation of photons in the cosmic microwave background via

$$\gamma + \gamma(3\,\mathrm{K}) \to e^+e^-\ .$$

The energy-dependent attenuation length $l(E)$ has been calculated by Protheroe [17].

The effective area as a function of energy $A(E)$ is determined by Monte Carlo calculations: A large number of trial showers, $N(E)$, is generated at various energies. The shower core position is randomized and confined to a circle with radius 200 m centered at the array center. Monte Carlo simulations show that this is far enough such that showers outside the 200 m radius have a negligible probability of triggering the array. The effective area can then be calculated from the number of triggers at each energy with cores inside the central array, $N_{\rm tr}(E)$:

$$A(E) = \pi \times 200^2 \times \frac{N_{\rm tr}(E)}{N(E)} . \tag{6}$$

Consequently, the 95% C.L. upper limit on the value of the constant C in Eq. (3) is given by

$$C \le K = \frac{\frac{1.64}{0.71}\sqrt{B}/T}{\int E^{-(\gamma+1)}\, A(E)\, f(E,d)\, dE} . \tag{7}$$

As pointed out by Gaisser *et al.* [18], a flux or flux limit that is evaluated near the median energy of detected showers is relatively independent of the spectral shape. If we define

$$g(E,d) = \frac{dN}{dE}\, f(E,d)\, A(E) , \tag{8}$$

then the median energy is given by

$$\int_{E_0}^{E_{\rm med}} g(E,d)\, dE \bigg/ \int_{E_0}^{E_{\rm cut}} g(E,d)\, dE = 0.5. \tag{9}$$

A value of 10^{17} eV is assumed for the cutoff energy $E_{\rm cut}$. The function $A(E)$ essentially describes the detector efficiency at energy E. Once the median energy and the upper limit on constant C are known, the 95% C.L. upper limit on the flux can be computed:

$$\left(\frac{dI}{d\ln E}\right)_{E_{\rm med}} \le K\, E_{\rm med}^{-1}\, f(E_{\rm med}, d) , \tag{10}$$

$$I(> E_{\rm thr}) \le K \int_{E_{\rm thr}}^{E_{\rm cut}} E^{-2}\, f(E,d)\, dE , \tag{11}$$

where $\gamma = 1$ has been substituted. Ultrahigh energy γ rays from compact objects such as binary stars and supernovas are believed to be produced in the interaction of a proton beam, generated near the surface of the object, with matter in the immediate surroundings of the object, e.g., an accretion disk. To compute the proton luminosity the spectrum weighted moments $Z_{N\to\pi^c}$ and $Z_{\pi^0\to\gamma}$ are needed. The spectrum weighted moment of the inclusive cross section is defined as

$$Z_{ac} = \int_0^1 x^{\gamma-1} F_{ac}(x)\, dx \tag{12}$$

and the inclusive cross section F_{ac} as

$$F_{ac}(E_c, E_a) \equiv E_c \frac{dN_c(E_c, E_a)}{dE_c} , \tag{13}$$

with $x = E_c/E_a$.

The photon flux can be written as

$$\frac{dN}{dE_\gamma} = \int_{E_\gamma}^{\infty} \frac{dN_\gamma}{dE_\gamma}(E_\gamma, E_\pi) \times \int_{E_\pi}^{\infty} \frac{dN_\pi}{dE_\pi}(E_\pi, E_p)\, \phi(E_p)\, dE_p\, dE_\pi . \tag{14}$$

Assuming that the proton flux follows a power law

$$\phi(E_p) = C_p\, E_p^{-(\gamma+1)} \tag{15}$$

and using the fact that $dN/dE_\gamma = 2/E_\pi$ for $\pi^0 \to 2\gamma$, Eq. (14) can be written as

$$\frac{dN}{dE_\gamma} = \int_{E_\gamma}^{\infty} \frac{dN_\gamma}{dE_\gamma}(E_\gamma, E_\pi)\, C_p E_\pi^{-(\gamma+1)} \int_0^1 F_{N\to\pi_0} x^{\gamma-1}\, dx \tag{16}$$

$$= C_p Z_{N\to\pi^0} \int_{E_\gamma}^{\infty} \frac{2}{E_\pi} E_\pi^{-(\gamma+1)}\, dE_\pi \tag{17}$$

$$= C_p Z_{N\to\pi^0} \frac{2}{\gamma+1} E_\gamma^{-(\gamma+1)} . \tag{18}$$

Hence, $Z_{\pi^0\to\gamma} = 2/(\gamma+1)$ is 1 for a spectral index γ of 1 and:

$$C_p = C_\gamma / Z_{N\to\pi^0} . \tag{19}$$

The upper limit on the proton luminosity at the source may be set at

$$L_p \le K \int_{E_{\rm thr}}^{E_{\rm cut}} E\, E^{-(\gamma+1)}\, dE\, 4\pi d^2 / (Z_{N\to\pi^0} Z_{\pi^0\to\gamma}) . \tag{20}$$

The value for $Z_{N\to\pi^0}$ is approximately 0.1 for a spectral index of 1 [19]. The attenuation in the cosmic microwave background has been accounted for in the calculation of the upper limits on the photon flux, which are given in Figs. 3–6 together with several observations from other groups.

B. Overview of dc search results

The dc search was conducted to look for an excess of events in bins centered on the nine candidate sources, averaged over the observing period. The average of the counts in the eight adjacent bins is used to estimate the background. No significant dc excess was detected from any of the nine candidate sources. The highest count excess, corresponding to 2.5σ, was observed from the direction of BL-1 in the 1988 database. Results averaged over the whole 3-yr data set are given in Table II.

We will now discuss the observations at other wavelengths for each source separately and compare the results of other very high energy (VHE) and ultrahigh energy (UHE) experiments with the SPASE upper limits.

TABLE II. Results for the combined dc search in 1988, 1990, 1991. All σ values are defined according to Li and Ma. Upper limits at 95% C.L. for the combined dc search in 1988, 1990, 1991. The flux upper limits $dI/d(\ln E)$ and $I(> E_{\rm thr})$ are given in $10^{-13}\,{\rm cm}^{-2}\,{\rm s}^{-1}$. $E_{\rm med}$ is the median energy of photon showers from the direction and assumed distance of the potential source that trigger the array. A differential spectral index of 2 is assumed in extrapolating away from $E = E_{\rm med}$. L_p is an estimate of the power in accelerated ions at the source that would be required to produce a signal at the quoted upper limit.

