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The Search for Cosmic-Ray Anisotropies [and Discussion]

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The search for cosmic-ray anisotropies

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At the present time there is no generally accepted evidence for any statistically significant anisotropy in the energy range 10^{17}–10^{19} eV. The upper limits on the possible anisotropy provide strong evidence that these particles are extra-galactic.

In that part of the cosmic-ray magnetic rigidity spectrum below *ca.* 2×10^{11} V the interplanetary magnetic field effectively prevents the detection of anisotropies in interstellar space and the only isotropies measured are associated with the solar wind and its associated magnetic field.

In the range of magnetic rigidities extending from 10^{11} to 10^{12} V the cosmic-ray intensity shows evidence for a small anisotropy of about 2×10^{-4} which can be explained as the result of solar motion relative to the average galactic rotation in our neighbourhood. When this is removed the residual deviations from the mean intensity preclude any systematic sinusoidal variation greater than 2×10^{-4}. This high degree of isotropy is most easily understood if these particles are members of an extra-galactic population and it is suggested that this extra-galactic component predominates from the highest cosmic-ray energies down the spectrum at least as far as *ca.* 10^{11} V rigidity.

INTRODUCTION

In discussing the isotropy of the primary cosmic rays it is necessary to distinguish between different ranges of energy, or perhaps more appropriately, magnetic rigidity. Figure 1 shows one version of the primary spectrum for the protons where it has been assumed that the air showers are produced predominantly by protons rather than heavy nuclei. At rigidities below a few tens of GV the intensity is variable from day to day and over the solar cycle because of modulation by the solar wind and interplanetary magnetic field whereas at higher rigidities it remains constant. It is conventional practice to represent the spectrum in this constant intensity region above about 30 GV by a power law with a constant exponent. In order to produce an acceptable fit to the data with this form of representation it is necessary to postulate two such power laws, one with exponent 2.5–2.6 in the range 3×10^{10} V to *ca.* 10^{15} V and a second with exponent *ca.* 3.0 from 10^{15} upwards. The dotted lines in figure 1 represent these two power laws.

This representation of the spectrum implies that there is some significant change in the character of the cosmic rays in the neighbourhood of 10^{15} V rigidity. As will be evident from the diagram there is some latitude in the choice of rigidity at which this change takes place, depending upon how much confidence is placed on the energy determination of primaries of 10^{15} eV and above. The dotted line would imply a somewhat more conservative estimate of these energies than that which is generally used.

There are two points that should be borne in mind in this connexion. First the primary particle energies in that part of the spectrum above about 10^{13} V rigidity are deduced from air shower measurements whereas below 10^{11} V they are measured directly and this change in the technique of measurement must inevitably introduce some uncertainty as to how the two regions should be joined together. Secondly, there is no *a priori* reason to suppose that the

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cosmic-ray spectrum is a power law with constant exponent. In the latter respect a reasonable representation of the spectrum which involves no sharp change in slope is given by an expression of the form

$$(\mathrm{d}N/\mathrm{d}R) = 10^4 R^{-(2.5+\alpha \lg R)}\ \mathrm{m^{-2}\ sr^{-1}\ GV^{-1}\ s^{-1}}$$

where α is between 0.02 and 0.03 and R is measured in GV. Admittedly this requires a slight downward revision of some of the estimates of the air shower energies but taking into account the uncertainties revealed by the published data it is not apparent to me that such a reduction can be excluded at this time. With these considerations and uncertainties in mind I shall place no special significance in the change in spectral slope in the 10^{15} V region in discussing the anisotropy data.

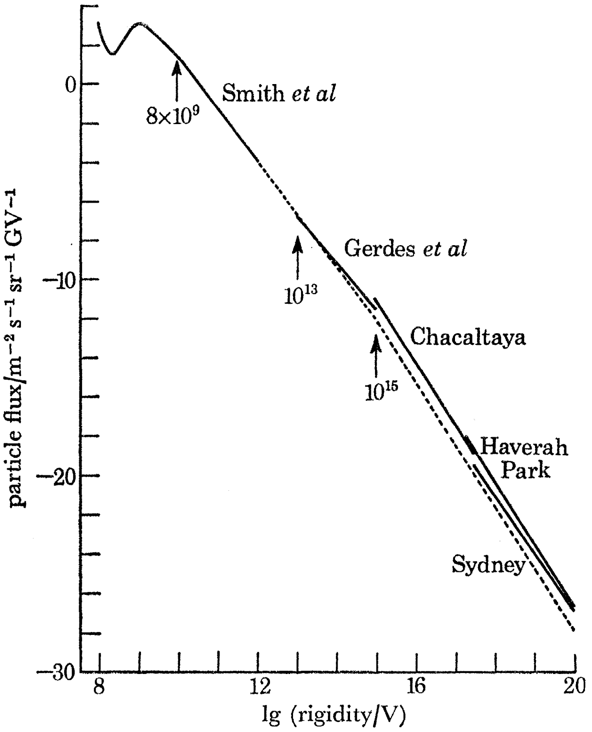

FIGURE 1. The magnetic rigidity spectrum for cosmic-ray protons. The full lines represent experimental data and it is assumed that air showers are produced predominantly by proton primaries. The dotted lines prepresent power laws with exponents 2.6 and 3.0 joined at 10^{15} V. (Haverah Park data from Edge *et al.* 1973; Sydney data from Bell *et al.* 1973; Chacaltaya data from Lapointe *et al.* 1968).

