ENERGY SPECTRA OF SEVERAL DISCRETE X-RAY SOURCES IN THE 20–120 keV RANGE

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1. Introduction

In this paper we report on our observations of hard X-rays from several X-ray sources in the energy range 20–120 keV. The results were obtained from the data collected during two balloon flights made from Hyderabad, India (latitude 17.6°N, longitude 78.5°E). The first flight was made on April 28, 1968, and the balloon reached a ceiling of about 5.3 g cm^{-2} residual atmosphere and floated from 0230 to 0800 hrs. IST (Indian Standard Time). The second balloon was launched on December 22, 1968 and floated at about 7.5 g cm^{-2} of residual air from 1000 to 1130 hrs. IST.

The X-ray telescope consisted of a NaI (Tl) crystal of area of 97.3 cm^2 and thickness 4 mm, coupled to a 5″ photomultiplier. The crystal was surrounded by both active and passive collimators. The passive collimator was a cylinder of graded shielding of lead, tin and copper and the active collimator, a cylindrical plastic scintillator. The field of view of the telescope was 18.6° at FWHM. The geometrical factor of the telescope for isotropic radiation was 13.2 cm^2 sr. The pulses from the NaI crystal were sorted out into 10 continuous channels extending from 17 to 124 keV. An Am^{241} source came in the field of view of the telescope periodically and provided in flight calibration of the detector. All the information was recorded on a continuously moving photographic film.

The X-ray telescope was mounted on an oriented platform which was programmed to look at specified directions in the sky. The axis of the telescope was kept inclined at a fixed angle to zenith, 25° in the first flight and 32° in the second. In the first flight it was planned that the azimuth of the telescope would be aligned to the north and the south directions alternately for about 10 min each. Although the telescope looked at the directions close to north and south for a considerable period of time, it also scanned some other directions of the sky for significant period due to oscillations and 'hunting' of orienting system. Fortituously this enabled us to make interesting observations on the X-ray intensities from these directions. A continuous record of the aspect of the telescope was made from the output of a pair of flux gate magnetometers.

In the second flight the oriented platform was programmed to look at four specified directions successively spending about 4 min in each direction during a cycle of about 16 min. The four specified directions were, N ($\phi = 0°$), S ($\phi = 180°$), NE ($\phi = 310°$, with the convention $\phi = 270°$ being due east) and SW ($\phi = 110°$). The performance of the orientor was very good in this flight and the telescope looked at the preselected directions of the sky successively for five cycles, from 0950 to 1115 hrs. IST.

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2. Sco X-1

On April 28, 1968 the balloon reached ceiling altitude of 5.3 g cm^{-2} at 0230 hrs. IST. During the period 0230–0330 hrs. IST Sco X-1 was in the field of view of the telescope intermittently for a total time of 1455 sec. The angle between the telescope axis and Sco X-1 was computed every 15 sec by noting the corresponding aspect and taking into account the drift of the balloon in longitude. The effective exposure time corresponding to 100% efficiency was deduced from these data to be 255 sec. The background counting rate was determined from the counting rates during the period when no known sources were in the field of the telescope. The relevant data are given in Table I. It is seen that finite fluxes from Sco X-1 are available in four energy channels I to IV (16–72 keV) and upper limits can be put in two higher energy channels V and VI (72–125 keV). The fluxes shown in Table I are not corrected for the escape probability of K X-rays and also for the resolution and the efficiency of the detector. This correction is small and amounts to about 10%. This will be taken into account in the final analysis of the data of the X-ray sources.