Source	On source	Off source	σ	$E_{\rm med}$ (TeV)	$dI/d(\ln E)$ at $E_{\rm med}$	$E_{\rm thr}$ (TeV)	I ($> E_{\rm thr}$)	L_p (10^{38} erg/s)
SMC X-1	67367	67558	-0.7	85	1.26	50	2.0	8.5
LMC X-4	53463	53328	0.5	98	1.10	50	2.0	5.1
Cen X-3	39528	39631	-0.5	120	0.85	50	2.1	1.9×10^{-1}
Vela X-1	4132	4173	-0.6	500	0.25	200	0.6	4.4×10^{-3}
BL-1	44596	44456	0.6	120	0.85	50	2.0	
4U1626-67	55481	55777	-1.2	110	0.83	50	2.0	3.5×10^{-2}
4U1145-61	43399	43489	-0.4	127	0.71	50	2.0	3.9×10^{-3}
SN 1987A	60007	60062	-0.4	93	1.13	50	2.0	5.0
47 Tuc	64451	64630	-0.7	104	0.89	50	2.0	3.6×10^{-2}

C. SMC X-1

X rays from the Small Magellanic Cloud were first observed by an x-ray detector carried by a Thor missile launched in 1970 [20]. Since the spatial resolution of the instrument was 1°, the SMC appeared as one single extended source. SMC X-1 was identified first by the Uhuru satellite taking data from 1971 to 1973 in the 2–6 keV range. Schreier *et al.* [21] measured the 3.89 day binary period of the object using the Uhuru data. X-ray pulsations in the 1.6–10 keV range were discovered in data

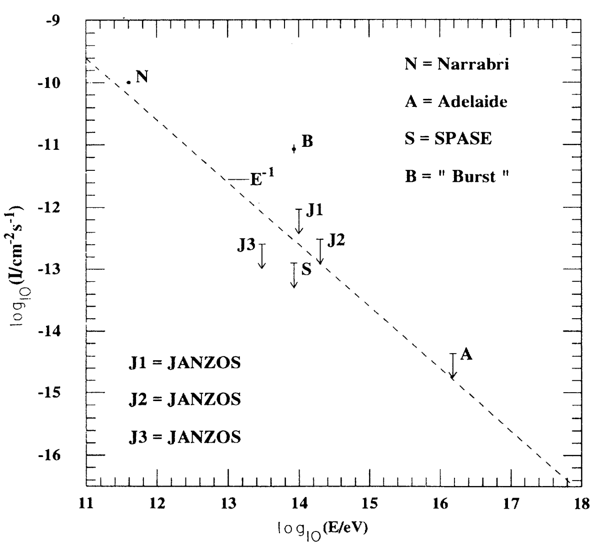

FIG. 3. Detections and upper limits for SMC X-1. Label "B" indicates a 5.3σ burst observed by SPASE in 1991, discussed later. The dashed line represents an E^{-1} integral spectrum.

taken with an Aerobee rocket launched in 1973, and during the Apollo-Soyuz mission two years later. Lucke *et al.* [22] measured a pulsar period of 0.7157 s. Several satellites, including Ginga, have since detected the x-ray pulsations.

At VHE energies the Durham group were the first and so far the only group to detect γ rays from SMC X-1 [23]. Pulsed emission was detected during all of the 11 observation periods each of which was made over $\sim$ 10 days. The time averaged signal strength was 1.8% of the cosmic-ray background of the telescope, which corresponds to a flux of $9.5\times10^{-11}\,{\rm cm}^{-2}\,{\rm s}^{-1}$ above 400 GeV. The derived γ-ray luminosity was $7.5\times10^{37}\,{\rm erg\,s}^{-1}$ [24] and the chance probability of obtaining the result was estimated as 3×10^{-5}. The flux estimate has been plotted in Fig. 3 and is indicated by the label "N."

Only upper limits for SMC X-1 have been reported at UHE energies so far. Protheroe and Clay [1] from the Adelaide group, using data taken with the Buckland Park air shower array in Australia, report an upper limit of $4.4\times10^{-15}\,{\rm cm}^{-2}\,{\rm s}^{-1}$ for energies exceeding 1.5×10^{16} eV (label "A" in Fig. 3).

The JANZOS group [25] presented a flux limit of $9.4\times10^{-13}\,{\rm cm}^{-2}\,{\rm s}^{-1}$ for air shower data taken from October 1987 to March 1989 above 100 TeV (labeled "$J1$"). Using different analysis techniques and including their most recent data [26] they obtain a slightly different result at a median energy of 200 TeV (labeled "$J2$"). The third JANZOS result ("$J3$") was not obtained with the air shower array at Black Birch, but with the Air Čerenkov facility operated at a low elevation. Their quoted upper limit above 30 TeV is $2.4\times10^{-13}\,{\rm cm}^{-2}\,{\rm s}^{-1}$ [27].

Also incorporated in Fig. 3 is the possible detection of a 24 h burst of γ-ray emission from SMC X-1 by the SPASE array on 17 October 1991, which will be discussed later.

D. LMC X-4

The discovery of x rays from the Large Magellanic Cloud by the same missile-borne x-ray instrument [20] that detected the first x rays from the SMC was followed by the identification of LMC X-4 as an x-ray point source by the Uhuru satellite [28]. The binary system is believed to consist of a neutron star accreting matter from its massive companion.

The first detection of ultrahigh energy γ radiation from LMC X-4 was reported by Protheroe and Clay [1] using data taken with the Buckland Park air shower array between 1979 and 1981. The detection at 99.1% confidence level resulted in a derived integral flux of γ rays above 10^{16} eV from LMC X-4 of $(4.6 \pm 1.7) \times 10^{-15}$ cm^{-2} s^{-1}. Figure 4 shows this result, indicated by label "A," along with various upper limits. The γ rays detected by the Adelaide group were modulated with the orbital period of 1.4 days, the maximum emission occurring between phases 0.9 and 0.95. However, no excess was seen between phases 0 and 0.05. It was discovered sometime later that the assignment of the Julian date in the Buckland Park data set was in error by 1 day [29]. This does not change the shape of the phasogram, but it does displace the light curve, resulting in a single peak at phase 0.17.

