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Correlation of pulsar positions and the arrival directions of air showers of energies 10^{17}–10^{18} eV observed at Chacaltaya

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Abstract. The arrival directions of 2598 air showers of energies between 10^{17}–10^{18} eV observed at Mt Chacaltaya during 1964–1966 have been examined in order to search for a possible correlation with the known positions of pulsars. A plot of the declination against right ascension of the observed air showers has been divided into a grid of 5° declination against 5° right acension. A distribution of the number of showers along each declination band is then constructed. In each declination band those groups of showers (bins within the grid) which are above 2 standard deviations in the distribution are selected for further analysis. There are 36 such groups and among these 19 coincide with the known positions of pulsars while 7·5 are expected from accidental coincidence. The results obtained from this preliminary analysis do not rule out the possibility that some at least of the cosmic ray primaries in the energy range studied originate in pulsars.

1. Introduction

The problem of the sources of cosmic rays is well known and several attempts have so far been made to correlate the arrival directions of ultra-high energy particles with several kinds of celestial objects. In this paper we attempt to correlate the arrival directions of particles of energies between 10^{17}–10^{18} eV and the known position of pulsars. These high energy particles are observed by the air showers they produce in the atmosphere.

The data on air showers used here come from a three year study (1964–66) made by the Bolivian air shower joint experiment (BASJE) at Mt Chacaltaya, Bolivia, 5200 metres above sea level. Although the experimental array was set up to observe showers at a lower energy region (10^{14}–10^{16} eV) about 3500 showers were observed which had energies larger than 10^{17} eV.

The data on pulsar positions and other pertinent information come from the summary of Terzian (1972) and IAU circulars (1972a, 1972b, 1973a, 1973b).

The results obtained in this analysis are not strong statistically and in this sense the paper should be considered preliminary; it is hoped that a more definite conclusion will be obtained with the analysis of large air showers ($> 10^{17}$ eV) which are now being observed at Mt Chacaltaya with a new experimental arrangement (Aguirre *et al* 1973a, 1973b, 1973c).

2. Experimental arrangement and selection of events

2.1. Experimental arrangement

The general features of the experimental arrangement have been given previously (Suga *et al* 1963). It consists basically of five concentric rings of unshielded detectors at distances up to 150 m from a central 60 m^2 shielded detector. The arrival directions of the showers (EAS) are determined by the fast timing method with the use of five detectors located at the centre of the array. The error in the arrival direction is less than 3° for EAS whose cores fall within about 100 m of the fast timing detectors and less than about 8° for EAS whose cores fall within 250 m of the timing detectors. The 2598 showers used in the present analysis are selected from a total of about 3500. These selected showers have zenith angles less than 60° and, further, only those which give a good fit (DFIT and TFIT less than 3·0, see below) in both the fast timing and density systems are used. Also, about 90% of the selected EAS have cores within 250 m of the centre of the array, so that the error in angle is less than 10° for most showers.

2.2. *Fitting program*

The analysis of the showers is made by a computer and the program is designed to calculate the best values for size, axis location and s parameter. In the computation it is assumed that the detectors' signals observed will not be exactly the signals calculated by the expression

$$\rho = Nc(s)r^{s-2}(1+r)^{s-4\cdot 5}$$

where N is the size and r the distance from the core, but will differ from the calculated value due to fluctuations in shower development and to measurement errors. The fluctuations are assumed to be normal, or gaussian, in nature. The values chosen for axis coordinates, size, and s are those which give a shower the greatest probability of producing the observed detectors' signals.

To determine the reliability of the fitting process, a quantity called DFIT is calculated. Basically, this is the root-mean-square value of the fluctuation of the detectors signals from their predicted values in terms of standard deviations. Given values of shower size, s, and axis location (and arrival directions from the fast timing data) allow the computation of the signals $\bar{n}_i$ expected at all density detectors. If n_i are the observed signals, and σ_i are the standard deviations of the expected fluctuations, then

$$\text{DFIT} = \left(\frac{\sum_{i=1}^{N} (\bar{n}_i - n_i)^2/\sigma_i^2}{N-4}\right)^{1/2}$$

where N is the number of detectors. The showers selected for the present analysis are required to have a DFIT value less than 3·0 (obviously, DFIT may be made as large or small as one chooses by suitable choices of σ_i and here is chosen as $(\bar{n}_i)^{1/2}$).

