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LETTER TO THE EDITOR

Evidence of an anisotropy in the arrival direction of cosmic rays with energies above 10^{19} eV

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Abstract. Evidence is presented that the arrival direction distribution of cosmic rays with energies above 10^{19} eV is not isotropic. Harmonic analyses indicate that there is, *prima facie*, a first harmonic (amplitude = 44%, chance probability = 2·6%, phase (in right ascension) = 13·3 ± 1·5 h) at declinations above 0°, and that there is a significant second harmonic (amplitude = 101%, chance probability = 0·2%, phase 7·8, 19·8 ± 1 h) at declinations below −30°. Supporting evidence from low energy data is also discussed.

A suggestion by Krasilnikov at the Fourth European Symposium on Cosmic Rays (Lodz, 1974) has prompted further analysis of the arrival direction distribution of large air showers produced by primary cosmic rays of energies in excess of 10^{19} eV. Data in this energy range have been accumulated over a number of years at Volcano Ranch (1959–1962), Haverah Park (1968–1972), Sydney (1968–1972) and Yakutsk (1970–1973). The statistical weight of the data now available is not to be regarded as conclusive, but much improvement cannot possibly be available for several years, and in view of the implications emerging, an interim statement seems sufficiently important to be given at this stage. Briefly, we find that there is evidence of a first harmonic of amplitude about 40% in the arrival direction distribution of primary cosmic ray particles above 10^{19} eV in the northern celestial hemisphere with maximum occurring at about 13 h RA. Our data are discussed below together with tentative conclusions, which rest both on the significance of the amplitude and on the persistence of the phase through the different experiments.

In table 1 we give the amplitudes and phases resulting from harmonic analyses of the data sets with declination, $\delta > 0°$, from the individual experiments. The harmonic analyses were carried out with the data grouped in 2 hour bins of RA (0–2, 2–4, ...). Most of the data, except those from Yakutsk, have been recently discussed by Linsley and Watson (1974a) in a search for point sources. None of the individual sets separately gives an amplitude which is significant, and for the 76 northern hemisphere events the overall significance of the 40% amplitude is only 2·6%. Strikingly, however, the phases of the harmonics for the individual experiments are consistently in agreement, a result which reinforces strongly the significance of the amplitude measurement. It has been noted by a number of authors previously (see, for example Sakakibara 1965) that there

Table 1. Energy $>10^{19}$ eV, declination $>0°$

Detector array	Showers	Amplitude of 1st harmonic (%)	$p\,(>a)$	Phase (RA) (h)
Volcano Ranch + Cornell	14	48·3	0·44	17·4 ± 3·4
Haverah Park	31	53·5	0·11	13·8 ± 2·0
Sydney	11	61·5	0·35	7·5 ± 2·8
Yakutsk	20	67·3	0·10	13·0 ± 1·9
All groups	76	43·7	0·026	13·3 ± 1·5

is often remarkable consistency in phase between different experiments even when the measured amplitudes are themselves of negligible significance. A full discussion of this feature will be given in a paper in preparation (Linsley and Watson 1974b).

In figure 1(*a*) we show how the significance of the amplitude of the first harmonic has increased as a function of the number of events which have been recorded. The significance of the amplitude is expressed as the probability that the measured fractional amplitude, a, would be exceeded by chance if the true arrival direction distribution was random. The probability can be expressed as $p(>a) \sim \exp(-a^2N/4)$, where N is the number of events recorded (Chapman and Bartels 1940). It is natural to have reservations about the applicability of this equation to samples as small as those of table 1. However, Monte Carlo checks have been made on this formula and it has been found to be accurate to about 10% for values of N as small as 10.

In figure 1(*b*) we show the way in which the phase of the maximum amplitude has changed as the number of events has increased. The error bars on the phase measurements represent 66% confidence levels and it is important to notice that the uncertainty has changed very little for a five-fold increase in data. The 66% confidence limits have been calculated from the differential probability distribution function for the phase:

$$p(\theta)\,\mathrm{d}\theta \sim \exp\left(-\frac{a^2N}{2}(1-\cos\theta)\right)\mathrm{d}\theta.$$

The derivation and justification for the use of this expression in general situations are given in Linsley and Watson (1974b).

