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Cosmic Ray Anisotropy below 10^{15} eV

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Abstract

Measurements have been made of the cosmic ray anisotropy at 35°S with a sea-level unshielded air shower array sensitive primarily to the proton component of the cosmic ray beam with energies between 10^{14} and 3×10^{15} eV. The first harmonic of the anisotropy was found to have an amplitude of $0\cdot34(\pm0\cdot09)$% at a phase of $318(\pm18)$°.

1. Introduction

The origins of the cosmic ray beam are uncertain and the processes of its propagation through the galactic magnetic fields remain the province of untested conjecture at energies above $\sim10^{14}$ eV. Progress is now being made towards a solution of the origin problem through searches for sources of energetic gamma-radiation, particularly from neutron star binary systems (Protheroe 1987). It is believed that the production of such gamma-rays is a signature of some cosmic ray sources. Indeed, below $\sim10^{16}$ eV it is possible, at least on energetic grounds, that such sources might provide the whole of the cosmic ray beam (Hillas 1984). However, at any one time, it is believed that there are very few sources of this kind operating and, also, that they are largely confined to the galactic plane. This leads one to expect an observable directional dependence in the cosmic ray beam. Thus, to approach a proper understanding of the cosmic ray beam we must address the problem of the extreme isotropy of the observed cosmic rays.

It appears that very few experiments have measured a statistically significant anisotropy above energies of $\sim10^{14}$ eV which thus must be characteristically below the 1% level (Clay 1987*a*). It would appear either that propagation of cosmic rays within the galaxy is dominated by an efficient randomising process or that our ideas of cosmic ray sources are quite wrong. Clearly, it is important to perform experiments which reduce to as low a level as possible the observational limits on the magnitude of the anisotropy and perhaps reach a level giving statistically significant results.

The study of cosmic radiation is unique in astronomy in terms of the energy range it covers. There is roughly a factor of 10^{10} between the energy extremes of the known cosmic ray beam. It would seem unlikely that the propagation process would be the same over the whole energy range and so we

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must treat limited energy ranges separately. At the lowest energies, the local cosmic ray propagation is dominated by heliospheric processes and it is only with great difficulty that measurements of an interstellar beam can be inferred (Elliot 1979). Above $\sim 10^{12}$ eV this problem is eased and galactic processes, corresponding to rather small radii of curvature in the galactic magnetic field, presumably become important in determining the observed anisotropy. At higher energies, in magnetic fields of a few microgauss one would expect a change in propagation characteristics due to the limited galactic dimensions since the proton radius of curvature exceeds a few parsecs when the energy exceeds a few times 10^{15} eV. At substantially higher energies one presumes that galactic loss mechanisms dominate the propagation.

It is disturbing to note that, except perhaps well below 10^{14} eV, there are no directional cosmic ray observations which are clearly above statistical background expectations (Clay 1987*a*). The measured first harmonic amplitude in right ascension is rarely large compared with the expected amplitude from a random selection of the number of observed events. On the other hand, it is remarkable that the phases of the first harmonics do seem consistent between many experiments over the whole energy range.

In order to properly understand the anisotropy, there is a need to lower the level of the statistical background through observations including very large datasets. There is also a great need for southern hemisphere (and equatorial) observations to complement the present bias towards northern hemisphere mid-latitude observations. We have taken data recorded by the recently upgraded Buckland Park air shower array over two years from mid-1984 and analysed these data consisting of $\sim 3\times10^{6}$ cosmic ray events to determine a southern hemisphere anisotropy at primary energies a little below 10^{15} eV.

2. Buckland Park Air Shower Array

The Buckland Park air shower array consists of 27 scintillator detectors with a total enclosed area of $\sim 3\times10^{4}$ m^{2}. It has a threshold shower size of $\sim 10^{4}$ particles, roughly corresponding to a primary particle energy of 10^{14} eV for this sea-level based array. The median shower energy is $\sim 9\times10^{14}$ eV and the most probable energy about 4×10^{14} eV. The array is located at sea-level at a latitude of 35°S. The operation of the array has been described extensively elsewhere (Ciampa *et al.* 1986). Over the observation period, the angular resolution of the array in its normal trigger mode had a worst case of $\sim 8°$ and a typical value of $\sim 2°$.