The greater part of the cosmic-ray energy density in space lies in that part of the particle energy spectrum below 10^{10} eV and if we take the value of the galactic magnetic field to be about 3×10^{-10} T individual cosmic rays of this energy, whether they be protons or heavier nuclei, have trajectories with a radius of curvature of the order 10^{13} cm or less. This is tiny compared with galactic dimensions and it follows therefore that the motion of the bulk of the cosmic rays in the galactic field is strictly adiabatic, that is to say the particles will be closely constrained to follow the magnetic lines of force. However, at the other end of the spectrum a primary with magnetic rigidity 10^{19} V has a Larmor radius of 10^{22} cm in the galactic field which is large compared with the thickness of the galactic disk and consequently at this energy broad features of a galactic source distribution should be discernible. It will be clear, therefore,

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that because of the enormous energy range spanned by the cosmic-ray spectrum it is necessary to distinguish between different spectral regions when discussing isotropy or anisotropy measurements.

THE SEARCH FOR ANISOTROPIES AT HIGH ENERGIES

I shall begin with this high energy region where one might reasonably expect to obtain evidence for a non-symmetrical source distribution in the Galaxy if it exists. Let me also say at the beginning that up to the present time no generally accepted evidence for any departure from isotropy has been found at these energies.

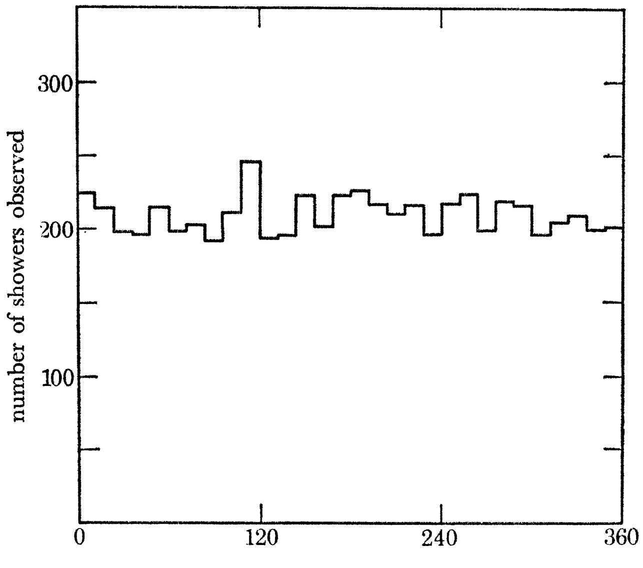

FIGURE 2. Distribution of arrival directions of showers with $E_p \geqslant 3 \times 10^{17}$ eV (taken from Brownlee *et al.* 1973). 6292 showers: $-7.5° < \delta < 7.5°$.

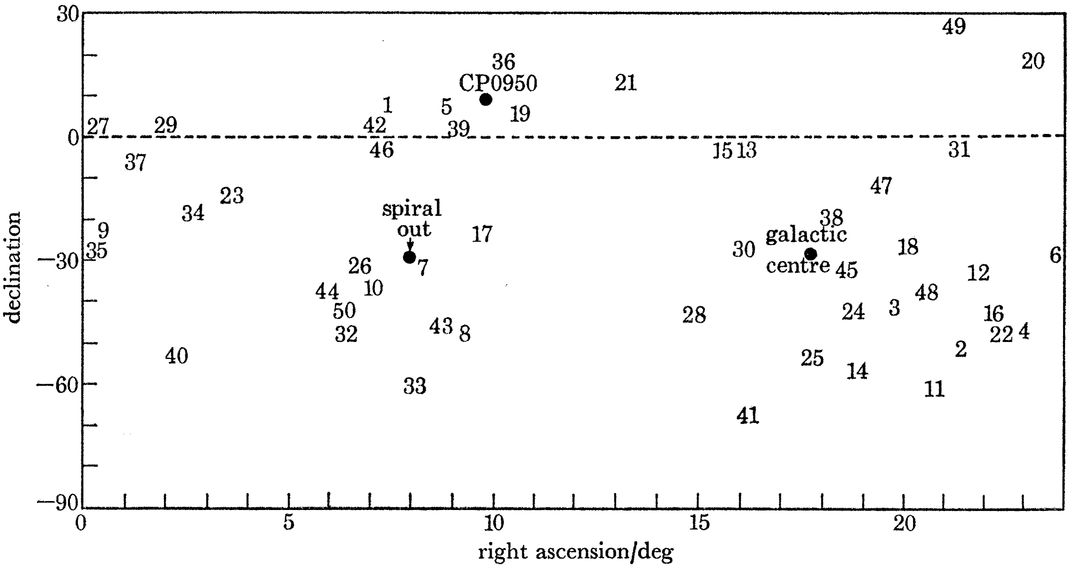

FIGURE 3. Directions of arrival for 50 showers with $E_p \geqslant 1.5 \times 10^{19}$ eV (taken from Bell *et al.* 1973).