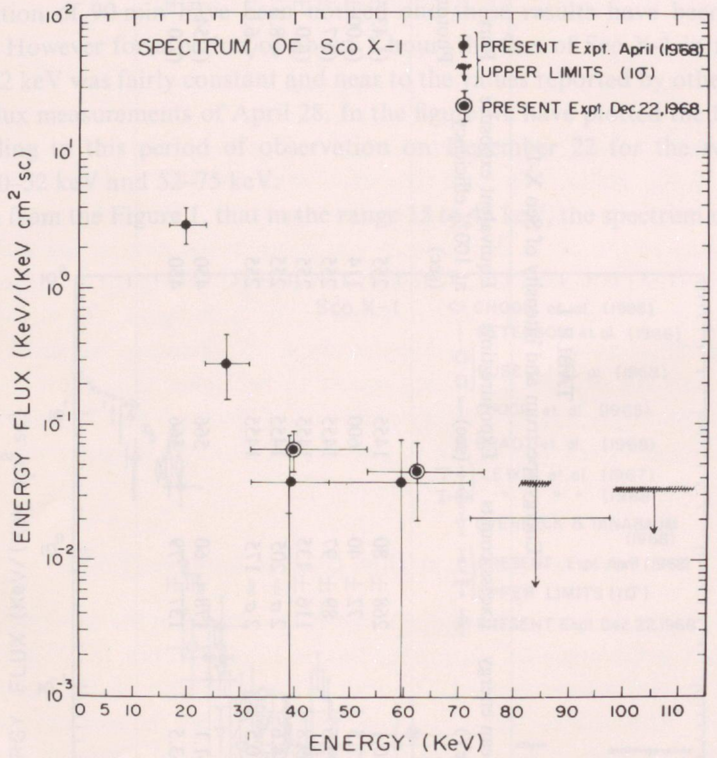

Fig. 1. X-ray intensities of Sco X-1 measured on April 28, 1968 and December 22, 1968.

During the flight on December 22, 1968, Sco X-1 was in the field of view of the

TABLE I

Energy spectrum and intensity of Sco X-1

Date	Energy band (keV)	Mean energy (keV)	Excess counts	Exposure time (sec)	Equivalent exposure at 100% efficiency (sec)	Flux	
						Photons/keV cm² sec	keV/keV cm² sec
28.4.68	16.6–23.4	20.1	268 ± 80	1455	255	$(1.43 \pm 0.43) \times 10^{-1}$	2.86 ± 0.85
	23.4–31.5	27.5	72 ± 40	600	114	$(1.00 \pm 0.55) \times 10^{-2}$	$(2.76 \pm 1.6) \times 10^{-1}$
	31.5–47.7	39.6	89 ± 97	1455	255	$(9.7 \pm 10.6) \times 10^{-4}$	$(3.85 \pm 4.2) \times 10^{-2}$
	47.7–72.0	59.8	116 ± 135	1455	255	$(6.0 \pm 7.0) \times 10^{-4}$	$(3.61 \pm 4.2) \times 10^{-2}$
	72.0–97.4	84.6	$2\sigma = 205$	1455	255	$< 8.9 \times 10^{-4}$	$< 7.5 \times 10^{-2}$
	97.4–123.7	110.5	$2\sigma = 175$	1455	255	$< 6.0 \times 10^{-4}$	$< 6.6 \times 10^{-2}$
22.12.68	29.9–52.3	41.1	178 ± 60	566	450	$(1.54 \pm 0.52) \times 10^{-3}$	$(6.3 \pm 2.1) \times 10^{-2}$
	52.3–74.7	63.5	137 ± 79	566	450	$(7.0 \pm 4.0) \times 10^{-4}$	$(4.5 \pm 2.5) \times 10^{-2}$

telescope periodically (for about 4 min at a time) over a time period of about 90 min, from about 1000 hrs. to 1130 hrs. IST. The detector looked at Sco X-1 for a total time of 566 sec. Since the orientor performed very satisfactory the mean efficiency was as high as ~80% and the effective exposure time with 100% efficiency was 450 sec. This long exposure enabled us to obtain finite and statistically significant flux in the two energy intervals of 30–52 keV and 52–75 keV (Table I), in spite of the fact that the atmospheric thickness along the line of sight to Sco X-1 was as high as 9.2g cm^{-2} of air. In estimating the excess counts the background rate was obtained from the north region of sky which included no discrete X-ray sources.

The measured intensities of Sco X-1 during the two flights are plotted in Figure 1. In the December 22 flight rapid variations in the intensity of Sco X-1 within the period of observation of 90 min have been noticed and these results have been reported earlier [1]. However for a period of about 1 hour, the flux of Sco X-1 in the energy range 30–52 keV was fairly constant and near to the values reported by others, as well as to our flux measurements of April 28. In the figure we have plotted the flux values corresponding to this period of observation on December 22 for the two energy channels 30–52 keV and 52–75 keV.