The array recording system is located in a temperature controlled laboratory but the detectors themselves, though insulated, are located in the open. In addition to air, detector and laboratory temperatures, a record is kept, for each event, of the local atmospheric pressure.

3. Observations

Data were recorded from June 1984 until July 1986 with a 74% on-time efficiency. The mean event rate for the array when operating normally was about one event each ten seconds. Data were stored on magnetic tape, each of which was filled in about four days so that a gap in the dataset occurred typically at this period, usually at about the same solar time.

We have used the mean rate of events in 15 minute intervals to determine the barometric coefficient of our event rate. This gave a value of $-0 \cdot 8\%\,\mathrm{mb}^{-1}$ which is consistent with results from other arrays based on unshielded scintillators and also with results from this array in a previous configuration (Gerhardy and Clay 1983).

There is a serious problem with measurements of small anisotropies as a result of spurious effects arising from the incomplete cancelling of (solar) rate variations, due to extraneous factors over the measurement period. In the case of this experiment, observation over an integral number of years is useful in helping to cancel out solar effects. However, there will still not be completely uniform coverage in sidereal time due to breaks in the data when data tapes are changed and array maintenance is performed, nor will there be a complete cancellation of any spurious effects due to atmospheric pressure variations. In analysing a dataset such as this, an option is to apply the procedure of Farley and Storey (1954) which examines other Fourier components in the event sequence to correct the sidereal harmonics. Such a procedure was rejected in this case because we found that a large correction was necessary resulting from some equipment breakdowns in the second year of operation. As an alternative, we separately allowed for any on-time effect in our sidereal data by using only data recorded over full sidereal days and rejecting incomplete sidereal days at the end of each tape run. We also allowed for the known barometric dependence of the rate by weighting each event by a factor derived from the measured barometric pressure and the barometric coefficient. As a result of this selection process, $2 \cdot 7 \times 10^6$ weighted events were available for processing.

A periodic analysis of the data was carried out by examining the amplitude and phase of the first and second harmonics of periods ranging from 23 to 25 hours. We found a large residual first harmonic solar component ($1 \cdot 4\%$) which peaked at ~2 p.m. local time and was presumably a temperature effect in our detectors. This effect had not been previously identified, probably due to the dominating pressure effect. We removed this solar effect in a similar manner to the barometric effect through a weighting of each event using the measured temperature coefficient of the event rate.

The dataset of weighted events was used to produce a sky map of event arrival directions in a right ascension/declination grid. This grid was then analysed to obtain a right ascension first harmonic amplitude of $0 \cdot 34(\pm 0 \cdot 09)\%$ at a phase of $318(\pm 18)°$. The second harmonic had an amplitude of $0 \cdot 12(\pm 0 \cdot 09)\%$ at a phase of $163(\pm 41)°$.

4. Discussion

Cosmic ray anisotropy measurements between 10^{14} and 10^{15} eV are sparse. The available dataset is dominated by the measurements of Daudin *et al.* (1956) in the northern hemisphere. In two experiments at 43°N they found first harmonics of $0 \cdot 09(\pm 0 \cdot 02)\%$ at $306(\pm 15)°$ R.A. and $0 \cdot 12(\pm 0 \cdot 05)\%$ at $298(\pm 25)°$ R.A. with $3 \cdot 5 \times 10^6$ and $7 \cdot 1 \times 10^6$ events respectively. Citron and Stiller (1958) at 48°N did not claim a true sidereal variation with 6×10^6 events at 4×10^{14} eV, but Linsley and Watson (1977) examined their uncorrected histograms and deduced a value of $0 \cdot 09 \pm (0 \cdot 06)\%$ at $332(\pm 38)°$ R.A. Escobar *et al.* (1960) analysed a total of 415 days of data taken at 16°S with an energy of 5×10^{14} eV. They claimed no significant sidereal effect, but Linsley and Watson (1977) deduced $0\cdot1(\pm0\cdot1)$% at $148(\pm57)°$ R.A. from their histograms. Farley and Storey (1954) (37°S) with $8\cdot9\times10^5$ events at 10^{15} eV obtained a dataset interpreted by Linsley and Watson as giving an anisotropy of $0\cdot14(\pm0\cdot15)$% at $214(\pm61)°$ R.A.