Examination of the northern hemisphere data in table 1 shows that the measurements of the Sydney group, which are all at declinations less than 30°, suggest a phase of maximum amplitude rather earlier in sidereal time than for the northern latitude arrays. Although this phase measurement is not particularly inconsistent with the mean value of (13·3 ± 1·5) h, it prompts an investigation of the phase and amplitude as a function of declination. Such a break-down is shown in table 2 for 60° bands of declination. The data show that the first harmonic (phase about 13 h, amplitude ~68%) at northern declinations ($\delta > 30°$) dies away at equatorial latitudes and is replaced by a very significant second harmonic at southern latitudes ($\delta < -30°$).

In table 3 we show the results of first and second harmonic analyses for showers of lower energy. Insofar as more data exist although not in a form for immediate use, these results may be regarded as preliminary. For the Volcano Ranch and Haverah Park data it has been possible to use a relatively narrow energy band from about 5×10^{18} to 10^{19} eV, but for the Sydney data (Bell *et al* 1973) the data at present cover a

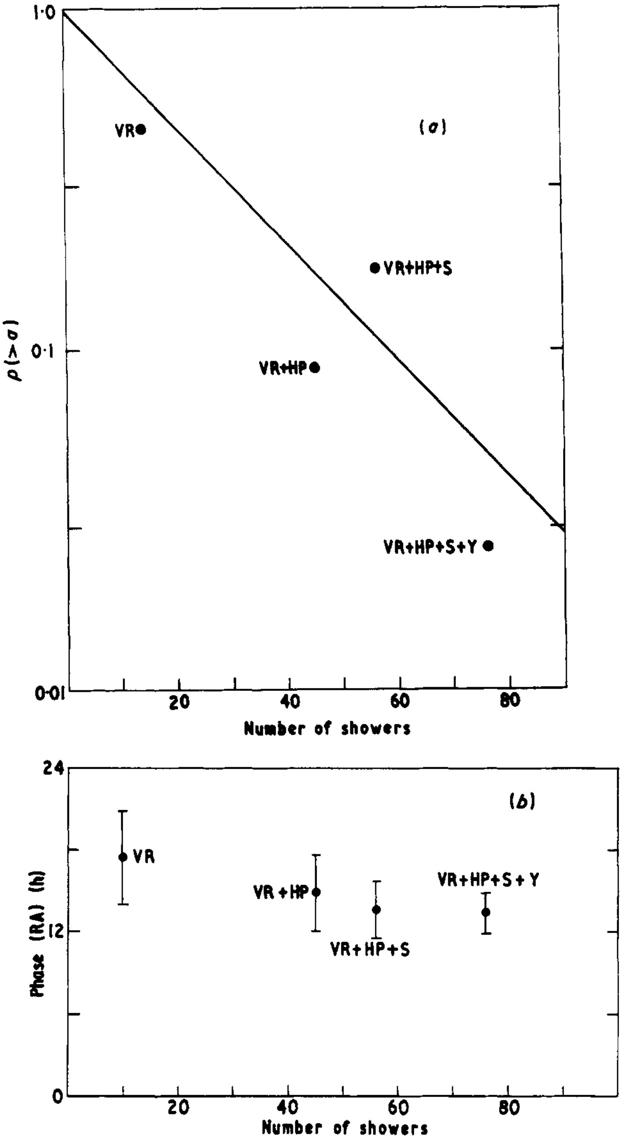

Figure 1. (*a*) Probability of the observed first harmonic being exceeded by chance as a function of the (cumulative) number of showers recorded. Data are the events with energies above 10^{19} eV recorded with declination greater than zero, and the points show the decrease in the probability as the number of events was increased. (*b*) The phase of the observed first harmonic as a function of the number of showers recorded. The error bars indicate 66% confidence limits. The line is that expected for $a = 0{\cdot}4$.

In these figures the data for the points are:

1, Volcano Ranch + Cornell (VR);

2, Volcano Ranch + Cornell + Haverah Park (VR + HP);

3, Volcano Ranch + Cornell + Haverah Park + Sydney (VR + HP + S);

4, Volcano Ranch + Cornell + Haverah Park + Sydney + Yakutsk (VR + HP + S + Y).