It is seen from the Figure 1, that in the range 15 to 45 keV, the spectrum of Sco X-1

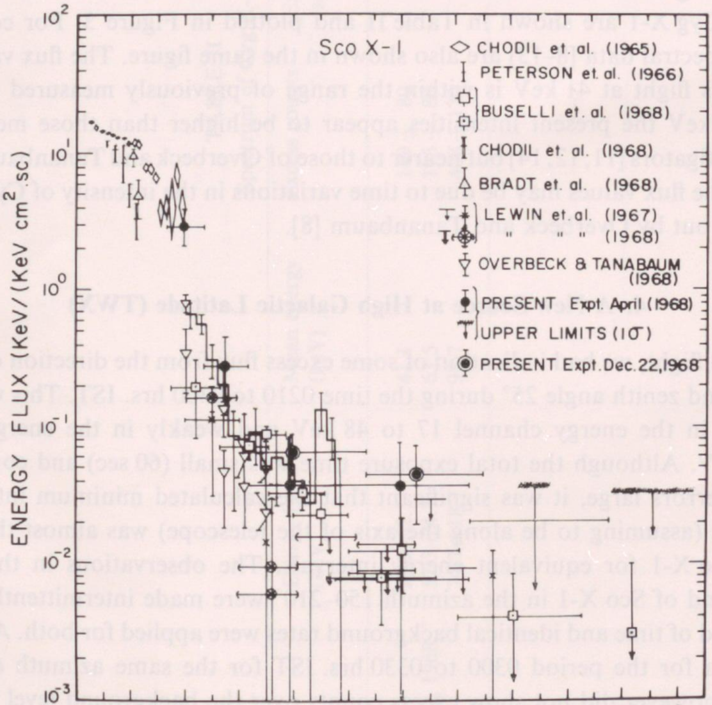

Fig. 2. X-ray intensities of Sco X-1 measured in the present experiments on 28.4.1968 and on 22.12.1968 together with available spectral information on Sco X-1.

can be represented by an exponential of the form $N(E)=(K/E)\exp-E/E_0$, where $E_0 \sim 5$ keV the corresponding temperature being $T=5.8\times10^7$K. In the energy interval 45–75 keV, our data indicate a rather flat spectrum $E_0 \sim 20$ keV or more, suggesting that the same spectral exponent is not valid for energies below and above 45 keV.

A comparison of the present data with the available spectral data [2–8] on Sco X-1 is shown in Figure 2. It is clear from the figure that at any given energy the agreement in the absolute flux values is not better than by a factor of 2–3, at energies below 40 keV. At higher energies the spectral information on Sco X-1 is still rather poor. Our flux values at 60 and 63 keV obtained in two different flights agree with others. But the values are considerably higher than those of Buselli *et al.* [6], who also find a flattening of the spectrum at high energies ($KT \sim 15$ keV).

3. Cyg X-1

On December 22, the X-ray telescope looked at Cyg X-1 in the eastern sky during the 3rd, 4th and 5th cycles. The total time of exposure at 100% efficiency was 202 sec. Excess flux was detectable in three energy channels. The background was taken corresponding to the north direction as was done in the case of Sco X-1. The flux values of Cyg X-1 are shown in Table II and plotted in Figure 3. For comparison available spectral data [8–13] are also shown in the same figure. The flux value measured in this flight at 41 keV is within the range of previously measured values. At 64 and 97 keV the present intensities appear to be higher than those measured by some investigators [11, 12, 14] but nearer to those of Overbeck and Tananbaum [8]. The spread in the flux values may be due to time variations in the intensity of Cyg X-1 also as pointed out by Overbeck and Tananbaum [8].

4. A New Source at High Galactic Latitude (TWX)

In April 28 flight, we had indication of some excess flux from the direction of azimuth 90°–120° and zenith angle 25° during the time 0210 to 0300 hrs. IST. This was clearly noticeable in the energy channel 17 to 48 keV and weakly in the energy channel 48–97.5 keV. Although the total exposure time was small (60 sec) and consequently statistical errors large, it was significant that the calculated minimum intensities of this source (assuming to be along the axis of the telescope) was almost the same as that of Sco X-1 for equivalent energy intervals. The observations in the azimuth 90–120°, and of Sco X-1 in the azimuth 150–210° were made intermittently over the same period of time and identical background rates were applied for both. An analysis of the data for the period 0300 to 0330 hrs. IST for the same azimuth and zenith direction, however did not show excess counts over the background level suggesting that the source probably moved out of the field of view of the telescope.

