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The anisotropy of cosmic rays of galactic origin above 10^{17} eV

S KARAKULA†§, J L OSBORNE†, E ROBERTS† and W TKACZYK‡

† Department of Physics, University of Durham, Durham City, UK
‡ Department of Physics, University of Lodz, Poland

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Abstract. By following the trajectories of protons in the galaxy we predict the detailed form of the anisotropy of ultrahigh energy cosmic rays of galactic origin for given magnetic fields and source distributions. Three specific magnetic field models based on interpretations of the observational data are used and we consider sources uniformly distributed throughout the galactic disc or spiral arms, or concentrated at the galactic centre. Data on the arrival directions of extensive air showers are then compared with the predicted distributions for these models, and, assuming that metagalactic cosmic rays are isotropic, upper limits are given for the fraction of cosmic rays of galactic origin.

1. Introduction

A fundamental question concerning cosmic rays at the high energy end of the spectrum is whether they originate in the galaxy or are incident from metagalactic space. Supernovae or a centre of activity in the galactic nucleus are possible candidates for the main galactic sources of cosmic rays and in fact, the observed energy density of all relativistic cosmic rays of about 1 eV cm^{-3} can be accounted for by the observed frequency and energy output of supernovae (Ginzburg 1969). Cosmic rays with energies greater than 10^{17} eV have an energy density of only $1{\cdot}5 \times 10^{-6}$ eV cm^{-3} but it is very difficult to see how they could be accelerated in the supernova explosion itself or in the supernova shell. The discovery of pulsars, however, and their probable explanation as rotating neutron stars formed in supernova explosions provides a possible source of these extremely high energy particles. The postulated magnitude and dimensions of the pulsar's magnetic field leads to the possibility of its accelerating particles up to about 3×10^{20} eV although, as Ginzburg has emphasized, no detailed mechanism for the acceleration has yet been worked out.

Syrovatskii (1969) has pointed out that, in the case of galactic origin, the observed shape of the primary cosmic ray spectrum reflects the different kinds of propagation in the galactic magnetic field in different energy intervals. In the low energy region, where the radius of curvature of the particles is less than the scale of the local irregularities in the galactic magnetic field, quasidiffusional motion will occur. Next there is the intermediate energy region where the radius of curvature is greater than this but less than the characteristic scale of the regular magnetic field; here drift motion generally along the magnetic field lines occurs. The steepening of the primary spectrum at about 3×10^{15} eV can be interpreted as the boundary between these two regions and implies that the maximum size of the magnetic field irregularities is about 1 pc. In the high energy region

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§ On leave of absence from the Department of Physics, University of Lodz, Poland.

where the radius of curvature is greater than the characteristic scale of the regular magnetic field, quasirectilinear motion of the particles occurs and the magnetic field serves to pick out regions of sources that can contribute to the flux of cosmic rays arriving at the earth in a particular direction. The possible decrease in slope of the primary spectrum which may occur above 10^{18} eV could mark the boundary between drift motion and quasirectilinear motion. Thus a consequence of the galactic origin of cosmic rays above about 10^{17} eV is that one would expect anisotropy in the distribution of arrival directions at the earth due both to the presumed concentration of sources in the region of the galactic disc and to the effects of the galactic magnetic field. This has long been recognized and a number of investigations have been made of the arrival directions of extensive air showers (EAS) produced by these very high energy cosmic rays (eg Linsley 1963, Blake *et al* 1968 and Brownlee *et al* 1970a), using air shower arrays at locations in both the northern and southern hemispheres. The rotation of the earth ensures that there is a uniform exposure with respect to right ascension and the data have, in the main, been analysed to look for anisotropies in the right ascension distribution, the results being presented in the form of amplitude and phase of the first and second harmonics. In almost all of the experiments performed to date the data have been consistent with isotropy within the statistical limits.

The simplest explanation for the isotropy of these very high energy cosmic rays is that they are of metagalactic origin and fill the whole of the universe; in which case the existence of the 2·7 K relict radiation imposes a cut off on their spectrum at around 3×10^{19} eV (Greisen 1966, Zatsepin and Kuzmin 1966). There are indications, however, that the spectrum continues without a break to beyond 10^{20} eV (Brownlee *et al* 1970b). Berezinskii and Zatsepin (1971) have discussed ways to resolve this dilemma which include the possibility that cosmic rays originate in the local supercluster of galaxies and thus travel only about 10 Mpc through the relict radiation and the suggestion that the particles of the very highest energy may in fact be neutrinos.

