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The anisotropy of ultra-high-energy cosmic rays II. Search for correlations with astronomical objects

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Abstract. The study of anisotropies of arrival directions of ultra-high-energy cosmic rays made by Kiraly and White, which referred to large-scale effects, has been continued by searching for intensity enhancements on smaller angular scales around specific Galactic and extragalactic objects. The searches have included Galactic pulsars and supernova remnants as well as extragalactic supernovae, radio and x-ray sources, Seyfert galaxies and quasars. Although some statistical indications for directional correlations have been found, none of them is significant enough to give strong support to any specific model of the origin of ultra-high-energy cosmic rays.

1. Introduction

In the previous paper by Kiraly and White (1975, to be referred to as I), an analysis was made of possible large-scale anisotropies in arrival directions of energetic cosmic rays. In the present work attention is devoted to a search for correlations of individual arrival directions with specific astronomical objects.

In view of the presence of magnetic fields in the Galaxy (and perhaps beyond) attention can essentially be devoted only to charged particles of very high energy (say above 10^{19} eV) where the deflections, from nearby objects at least, are relatively small (and to some extent calculable), and to neutral particles.

The ultra-high-energy primary cosmic rays giving rise to the large extensive air showers observed are usually considered to be charged particles: protons and heavier nuclei. Since, however, the sea level characteristics of a shower depend much more on the energy of the primary than on its atomic number, the composition is still quite uncertain. There is some recent indication based on fluctuation studies for at least a substantial proton fraction at 10^{18} eV (Watson and Wilson 1974, Lapikens 1975), and the results are not incompatible with a pure proton composition. In the present paper emphasis is laid on primary protons.

Under the heading of 'neutral particles' can be included neutrons, γ rays and neutrinos. Although the neutron is unstable it can travel significant distances on an astronomical scale if sufficiently energetic because of its consequent large Lorentz factor. The decay length of a neutron of energy E (eV) is of the order of $10^{-14}E$ pc. Thus, for a Galactic source at a typical distance of 100 pc, decay ceases to be of great importance at energies significantly above 10^{16} eV. For extragalactic sources, however, even those within the Local Group (distances 0·1 to 1 Mpc) can produce detectable

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neutrons only at energies approaching 10^{20} eV where the statistical precision of the data is severely limited. It should be remarked that above 10^{16} eV or so, where neutrons might be expected, there can be no possibility of making a positive identification from the type of extensive air shower produced: proton- and neutron-induced showers will be quite indistinguishable. The objection might be raised against primary neutrons that they are very difficult to accelerate. However, a likely origin would be from the fragmentation of heavy nuclei, in the source. These nuclei are easy to accelerate and may well predominate in some sources, such as supernovae and pulsars.

Turning to γ rays, low-energy quanta have indeed been detected from discrete sources but the measurements have been limited mainly to a few hundred MeV (Fichtel *et al* 1975 and others). At air shower energies ($E \gtrsim 10^{14}$ eV) a γ ray will produce a shower significantly different from that produced by a proton in that, specifically, it will be deficient in muons. So called 'muon-poor' showers have been detected by the Paris–Lodz and Chacaltaya groups (eg Firkowski *et al* 1962, Suga *et al* 1963) but their identification with primary γ rays is debatable (see Maze *et al* 1969). The data on these 'muon-poor' showers are, so far, insufficiently precise to allow a search for correlations with astronomical objects. At higher energies, $E > 10^{19}$ eV, Wdowczyk *et al* (1972) have made out a case for a significant flux of primary γ rays, the ratio of γ rays to protons being predicted to be as high as 10% under certain assumptions.

Neutrinos could produce extensive air showers only if the neutrino–nucleon cross section rises to about 10^{-27} cm^2 by an energy of 10^{19} eV. This requires a faster-than-linear increase in cross section with energy, continuing from the present measured cross section at 10^{11} eV. Such a proposal was made by Berezinskii and Zatsepin (1970) to account for the observations of air showers apparently with energy beyond 10^{20} eV while maintaining a universal origin for cosmic rays. The spectrum of nuclei of universal origin would be cut off by interactions with the 2·7 K background radiation above an energy of approximately 6×10^{19} eV but the neutrinos produced as a result of these interactions could account for a continuing spectrum of air showers.