We scanned this region of the sky in the direction (SE($\phi=110°$)), on December 22, 1968 and detected considerable excess counts in the energy channels 30–52 keV and

TABLE II
Spectrum of Cyg X-1

Date	Energy band (keV)	Mean energy (keV)	Excess counts	Exposure time (sec)	Equivalent exposure at 100% efficiency (sec)	Flux photons/keV cm² sec
December 22, 1968	29.9–52.3	41.1	149 ± 80	688	202	$(4.7 \pm 2.6) \times 10^{-3}$
	52.3–74.7	63.5	195 ± 88	688	202	$(3.4 \pm 1.6) \times 10^{-3}$
	74.7–118.7	95.7	403 ± 130	688	202	$(2.6 \pm 0.8) \times 10^{-3}$

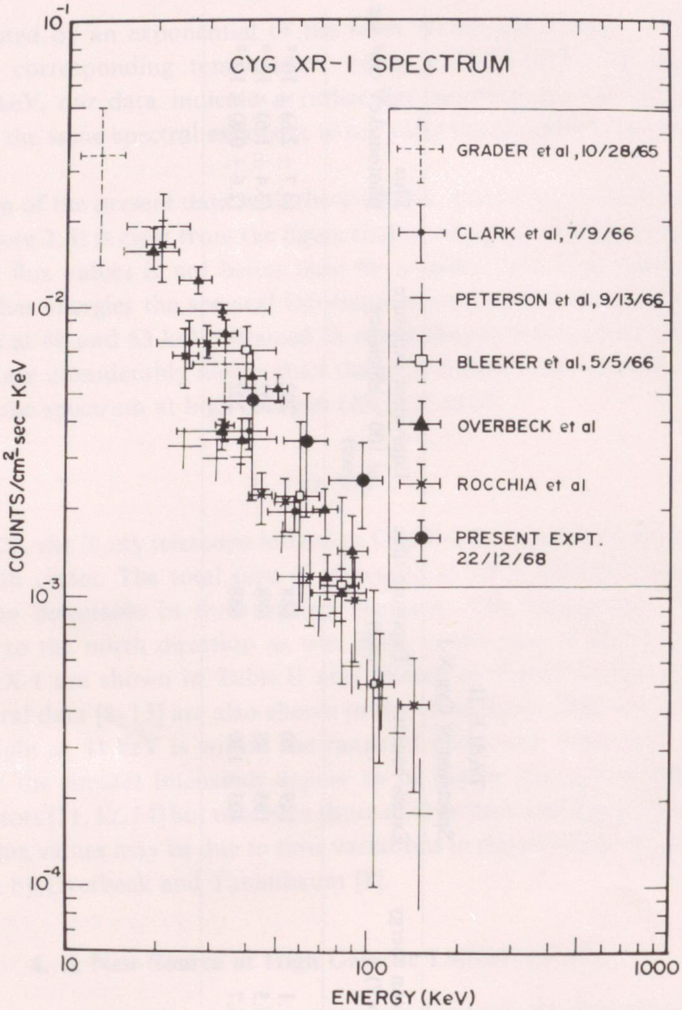

Fig. 3. Flux values of Cyg X-1 measured on 22.12.1968 together with available flux data of Cyg X-1

52–86 keV. The exposure time on this source region was 755 sec. During the same rotational cycles of the telescope Sco X-1 was detected in the direction S ($\phi = 180°$) and Cyg X-1 in the direction NW ($\phi = 310°$). Figure 4 shows the counting rates for the four directions scanned. Using the same value of the background counting rate as used for Sco X-1 and Cyg X-1, the flux values of the new source were calculated assuming it to be along the axis of the telescope. The flux values are given in Table III. The intensities measured on April 28 and December 22, are plotted in Figure 5 together with measurements on Sco X-1 and Cyg X-1 during these flights. The energy spectrum of the source seems to be similar to that of Sco X-1.