In the present work we predict the form of the anisotropy of the cosmic rays of galactic origin as a function of energy for various assumed source distributions and magnetic field configurations. If one then compares these predictions with the experimental data it may be possible to obtain more stringent limits to the fraction of the anisotropic component than can be got when the form of the anisotropy is not specified. We follow the method of Thielheim and Langhoff (1968) where, for a specific mathematical model of the magnetic field, individual proton trajectories are calculated.

2. Galactic magnetic field models

In recent years considerable advances have been made in the observations of the galactic magnetic field (Verschuur 1970 has given a comprehensive review). There are three main ways of determining the structure of the magnetic field. Measurements of the Faraday rotation of the plane of the electric vector of linearly polarized extragalactic radio sources allow the direction of the line of sight component to be determined. The magnitude of the field that is deduced from the rotation measure depends upon the assumed electron density distribution in the galaxy. The rotation measures for a number of pulsars have also been obtained and in this case the dispersion measure of the pulses gives the integral of the electron density. The mean magnitude of the line of sight component of the field between the earth and the pulsar, weighted according to the electron density, can therefore be determined. Secondly measurements of the polarization of starlight give the direction, but not the sign or the magnitude, of the component of the magnetic field perpendicular to the line of sight in the region between the earth and the star. The polarization is assumed to be due to scattering by long interstellar dust particles which have been aligned by the magnetic field. Thirdly the distribution of brightness of the synchrotron radiation emitted by relativistic electrons gives information on the relative magnitude of the perpendicular component of the magnetic field as a function of direction from the earth. The absolute magnitude that is derived for the field depends upon the energy spectrum of interstellar electrons that is assumed.

It should be stressed that the experimental data on the magnetic field refer in the main to the region extending only a few kiloparsecs from the earth. Within this region a number of interpretations are possible and one must extrapolate considerably to get the field for the whole galaxy. We have therefore considered three models, denoted A, B and C, for the large scale regular component of the galactic magnetic field that are consistent with experimental measurements and theoretical arguments as to its form. We later describe further modifications to these models.

2.1. Field A

This is the quasilongitudinal model of Thielheim and Langhoff (1968) based on the interpretation by Berge and Seielstad (1967) of rotation measures of extragalactic sources. The field lines are parallel to the spiral arms but with opposite orientations above and below the galactic plane. One takes an idealized form of the spiral arms in that they are continuous and have a geometry in cylindrical coordinates R, ϕ, Z given by

$$\phi = \frac{2R}{3}\tan^{-1}\left(\frac{2R}{3}\right) + \phi_0. \tag{1}$$

R is the distance from the galactic centre, Z is perpendicular to the galactic plane and $\phi_0 = 0$ and π give the two spirals. Throughout this paper R, Z and other lengths are always expressed in kiloparsec. For $R > 3$ the windings are equally spaced with a constant separation of 3·2. The position of the sun is $R = 10$, $\phi = 6{\cdot}5°$, $Z = -0{\cdot}085$. It is thus at the centre of its spiral arm and below the plane of the field reversal.

The component of the field parallel to the arms, H_{a} (μG) is given by

$$H_{\mathrm{a}} = \left[50Z\exp\left\{-\left(\frac{Z}{Z_0}\right)^2\right\}\right]\left[\exp\left(\frac{-R^2}{100}\right)\left\{1-\exp\left(\frac{-R^2}{4}\right)\right\}\right]\{1+4\cos^2(\phi-\phi(R))\}. \tag{2}$$

The first square bracket gives the variation of field strength with distance from the galactic plane; Z_0 is set equal to 0·175. The second square bracket gives the variation of the field on the axis of a spiral arm as a function of R; it has a maximum value for $R = 3{\cdot}6$, is zero at $R = 0$ and becomes negligible beyond $R = 16$. The third term sets the field at the midpoint between two adjacent arms to be 0·2 of that on the axes of the arms. The vertical component of the field is obtained by setting div $H = 0$ and has values typically 1 % of H_{a}. The mean field strength in the galactic disc in the neighbourhood of the sun is about 5 μG.

