Anisotropy and the Knee of the Energy Spectrum

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1. Introduction The measured cosmic ray energy spectrum exhibits clear structure (the knee) at ~ 3×10^{15} eV (sea level shower size ~ 3×10^5 particles). Additionally, at energies in this general region, there occur apparent changes in shower development such that the observed characteristics of showers at this energy appear different to those characteristics observed at somewhat higher energies (see eg. Linsley 1983). At energies just below this region, the cosmic ray anisotropy amplitude apparently begins a progressive increase with energy. The latter effect does not clearly fit with the first two since there appears to be no significant change exactly at the knee. However, the phase of the first harmonic of the anisotropy appears to show a substantial change just where the energy spectrum shows structure and in the middle of the shower development changes. The first harmonic phase appears to change from ~ 18 hours R.A. to ~ 5 hours R.A. (see eg. Clay (1984)) as the energy of observation moves through the knee. In this paper I wish to examine the latter change in some detail by taking into account information contained in the second harmonic of the anisotropy.

2. Anisotropy measurements near the Knee Anisotropy measurements at one location are not sufficient to define the true celestial anisotropy since only a limited range of declinations is observable at a given latitude. This limitation is particularly severe for air shower arrays which use scintillators to sample the electron-photon component since atmospheric attenuation with increasing zenith angle is severe. This effect was useful for collimation in early experiments. Available anisotropy results are therefore, unfortunately, rather incomplete with measurements being biased towards temperate latitudes with convenient land sites. The overall sky coverage of most experiments is ~ 20° to 60° N and ~ 15° to 40° S. At ~ 10^{15} eV, just below the knee, there is a good deal of agreement between the various experiments on the observed phase of the first harmonic. This is remarkable because the southern observations really view an independent part of the celestial sphere to the northern observations.

There is an ambiguity in anisotropy results presented in terms of first harmonics. A sine wave is fitted to the data in right ascension but there is no information on what properties of this fourier component are of physical significance. It is not obvious, although it is conventionally stated, that the phase of the maximum of the fitted wave is physically appropriate, unless, for instance, one is interested in searching for the superposition of a number of high energy gamma ray sources. In the latter case, the anisotropy maximum will indicate a direction with an excess of sources. However, for the diffusion of charged particles, the position of maximum on the celestrial sphere will give the direction of the "upstream" diffusion direction and there will be a minimum in the "downstream" direction. In general, a particular declination will not include both the upstream and downstream directions leading to an ambiguity for latitudes which include observation of only the downstream direction.

I have pointed this out before (Clay 1984) and shown that, on the basis of the observed directions of first harmonic maxima at $\sim 10^{15}$ eV , one might interpret the global data as representing a diffusive flow of cosmic rays along the galactic spiral arm. In order that this be so, it is necessary that, at energies below the knee, the southern hemisphere phase of the first harmonic minimum is the physically interesting parameter since this represents the direction towards which diffusion is occurring. Other explanations of the overall anistropies at these energies are possible and one suggestion has been that they may be due to unresolved ultra high energy gamma ray sources (Wdowczyk and Wolfendale 1983). A test between these possibilities would be to see whether or not there is any additional reason in the data for the first harmonic minimum to appear to be more physically significant rather than the maximum.

In the diffusive model, since the spiral arm is of limited extent in the sky, one would expect a relatively sharp peak of the anisotropy in the source direction and a similar trough in the downstream direction. In the gamma ray source model, only positive effects due to an admixture would be expected and no particular sharp dips or peaks would be necessary. In the latter case, one might in general expect only a diffuse excess for general galactic directions unless only specific galactic region contained the most powerful sources. An examination of the second harmonic can help resolve these possibities.

3 Inclusion of the Second Harmonic Figure 1 shows data obtained by Farley and Storey (1954). The phase of the first harmonic maximum is indicated and it would appear that there is no particular significance in this phase. The total data set can be described quite well with the inclusion of the second harmonic as illustrated. Also, an examination of figure 1 suggests that the region at about 8 hours is likely to be physically interesting rather than the 20 hour phase. This is in the vicinity of the minimum of the first harmonic.

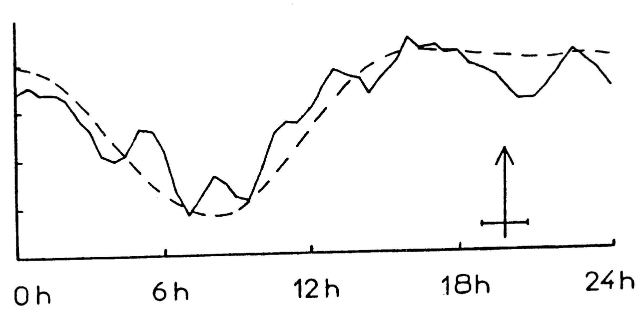

Fig. 1 Data presented by Farley and Storey 1954. The combination of their first and second harmonics are included (unnormalised) together with an indication (arrow) of the phase of the first harmonic maximum.

I have examined the data included in the compilation of anisotropies by Linsley and Watson (1977) and have also included more recent Adelaide data (Gerhardy and Clay 1983). Where appropriate I have combined data from similar latitudes and energies and have added first and second harmonics to derive representations of the original data in terms of R.A. or sidereal time. I then examined these distributions to see whether or not they subjectively contained a peak or a trough and, at what celestial direction this occurred. Some results of this procedure are shown in figure 2 with peaks indicated by + and troughs by −.

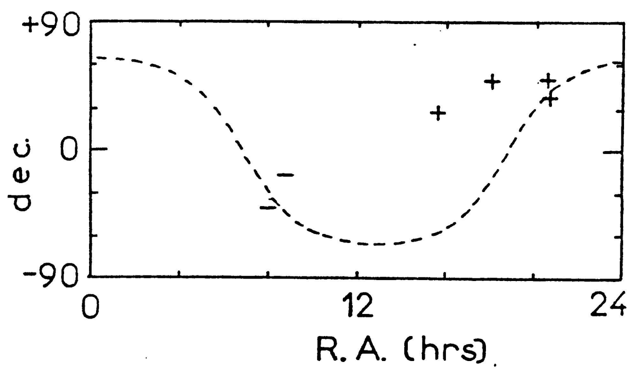

Fig. 2 The positions of peaks (+) or troughs (−) in anisotropy data available for energies ~ 10^{15} eV.

Figure 2 indicates that this procedure lends weight to the hypothesis that the cosmic ray flow below the knee is diffusive with its source in the inward spiral arm direction. There are peaks from a number of experiments clustering generally in that direction and there are also apparently troughs in the opposite direction from independent experiments in the other hemisphere.

At higher energies, the situation is much less clear. It seems to me likely that the statistical uncertainty in detail of the anisotropy is such that the technique cannot be used for such small data sets where the overall flux is low.

4. Conclusions When anisotropy results are presented in terms of the phase of first harmonic maximum, that particular direction may not be the physically significant direction for the data set. Additional use of the second harmonic can clarify this when data with sufficient statistics are available. It appears that, at least at 10^{15} eV, cosmic ray anisotropy data are most compatible with diffusion along the galatic spiral arm from the inner to outer galactic regions.

References

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