Recently [29] evidence was found in the SUGAR (Sydney University Giant Air-Shower Recorder) data set, comprising the period 1968–1979, for a signal from LMC X-4 above 2×10^{17} eV, modulated by the orbital period (99.6% C.L.). The SUGAR array was located at sea level in Australia and had an area of 70 km^2, giving it a threshold of 1.8×10^{17} eV. Since the detectors were buried, the telescope was only sensitive to the penetrating muon component of extensive air showers. The flux estimate is $(5.2 \pm 1.5) \times 10^{-16}$ cm^{-2} s^{-1}, and the derived proton luminosity above 10^{17} eV is 10^{38} erg s^{-1}, which would make LMC X-4 the most luminous object reported at these energies. The observed excess was confined to orbital phase bands 0.1–0.2 and 0.6–0.7, consistent with the earlier Buckland Park result.

The JANZOS Collaboration, using the low transit Čerenkov facility during May–July 1988 and May–June 1990, give an upper limit of 3.5×10^{-13} cm^{-2} s^{-1} at energies > 140 TeV for LMC X-4 [27].

At VHE energies the Durham [23] group have reported pulsed emission above 400 GeV during January and February of 1987 with a continuous flux of 1.4×10^{-10} cm^{-2} s^{-1} and a peak flux of 2.0×10^{-10} cm^{-2} s^{-1} between orbital phases 0.5 and 0.7. The chance probability of the observation was 2.2×10^{-4}. Later measurements (1987–1989) at Narrabri failed to yield a definite result, and, consequently, they give a time-averaged flux limit of 4.4×10^{-11} cm^{-2} s^{-1} above 400 GeV.

E. Centaurus X-3

Cen X-3 was discovered in May of 1967 in an experiment involving rocket-borne proportional counters [30]. Soon after, the Uhuru mission detected periodic x-ray pulsations with a period of 4.8 s from Cen X-3 [31]. The orbital period was shown to be 2.08 days [32].

The first detection at TeV energies was made by the Durham group with their Čerenkov telescope in Narrabri [33]. The data were taken between January 1987 and January 1988. γ rays modulated with the pulsar period were detected at a significance of 2×10^{-5} after accounting for all the trials. The excess was confined to an orbital phase interval between 0.7 and 0.8, with an estimated peak flux of 3.0×10^{-10} cm^{-2} s^{-1} and an average flux of 1.0×10^{-10} cm^{-2} s^{-1} for energies above 250 GeV. This result is indicated by label "N" in Fig. 5.

This result was subsequently confirmed by the Potchef-

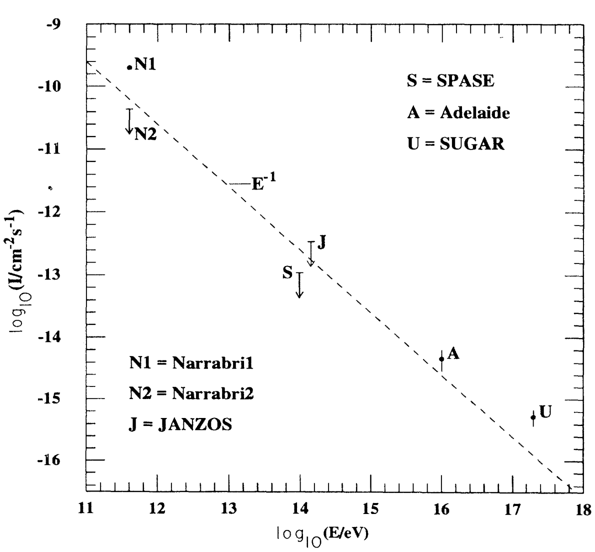

FIG. 4. Detections and upper limits for LMC X-4. The dashed line represents an E^{-1} integral spectrum.

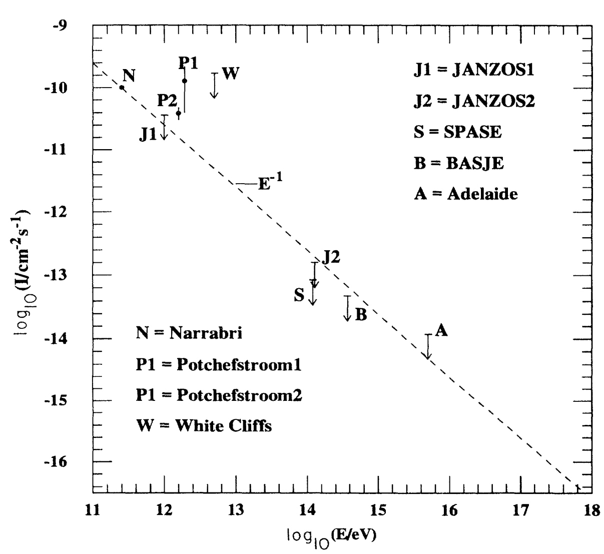

FIG. 5. Detections and upper limits for Cen X-3. The dashed line represents an E^{-1} integral spectrum.

stroom group in South Africa using their Nooitgedacht TeV γ-ray telescope [3]. The reported average flux above 1.9 TeV, derived from 71 h of data taken between May 1986 and April 1989, was $(1.3 \pm 0.9) \times 10^{-10}$ cm^{-2} s^{-1} (label "$P1$"). Here, too, pulsed emission occurred only in the 0.7–0.8 band.

In two later papers [34,35] both groups presented additional evidence for the existence of pulsed γ rays from Cen X-3, still only detectable between phases 0.7 and 0.8. The average flux given by the Durham group for 200 h observation between January 1987 and June 1989 is 10^{-10} cm^{-2} s^{-1}, the maximum flux ($0.7 < \phi_0 < 0.8$) being a factor of 6 larger. The data taken with the Nooitgedacht telescope between 1986 and 1990 revealed the presence (98% C.L.) of pulsed γ rays during the orbital phase interval from 0.52 to 0.76, the time-averaged flux being $(3.9 \pm 0.9) \times 10^{-11}$ cm^{-2} s^{-1} (labeled "$P2$"). The Potchefstroom group notes that the phase interval in which emission occurs coincides with the position of an accretion wake observed in the x-ray energy region [36]. This wake appears to have a favorable column density to act as a target for high energy collisions and subsequent TeV γ-ray production from pion decay without reabsorbing the photons.

The γ rays detected by these experiments are modulated with periods that are somewhat in contradiction with the small value of $\dot{P}_r$ demonstrated by contemporary x-ray measurements [14,24]. More affirmative observations at TeV energies are required to draw definitive conclusions.

Other observations at TeV energies have yielded negative results. The air Čerenkov telescope at White Cliffs, Australia, failed to detect an excess from the direction of Cen X-3 in the period March–April 1986 [37]. An upper bound on the γ-ray flux (labeled "W") above 5 TeV was set at 0.17×10^{-9} cm^{-2} s^{-1}. The JANZOS group observed Cen X-3 in April of 1988 with the Čerenkov telescope at Black Birch [25], also with a negative outcome. They give a flux limit above 1 TeV of 3.6×10^{-11}cm^{-2} s^{-1} (label "$J1$").