Thielheim *et al* (1971) have examined the consistency of this model with the observational results. There is reasonable agreement with the distribution of synchrotron radiation, although the agreement would probably be as good for a unidirectional longitudinal model. The model fits the rotation measure data of Gardner and Davies (1966) quite well as it is specifically designed to do this. It should be mentioned, however, that the more recent survey of Gardner *et al* (1969) with five times as many sources gives a more complex distribution of rotation measures. The predictions of the model do not give good agreement with the stellar polarization observations particularly for stars within 1 kpc of the earth. A better fit to these is given by the second model.

2.2. Field B

This model is based on the interpretation by Mathewson and Nicholls (1968) of the stellar polarization data. A best fit is obtained for a local field that is helical in form. The field lines are right handed helices of pitch angle 7° lying on the surfaces of tubes coaxial with the spiral arm and of elliptical cross section. The axial ratio of the ellipses is three and, to satisfy div $H = 0$, the field is correspondingly three times stronger on the minor axis than on the major axis. The helices are sheared through an angle of 40° anticlockwise looking downward from the north. The sun is 0·1 kpc towards the galactic centre from the spiral arm axis and 0·01 kpc below the plane. It is therefore close to the major axis of the ellipse on which it lies. In order to make the average field strength in the neighbourhood of the sun approximately equal to 5 μG as for field A the field at the sun's position is taken to be 2·5 μG. The polarizations of the more distant stars and the rotation measures of the extragalactic radio sources indicate that this helical region is limited to a cylinder of elliptical cross section with major axis 0·5 kpc and extending to $\pm 0{\cdot}5$ kpc along the spiral arm. Outside this region Mathewson proposes that there is a simple longitudinal field directed towards $l = 90°$. The mathematical formulation that we use for this is obtained by replacing the first term in square brackets in equation (2) by the expression $[-3{\cdot}8 \exp\{-(Z/0{\cdot}24)^2\}]$. This gives a field of approximately the same magnitude and extent as field A but not reversing its direction across the galactic plane. Since any regular model must be only an approximation to the true field we do not attempt to join the helical region to the longitudinal region smoothly.

Parker (1971) has shown that a combination of differential rotation and turbulence in the gaseous disc can result in cyclonic motion which in turn can generate a longitudinal magnetic field. Fields A and B would represent respectively the lowest odd and even modes of such a field. The helical region in field B would be a local perturbation. Manchester (1972) has examined the rotation measures of 21 pulsars and concludes that they indicate a simple longitudinal field directed towards $l = 90°$. This suggests that the helical region is smaller in extent than that adopted in field B.

In the past, when the magnetic field was generally considered to be an order of magnitude stronger than the current estimates there were suggestions (eg Hoyle and Ireland 1961) that the spiral structure of the galaxy could be maintained by a helical field winding around the arms. Our third model was constructed in order to find the effect of such a field upon particle trajectories.

2.3. Field C

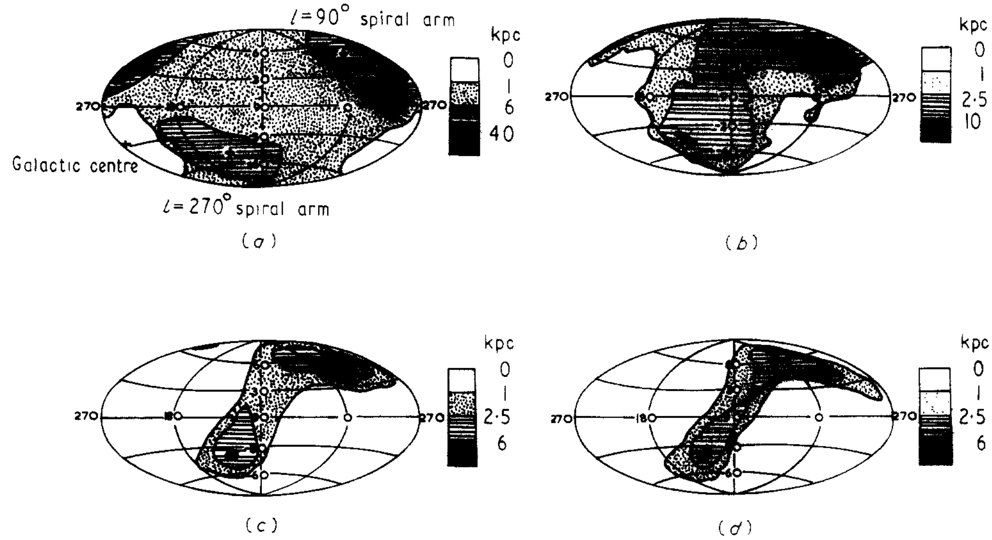
Here the helical field of Mathewson is taken to be of galactic extent. The field lines wind around the spiral arms from the galactic centre out to $R = 15$. In order to simplify the calculations the axes of the spiral arms were in this case given by