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Having said that, I will now briefly mention some representative observational data. In recent years some evidence has been presented for an excess radiation in the energy region $> 10^{17}$ eV coming from the direction $-7.5^\circ < \delta < 7.5^\circ : 132^\circ < RA < 144^\circ$ (Bell *et al.* 1971) but these authors point out that the excess in the 3478 showers sampled could also be interpreted as a statistical fluctuation. The latter interpretation is borne out by figure 2 which shows some more recent data for 6292 showers of energy $\geqslant 3 \times 10^{17}$ eV from the Haverah Park array for this region of the sky. It will be apparent that there is no significant enhancement of intensity in the latter data in the direction in question (Brownlee *et al.* 1973).

Figure 3 shows the distribution of arrival directions of 50 large showers with energy estimated $> 1.5 \times 10^{19}$ eV obtained using the Sydney air shower array (Bell *et al.* 1973) which, in the words of the report in which they were presented, 'are not obviously isotropic'. However, rather more recently Linsley & Watson (1974) have taken all available showers of this energy, 37 in number, detected by the Cornell, Volcano Ranch and Haverah Park arrays and adding them to the 50 Sydney showers come to the conclusion that there is no statistically significant departure from isotropy for these 87 giant showers.

It is perhaps useful to quote some other upper limits to departure from true isotropy at slightly lower energies. These are shown in table 1 which is taken from the paper presented at the recent Denver Conference by the Haverah Park group (Brownlee *et al.* 1973).

TABLE 1

shower sample	number	% harmonic 1st	% harmonic 2nd
$10^{18} < E_p < 3 \times 10^{18}$ eV			
$\theta < 30^\circ$	344	4 ± 8	7 ± 8
$\theta < 60^\circ$	951	6 ± 5	1 ± 5
$3 \times 10^{18} < E_p < 10^{19}$ eV			
$\theta < 30^\circ$	62	—	—
$\theta < 60^\circ$	192	4 ± 10	24 ± 10
$E_p > 10^{19}$ eV			
$\theta < 60^\circ$	31	—	—

θ is the zenith angle of the shower axes.

It seems then that at the present time we have no conclusive evidence for a measured anisotropy in that energy region where we might reasonably expect to see signs of a galactic source distribution if it existed. If we accept the radio astronomical evidence which leads to a galactic magnetic field strength of a few 10^{-10} T this absence of discernible anisotropy leads inescapably to the conclusion that primary cosmic rays with energy greater than 10^{18} eV are of extragalactic origin.

Accepting that the highest energy cosmic rays do not originate predominantly in the Galaxy the question then arises as to which part of the spectrum is extra-galactic and which part galactic. I shall return to this question in a moment. Meanwhile I want to deal next with the low energy end of the spectrum.

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Anisotropies at low energies

In searching for anisotropies in the energy range 10^9–10^{10} eV where much of the cosmic-ray energy density resides, we immediately encounter an obstacle in the form of the interplanetary magnetic field associated with the outward streaming solar wind. In the neighbourhood of the Earth's orbit this field has a strength of round about 6 nT (6×10^{-5} G). In the ecliptic plane this field is in the form of an irregular spiral with alternate sectors of outward and inward directed field. The number of sectors seems to vary from four or more at sunspot minimum to two at sunspot maximum and the field strength is now known to fall off with distance in reasonable accordance with the predictions of the Parker (1963) theory, at least as far out as the orbit of Jupiter at 5 AU.