As mentioned in § 2.1 the arrival directions of the EAS are determined by the fast timing method. In the experimental arrangement there were five detectors. Four of these were in the same plane forming a square lattice of 30 m side. The fifth detector was located at the centre of the square and at a height of 9·6 m above the plane of the other four. This detector was used as the reference detector. The time differences (in μs) between each of the four detectors (T_i, $i = 1, \ldots, 4$) and the reference detector (T_5) were recorded for the determination of the arrival directions. Also, the signal from each ($T_i - T_5$) was delayed for purposes of recording the time differences.

For the computation of arrival directions from fast timing data a quantity called TFIT is constructed, as follows:

$$\text{TFIT} = \left(\sum_{i=1}^{U} \frac{(\text{TIMEOBS}(i) - \text{TIMECOMP}(i))^2}{U-2}\right)^{1/2} = \left(\sum_{i=1}^{U} \frac{(\text{ERROR}(i))^2}{U-2}\right)^{1/2}$$

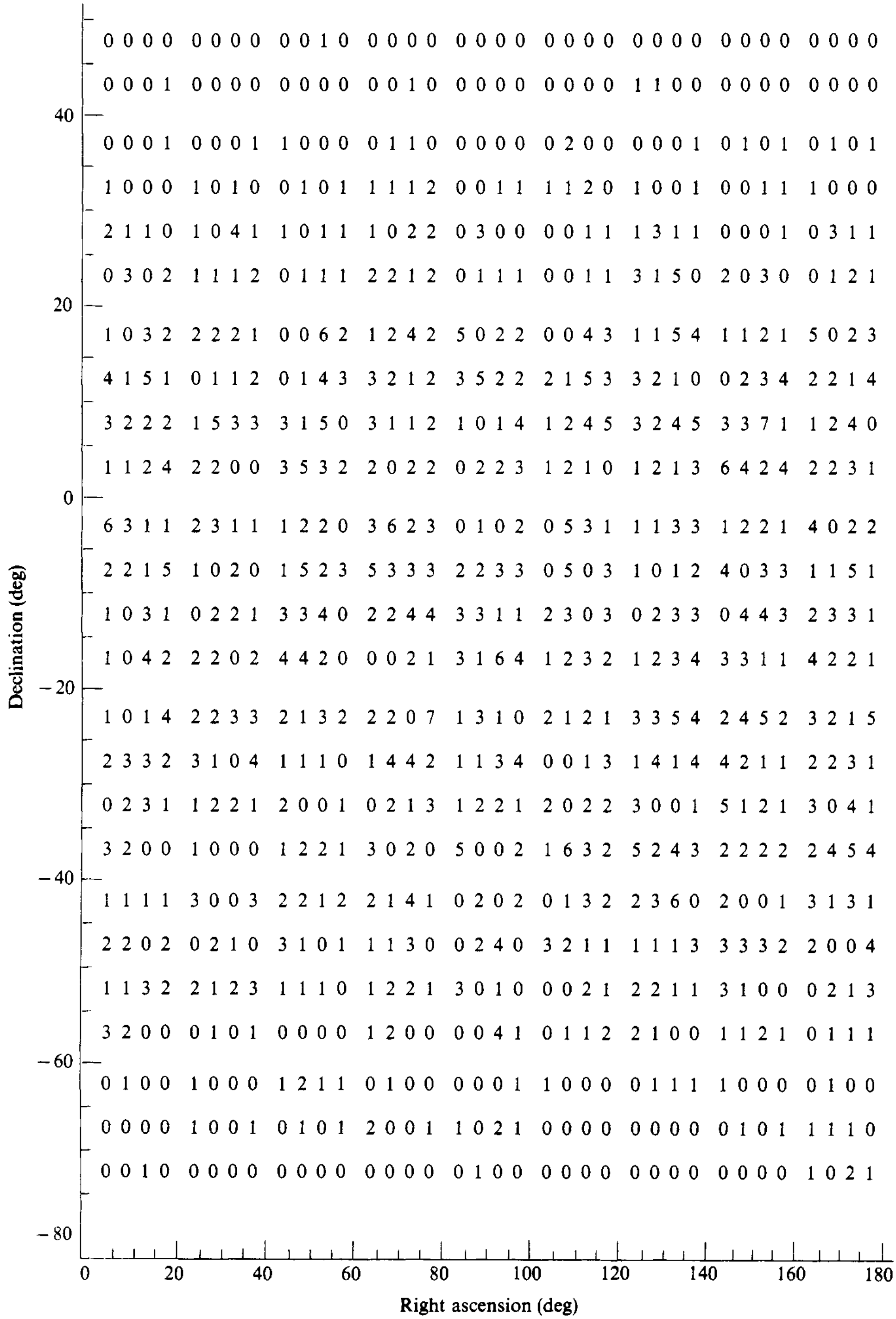

Figure 1. The arrival directions of observed showers.