In what follows, results are given of searches for correlations of arrival directions with Galactic pulsars and supernova remnants, extragalactic supernovae and x-ray sources, radio and Seyfert galaxies and quasars.

2. Preliminary analysis

The most straightforward method of looking for intensity enhancements around suspected sources of a given type is to calculate the statistically expected number of showers falling within a certain angular distance of the sources and compare it with the observed values. The technique is essentially the same as described in the appendix of I, with the only difference that the given region of the sky is now not contiguous but consists of the union of all circles (or cones) of given radius centred on source candidates. The results are presented in table 1. As cosmic ray data, the same 119 shower directions ($E > 10^{19}$ eV) have been used as in I and in Krasilnikov *et al* (1974). The limiting angular distances have been chosen as 5° and 10°, the first representing the experimental uncertainty in the arrival directions of showers, while the second makes some allowance for deflection effects.

Table 1 gives a slight indication for enhancements in the directions of Galactic supernova remnants, extragalactic supernovae and quasars. None of the data are, however, statistically significant and their overall distribution is roughly what one

Table 1. Observed and expected numbers of showers coinciding with the selected source candidates.

The source candidates		5° circles			10° circles		
Type	Number	Observed	Expected	(Obs-Exp)/σ	Observed	Expected	(Obs-Exp)/σ
Galactic pulsars	118	13	16·3	−0·9	34	42·9	−1·7
Galactic supernova remnants	27	10	6·5	+1·4	18	17·1	+0·3
Extragalactic supernovae	92	11	9·6	+0·5	30	28·4	+0·4
Extragalactic radio sources	13	2	2·5	−0·3	4	9·6	−2·0
Extragalactic x-ray sources	39	8	10·3	−0·8	33	33·0	0·0
Seyfert galaxies	32	11	9·4	+0·7	19	23·5	−1·1
Quasars	110	19	17·5	+0·4	55	45·1	+2·1

would expect for random fluctuations, just as was the case for large-scale features (compare with table 3 of I).

The method adopted is completely unbiased in the sense that the expectation value of (Obs–Exp)/σ is zero for an isotropic distribution of the arrival directions, whatever the celestial distribution of the 'source candidates'. On the same assumption, the expectation of $(\text{Obs–Exp})^2/\sigma^2$ is always unity. Thus, if the hypothesis of isotropy is checked separately for the various types of source candidates, then any directional correlations among candidates of different types have no immediate effect, although the (Obs–Exp)/σ values are slightly correlated. Of course if significant enhancements had been found for two or more source types a closer scrutiny of the correlations between these types would have been necessary.

The distribution of the adopted source candidates on the celestial sphere is not completely isotropic, the deviations being due partly to genuine concentrations (as seen in figure 1 for Galactic sources) and partly to observational coverage effects. For extragalactic supernovae, x-ray sources, Seyfert galaxies and quasars, the latter introduce a large-scale structure; in particular, southern declinations are under-represented. For extragalactic radio sources the coverage is fairly uniform, except in the close vicinity of the Galactic plane. While an incomplete coverage does not introduce any bias, it obviously impairs the efficiency of the search.

It is of course somewhat arbitrary to decide which sources of a given type should be included in the analysis. In some cases the sources can be ranked in decreasing order of expected contributions (ie a 'figure of merit' can be introduced), and one might include only those sources with the highest 'figures of merit'. In other cases the expected contributions are quite uncertain and those objects which are nearest or brightest in some well defined waveband can be selected. The samples analysed in table 1 which comprise the largest sets of objects used in later analyses are not quite homogeneous from this point of view as will be seen from later discussions. The number of sources