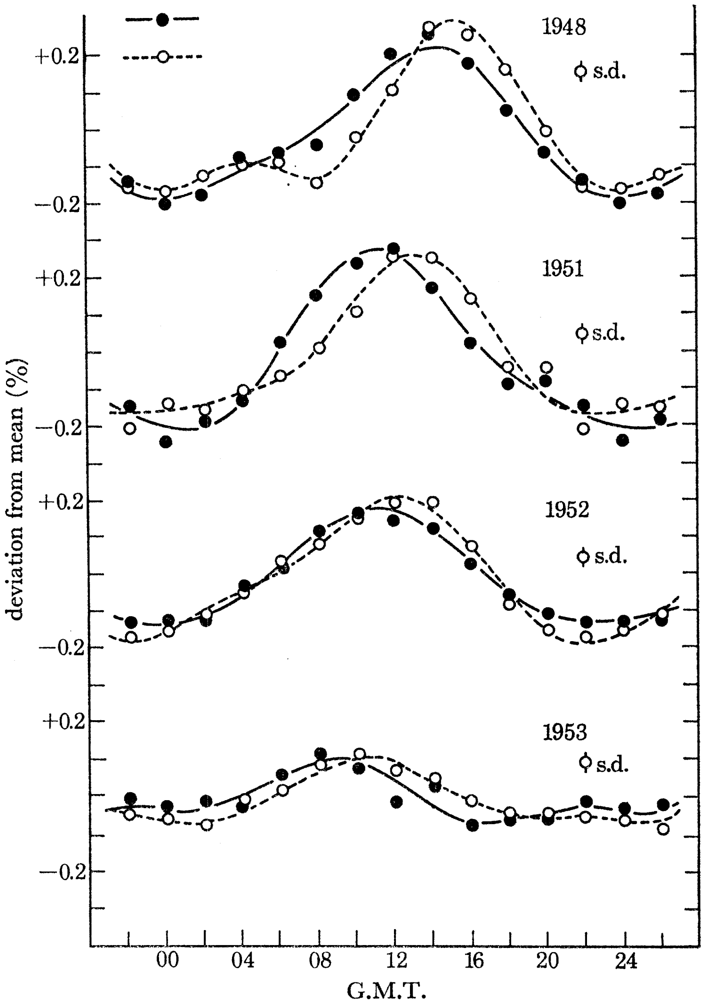

Figure 4. The solar daily variation in the cosmic-ray intensity at ground level for counter telescopes inclined at 45° to the zenith in the north–south plane (taken from Possener & van Heerden 1956).

In the neighbourhood of the Earth's orbit a cosmic ray with magnetic rigidity 10^{10} V has a Larmor radius in such a field of only some 10^{12} cm, i.e. < 0.1 AU. It follows that any anisotropy in interstellar space that exists at these energies is completely smeared out by this field and we

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would have no chance of detecting it at Earth. The interplanetary magnetic field completely ruins the cosmic ray 'seeing' at these low energies.

Symptomatic of this state of affairs is the existence of the solar daily variation of cosmic-ray intensity observed in the sea level muon intensity. Figure 4 shows an example of such observations using meson counter telescopes. We see a variation with amplitude $\sim 0.2\%$ over the solar day. Maximum intensity occurs in the early afternoon, is dependent on the direction of viewing and changes in magnitude over the solar cycle. This variation is due to an anisotropy in the primary radiation whose direction is related to the Sun and which arises as a result of the competing processes of outward convection by the solar wind and inward diffusion along the spiral interplanetary magnetic field.

The only possibility of detecting the interstellar anisotropy that may well exist at these low energies will depend on making the necessary measurements far beyond the orbit of Jupiter where the interplanetary magnetic field is so weak that it cannot influence the interstellar cosmic-ray trajectories to any great extent. Such measurements may be possible during the next decade but success in this will of course depend, among other things, on the magnitude of the anisotropy to be measured. However, as we shall now see, if we are prepared to go to rather higher energies we have the possibility of making significant measurements at Earth at the present time.

Cosmic-ray anisotropy at intermediate energies

At primary energies in excess of 10^{11} eV the magnitude of the deflexion of cosmic-ray particles in the interplanetary field starts to diminish rapidly with increasing energy and corresponding magnetic rigidity. It therefore becomes possible at these energies to observe broad anisotropies which lead to a sinusoidal variation of the intensity in sidereal time. This is the kind of anisotropy that would be produced by general cosmic-ray streaming in the galactic magnetic field. The Larmor radius for particles of magnetic rigidity 10^{11}–10^{12} V in the galactic magnetic field is in the range 10^{14}–10^{15} cm and is therefore still very small compared with the distance to possible sources so that it would be unreasonable to expect to see any anisotropy directly related to a source distribution at these rigidities.

In 1960 the Imperial College group began a long series of observations in an underground laboratory in a disused part of the Holborn Underground Station which were directed towards measuring any possible anisotropy in the magnetic rigidity range 10^{11}–10^{12} V. These measurements were begun by Dr T. Mathews and the work has been continued over the years by Dr Thambyahpillai, together with Drs Dutt, Peacock and Speller. As a design aim for the experiment we used, at the start, the following criterion. If the cosmic rays of this energy are completely isotropic in the Galaxy this state of affairs can, of course, be true for only one frame of reference which is most likely to be that of the average galactic rotation velocity in our neighbourhood. This is to say, we assume that the cosmic rays are constrained to rotate with the Galaxy because of its magnetic field. Relative to this rotational frame the Solar System has a velocity of *ca.* 20 km s^{-1} in the direction of the constellation Hercules and consequently an observer on the Earth should see an anisotropy of two or three parts in 10^4 as a sidereal daily variation due to this motion. Such an anisotropy ought to be observable in the Holborn laboratory and it was this variation we set out to detect.