$$\phi = 0{\cdot}943R + \phi_0. \tag{3}$$

This gives a geometry not significantly different from equation (1). For the majority of the calculations we omitted an R dependent factor as in equation (2) and took the field strength to fall linearly from a maximum at the centre of a spiral arm to zero at the midpoint between two adjacent arms. Some modifications to this are described below.

3. Path lengths of protons in the galaxy

With these mathematical models of the galactic magnetic field the trajectories of protons moving in the galaxy and arriving at the earth in particular directions were calculated using an electronic computer. The trajectories were calculated in small steps, the acceleration due to the magnetic field being assumed constant over the step length. By trial it was found that steps of 0·01 kpc were sufficiently small for energies of 2×10^{18} eV and above. For lower energies the step size was reduced in proportion to the energy. The actual procedure used was to follow an antiproton of a particular energy starting from the earth in a given direction and continuing until it reached $|Z| > 1$ or $R > 15$. At these distances the field, in our models, is so weak that the particle could be assumed to have left the galaxy. The galaxy was divided up into regions where cosmic ray sources might be expected and the aggregate path length in each of these was recorded. The regions are (i) spheres of radius 1, 2 and 3 kpc about the galactic centre, (ii) the galactic disc defined by $|Z| < 0{\cdot}3$ and $R < 15$, and (iii) the spiral arms which were assumed for simplicity to have rectangular cross section 0·6 kpc by 1·2 kpc. A set of 146 trajectories were calculated for each of a number of energies covering the range $4{\cdot}5 \times 10^{17}$ to 10^{20} eV. For lower energies the number of steps required for each trajectory becomes so large that the method is no longer feasible if a reasonable number of trajectories are to be followed. Contour maps were then drawn showing the maximum path length in a specified region of the galaxy for a proton arriving at the earth from a given direction. Examples of these maps are shown in figures 1, 2 and 3. For clarity, only three contours



(a) (b)

(c) (d)

Figure 1. Plots in celestial coordinates of path lengths in the spiral arms for field A; (*a*) for 6×10^{17} eV protons, (*b*) for 10^{18} eV protons, (*c*) for 3×10^{18} eV protons and (*d*) for 10^{19} eV protons.

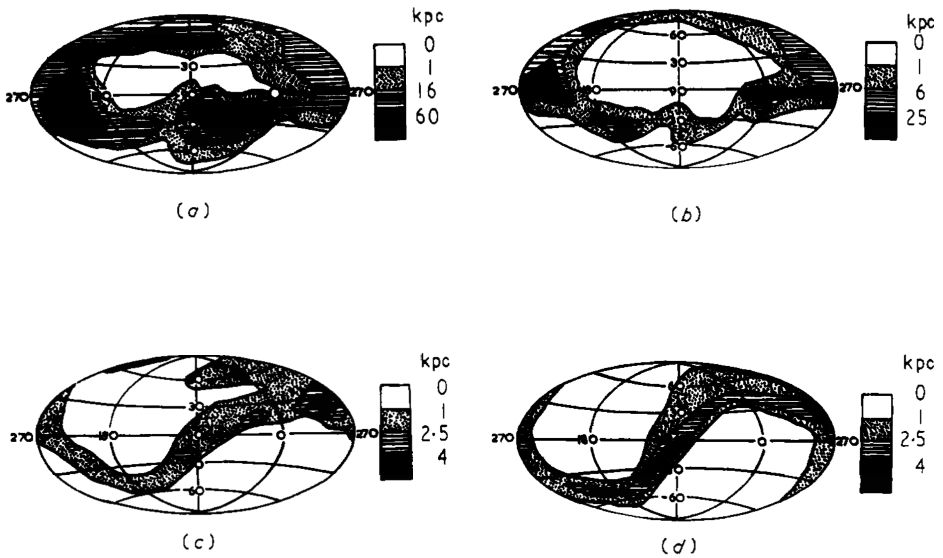


Figure 2. Path lengths in the galactic disc for field B; (*a*) for $7{\cdot}5 \times 10^{17}$ eV protons, (*b*) for 10^{18} eV protons, (*c*) for 3×10^{18} eV protons and (*d*) for 10^{19} eV protons.