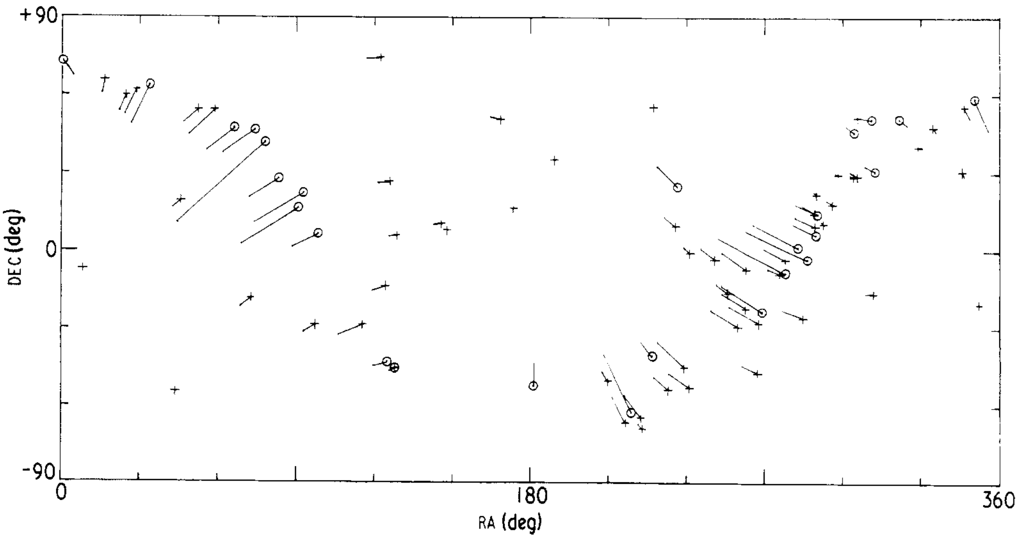

Figure 1. Positions of 'nearby' pulsars and supernova remnants. Crosses + indicate 60 pulsars with dispersion measures below 80 cm^{-3} pc; open circles ○ indicate 27 supernovae remnants within 3 kpc. Lines from the points end at the arrival directions of 10^{19} eV protons after deflection in the Galactic magnetic field

included should not be too large in order to avoid saturation effects, ie an almost complete coverage of certain declination bands. Any such effect present in the largest preliminary samples will be eliminated later by subdividing them according to some 'figure of merit'. The above preliminary analysis has made no use of 'figures of merit' (except in the selection of the astronomical objects to be included in the analysis).

3. Correlation with Galactic pulsars and supernova remnants

3.1. Cosmic rays above 10^{19} eV

The 118 pulsars used in the preliminary analysis are those with known dispersion measures (DM), taken from an unpublished compilation of J H Seiradakis (1974, 'Jodrell Bank Catalogue of Pulsars'). As we have seen in table 1, the whole set of pulsars shows a negative correlation with the arrival directions of showers.

If pulsars could indeed produce cosmic rays above 10^{19} eV one would not expect all of the observed pulsars to contribute similar fluxes at the earth. We have therefore examined the effects of subdividing the list of pulsars according to a figure of merit. For this we take the quantity $(\text{DM} \times P)^{-2}$, following Aguirre (1974), where P is the pulsar period. The dependence on dispersion measure, which is on average proportional to the distance of the pulsar, assumes that there are no selection effects which cause the more copious cosmic ray producers to be seen out to larger distances. The period dependence follows from the Gunn and Ostriker (1969) model in which the rate at which particles are injected into the pulsar wave zone is proportional to P^{-2}. Two points need to be made regarding this figure of merit. Firstly, the Gunn and Ostriker model goes on to predict that 10^{19} eV particles, if produced at all, would be produced only when the pulsar was very young, yet our search is for correlations with pulsars, the bulk of which have deduced ages from 10^5 to 10^8 years. Secondly, the figure of merit has a range of a factor of 10^5 for the observed pulsars. It is immediately apparent that, if some of the observed cosmic rays do come from pulsars, this could not be the only factor affecting the flux; the flux from the four 'brightest' pulsars (1929+10, 0950+08, 0531+21, and 1451−68) would be about 10 times greater than that from all the others combined, yet none of the 'observed coincidences' involves these pulsars. Nevertheless, correlations with pulsars having figures of merit above various threshold values were examined. It was found that for all thresholds the observed number of coincidences was slightly less than the chance number. This is apparently a reflection of the fact, mentioned in paper I, that there is a deficit of cosmic rays within 30° of the Galactic plane while there is an excess of pulsars in this region.