0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0
0 0 0 0	0 0 0 1	0 0 0 1	0 1 1 0	0 0 0 0	0 0 0 1	0 0 0 0	2 0 0 0	0 0 0 0
0 0 0 1	0 0 0 0	0 3 0 0	0 0 1 1	0 0 0 2	1 2 0 0	0 0 0 1	0 0 1 0	1 0 2 0
2 0 2 0	0 0 0 0	1 0 0 2	1 0 0 1	1 1 0 0	1 1 0 0	1 0 0 1	1 1 1 0	0 0 3 0
5 1 2 0	0 0 0 3	1 1 1 2	2 1 0 2	2 1 2 1	1 2 2 0	0 1 2 3	1 2 5 0	0 1 2 3
1 1 2 1	2 1 0 2	2 0 1 3	1 0 1 0	0 5 1 3	3 1 0 2	1 2 1 1	3 1 2 1	1 0 1 0
1 0 4 4	6 2 1 3	3 0 0 0	1 5 1 3	0 2 2 1	1 4 1 1	3 2 1 2	4 0 4 1	2 3 2 0
1 1 2 0	5 1 5 4	3 2 0 8	4 1 2 1	2 1 3 3	5 2 2 2	2 1 1 0	1 3 2 0	2 3 2 4
2 3 5 3	3 2 0 1	2 0 2 3	2 3 1 4	4 3 4 3	5 2 3 3	2 1 2 2	3 0 0 3	3 3 1 0
1 2 1 0	2 2 3 3	2 2 2 3	6 4 4 5	1 1 0 2	0 4 3 1	3 1 2 3	0 4 2 3	3 5 5 3
3 1 3 1	4 1 2 1	4 3 4 2	1 1 3 1	3 2 2 0	1 2 2 5	4 1 4 3	1 2 1 2	3 3 3 2
3 2 2 2	1 5 4 1	3 3 4 3	1 0 0 3	3 3 2 0	2 4 2 4	10 3 0 2	2 2 3 1	1 1 3 7
3 5 1 3	4 2 4 3	4 1 2 2	1 1 7 1	3 4 2 4	5 7 3 2	2 2 1 2	2 3 0 4	6 3 1 3
0 1 2 2	4 4 3 5	0 3 3 0	5 1 2 1	1 1 0 2	0 2 2 0	3 3 2 3	1 3 3 5	2 1 3 6
2 2 1 2	3 2 1 0	1 4 4 3	1 3 4 3	3 0 1 3	3 4 4 0	4 4 2 0	2 1 1 1	4 2 2 2
3 4 5 5	3 2 3 1	4 2 3 1	2 0 3 1	2 4 2 5	6 2 2 2	4 2 1 2	4 5 1 2	3 3 1 2
2 0 1 2	1 1 0 1	1 2 0 1	0 1 1 0	0 0 1 1	2 6 3 1	2 0 2 0	3 1 1 4	1 2 0 2
4 2 1 1	2 5 4 0	4 4 2 2	2 1 2 4	3 3 3 1	5 3 1 3	2 4 1 1	0 3 4 1	0 3 2 1
1 0 2 2	0 0 1 2	1 4 1 1	1 4 3 1	2 1 2 2	3 2 4 0	3 1 0 1	2 0 4 0	1 5 0 1
1 1 0 1	1 3 0 0	1 1 0 2	1 2 5 0	1 2 2 2	1 1 2 2	2 4 1 3	3 1 3 0	2 2 1 3
1 1 2 1	1 1 1 1	1 1 1 0	0 5 1 0	2 2 2 0	1 3 2 2	2 2 1 1	3 1 1 1	1 1 0 2
1 1 1 0	4 1 2 1	0 0 2 1	1 1 1 1	0 0 1 0	0 0 0 0	1 1 1 0	0 1 3 0	0 0 2 1
2 0 1 1	0 0 0 2	0 3 0 0	1 0 0 0	2 0 2 0	0 0 0 0	1 1 2 0	1 1 0 1	0 1 1 0
3 1 0 3	1 0 0 0	0 0 0 0	1 1 0 0	0 0 0 1	0 0 0 1	1 0 1 0	0 0 1 1	0 0 0 0
0 0 0 0	0 0 0 1	0 0 0 0	0 2 0 0	0 0 0 0	1 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0

200 220 240 260 280 300 320 340 360

Right ascension (deg)

where $U = 5$ for four good time differences and TIMEOBS values are the input differences determined by the expression

$$\text{TIME}(i) = \text{delay}(i) - \text{slope}(i) \times \mu\text{s printout } (T_i - T_5)$$

where slope (i) is a quantity depending on the calibration of the detector.