From the observations on April 28, the source location was deduced to be in the celestial region, R.A. = 14.0 hrs. to 15.6 hrs., and $\delta = -5.5°$ to $+24.9°$. In the De-

TABLE III

Intensity and energy spectrum of the new source
(The source is assumed to be along the axis of the telescope)

Date	Energy band (keV)	Mean energy (keV)	Source counting rate-c/sec	Background counting rate-c/sec	Excess counts due to source	Total exposure Time (sec)	Flux photons/keV cm² sec
April 28, 1968	16.6–47.7	32.2	8.08	7.39	40 ± 23	60	$(2.6 \pm 1.5) \times 10^{-3}$
	47.7–97.4	72.5	13.30	12.61	38 ± 28	60	$(5.3 \pm 4.0) \times 10^{-4}$
December 22, 1968	29.9–52.3	41.1	5.29	4.98	231 ± 94	755	$(1.1 \pm 0.5) \times 10^{-3}$
	52.3–74.7	63.5	6.03	5.65	290 ± 94	755	$(8.9 \pm 2.9) \times 10^{-4}$
	74.7–118.7	96.7	11.87	11.60	203 ± 135	755	$(2.4 \pm 1.6) \times 10^{-4}$

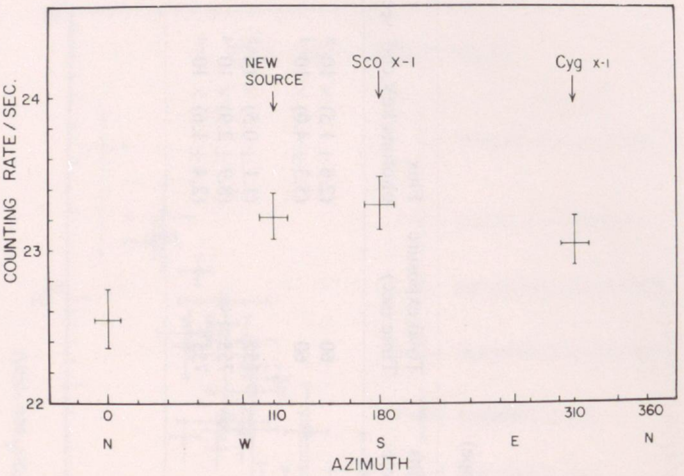

Fig. 4. Counting rates of the X-ray telescope in the energy interval 30–119 keV on 22.12.1968 for the 4 different directions of the sky. This shows the counting rate due to the new source as compared to that of the background ($\phi = 0°$), Sco X-1 ($\phi = 180°$) and Cyg X-1 ($\phi = 310°$).

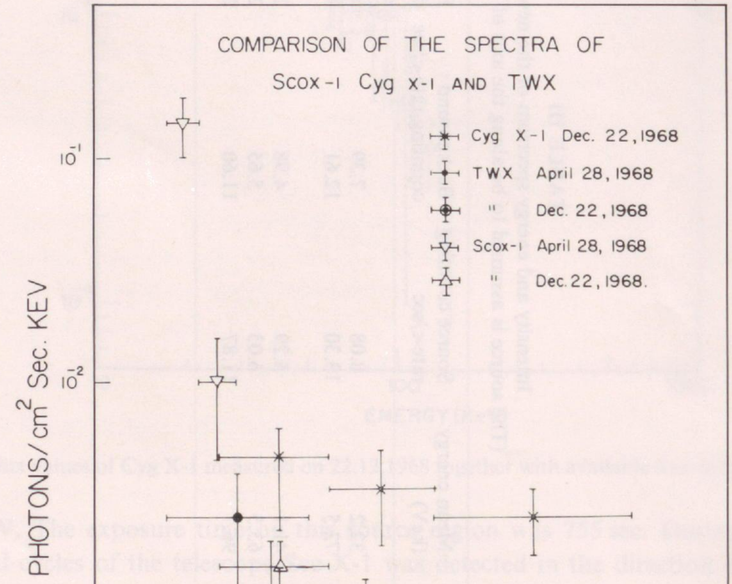

Fig. 5. Comparison of the spectra of the new source (TWX) and Sco X-1 measured on 28.4.1968 and 22.12.1968 and of Cyg X-1 on 22.12.1968.

cember 22 flight, the location of the source was in region, R.A. = 13.5–15.2 hrs. and $\delta = -9.5°$ to $+23.8°$. Fortuitously since the measured intensities in the two flights were nearly the same, it is estimated that the source is located in the overlapping region of the sky at R.A. = 14.0–15.2 hrs. and $\delta = -5.5$ to $+23.8°$, which lie in the constellations of Virgo-Bootes-Serpens. In galactic coordinates the source lies at high galactic latitude, at $l^{\mathrm{II}} \approx 359°$ and $b^{\mathrm{II}} \approx +58°$.