Only upper limits have been reported at UHE energies. Apart from SPASE, the Adelaide group at Buckland Park [1] and JANZOS [26] have failed to detect γ rays from Cen X-3. The reported 95% C.L. upper limits are 1.2×10^{-14} cm^{-2} s^{-1} above 5 PeV, and 1.6×10^{-13} cm^{-2} s^{-1} at a median energy of 130 TeV, respectively (labels "A" and "$J2$"). The Bolivia Air Shower Joint Experiment (BASJE), using data taken from September 1987 to December 1990, report an upper bound (label "B") on the flux above 372 TeV of 4.8×10^{-14} cm^{-2} s^{-1} after selection of muon-poor showers [38].

F. Vela X-1

A rocket-borne x-ray monitor discovered Vela X-1 in September of 1966 [39], and its presence was confirmed by three more rocket experiments during the late 1960s. Its position was determined to 0.1° accuracy with the first Uhuru observations [28]. Further observations with the Uhuru satellite revealed an 8.96 day periodicity in the x-ray intensity [40]. Subsequent observations with SAS-3 unveiled the 283 s pulse period of the compact companion [41], which is most likely an accreting neutron star. The stable pulsations rule out a black hole, and the high x-ray luminosity does not allow for a white dwarf [42].

Vela X-1 was discovered in the TeV energy range by the Potchefstroom group in their data set covering 11 nights during 1986 [43]. The signal was modulated by a period of 282.205 s, somewhat below the x-ray measurements of that epoch. The significance of the result was 5×10^{-4} with a deduced time-averaged flux of $(2.0 \pm 0.4) \times 10^{-11}$ cm^{-2} s^{-1} at energies above 2 TeV. The same observations showed an enhancement of the pulsed signal during x-ray eclipse, which was attributed to the interaction of the charged particle beam with the limb of the companion star. The deduced flux during eclipse was 1.6×10^{-10} cm^{-2} s^{-1} with a probability of arising by chance of 1.1×10^{-5}.

Further observations with the Nooitgedacht telescope during 1987 established Vela X-1 as a persistent emitter of TeV γ rays [44]. Pulsed emission was observed at 97.7% C.L. with a period of 283.14 s, in good agreement with contemporary x-ray measurements. A slight enhancement continued to be detected during eclipse at the 98.7% confidence level. The time-averaged γ-ray flux above 3 TeV was deduced to be $(1.5 \pm 0.4) \times 10^{-11}$ cm^{-2} s^{-1}.

Independent confirmation for emission above 10^{11} eV from Vela X-1 came from the Durham group at the Narrabri site, who detected γ rays modulated with the pulsar period in their 1986–1988 data set [45]. The derived pulse periods for 1987 and 1988 were (283.14 ± 0.02) s and (283.09 ± 0.02) s, respectively. The significance of the Durham result, after accounting for degrees of freedom, was 1.1×10^{-4}. No evidence for a preferred orbital phase of emission was seen, in contrast with the Potchefstroom group. The deduced flux of γ radiation in excess of 300 GeV was $(7.4 \pm 1.5) \times 10^{-11}$ cm^{-2} s^{-1}.

Including their latest data (up to 1990), the Potchefstroom group found Vela X-1 to emit at the expected x-ray period, as determined by Ginga and Mir-Kvant observations, throughout its orbit (including x-ray eclipse) at a significance level of 4.7σ [46]. The flux above 1 TeV was deduced to be $(6.6 \pm 1.5) \times 10^{-11}$ cm^{-2} s^{-1}.

The latest detection of TeV γ rays was reported by the Durham group using data taken in February of 1991 [47]. Weak continuous pulsed emission, consistent with earlier observations by the same group, was observed with a signal strength of 1.8% of the cosmic-ray background and a chance probability of 0.06. In addition, two episodes of enhanced signal strength (15.7%) were seen at exactly the same orbital phase of 0.68 for a duration of 1800 s. The probability of this effect arising by chance was estimated to be 2×10^{-5}. The observed pulsar period was 283.4 ± 0.1 s.

Other groups working at energies around 10^{12} eV did not find evidence for γ-ray emission (see Table III).

Vela X-1 was discovered in the UHE energy range by the Adelaide group in data taken with the Buckland Park air shower facility from 1979 to 1981 [2]. Following the Kiel observation of Cygnus X-3, air showers with an age

TABLE III. Upper limits (95 % C.L.) reported for Vela X-1. The quoted upper limits for the SYS and SAS telescopes are derived from muon-depleted showers.

Group	Exposure	E_{thr}	$I(>E_{\mathrm{thr}})$ ($\mathrm{cm^{-2}\,s^{-1}}$)	Reference
White Cliffs	11/86–01/87	5 TeV	2.1×10^{-11}	[37]
JANZOS	01/88–03/88 03/89–04/89	1 TeV	2.7×10^{-11}	[25]
Woomera	01/91–08/91	600 GeV	7.5×10^{-11}	[50]
SUGAR	1968–1979	200 PeV	1.5×10^{-16}	[29]
BASJE (SAS)	09/87–12/90	237 TeV	6.5×10^{-14}	[38]
Chacaltaya (SYS)	02/86–07/90	87 TeV	9.4×10^{-13}	[51]
JANZOS	10/87–01/91	100 TeV	3.8×10^{-13}	[26]

parameter greater than 1.3 were selected in an attempt to enhance the γ-ray signal. A significant excess was found at orbital phase 0.63, the chance probability being $\sim 10^{-4}$. Attributing this observed excess to γ rays allowed a flux of $(9.3\pm3.4)\times10^{-15}\ \mathrm{cm^{-2}\,s^{-1}}$ to be calculated at a median energy of 3×10^{15} eV. After correcting for the error made in the assignment of the Julian day number, Meyhandan *et al.* [29] showed that the excess in the phasogram is located in an orbital phase band from 0.5 to 0.54.

This latter value is in agreement with the weak detection of a UHE signal from Vela X-1 by the BASJE Collaboration upon reanalyzing Chacaltaya data recorded from 1964 to 1967 [48]. A slight correlation with the orbital period at a phase of 0.51 was found at the 94% confidence level. A flux estimate of $(1.6\pm0.8)\times10^{-13}\ \mathrm{cm^{-2}\,s^{-1}}$ above 1.1×10^{14} eV was given.