The TIMECOMP values are the solutions obtained from the least-square iteration process. Here the time is allowed to vary from the absolute time of T_5, for instance if the computed value of T_5 is positive it means that the zero of time is shifted upwards to a point above the T_5 detector and all times are computed from this point. This happened often for small showers which were centred on the array. The particles which strike T_5 are earlier than the ones which strike the outlying detectors T_1–T_4. If two differences (or more) are missing the arrival direction could not be computed and the shower was assumed vertical by the program. In the computer output this case had a special call and for the present analysis those showers were excluded. For all fast timing determinations that are usable TFIT is positive and for the showers selected in the present analysis it should have a value less than 3·0.

For the computation of arrival directions the quantity TFIT has the same significance as DFIT in the density fitting, the main difference is that TFIT represents the root-mean-square value of fluctuations in a gaussian distribution, as determined from only one or two samples.

3. Analysis of the arrival direction of air showers

A plot of the declination (δ) against right ascension (RA) for the 2598 EAS used in the analysis is made and this plot is divided into a grid of 5° δ and 5° RA. In figure 1 a 'map' (in the form of a table) is presented showing the number of showers in each bin. The distribution of the number of showers in each bin (5° $\delta \times$ 5° RA) along each declination band is then constructed. In each declination band those groups of showers (bins) which are above two standard deviations are then selected for further analysis. The procedure which defines 2σ here is as follows: in the Poisson probability $P = m^x e^{-m}/x!$, m is taken as the average number of showers per bin along each declination band (ie total number of showers in the band/72). The probability P, from a gaussian distribution (at 2σ) is 0·02275 (Pearson 1934, table 2, pp 2–8) and the number of showers per bin x which are above 2σ as defined above is then obtained. In order to consider the error in arrival direction and the deflection of particles by the galactic magnetic field, the bins are further enlarged so as to occupy a total area of $\pm 5°$ δ and $\pm 0·5$ h RA of the sky. The bins so selected are shown in figure 2. There are 36 such bins (39 expected). Figure 3 shows the distribution of pulsars' positions used. In the case of selecting the bins directly from a 10° × 15° plot, then are 9 bins above 2σ (~ 7 expected) and of these 3 coincide with known position of pulsars while 1·8 are expected from accidental coincidence; in this case however when there are only 7 (or 9) expected bins a somewhat different approach should probably be used to find any meaningful correlation.

The fact that the error considered in the arrival direction is of the order of $\pm 5°$, is equivalent to a search for particles which are not deflected by the galactic magnetic field (ie neutrons or protons arriving from nearby pulsars). The estimated angle between the arrival directions of cosmic rays of energies around 10^{17} eV and the earth–pulsar line is of the order of 7° for the closest pulsars if the primary is a proton. For the calculation of this angle the galactic magnetic field is assumed to be 1 μG and to be perpendicular

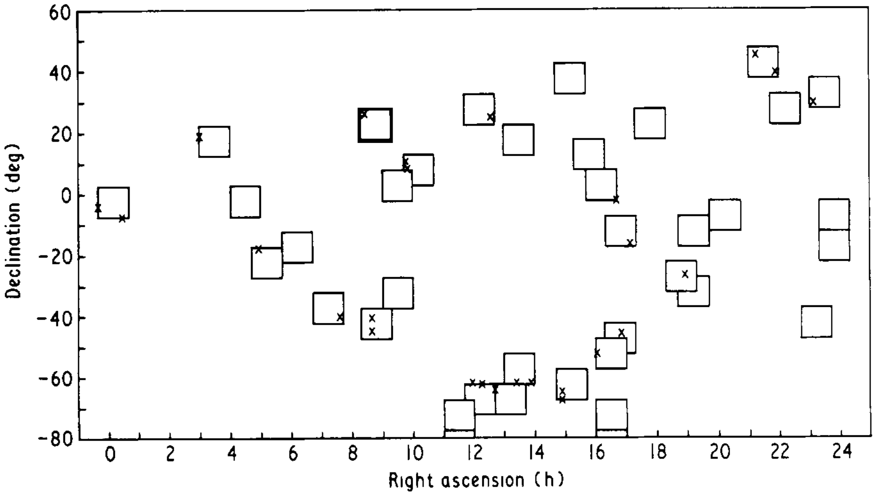

Figure 2. Selected groups (bins) of showers (cross in each bin in the position of corresponding pulsar).