The data used in points 1, 2 and 3 have previously been discussed by Linsley and Watson (1974a) and the data from Yakutsk were presented by Krasilnikov at the Lodz meeting.

Table 2. Energy $>10^{19}$ eV, in declination bands

δ bands (deg)	Showers	First harmonic			Second harmonic		
		Amplitude (%)	$p(>a)$	Phase (RA) (h)	Amplitude (%)	$p(>a)$	Phase (RA) (h)
90 to 30	47	64·6	0·007	$13{\cdot}5\pm1{\cdot}0$	11·3	0·86	$(1 \text{ and } 13)\pm7$
30 to −30	49	15·4	0·745	$21{\cdot}5\pm5{\cdot}6$	9·1	0·90	$(12 \text{ and } 24)\pm8$
−30 to −90	23	34·4	0·504	$21{\cdot}1\pm3{\cdot}8$	100·6	0·002	$(7{\cdot}8 \text{ and } 19{\cdot}8)\pm1$

Table 3. Energy $<10^{19}$ eV

δ bands (deg)	First harmonic			Second harmonic		
	Amplitude (%)	$p(>a)$	Phase (RA) (h)	Amplitude (%)	$p(>a)$	Phase (RA) (h)
Haverah Park + Volcano Ranch: 5×10^{18} eV $< E_p < 10^{19}$ eV						
90–30 (100 showers)	14·0	0·61	$13{\cdot}1\pm4{\cdot}7$	35·2	0·045	$(2{\cdot}6 \text{ and } 14{\cdot}6)\pm1{\cdot}6$
<30 (61 showers)	24·3	0·41	$10{\cdot}6\pm3{\cdot}2$	38·2	0·11	$(5{\cdot}0 \text{ and } 17{\cdot}0)\pm1{\cdot}2$
Sydney: $\bar{E}_p \sim 10^{18}$ eV						
30 to −30 (4900 showers)	0·8	0·92	$8{\cdot}7\pm7{\cdot}8$	4·8	0·056	$(6{\cdot}5 \text{ and } 18{\cdot}5)\pm1{\cdot}7$
−30 to −90 (4148 showers)	4·2	0·16	$9{\cdot}4\pm2{\cdot}1$	3·2	0·34	$(7{\cdot}5 \text{ and } 19{\cdot}5)\pm2{\cdot}8$

broader energy band for which the mean energy must be less than 3×10^{18} eV. In these energy bands the amplitudes of the first harmonics are generally insignificant but it is interesting to note that the phase from the data with $\delta > 0°$ remains near to 13 h. Significant second harmonics are also shown by the data (except for the low declination Sydney band); the phase of the second harmonic appears to become later at lower latitudes.

Conclusions

We are satisfied that there is *prima facie* experimental evidence for:

(i) A large amplitude first harmonic of phase about 13 h in northern celestial latitudes for showers of cosmic rays with energies above 10^{19} eV.

(ii) A large amplitude second harmonic for showers of cosmic rays with energies above 10^{19} eV at southern latitudes.

(iii) Significant second harmonics in data for showers of cosmic rays with energies below 10^{19} eV at declinations greater than $-30°$.

(iv) A persistence of the 13 h phase of the first harmonic in northern latitude data to lower energies, but with rather quickly falling amplitudes.

At the present time the origin of the observed anisotropies is obscure, but it may be relevant that of the 12 clusters of galaxies within 300 Mpc of our own galaxy, seven are in RA band 12 ± 4 h, and six of these at declinations greater than 10°. Two of the largest galactic clusters, Virgo and Coma, are in this right ascension band, and it may be that the first harmonic at high energies results as a feature of storage in the Virgo supercluster. Within the limits of the present data the second harmonics measured could be interpreted as extending more or less unaltered over a wide range of declinations and thus might be thought of as caused by a magnetic field effect on a local galactic scale as suggested by Syrovatsky (1969, 1971). A second harmonic at northern latitudes and at energies above 10^{19} eV would be masked by the strong first harmonic observed there.

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