The Potchefstroom group, using data collected between 1979 and 1981, also detected an UHE γ-ray signal from Vela X-1 [49]. After folding the data with the orbital period, a clear enhancement (95% C.L.) is seen at phase 0.13 ± 0.02, in contradiction with the preferred emission phase seen by the Adelaide and BASJE groups. The γ-ray flux at an energy of 2 PeV is estimated to be $(9.6\pm5.4)\times10^{-14}\ \mathrm{cm^{-2}\,s^{-1}}$ (see also Ref. [42]).

No further detections of UHE γ-ray emission from Vela X-1 have been reported, although several groups have presented upper limits on the γ-ray flux (see Table III).

The flux estimates and upper limits are plotted in Fig. 6. The dashed line in Fig. 6 shows an E^{-1} integral spectrum normalized to the JANZOS upper limit for 1 TeV emission [25]. The BASJE and SPASE upper limits are marginally inconsistent with the earlier result (labeled "A") of Protheroe *et al.* [2].

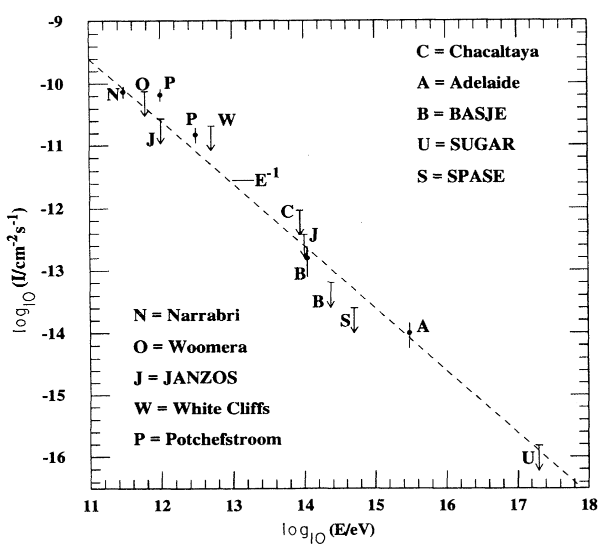

FIG. 6. Detections and upper limits for Vela X-1. The dashed line represents an E^{-1} integral spectrum normalized to the JANZOS upper limit for 1 TeV emission.

G. BL-1

In a preliminary general sky search applied to SPASE data taken between April and October 1988, a 4.9σ excess was detected at a declination $-62.5°$ and right ascension $174.5°$. The probability of this occurring by chance is 0.17% after accounting for the number of trials [6]. BL-1 (Bartol Leeds 1) was the working name adopted for the tentative source. Following this result, the BL-1 sky bin was added to the list of potential sources, together with the two close x-ray binary systems 4U1145-61 and 4U1626-67. The analysis was repeated with more recently measured system delays, which reduced the excess for the 1988 data set to 2.5σ.

A tentative positive detection of BL-1 at the 3.4σ level was found in the air shower data set of the JANZOS group [25], spanning a period from October 1987 to March 1989. The position that was found to contain the highest excess had declination $-62.3°$ and right ascension $174.3°$, i.e., $12'$ away from the original position. The derived γ-ray flux above 100 TeV was $(6.3\pm1.8)\times10^{-13}\ \mathrm{cm^{-2}\,s^{-1}}$, consistent with the original SPASE result. However, in a more recent publication [27] an all-sky search in the 1987–1991 data set failed to show any excess of more than 3σ, including the suspected position of BL-1.

Since the SPASE data set also fails to present any evidence for a dc or sporadic signal from BL-1 in any of the three years of observation, the evidence for a discovery of a new UHE γ-ray emitter becomes very weak.

H. 4U1626-67

The low-mass x-ray binary 4U1626-67 was discovered in the 2–6 keV range during the 1971–1973 Uhuru mission [52]. Rappaport *et al.* [53] discovered x-ray pulsations with a period of 7.68 s in the SAS-3 data taken in March and April of 1977.

The optical counterpart is Kz TrA [54], a faint blue star with $V \simeq 18.5$. Optical pulsations at the 7.68 s pulsar period were discovered by Ilovaisky, Motch, and Chevalier [55]. Observations made by Middleditch *et al.* [56] with the 4 m Cerro Tololo Observatory (CTIO) telescope in 1979 subsequently revealed the presence of two optical pulse periods, one at the frequency of the x-ray pulsations, the other downshifted by ~0.4 mHz. This was attributed to reprocessing of x radiation near the surface of the optical star. The shifted frequencies allowed an estimate of the orbital period, which was calculated to be either 2491 or 2492 s. Later observations [57] yield a value of 2485 s for the binary period, the shortest one known for an x-ray binary.

Apart from SPASE, the only group to observe 4U1626-67 at energies exceeding 10^{11} eV is Durham University with the Mark III Čerenkov telescope in Narrabri [58]. Their longest continuous observation of 9 h on 1 June 1987 shows some evidence for pulsed emission with a period of 7.6648 s, the probability of the effect arising by chance being 1.4×10^{-3}. However, subsequent observations during 1987–1990 fail to reveal a signal [59] and an upper limit on the γ-ray flux above 400 GeV is set at 7.6×10^{-11} cm^{-2} s^{-1}.

I. 4U1145-61

The x-ray binary system 4U1145-61 was first detected by a rocket-borne x-ray monitor on 13 May 1970. The source was included in the Uhuru catalog [28] after subsequent observations with this satellite. Observations with the Ariel-V satellite [60] and the Einstein observatory [61] revealed pulsations with a period of 292 s. Warwick, Watson, and Willingale [62] discovered a 186.5 day outburst cycle in the x-ray data from EXOSAT observations during 1983 and 1984. The change in the pulsar period is consistent with a binary system in a highly eccentric orbit ($e > 0.6$) of 186.5 days. The system is most likely a neutron star moving through an extended circumstellar envelope at a shallow angle ($< 10°$) in a highly eccentric orbit of 186.5 days [63].