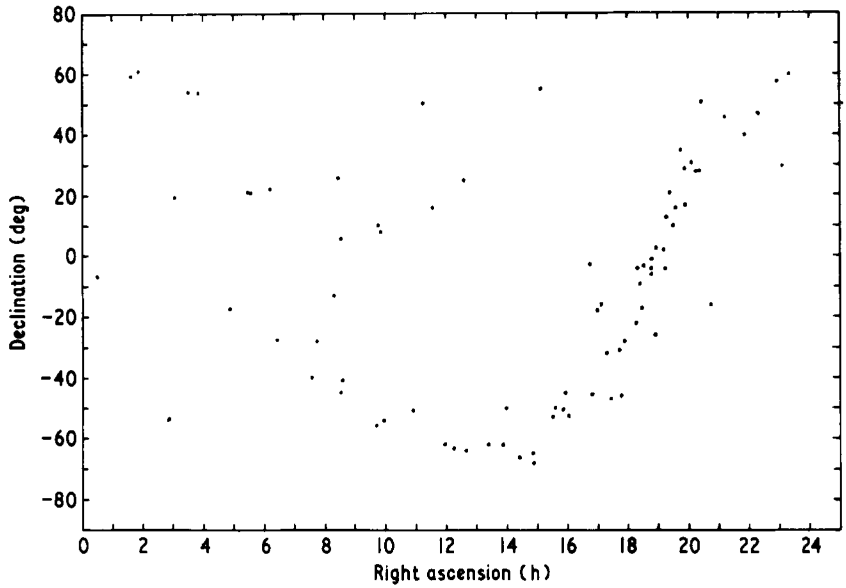

Figure 3. Position of pulsars.

to the passage of cosmic rays. Of course, the intensity of the field may not be the same in all given directions (see for example the work of Manchester 1972) so for a more accurate calculation the figure above should be revised for particular pulsar directions. The search for neutrons at a few times 10^{17} eV is also possible and has already been discussed (Osborne and Wolfendale 1972).

To search for a correlation between the bins of EAS selected and the direction of pulsars, a tracing of figure 2 is placed over figure 3 and the number of coincidences is then determined. If more than one pulsar falls inside the bin or if one pulsar falls in two bins, this is still counted as a single coincidence. In figure 2 those coinciding pulsars are marked with a cross. The number of accidental coincidences is determined by displacing the overlay by a phase $\Delta = +2, 4, \ldots, 12$ h and $-2, -4, \ldots, -12$ h RA and counting the number of coincidences in each case. Figure 4 shows the results obtained. It is seen from the figure that a significant peak appears when the phase is equal to 0, here the number of coincidences is 19 (21 if we consider two overlapping bins with two pulsars in each pair), while the number of accidental coincidences is 7·5. Also, a similar analysis has been carried out for 36 randomly selected bins and no correlation has been found in this case.

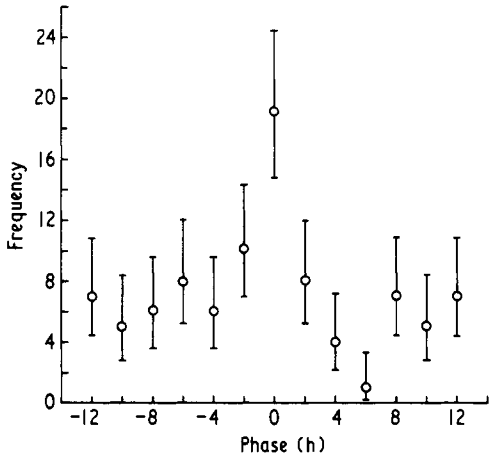

Figure 4. Frequency of pulsar–bin coincidences.

As is well known, the largest concentration of pulsars is in the RA range 17 h to 20 h; a plot of the distribution of the number of showers along RA is shown in figure 5. Fom the figure it is seen that a peak appears in the direction where the concentration of pulsars is largest, and, in the region of lowest concentration (about 0 h to 3 h) the number of showers is small. These peaks are just above (below) 2σ ($\sigma = \sqrt{\mu}$) respectively.