Figure 5 shows the response of a muon telescope in terms of primary particle rigidity at a

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depth of 60 m water equivalent corresponding to that of the Holborn Laboratory (Speller, Thambyahpillai & Elliot 1972). Curve *b* is based on a calculation by Professor Wolfendale modified to take account of the contribution to the underground muon component by cosmic-ray nuclei heavier than protons. Curves *a* and *c* are alternative versions produced by other workers, one of which overemphasizes the contribution of low rigidity primaries while the

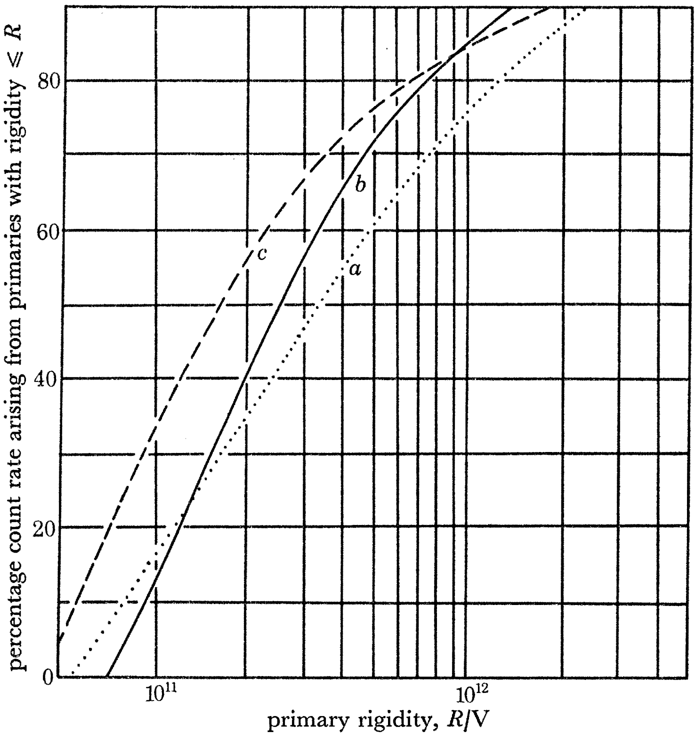

FIGURE 5. The response functions for a meson detector at a depth of 60 m water equivalent corresponding to the Holborn underground laboratory (taken from Speller *et al.* 1972).

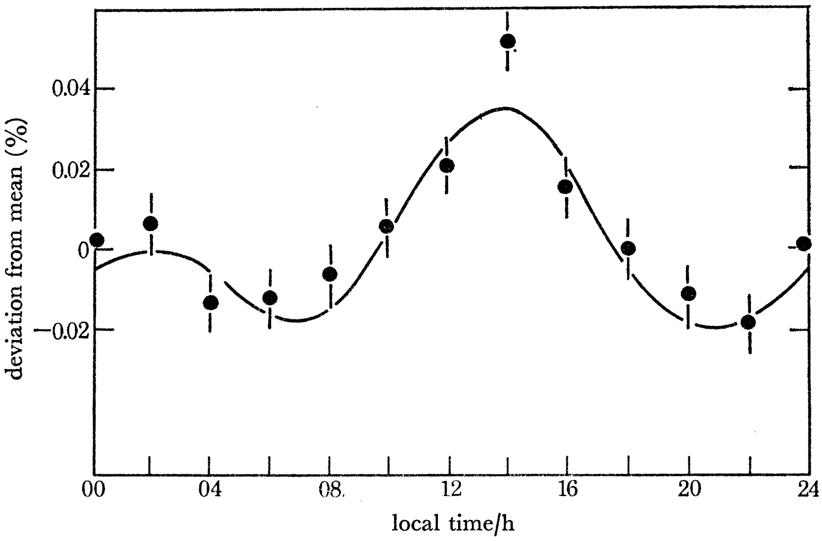

FIGURE 6. The solar daily variation measured in the Holborn laboratory. This variation is less than a tenth the amplitude of the variation at ground level shown in figure 4 and illustrates the much diminished effect of the interplanetary magnetic field at the higher energies.

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other overemphasizes the importance of the high rigidities as shown by the more recent and more detailed calculations of Gaisser (1974).

The much diminished effect of the interplanetary magnetic field at these higher primary energies compared with the situation prevailing at ground level is well illustrated in figure 6 which shows the average solar daily variation measured in the Holborn laboratory. It is an order of magnitude smaller in amplitude than the 0.2 % observed at ground level.