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Search for High Energy Gamma Rays from Four Pulsars

It has been suggested[1,2] that high energy cosmic rays originate in pulsars. If this is true, it is conceivable that the pulsars might also be emitting ultra high energy, pulsed gamma rays with the same periodicities as observed at radio frequencies. These gamma rays might be the result of either the decay of π^0-mesons or the bremsstrahlung of electrons in the regions surrounding the pulsars. There is no precise theory yet on this aspect. There have already been several searches for high energy gamma rays from pulsars[3-5].

During the latter part of April 1969 we tried to detect the possible emission of high energy pulsed gamma rays ($\gtrsim 10^{13}$ eV) from four pulsars: CP 0950, CP 1133, AP 1541 and PSR 1642. Detectable Čerenkov light flashes are produced in the atmosphere by the relativistic electrons of cascade showers induced by gamma rays and charged cosmic rays of high energy ($\gtrsim 10^{12}$ eV). The latter constitute the main background of noise limiting the minimum measurable gamma ray flux. The method in our experiment, as in the others, is based on looking for these nanosecond duration Čerenkov light signals in excess of the background from the direction of pulsar under investigation. If pulsars emit gamma rays in a pulsed mode with the same periodicity and similar pulse widths as in the case of the radio signals, time averaging by superposition of the gamma ray signals over a large number of time periods can reveal such a gamma ray flux even if it is much weaker than the background.

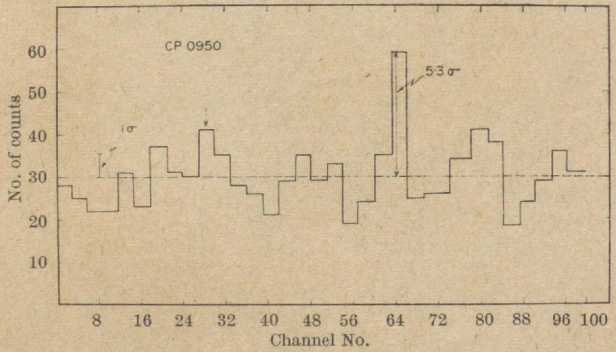

Fig. 1. Phase histogram obtained for CP 0950. The pulsar period is divided into 100 phase channels which are grouped in threes in the figure. The position of the interpulse as observed by Rickett and Lyne[7] at 408 MHz is shown by the arrow approximately at the 29th channel. The average of the histogram is shown by the dashed line.

Table 1. GAMMA RAY FLUXES FROM PULSARS

Object	O'Mongain *et al.* Threshold* (eV)	O'Mongain *et al.* Flux (cm^{-2} s^{-1})	Charman *et al.* Threshold* (eV)	Charman *et al.* Flux (cm^{-2} s^{-1})	Fazio *et al.* Threshold* (eV)	Fazio *et al.* Flux (cm^{-2} s^{-1})	This experiment Threshold* (eV)	This experiment Flux (cm^{-2} s^{-1})
CP 0950	—	—	—	—	4×10^{12}	$\lesssim 2 \times 10^{-11}$	10^{13}	$\approx 4 \times 10^{-11}$
CP 1133	3×10^{12}	5×10^{-11}	7×10^{13}	$\lesssim 1{\cdot}7 \times 10^{-12}$	2×10^{12}	$\lesssim 2 \times 10^{-11}$	10^{13}	$\lesssim 2 \times 10^{-11}$
AP 1541	—	—	—	—	—	—	10^{13}	$\lesssim 1 \times 10^{-11}$
PSR 1642	—	—	—	—	—	—	10^{13}	$\lesssim 1{\cdot}6 \times 10^{-11}$

* The threshold energies are to be trusted only to within a factor of 3.