The test for 5° coincidences with pulsar distributions should be regarded as applying to neutral particles since even above 10^{19} eV the Galactic magnetic field would appreciably deflect protons coming from the majority of the observed pulsars. Calculations have therefore been made of the expected deflections of 10^{19} eV protons in this field. The 'Model D' field of Osborne *et al* (1973) was used and the calculations were restricted to the 60 pulsars having dispersion measures less than the median value of 80 cm^{-3} pc. We assume a mean interstellar thermal electron density of 0·06 cm^{-3} so that this limit corresponds to a distance of 1·3 kpc. Our model field should be reasonably close to reality in this restricted region and the deflections, which do not exceed 15°, should be sufficiently reliable. The deflections are shown in figure 1, where the crosses mark the pulsar positions and the short lines extend to the position from which a 10^{19} eV proton would appear to come. In the absence of complete data on the energies of individual showers we have compared the cosmic ray arrival directions with deflected positions for an energy of 2×10^{19} eV. The result is that 8 showers are found within 5° of the deflected positions compared with 13·1 expected by chance. Again a subdivision of the pulsars according to a threshold 'figure of merit' did not appreciably enhance the ratio of observed to chance coincidences.

In spite of this lack of correlation it is still possible that an appreciable fraction of the cosmic rays come from pulsars younger than those so far considered. Because of the narrowness of the beam of electromagnetic radiation emitted by a pulsar the observed pulsars will represent the small fraction, perhaps one in ten, that are favourably oriented with respect to the earth. It is plausible that pulsars are always produced in supernova explosions and the orientation effect accounts for the fact that a pulsar is observed in only two supernova remnants (the Crab and Vela X). From the catalogue of supernova remnants of Ilovaisky and Lequeux (1972) we have selected the 27 that are, according to their adopted diameter–surface brightness relation, within 3 kpc of the earth. This includes a complete sample of those with diameters less than 30 pc and thus with ages less than about 3×10^4 years and a large proportion of those with diameters up to 50 pc (age $\lesssim 10^5$ years). We regard the list then as a relatively complete sample of the probable sites of pulsars, within 3 kpc, which are considerably younger than the observed pulsars considered above. We searched for 5° coincidences as before. For undeflected particles 10 coincidences were found. When deflections appropriate to 2×10^{19} eV protons are applied there are 9 coincidences, 6 of them being the same as before. The positions of the supernova remnants are shown by circles in figure 1 joined by lines to the deflected positions for 10^{19} eV protons. The expected number of random coincidences for both cases is 6·5 and the observed coincidences have significance levels of 23 % and 12 % for the deflected and undeflected cases. It is difficult to define a 'figure of merit' for each remnant. The inverse square law must operate and the younger remnants may be favoured. However, other unknown properties such as the strength of the pulsar's surface magnetic field are important. It is interesting that the 10 remnants coinciding with undeflected particles include the three nearest (Vela X, the Lupus Loop, CTB 13) and the youngest (Cas A). Only the coincidence with Vela X remains, however, when magnetic deflection is included.

3.2. Cosmic rays between 10^{17} and 10^{18} eV

In view of the possibility of neutron primaries it is important to examine the region below 10^{19} eV for coincidences with Galactic sources. A correlation of pulsar positions and arrival directions of air showers with energies between 10^{17} eV and 10^{18} eV has in fact been reported by Aguirre (1974). The statistical evidence appears to be very significant but there are a number of physical arguments against the effect being real. The basic data are the arrival directions of 2598 air showers observed at Mount Chacaltaya. These were sorted into bins of $5^\circ \times 5^\circ$ in right ascension (RA) and declination (DEC). In each declination band those bins having a number of showers more than two standard deviations above the mean were selected; there were 36 of these. The bins were then extended to $15^\circ \times 10^\circ$ in RA and DEC and compared with the positions of the 80 pulsars known in mid-1973. 19 of these bins contain pulsars compared with 7·5 expected from random coincidences. We note that this apparently very significant result depends quite critically, however, upon the method of choosing the bins. Only two of the coincidences remain if the original $5^\circ \times 5^\circ$ bins are used. The author remarks that, selecting directly from a $15° \times 10°$ plot, there are 9 bins of which 3 give coincidences compared with 1·8 expected. The original selection from $5° \times 5°$ bins implies about 5° uncertainty in the measurement of the arrival direction. The extension to $15° \times 10°$ would be justified if the particles from each pulsar were deflected by a small (about 10°) but unknown amount. It can be deduced, however, from figure 1 that 10^{17}–10^{18} eV protons would be in general deflected through very large angles. Only those from the nearest pulsar could suffer such a small deflection. On the other hand, neutrons would not be deflected at all so no extension of the bin size would be justified for them.