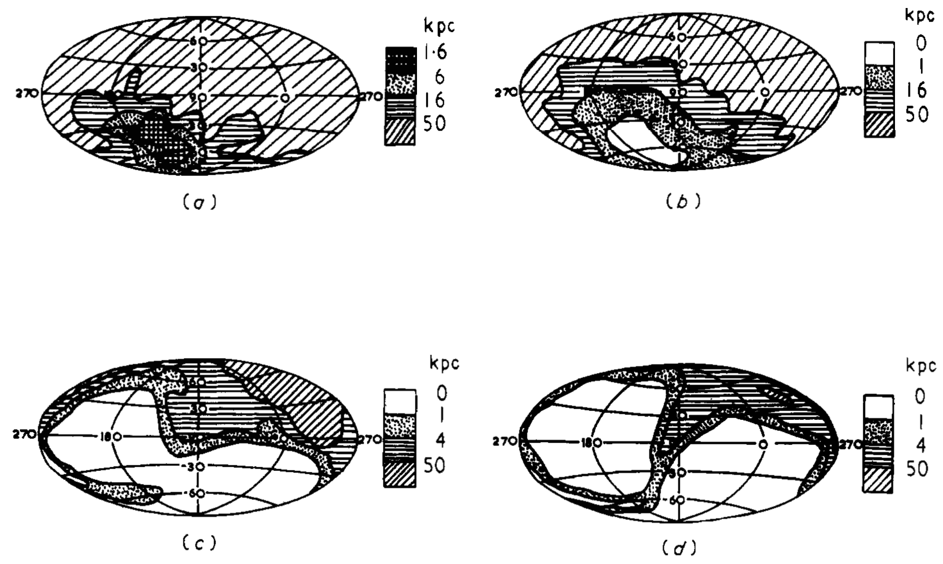


Figure 3. Path lengths in the galactic disc for field C; (*a*) for 8×10^{17} eV protons, (*b*) for 10^{18} eV protons, (*c*) for 3×10^{18} protons and (*d*) for 10^{19} eV protons.

are shown in each. All are plotted on an equal area projection in celestial coordinates. Figure 1 gives the path lengths in the spiral arms for field A while figures 2 and 3 give the path lengths in the disc for fields B and C respectively. It is found for all fields and energies that the distributions of path lengths in the whole disc are similar in form to those in the spiral arms only but the paths are approximately twice as long in the former case. For field A one sees that, as one might expect, the longest path lengths are in the directions along the spiral arms. The paths in the $l = 90°$ arm are greater than those in the $l = 270°$ arm, however. In the direction of the galactic centre the path lengths are very short for energies from 6×10^{17} eV upwards. At 10^{18} eV the minimum around the galactic centre has widened considerably and at 3×10^{18} eV only those directions near to the spiral arms or the anticentre have paths longer than 1 kpc.

For field B above 3×10^{18} eV the longest paths are also to be found along the galactic equator; the peaks are, however, not so close to the spiral arm directions as for field A. At lower energies the distribution is more complex. To find the effect of the local helical field the calculations were repeated for the simple longitudinal field only. The results, above 2×10^{18} eV were not significantly different from those of field B indicating that a local helical perturbation is not very important for these energies. At lower energies the differences in the path length distributions become progressively more marked. One can say, however, that the degree of anisotropy is the same with or without the local helical perturbation.

Particles are more easily trapped in the helical field C. In figure 3 the regions shaded to denote path lengths greater than 50 kpc in fact refer, in the main, to very long trajectories where the particles are effectively trapped within the galaxy. Progressing towards lower energies from 10^{19} eV this trapping region centred on the $l = 90°$ spiral arm spreads until it covers the whole celestial sphere at 6×10^{17} eV. A representative number of trajectories were subsequently recalculated with a modified form of helical field. The linear decrease of the field strength with distance from the centre of the spiral arm was replaced by a gaussian dependence, $\exp\{-(b/b_0)^2\}$, where b is the minor axis of the ellipse that passes through the point at which the field is being determined. The field on the axis of the spiral arm was taken to vary with R as in equation (2). In order to conserve the number of flux lines b_0 was also taken to be a function of R. For the sun's position $b_0 = 0{\cdot}392$. The distribution of path lengths for the modified helical field was found to be practically identical to that for field C. We therefore conclude that it is the helical form of the field that is important rather than the detailed behaviour of the field strength.