The Čerenkov light is detected by two large searchlight mirrors (90 cm diameter and 41 cm focal length) and focused onto two fast photomultipliers (56 AVP) placed at their foci. The mirrors track each pulsar for about an hour when it is close to meridian transit. Whenever a coincidence occurs within the resolving time of 5 ns between the two photomultipliers, the time as shown by a crystal controlled digital clock is recorded to a precision of 5·1 ms. The short term drift (typically over a few hours) of the crystal oscillator is found to be less than one part in 10^6. The full field of view of each mirror is 3° and the ratio of genuine Čerenkov light signals (which are mostly due to showers induced by cosmic rays) to chance coincidences is about 1 : 2. From the background Čerenkov signal rate, the known aperture of the field of view and the approximate area of collection of high energy gamma rays of 3×10^4 m^2 (see ref. 6, for example), the threshold energy of detection in our experiment is estimated to be $\approx 10^{13}$ eV. Observations were made on clear nights during the period April 16–28, 1969, at Mukurthi located at an altitude of 7,200 feet above sea-level in the Nilgiri Hills in South India.

Time averaged phase histograms were made for each pulsar, with the recorded Čerenkov coincidence times for the corresponding geocentric period of the epoch, using a computer. A calibration procedure and measured value of the clock drift permitted us to establish that the clock was accurate within ± 50 parts in 10^6. The phase histograms were therefore made for a scan of the clock calibration extending over this range of uncertainty. The scan resolution used of 2 parts in 10^6 was determined by the duration of the run and an assumed minimum pulse width of about 1 per cent of the corresponding pulsar period for the pulsed gamma ray emission.

Of the four pulsars, only CP 0950 showed a significant peak in one of the channels, of 5·3 standard deviations above the average (Fig. 1). Fig. 1 also shows the position where Rickett and Lyne[7] found the interpulse at a frequency of 408 MHz. They estimate that the energy in the interpulse is about 1·8 per cent of that in the main pulse[7].

A χ^2 test on the histogram, excluding the channel in which the peak appeared, shows that $P(\chi^2) = 0{\cdot}38$ for the assumption that the distribution is Poissonian. The probability of statistical fluctuations accounting for the peak observed in Fig. 1 is deduced to be $2{\cdot}5 \times 10^{-3}$. This value was arrived at as follows. (i) The Poisson probability of obtaining ≥ 59 counts when the expected average is 30 is $1{\cdot}88 \times 10^{-6}$. (ii) The number of ways of grouping into three adjacent bins, when the total number of bins is 100, is = 100. (iii) The number of trial clock periods is 50, and the number of adjacent trial periods in which the same peak has appeared with appropriate phase shift is 4.

The expectation value is therefore

$$1{\cdot}88 \times 10^{-6} \times 100 \times \frac{50}{4} \sim 2{\cdot}5 \times 10^{-3}$$

We also made a total of ten attempts on the other pulsars which showed no significant peaks. Depending on the caution one wishes to exercise, one might say that the statistical chance of observing a peak which is $\geq 5{\cdot}3$ standard deviations above the average is $2{\cdot}5 \times 10^{-3}$ for that particular run on CP 0950 or $2{\cdot}5 \times 10^{-3} \times 11 \sim 3 \times 10^{-2}$ for the whole experiment. A second observation on CP 0950 would have established unambiguously whether it is steadily pulsating in gamma rays or not. This was not feasible because the experiments were started late in April. The number of clear nights were few and when the atmospheric conditions were good the Moon interfered with the observations on CP 0950. Further observations are feasible on this pulsar only after December 1969.

In the case of the other pulsars, CP 1133, AP 1541 and PSR 1642, at least two observations were made on each and no significant peaks ($\geq 5\sigma$) were observed. Only upper limits could therefore be deduced for their gamma ray fluxes. Our results along with those of others[3-5] are listed in Table 1. The upper limits given by us are such that, if the true gamma ray fluxes were higher than those given, we would have seen them as five standard deviations or higher from the average. The threshold energies quoted can be trusted only to a factor of ~ 3. This uncertainty is due to assumptions of the lateral and angular spread, time distribution and atmospheric absorption and so on of Čerenkov light.

It is unlikely that CP 1133, AP 1541 and PSR 1642 are emitters of pulsed gamma rays resulting in intensities higher than the limits given by us. CP 0950 seems to be a good candidate for further observations. It may be significant that CP 0950 is also probably the nearest pulsar, considering that it has the lowest dispersion measure[8] ($\int N_e \mathrm{d}s = 2{\cdot}94$ electrons cm^{-3} pc).

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