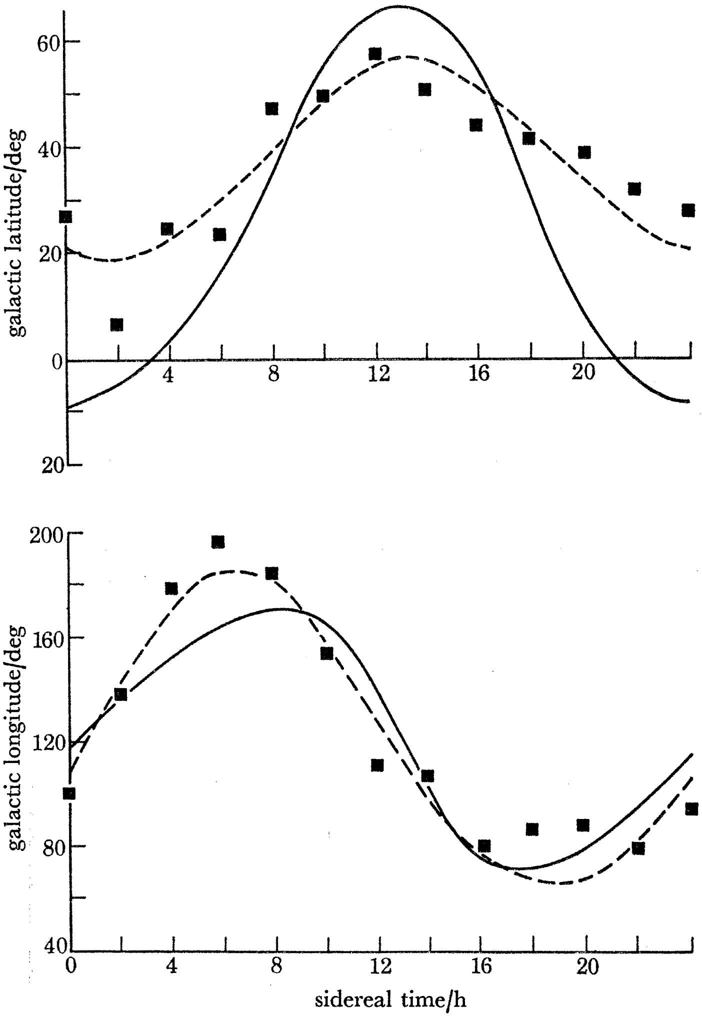

FIGURE 7. The 'direction of look' of the Holborn meson detector plotted in galactic coordinates as a function of sidereal time. The dashed line is the sine curve of best fit through the points which are averages over a representative set of positions of the Earth throughout the year relative to the interplanetary field. The solid line would be the corresponding directions for cosmic rays of infinite energy.

The response curve *b* of figure 5 shows that the counting rate of the muon recorder in the Holborn laboratory arises mainly from primary particles in the magnetic rigidity range 10^{11}–10^{12} V and in making the relevant calculations it is important to remember that cosmic primaries with $Z/A \approx \frac{1}{2}$ must be taken into account as well as the protons with $Z/A = 1$ because it is magnetic rigidity and *not* energy which determines the deflexion of the primary particles in the interplanetary magnetic field.

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The effect of the field can be taken into account by integrating the equation of motion for negative particles travelling outwards from the Earth through a model of the field and investigating the way in which the final directions outside the field relate to the starting conditions at the Earth. Such calculations have been made by Speller *et al.* (1972) and by Barnden & McCracken (1973). The results from the two sets of calculations are in good agreement and by way of illustration I will show some of Speller's results.

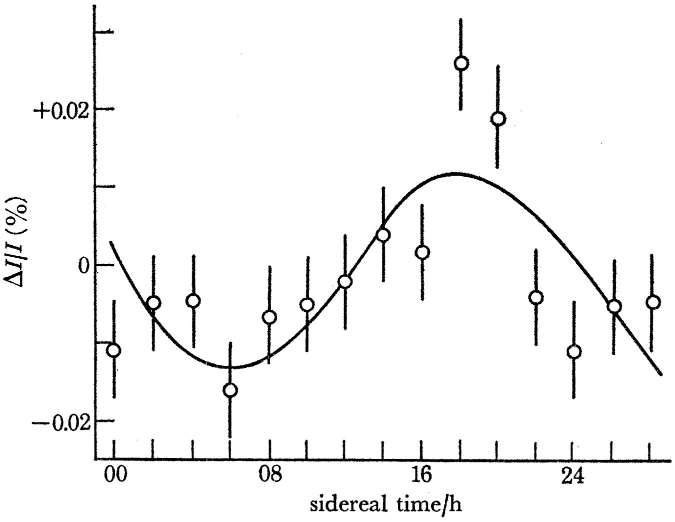

FIGURE 8. Average bi-hourly departures from the mean of the muon intensity at 60 m w.e. plotted as a function of sidereal time. The solid line is the variation to be expected on account of the solar motion relative to galactic rotation (taken from Speller *et al.* 1972).