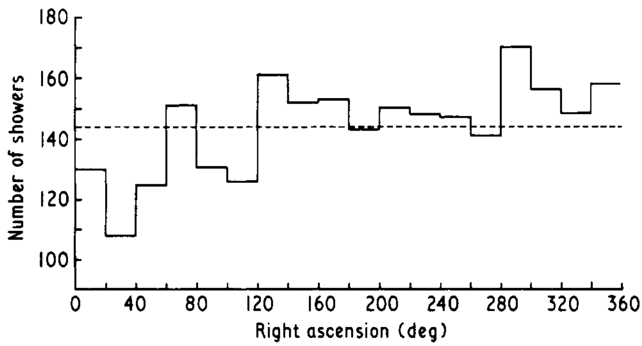

Figure 5. Distribution of showers along right ascension.

5. Discussion

Several attempts have been made to find a correlation between the arrival direction of air showers and the known position of pulsars. Many of these have been directed towards finding such a correlation for cosmic rays greater than 10^{19} eV (eg Suga 1972, Osborne and Wolfendale 1972); in both cases the approach was similar, considering (or not) the galactic magnetic field a one-to-one correlation was sought for. Brownlee *et al* (1970) considered showers of energies greater than 10^{18} eV and divided the sky into boxes one hour wide in RA by 10° declination and looked for a statistically significant increase in the shower number in each box with respect to CP0950. A similar approach was taken by Lapikens *et al* (1971) who divided the sky into a grid 10° RA by 10° δ, its results indicated that no strong preferred source region existed in the northern celestial hemisphere.

As far as the present results are concerned, for a more precise determination of the correlation of arrival direction and positions of pulsars the configuration of the galactic magnetic field should certainly be taken into consideration. It should be noted however that of the total number of coincident bins of showers 16 (or 18) coincide with pulsars which have distances less than 110 DM, while only 3 (or 1) at distances greater than 200 DM (DM stands for 'dispersion measure', the earth–pulsar distance is approximately proportional to the quantity). In this case if particles are accelerated from these closer pulsars the magnetic fields will have a 'weaker' effect and these cosmic rays will be virtually undeflected ($\pm 10°$).

It is also interesting to note that a large number of bins are concentrated along the galactic plane where also most of the pulsars lie.

Furthermore, according to Gunn and Ostriker (1969), the flux of cosmic rays at the earth is proportional to $(\mathrm{DM})^{-2}$ $(\mathrm{period})^{-2}$. In the present analysis, 10 bins of showers coincide with 10 of the 20 most 'intense' pulsars while 16 coincide with 16 of the 40 most intense.

A very crude estimate of the observed intensity from each pulsar gives 10^{-13} $\mathrm{m}^{-2}\,\mathrm{s}^{-1}$. The significance of this value will be discussed together with some refinements of the analysis procedure in a future paper.

In conclusion, the present preliminary analysis suggests that some at least of the cosmic rays in the energy range 10^{17}–10^{18} eV may originate in pulsars.

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References

Aguirre C *et al* 1973a *Proc. 13th Int. Conf. on Cosmic Rays, Denver* vol 4 (Denver: University of Denver) p 2576

Aguirre C *et al* 1973b *Proc. 13th Int. Conf. on Cosmic Rays, Denver* vol 4 (Denver: University of Denver) p 2592

Aguirre C *et al* 1973c *Proc. 13th Int. Conf. on Cosmic Rays, Denver* vol 4 (Denver: University of Denver) p 2598

Brownlee R G *et al* 1970 *Acta Phys. Acad. Sci. Hung.* **29** *Suppl.* 3 383

Gunn J E and Ostriker J P 1969 *Phys. Rev. Lett.* **22** 728–31

International Astronomical Union Circular 1972a No 2435
—— 1972b No 2436
—— 1973a No 2505
—— 1973b No 2563
Lapikens J *et al* 1971 *Proc. 12th Int. Conf. on Cosmic Rays, Hobart* vol 1 (Hobart: University of Tasmania) p 316
Manchester R N 1972 *Astrophys. J.* **172** 43–52
Osborne J L and Wolfendale A W 1972 *Proc. 3rd Eur. Symp. on Cosmic Rays* preprint
Pearson K 1934 *Table for Statisticians and Biometricians* vol 1 (Cambridge: Cambridge University Press)
Suga K 1972 *University of Tokyo INS Report* 180
Suga K *et al* 1963 *Proc. 8th Conf. on Cosmic Rays, Jaipur* vol 4 (Bombay: TIFR) pp 9–26
Terzian Y 1972 *Earth Extraterrestr. Sci.* **2** 63