The sole detection of γ rays from this source at VHE energies was made by the Durham group at the Narrabri site in April of 1987 [58]. The reported flux above 400 GeV was $(1.4 \pm 0.1) \times 10^{-10}$ cm^{-2} s^{-1} with the chance probability being 1.5×10^{-4}. The signal was modulated with a period of 292.4 ± 0.5 s and occurred exactly 4.5 cycles after the x-ray burst. The measured pulse period was changing rapidly at a rate of $\dot{P} = 1.9 \times 10^{-7}$ s $^{-1}$, which is equal in magnitude but opposite in sign to the period derivative measured in the x-ray data on the opposite side of the 186.5 day orbit. Since no evidence for a signal was seen at any other day, the Durham group conclude that VHE γ-ray emission appears to occur only during apastron (see also Ref. [24]). The time-averaged flux limit based on observations from 1987 to 1989 by the

TABLE IV. Upper limits (95 % C.L.) reported for SN 1987A. L_p refers to the proton luminosity at the source. The flux upper limit $I(> E_{\rm thr})$ is given in cm^{-2} s^{-1}. The JANZOS detection of a TeV γ-ray burst is given as the first entry in the table. The SPASE data set excludes the 1989 season.

Group	Exposure	$E_{\rm thr}$ (TeV)	I $(> E_{\rm thr})$	$L_{\rm p}$ (erg s^{-1})	Reference
JANZOS (detection)	(14–15) 01/88	3	1.9×10^{-11}	2×10^{39}	[65]
Adelaide	02/87–08/87	100	1.3×10^{-11}	10^{41}	[64]
JANZOS	12/87–01/88	3	6.1×10^{-12}	5×10^{38}	[65]
JANZOS	05/88–07/88 05/90–06/90	65	3.8×10^{-13}	8×10^{37}	[27]
JANZOS	10/87–01/91	190	1.3×10^{-13}	$\sim 10^{38}$	[26]
BASJE	01/88–05/90	100	2.3×10^{-13}	8×10^{38}	[69]
SPASE	01/88–02/88	93	0.9×10^{-12}	3×10^{39}	[18]
SPASE	03/88–10/91	93	1.1×10^{-13}	5×10^{38}	
Durham	01/88–02/88	0.4	1.6×10^{-10}	2×10^{39}	[70]
Durham	03/88–04/88	0.4	3.4×10^{-10}	4×10^{39}	[70]
Durham	1987–1991	0.4	2.8×10^{-10}	3×10^{39}	[59]
Potchef.	11/87	1	2.3×10^{-11}	10^{39}	[71]

same group was set at 5.4×10^{-11} cm^{-2} s^{-1} for energies exceeding 400 GeV [59].

At UHE energies the JANZOS collaboration, using air shower data from 1987 to 1991, recently reported an upper limit for 4U1145-61 of 0.56×10^{-13} cm^{-2}s^{-1} for γ-ray emission at a median energy of 130 TeV [26].

J. SN 1987A

At the time of the supernova explosion the Buckland Park Air shower array was the only facility in the Southern hemisphere capable of detecting UHE γ rays from SN 1987A. After 6 months of observing, no evidence was seen in the data for a signal, and an upper limit on the γ-ray flux in excess of 10^{14} eV was set at 1.3×10^{-11} cm^{-2} s^{-1} [64]. The corresponding limit on the proton luminosity at the source was estimated to be 10^{41} erg s^{-1}.

The only detection of γ rays with energy above 10^{11} eV was reported by the JANZOS group using their Čerenkov telescope [65]. The total observation period, lasting from December 1987 to January 1988, showed no overall dc excess. However, data obtained on January 14 and 15 were found to have a 3.9σ excess of counts, the corresponding chance probability being 1.6×10^{-3}. Calculation of the flux above 3 TeV yielded a value of $(1.9 \pm 0.5) \times 10^{-11}$ cm^{-2} s^{-1} and a proton source luminosity of 2×10^{39} erg s^{-1}. The TeV γ-ray burst seen by JANZOS was coincident with a 20 day x-ray outburst observed by the Ginga satellite [66]. Two possible models have been presented to explain the TeV burst which occurred 11 months after the supernova became visible [67,68]. The SPASE telescope was not operational at the time of the burst.

No further VHE or UHE γ rays from SN 1987A have been detected. Table IV gives an overview of most of the reported flux and luminosity limits, together with the detection by JANZOS.

K. 47 Tucanae

The globular cluster 47 Tuc (=NGC 104) is the second brightest object of this type, after Omega Centauri. Its apparent brightness is 4.03, at a distance of 4.6 kpc, which translates into an absolute visual magnitude of $M_v = -9.43$ [72]. Its age is estimated to be 13 Gyr. The entire cluster is treated as a single candidate source for UHE γ rays, since the apparent diameter of 30.9 arc min makes it impossible to resolve any individual sources with the SPASE telescope.

The first luminous x-ray sources in globular clusters were discovered by the Uhuru satellite [73]. The 47 Tuc cluster was not discovered as an x-ray source until 1979, however, when the Einstein observatory detected x rays from the direction of the cluster [74].

In 1988 two millisecond pulsars in binary systems were discovered in 47 Tuc by a group using the Parkes radio telescope in Australia [75]. The periods of the two pulsars, designated 0021-72A, and 0021-72B, were measured to be 4.5 ms and 6.1 ms, respectively. The observations of 0021-72A were consistent with a binary system containing a $1.4M_\odot$ neutron star and a white dwarf companion with mass $0.8M_\odot$. The orbit of the 0021-72A system has a period of 32 min, and an eccentricity of 0.32. The second pulsar orbits around its companion in 7.95 days.

Shortly after, a group using the same telescope discovered a third millisecond pulsar (0021-72C) in the cluster with a period of 5.75 ms [76]. The pulsating star is a so-called isolated pulsar; i.e., it is not part of a binary system.

After the discovery of millisecond pulsars in 47 Tuc, the Einstein data unveiled periodic pulsations in the x-ray source located in the core of the cluster. X-ray variability was shown to be present at time scales of days, hours, and minutes, in addition to transient periodic pulsations at 120 and 4.6 s [77]. These features suggest the existence of a cataclysmic variable, designated X0021.8-7221, in the center of the globular cluster.

The Potchefstroom group have detected TeV γ rays from the central source X0021.8-7221, modulated with the 120 s period [78]. The data were recorded between July and September 1989, and the chance probability was reported to be 1.3×10^{-4}. Also at VHE energies, observations of 47 Tuc have been reported by the Durham group who have tracked the four objects in the cluster described above with their Čerenkov telescope located in Narrabri, Australia [59]. They report an upper limit to the flux above 450 GeV of 4.4×10^{-11} cm^{-2} s^{-1} for data taken from 1988 to 1990.

VII. SEARCH FOR SPORADIC EMISSION

A burst search was conducted for each of the nine potential sources on time scales of 1 h, 1 day, and 1 week.