It can be seen that at 10^{19} eV the distributions are similar for all three fields, the longer path lengths being restricted to a band along the galactic equator. Above a few times 10^{19} eV the magnetic fields have a minimal effect and the distribution is determined by the geometry of the galaxy.

If one assumes that, for example, the cosmic ray sources are uniformly distributed throughout the spiral arms then, at least for that energy region where the motion is quasirectilinear, the intensity of cosmic rays from a given direction will be proportional to the maximum path length in the spiral arms for particles arriving from that direction. Thus the path length maps are also maps of relative intensity distribution. These predicted distributions may be compared with observations.

4. Comparison with experimental data

We have compared our predicted anisotropies with the data from the three large air shower arrays capable of measuring the arrival directions of showers initiated by cosmic ray primaries having energies above 10^{17} eV. These are the 8 km^2 MIT array at Volcano Ranch (latitude 30°N), the 11 km^2 Haverah Park array (54°N) and the 40 km^2 Pilliga Forest array of the University of Sydney (30·5°S). The Haverah Park results from 1963 to 1966 (Hollows 1968 and private communication) cover the range of declinations from $+90°$ to $-6°$; the Sydney data (Brownlee *et al* 1970a and private communication) cover

+30° to −90° and the Volcano Ranch data (Linsley 1963 and private communication) go from +90° to −30°.

Of the total flux of particles of a particular energy incident on the earth from all directions we assume a percentage G as being of galactic origin and thus having the predicted anisotropic distribution of intensities. The remainder is then of metagalactic origin and is isotropically distributed. For successive values of G running from 0 to 100 one may predict the number of particles in each $10° \times 10°$ bin of right ascension and declination to compare with the observed numbers. To do this, however, one has to take into account the variation of aperture with azimuth and zenith angle of the air shower array. This depends on the geometry of the array and the way in which the showers propagate through the atmosphere. One may avoid this complex problem by summing the number of showers over the whole range of declination for each RA bin and making the comparison for the distribution in RA only. Since the aperture variation only affects the weighting in the summation, knowledge of its exact form is not essential and the empirical variation obtained from the observed zenith angle distribution of showers can be used instead. A comparison of observation with prediction for the distribution in both RA and declination would be necessary only if a good fit were found for the distribution in RA only.

As an example figure 4 shows the Haverah Park distribution for energies between $7{\cdot}5 \times 10^{17}$ eV and $1{\cdot}5 \times 10^{18}$ eV and two corresponding predictions for field A and sources uniformly distributed in the spiral arms. Predictions are shown for $G = 100\,\%$

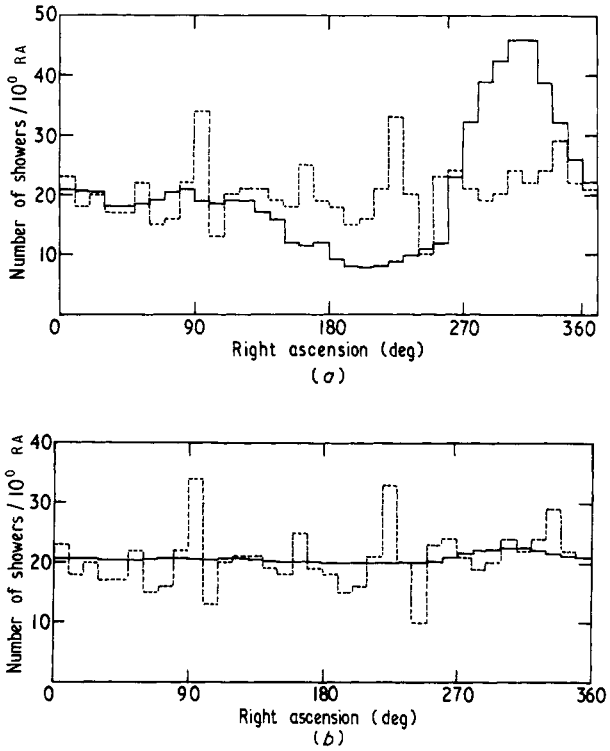


Figure 4. The Haverah Park right ascension distribution for $7{\cdot}5 \times 10^{17}$ eV $< E < 1{\cdot}5 \times 10^{18}$ eV (broken line) and predictions for field A (full line) for (*a*) $G = 100\,\%$ and (*b*) $G = 5\,\%$, with the sources distributed throughout the spiral arms.