Figure 7 shows plots of the final direction of the cosmic-ray trajectories – averaged for a variety of starting conditions relative to the sector structure of the interplanetary field and after folding in the response function *b* of figure 5. The directions are shown in galactic latitude and longitude and plotted as a function of sidereal time. In these calculations the field was assumed to have four sectors with $|B| = 5 \times 10^{-9}$ T at 1 AU and to decrease with distance from the Sun in accordance with Parker theory so that (in 10^{-4} T):

$$B_r = \frac{3.5 \times 10^{-5}}{r^2},$$
$$B_\theta = 0,$$
$$B_\Phi = \frac{3.5 \times 10^{-5}}{r} \cos\theta,$$

where *r* is the distance from the Sun measured in AU and θ and Φ are heliographic latitude and longitude respectively. As Speller *et al.* (1972) showed, at rigidities of 10^{11} V the interplanetary field smears out all directional information whereas at 3×10^{11} V the effect of the field has already become quite small. Overall, the effect of the interplanetary field is to reduce the measured anisotropy relative to the true primary anisotropy and the results quoted here are consistent with Barnden & McCracken's (1973) estimate of a reduction by a factor of about 2.4.

Figure 8 shows the bi-hourly deviations from the mean counting rate for the Holborn detectors averaged over nine years and plotted as a function of sidereal time. The full line is the

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variation expected as a result of the solar motion effect mentioned above and if we subtract this as a correction for the motion we are left with the residual departures shown in figure 9. Analysis of these residuals shows that at the 95 % confidence level there is no sinusoidal variation present with amplitude > 0.02 % along the directions scanned across the celestial sphere as shown in figure 7.

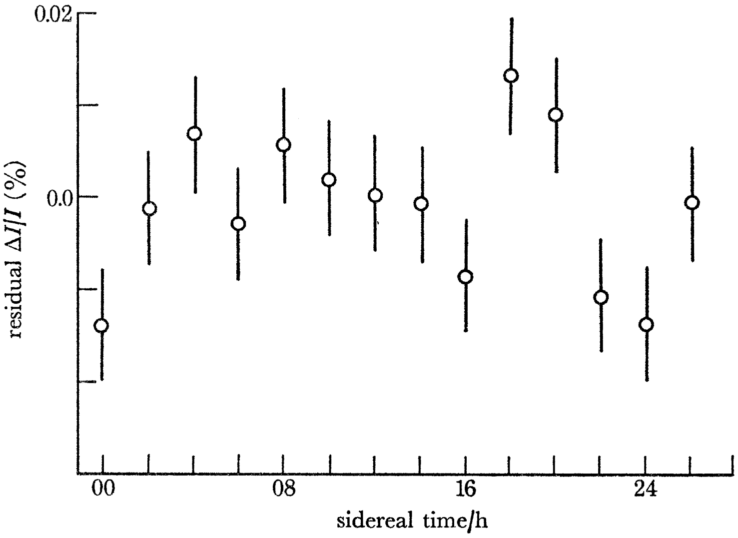

Figure 9. The bi-hourly residual departures from the mean of the muon intensity in the Holborn laboratory after correction for solar motion (taken from Speller *et al.* 1972).

INTERPRETATION OF THE UPPER LIMIT TO THE ANISOTROPY

We can use this result to set an upper limit to the bulk streaming velocity of cosmic rays for this energy range in the following way. Streaming with a velocity v leads to an angular distribution of intensity given by

$$I = I_0\,[1+(2+\gamma)\,(v/c)\cos\alpha]$$

where I_0 is the mean intensity, γ is the exponent of the differential energy spectrum assumed to obey a power law, α is the angle between the direction of streaming and the direction of observation.

Taking $\gamma = 2.6$ and using the directional scan curves of figure 7 we arrive at values for the streaming velocity of:

$V \leqslant 30$ km s^{-1} along the spiral arm direction

and $V \leqslant 100$ km s^{-1} for the direction perpendicular to the spiral arm.

In interpreting these upper limits to the streaming velocity it is necessary to relate them to the dwell time of cosmic rays in the Galaxy deduced from the relative abundances of primary and secondary nuclear species in this energy range. It now appears that the amount of material traversed between source and Earth is in the region of 1 g cm^{-2} for arriving cosmic rays of rigidity > 10^{11} V. Using this figure together with the generally accepted number density for interstellar hydrogen of one proton cm^{-3} leads to a dwell time in the Galaxy of 6×10^5 years (a). If we exclude special circumstances with a low *a priori* probability, such as a very exact symmetry of the source distribution or a streaming direction closely alined with the Earth's axis

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of rotation, this figure for the time spent by the cosmic rays in the Galaxy leads to the conclusion that they have streamed a distance of no more than 20 pc along the spiral arm direction and no more than 60 pc perpendicular to it.

These distances are small compared with galactic dimensions and imply, if we insist on a galactic origin, that the cosmic rays we are sampling at the present time are of local origin occupying a volume of some 2×10^5 pc^3 and were generated only 6×10^5 a ago. If we accept that the most likely source of these cosmic rays is either a super nova explosion or its pulsar relic we face an immediate difficulty because there is only a 1 % chance that a super nova explosion took place in this volume in a time of 6×10^5 a.