A cumulative sum (CUSUM) method [79] was adopted to test for sporadic emission on a time scale of 1 h. The technique essentially looks for a sharp rise in the cumulative sum of on-source counts minus off-source counts. No conclusive evidence for any burst activity at the level of 1 h was found.

As an example, Fig. 7 shows the hourly cumulative excess in raw counts for BL-1 in 1988. The development of the hourly cumulative sum to the final value 2.5σ is very gradual. Therefore no burst activity was detected with the CUSUM method.

In the case of daily and weekly time intervals, the complete data set is divided into sliding time intervals of 1 day or 1 week. The window moves by a factor of 10% (i.e., 2.4 h for 1 day window and 16.8 h for a 1 week window). As usual, the on-source count in one window is compared to the mean off-source counts, obtained from the adjacent bins in the same declination band. The difference is expressed in terms of standard deviations $S = (N_{\rm on} - B)/\sqrt{B}$, where $N_{\rm on}$ is the on-source count accumulated during the 1 day (or 1 week) interval, and B is the average number of background events in the same time period.

Because the values of S in neighboring time windows are not independent, we cannot use the raw number of

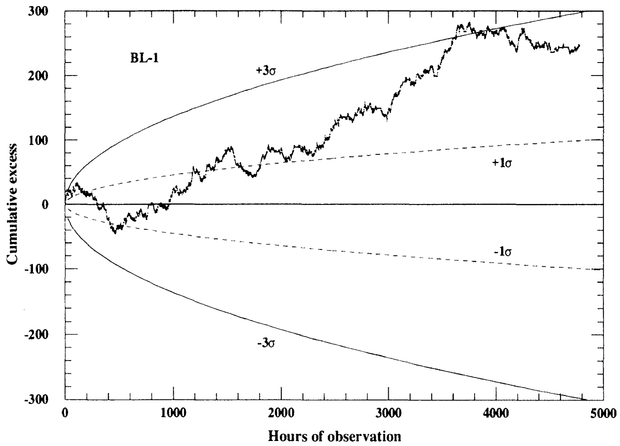

FIG. 7. Hourly cumulative excess for BL-1 from 3 April 1988 to 19 October 1988. The levels for $\pm 3\sigma$ and $\pm 1\sigma$ emissions are indicated.

TABLE VI. Weekly burst search. The same conventions as in Table V are used.

Source	1988		1990		1991	
	$S_{\max}/\sigma$	P	$S_{\max}/\sigma$	P	$S_{\max}/\sigma$	P
SMC X-1	2.1	1.00	2.6	1.00	3.6	0.62
LMC X-4	2.6	1.00	3.3	0.93	2.4	1.00
Cen X-3	2.9	1.00	2.3	1.00	2.7	1.00
Vela X-1	2.2	1.00	3.7	0.50	3.3	0.93
BL-1	4.0	0.20	2.8	1.00	2.8	1.00
4U1626-67	2.6	1.00	2.7	1.00	3.2	0.98
4U1145-61	3.2	0.98	3.0	1.00	3.1	0.99
SN 1987A	3.0	1.00	2.4	1.00	2.7	1.00
47 Tuc	2.7	1.00	3.6	0.62	2.2	1.00

windows when determining the probability of a chance occurrence. The effective number of windows is less than the total number of intervals, reducing the trial penalty. We calculated the effective number of windows, $n_{\rm eff}$, as a function of the size of the deviation using a Monte Carlo approach. The chance probability is given by

$$P = 1 - (1 - \mathrm{q})^{(9 \times n_{\rm eff})}, \tag{21}$$

where q is the single trial probability of obtaining a certain deviation, $n_{\rm eff}$ is the effective number of windows as determined with simulations, and the factor 9 accounts for the number of sources. The results for daily and weekly intervals are given in Tables V and VI. The columns labeled $S_{\max}$ and P give the highest excesses and their chance probabilities, respectively. No significant bursts are observed on the weekly time scale.

TABLE V. Daily burst search. $S_{\max}$ is the maximum excess in terms of standard deviations detected in each data set. P is the probability of obtaining this excess by chance, after accounting for all degrees of freedom, i.e., the number of time windows and the 27 data sets.

Source	1988		1990		1991	
	$S_{\max}/\sigma$	P	$S_{\max}/\sigma$	P	$S_{\max}/\sigma$	P
SMC X-1	4.0	0.80	4.0	0.80	5.3	0.004
LMC X-4	3.8	0.97	3.3	1.00	3.8	0.97
Cen X-3	4.2	0.51	4.6	0.12	3.0	1.00
Vela X-1	3.8	0.97	4.0	0.80	4.3	0.37
BL-1	4.2	0.51	4.1	0.66	4.1	0.66
4U1626-67	3.3	1.00	4.1	0.66	3.9	0.90
4U1145-61	4.7	0.07	3.4	1.00	5.1	0.01
SN 1987A	4.1	0.66	4.3	0.37	3.8	0.97
47 Tuc	3.8	0.97	4.3	0.37	3.3	1.00

A 5.3σ burst from the direction of SMC X-1 was observed during 1 day in 1991 (17-10-1991, 04:39 GMT to 18-10-1991, 04:39 GMT). The effective number of trials consisting of 1 day periods is 8200 (approximately 820 days of observation times 10). The chance probability is then 4.8×10^{-4}. This number has to be corrected for the fact that we have observed nine sources. The final chance probability becomes 0.4%. The number of on-source events during that particular day is 178, while 120 events constitute the background. This corresponds to an integral flux above 50 TeV of $(1.3 \pm 0.2) \times 10^{-11}\ \mathrm{cm^{-2}\,s^{-1}}$ or, alternatively, $dI/d(\ln E) = (8.6 \pm 1.2) \times 10^{-12}\ \mathrm{cm^{-2}\,s^{-1}}$ at the median energy of 85 TeV. We estimate that the proton luminosity at the source during the burst would have to be $(5.8 \pm 0.8) \times 10^{40}$ erg/s if the burst is produced by collisions of accelerated protons at or near SMC X-1. Figure 3 compares various upper limits obtained for steady emission from SMC X-1 with the derived flux during the burst. The orbital phases corresponding to the start time and end time of the "burst" are 0.18 and 0.44, i.e., during part of the first half of the orbit after coming out of eclipse. The 178 events arriving from the direction of SMC X-1 were searched for pulsed emission. In addition to solar center barycentering, the event arrival times were also adjusted to the focus of the binary orbit to correct for the motion of the x-ray pulsar. No evidence for a periodic signal was found. The Protheroe and Rayleigh tests were performed, but failed to yield evidence for emission modulated with the pulsar period: The Rayleigh power has a value of 1.53 with an associated chance probability of 0.47, while the Protheroe statistic has a value of 8.84 with a chance probability of 0.89.