and for the best fit value $G = 5\%$. If the anisotropy of the galactic component does indeed follow the predicted form then the most probable value of G will be that corresponding to the minimum χ^2. Figure 5 shows the values of χ^2 as a function of G from the comparison with the predictions of field B. One may estimate the limits to G corresponding to a χ^2 probability of 5 % (a χ^2 of 49·5 for 35 degrees of freedom). The best fit values of G are given in table 1 with the upper limits in parentheses. With this criterion all the data are consistent with $G = 0$ except the lowest energy Volcano Ranch distribution which has a χ^2 of 55 for $G = 0$. Finite values of G give only marginally better fits in this case (minimum χ^2 of 48 and 50 for fields A and B respectively) and it seems that the apparently significant observational anisotropy is not predicted by any of our field models. It is not confirmed by the Haverah Park observation in the same energy region.

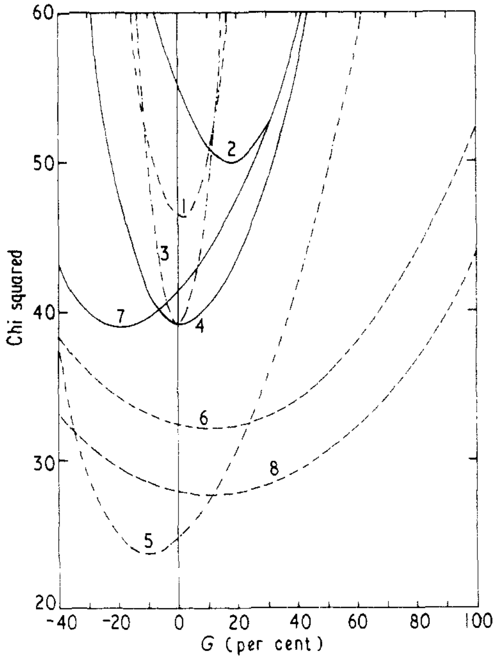


Figure 5. Plots of χ^2 against G for the predictions of field B. The numbers on the curves refer to the list of experimental data in table 1.

Table 1.

Location	Energy range (eV)	Number of showers	Values of G (%)		
			Field A	Field B	Field C
Haverah Park (1)	3×10^{17} to $7{\cdot}5 \times 10^{17}$	4222	2(4)	2(9)	
Volcano Ranch (2)	$6{\cdot}2 \times 10^{17}$ to $1{\cdot}2 \times 10^{18}$	538	6(9)	18(–)	..
Haverah Park (3)	$7{\cdot}5 \times 10^{17}$ to $1{\cdot}5 \times 10^{18}$	742	5(25)	0(11)	20(100)
Volcano Ranch (4)	$1{\cdot}2 \times 10^{18}$ to $3{\cdot}7 \times 10^{18}$	409	0(17)	1(31)	1(10)
Haverah Park (5)	$> 1{\cdot}5 \times 10^{18}$	249	−4(24)	−10(51)	−5(16)
Sydney (6)	10^{18} to 10^{19}	682	2(20)	10(95)	−12(50)
Volcano Ranch (7)	$> 3{\cdot}7 \times 10^{18}$	90	−10(10)	−20(24)	−4(10)
Sydney (8)	$> 10^{19}$	86	12(39)	10(100)	38(100)

The energies that we have assigned to the Volcano Ranch data are somewhat higher than the published values. We have done this in order to force consistency between the Haverah Park and Volcano Ranch energy spectra. Our energies, $6{\cdot}2 \times 10^{17}$ eV, $1{\cdot}2 \times 10^{18}$ eV and $3{\cdot}7 \times 10^{18}$ eV correspond respectively to shower sizes of $1{\cdot}6 \times 10^{8}$, $3{\cdot}2 \times 10^{8}$ and $1{\cdot}25 \times 10^{9}$ particles. The negative values of G for some of the best fits have no physical meaning. One would expect as many negative as positive values if the observed data represent a random sampling of completely isotropic radiation.