Alternatively, if we suppose that we have a steady state situation in which the cosmic rays fill the whole galactic disk with an equilibrium between the rate of escape and rate of production we run into the difficulty that the lifetime of 6×10^5 a is incompatible with escape from the Galaxy because of the low streaming velocity.

It may be possible to construct models of the source distribution and galactic magnetic field with special characteristics that can remove this incompatibility between a galactic origin and the measured values of lifetime and anisotropy but it seems to me that serious consideration must be given to the alternative hypothesis that the cosmic rays above 10^{11} eV are predominantly of extra-galactic origin and probably belong to the local cluster or super-cluster of galaxies. In this connexion, it should be noted that Brecher & Burbidge (1972) have recently proposed that the whole of the cosmic-ray flux is of extra-galactic origin.

If the particles in question do come from outside our Galaxy their isotropy is automatically explained and it is only necessary to account for the total amount of matter traversed independent of any constraint due to isotropy. We have already seen that there are good reasons for believing that the highest energy cosmic rays are extra-galactic and that the question to be answered is how far down the energy spectrum does the extra-galactic component predominate.

The suggestion here is that the extra-galactic flux exceeds that from the Galaxy at least as far down the spectrum as *ca.* 10^{11} V. Below 10^{11} V rigidity the observed isotropy of the radiation at the Earth provides no information on the streaming in interstellar space because of obscuration by the interplanetary magnetic field. If cosmic rays of 10^{11} rigidity and greater are extra-galactic this implies that the energy density in the local cluster of galaxies is at least 5–10 % of that in the Galaxy.

If there is indeed a change over from a predominantly extra-galactic population to one of galactic origin at rigidities below 10^{11} V it is to be expected that there would be manifestations of this change either in the energy spectrum of the radiation or the chemical composition or both. It is certainly the case that below about 10^{10} V the form of the rigidity spectrum deviates quite markedly from a power law with the fixed or slowly varying exponent characteristic of higher energies and that this deviation is only partly attributable to the effects of solar modulation. Furthermore, as Meyer has shown in an earlier paper, there is good evidence for a variation in the ratio of genuinely primary cosmic-ray nuclei to those produced by fragmentation in nuclear collisions between the source and the Earth which is a strong indication that the history of the cosmic rays below 10^{10} V is different from that of particles of $> 10^{11}$ V rigidity.

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Discussion

J. A. HOLMES (*Oxford University Department of Astrophysics, South Parks Road, Oxford*). The flattening of the cosmic-ray spectrum below a rigidity of about 8 GV can be explained in terms of the energy dependent 'leaky box' model which I outlined after Meyer's talk. A suitable choice of damping coefficient for the Alfvén waves would enable cosmic rays of rigidity below 8 GV to produce their resonant waves in the galactic plane in the vicinity of the Sun, while cosmic rays of higher rigidities would begin to produce their waves at corresponding distances from the plane. Accordingly we would sample the source spectrum for cosmic rays of rigidity below 8 GV, while the spectrum of those of higher rigidity would be modified by their energy dependent containment time.

T. GOLD. It must be said that a steepening of the spectral gradient at one point is by itself not a good indication of another production process taking over there. For this to be the case it is necessary that the former process has an even sharper downturn in the same region and that the second process has a flatter gradient at lower energies, followed by a less sharp downturn whose position coincides more or less with the former in both coordinates. Of course this is no argument against such a possibility, only logically it will require more evidence in its favour than, for example, a changeover to a flatter gradient would have required where no particular coincidence is implied.

J. SKILLING (*Department of Applied Mathematics and Theoretical Physics, Cambridge*). We are in the centre of the galactic disk, so might we not expect a factor of plausibly 5 or so on the cosmic ray anisotropy simply due to symmetry?

H. ELLIOT. On the Jokipii–Parker model of field lines wandering to the edge of the disk every 1500 pc or so, we may well not be particularly symmetrically placed in the restricted volume from which we see cosmic rays.

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J. Skilling. But the cosmic rays we see at the Earth come from many field lines, within a Larmor radius of ourselves. These field lines will go to very different places, because of the random turbulence, so we see an average over all these different field lines. This *will* presumably give us an average over a large region of space, within which we are symmetrically placed.

H. Elliot. But the field is observed to be smooth, not random.

J. Skilling. No, the random component will simply be turbulence sitting *on top of* the smooth field.

H. Elliot. Surely putting on a random field gives you a random field.

A. W. Wolfendale. Is the change of slope at *ca.* 10^{10} V not of the wrong sign to be consistent with a transition from galactic to extra-galactic sources?

H. Elliot. No. There is no *a priori* reason that I know of that says that the slope of the galactic spectrum should be greater than that of the extra-galactic spectrum.