VIII. SEARCH FOR PERIODIC EMISSION

Four sources were investigated for periodic emission: SMC X-1, LMC X-4, Cen X-3, and Vela X-1. Only orbital periods were searched. The search strategy consisted of applying the Rayleigh, Protheroe [80], and H test [81] for circular data to all four candidates for each year separately. The search was not restricted to the reported x-ray frequency, but was extended to periods differing by at least one independent Fourier spacing (IFS) and up to 1% from the central period P_0. The comparatively long orbital period of Vela X-1 (8.96 days) causes the size of the IFS to be relatively large. In 1991, for example, the SPASE telescope was operational for 297 days, leading to an IFS of $P_0^2/T = 0.27$ days or 3% of the orbital period. So, for all practical purposes, the search strategy meant that Vela X-1 was investigated up to one IFS from the central period and the three other sources up to 1%. The search was not only conducted at the exact $P_0 \pm n \times$ IFS, but also at periods within one IFS:

$$P_{\text{trial}} = P_0 \pm 0.1\,n \times \text{IFS} \ . \tag{22}$$

The number of periods examined is given for each year and source in Table VII. The total number of trial periods used in the period search is then 360, while the total number of IFS's spanned is approximately 44.

Both the off time of the SPASE array and the azimuthal distribution of air showers may cause an artificially high value of any of the test statistics. Protheroe [29,82] has developed a method to account for this effect by reassigning the phases according to

$$\phi' = \int_0^{\phi} p(\phi_b)\, d\phi_b \ , \tag{23}$$

where ϕ is the recorded on-source phase, ϕ' is the corrected phase, and $p(\phi_b)$ is the probability distribution of background phases. By "projecting" the set of on-source phases on the cumulative off-source distribution one obtains a set of new phases that are unbiased by off-time or azimuthal variations. This set can be tested for periodic emission.

However, for our application Protheroe's method only worked for the Rayleigh test, and *not* for the Protheroe and H tests. The reason is that the distribution $p(\phi_b)$, which obviously contains a finite number of phases, is discrete. The reassignment procedure will squeeze many of the phases slightly together. This will cause numerous minispikes in the new set of phases and consequently a very high value of the Protheroe statistic, and a very strong high order harmonic which blows up the H test statistic. In other words, the Protheroe statistic and the H test statistic are sensitive to a round-off error caused by the finite number of background phases. To account for nonuniform exposure in these last two cases, we used Monte Carlo simulations, thus obtaining reliable probability distributions for both statistics.

TABLE VII. Number of independent Fourier spacings searched for periodic emission. Each source is searched up to $\pm n_{\text{IFS}}$ Fourier spacings from the x-ray period.

Source	1988 n_{IFS}	1990 n_{IFS}	1991 n_{IFS}
SMC X-1	1.1	1.1	1.1
LMC X-4	1.7	2.3	2.3
Cen X-3	1.1	1.7	1.7
Vela X-1	1.1	1.1	1.1

TABLE VIII. Probabilities corresponding to the highest test statistic found in each of the four data sets in 1988, 1990, and 1991. The Rayleigh, Protheroe, and H probability are indicated by pR, pP, and pH respectively. The probabilities are not corrected for the number of degrees of freedom.

Source	Year	pR	pP	pH
SMC X-1	1988	4.1×10^{-1}	4.6×10^{-2}	1.5×10^{-2}
LMC X-4		2.2×10^{-1}	6.0×10^{-2}	2.3×10^{-1}
Cen X-3		5.9×10^{-2}	1.8×10^{-2}	1.4×10^{-2}
Vela X-1		5.1×10^{-2}	1.4×10^{-2}	8.2×10^{-2}
SMC X-1	1990	2.7×10^{-1}	2.8×10^{-4}	3.6×10^{-4}
LMC X-4		1.0×10^{-1}	2.0×10^{-3}	3.0×10^{-3}
Cen X-3		2.6×10^{-2}	1.7×10^{-2}	7.1×10^{-3}
Vela X-1		1.0×10^{-2}	5.5×10^{-2}	1.0×10^{-1}
SMC X-1	1991	3.1×10^{-1}	2.4×10^{-2}	3.2×10^{-2}
LMC X-4		3.6×10^{-1}	9.4×10^{-3}	3.2×10^{-2}
Cen X-3		4.3×10^{-1}	2.0×10^{-3}	3.7×10^{-1}
Vela X-1		6.8×10^{-2}	1.1×10^{-1}	1.9×10^{-1}

The highest value of each test statistic was singled out in each of the 12 data sets (4 sources times 3 years) and in Table VIII the probabilities of exceeding this maximum are given, not taking into account the number of trials.

When applying the Protheroe test to the 1990 data set, we obtain a chance probability of 2.8×10^{-4} for SMC X-1 at the reported x-ray period, i.e., $dP/P_0 = 0$.

Although de Jager [83] has carried out Monte Carlo calculations to estimate the effective number of trials for particular tests, it is sufficient in this case to calculate the probability for a best and a worst-case scenario.

(i) Consider each period that is tested as independent. This constitutes a total of 1080 trials (360 periods searched times 3 tests performed on each period), yielding a chance probability of 26%.

(ii) Consider only the number of IFS's spanned as independent. This constitutes a total of $44 \times 3 = 132$ trials, yielding a chance probability of 3.6%.

In addition, it was found that the high value of the Protheroe statistic did not show up in the 1988 data set ($p_P = 0.998$); nor did it persist through 1991 ($p_P = 0.990$). Therefore we cannot conclude that any evidence exists for periodic emission for the sources and periods that we have examined.

IX. CONCLUSIONS

No conclusive evidence was found for dc emission from any of the nine candidates. An all-sky search for a time-averaged signal was performed, but no significant excess was found. The upper limits calculated for the nine sources are, in general, consistent with observations from other VHE and UHE experiments.

The four x-ray binaries SMC X-1, LMC X-4, Cen X-3, and Vela X-1, which have well-established orbital periods, were investigated for γ-ray emission modulated with the orbital period. No evidence for a modulated γ-ray signal was found.

A statistically significant excess from SMC X-1 (99.6% C.L.) was detected during 1 day in 1991: 178 events on source versus 120 background events. The evidence for the reality of the burst is somewhat weakened, however, by the absence of any other burst of the same order of magnitude in three years of observation.

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