5. Discussion

In the region below 10^{18} eV the helical field C allows the largest galactic contribution consistent with observation, simply because it leads to the smallest anisotropy. One can see in figure 3 that below 8×10^{17} eV the northern hemisphere arrays would see a galactic component that is isotropic. We have assumed of necessity, however, that the intensity is uniform in the regions where the path length exceeds 50 kpc and the particles are, in the main, trapped in the spiral arms. This underestimates the anisotropy.

The small values of G for the 3×10^{17} eV showers and fields A and B are due to the predicted very sharp peaking of the galactic component. At these energies the effects of the small scale irregularities in the galactic magnetic field can most probably not be completely ignored. If they are important they will certainly tend to cancel out any sharp peaks in the path length distributions. More work needs to be done on this. A major difficulty is that the size spectrum of field irregularities is not known. It is also likely that much larger scale irregularities exist in that the geometry of the spiral arms is not as simple as that which we have assumed. For instance current surveys of neutral hydrogen in the galaxy suggest that the Orion arm, which contains the sun, is in fact an offshoot of the Sagittarius arm (Weaver 1970). We do not believe, however, that an irregular structure such as this would seriously affect our predictions for energies greater than a few times 10^{18} eV.

In all three models we have used, the strength of the magnetic field is assumed to decrease rapidly with Z in a similar manner to the gas density. An extensive halo field could have an appreciable effect on the anisotropies. A spherical halo of radius 15 kpc and having a magnetic field of about 3 μG is no longer required to explain the high latitude nonthermal radio emission from the galaxy. The current interpretation is in terms of a radio disc having thickness of about 1 kpc. On the other hand it is difficult to prove the absence of such a halo field. The chief difficulty in adding a halo field to our models is knowing what its structure should be. We have tried modifying field A by changing the Z dependent factor in (2) such that the field strength remains constant for Z greater than 0·28. This results in a regular halo field whose flux lines follow the spiral arm directions and whose average strength is about 2 μG. We find that this modification gives path length distributions which are practically the same as for field A above 3×10^{18} eV. At lower energies a third peak occurs in the direction of the galactic centre and to a certain extent fills in the minimum about this direction. The distribution is still far from isotropic, however, above 6×10^{17} eV. We would expect that, at these energies, an irregular halo field would have a smaller effect than the regular one that we have used.

The above discussion has been concerned with cosmic ray sources uniformly distributed in the disc (or throughout the spiral arms for which the intensity distribution is practically identical). We have also considered cosmic rays originating near to the galactic centre. For field A none with energies between 7×10^{17} eV and 3×10^{19} eV could reach the earth. At lower energies they could travel along the spiral arms as far as the earth and at higher energies the effect of the field is so small that they could travel directly. The addition of a regular halo field would facilitate the transfer of protons in this intermediate energy range from the galactic centre. Although they would be incident over a wide range of galactic latitudes they would all have longitudes close to zero. Field B has a similar effect to field A but would allow protons up to 10^{18} eV to reach the earth along the spiral arms. Field C, which focuses the particles on to the axes of the spiral arms would allow them to reach the earth from the galactic centre in those directions with paths longer than 50 kpc in figure 3. In general one can say that in the energy range we have considered, a source at the galactic centre would always result in a stronger anisotropy than is obtained for sources throughout the disc.

All the results that we have obtained are for primary protons. The trajectory of a nucleus of charge Z and energy E is the same as that of a proton of energy E/Z. If, as at low energies, the primary flux contains a proportion of heavier nuclei then a weighted average over a number of distributions corresponding to equivalent proton energies is required. Although the amplitudes of the peaks in the intensity distribution change with energy their positions do not alter much. Thus a mixed composition will not result in a cancelling out of the anisotropy.

The most probable conclusion that can be drawn from the comparison of the observed data with our predictions for the various field models is that, while a significant minority of cosmic rays with energy greater than 10^{18} eV could be of galactic origin, the majority come from outside the galaxy. If one proposes that they are all of galactic origin then it seems necessary, in order to account for their observed isotropy, to assume that they are mainly heavy nuclei ($Z > 20$) and that there is an extensive halo field.

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