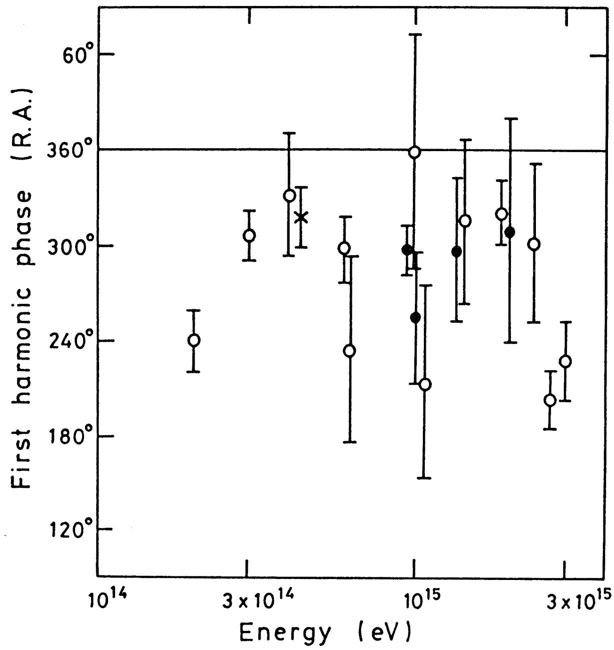

Fig. 1. Phase of the first harmonic of the cosmic ray anisotropy between energies 10^{14} and 3×10^{15} eV. Northern hemisphere results are identified by open circles and those from the south by filled circles. The result from the present observation at latitude 35°S is marked by a cross at the most probable energy of the dataset.

Data at somewhat lower energies have been reviewed by Elliott (1979) and above 10^{12} eV appear to give a roughly energy independent anisotropy of $\sim0\cdot08$% at ~1 hr R.A. At higher energies (10^{14}–10^{16} eV) characteristic first harmonic phases are ~180°–360° R.A. with amplitudes compatible only with the statistical uncertainty associated with the size of the dataset (see Clay 1987*a*, 1987*b*). The overall situation is shown in Fig. 1 which suggests that phase observations are in reasonable agreement over the range 10^{14} to 3×10^{15} eV. However, it is necessary to recognise that there is little agreement in direction in the sky between a right ascension of 300° measured at 43°N and one of 300° at 35°S; these are quite different directions.

It is possible that the data in Fig. 1 might still be compatible as discussed by Clay (1984) since cosmic ray streaming along a particular direction (in this case close to the direction of our spiral arm) results in a maximum intensity in the upstream direction and a minimum in the downstream direction. Since the first harmonic of the anistropy is quoted in terms of the direction of the maximum of a fitted sine wave, a minimum in a downstream direction would be reported as a maximum 180° away at a certain latitude/declination. Also, since the upstream and downstream directions differ by 180° in galactic coordinates they also differ by 180° in R.A. (now with differing declination). As a result, a first harmonic direction due to a minimum at a declination observing downstream will be reported as a maximum at the correct R.A. of the upstream direction even when viewed from a hemisphere not containing the upstream direction. Thus, as observed, northern and southern observations at declinations near the streaming directions would obtain the same first harmonic result (the second harmonics, if well measured, would deviate by six hours). If the streaming is at high declinations, equatorial observations would produce an indeterminate result of lower statistical significance. Similarly, these predictions lead to the expectation that, at energies which might correspond to containment by the magnetic field of our spiral arm (perhaps up to $\sim 10^{16}$ eV), measured anisotropies would be most significant at middle latitudes (~35°) both north and south of the equator. The data presented in this paper support such a model.

5. Conclusions

A measurement has been made of the cosmic ray anisotropy in southern declinations at energies somewhat below 10^{15} eV. An anisotropy of ~0·3% has been found for declinations of ~35°S which is a little higher than previously reported values. The direction of the anisotropy is compatible with local streaming of cosmic rays roughly along the galactic spiral arm.

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