Data from the Haverah Park array provide an independent check of this result. The number of showers in the range 10^{17}–10^{18} eV exceeds that from the above experiment by a factor of 5 but no correlation with pulsar directions was found when an identical procedure was followed (A A Watson, private communication). The declination range covered is different but there is an overlap between +45° and −10°. The Chacaltaya array, being near to the height of maximum development of 10^{17}–10^{18} eV showers, might possibly have better directional resolution but it is hard to see how such a large effect, if real, could be completely wiped out of the Haverah Park data.

We have also checked whether there is any correlation betwen the directions of the 27 supernova remnants discussed in the previous section and the directions of upward fluctuations in the cosmic ray intensities ($E > 10^{17}$ eV) given in $10° \times 15°$ bins by Bell *et al* (1973). No correlation has been found.

4. Correlations with extragalactic source candidates

4.1. Propagation effects

Before discussing the results of searches for directional correlations between ultra-high-energy cosmic rays and various extragalactic objects it is natural to ask whether such coincidences should be expected at all. The answer is not straightforward and depends on the nature of cosmic ray particles, on the strength and configuration of Galactic and intergalactic magnetic fields as well as on the cosmic ray intensities of individual sources.

For neutral primaries there are virtually no angular deflections and time delays (relative to optical photons) and the only limiting factor is the intensity. Neutrons cannot contribute on account of their short lifetime. Although ultra-high-energy γ rays and neutrinos are not known to be copiously produced in identifiable sources, even that remote possibility should warrant some search for angular coincidences. For heavy nuclei as primaries, no coincidences are expected because of the huge deflections caused by Galactic magnetic fields. For protons the deflections are not so prohibitive and a closer scrutiny of propagation effects is justified.

The Galactic deflection suffered by a 10^{19} eV proton arriving from the direction of the Galactic pole ($b^{\mathrm{II}} = 90°$) is about 3° if the field has a maximum strength of 3 μG near the Galactic plane and falls off exponentially with a scale height of 150 pc (which is roughly the lowest acceptable value). The direction of the field is assumed parallel to the plane. For protons with higher energies, the deflections decrease as E^{-1}. The time delays suffered inside the Galaxy are of the order of years for 10^{19} eV and perpendicular incidence, but increase rapidly for protons arriving at lower Galactic latitudes. For higher energies, the time delay decreases as E^{-2}. Thus, accepting the above field model and neglecting intergalactic fields, intensity enhancements within 5° or 10°

circles around the sources might be observed. The small time delays might also allow us to detect intensity increases around the directions of recently recorded extragalactic explosions, eg supernova outbursts. The whole argument is of course strongly dependent on the very uncertain Galactic field structure. If the scale height of the field is 1 kpc or more, then only the primaries with the very highest energies would show a close association with source directions and the present poor statistics at those energies would rule out any positive identification.

Our knowledge about the magnitude and structure of intergalactic fields is even more uncertain. In order to illustrate the connections between the characteristics of the field and the propagation of protons we adopt a simple model consisting of independent cells with randomly oriented fields. Denoting by H (nG) the magnitude of the field and by l (Mpc) the cell size, the root mean square time delay δ and angular deflection β of a proton arriving from a source D (Mpc) away depends only on D and KE_{19}^{-1}, where E_{19} is the energy in units of 10^{19} eV and $K = H^2 l$ is a scattering constant. This multiple scattering approximation is only valid for sufficiently high energies and sufficiently large distances so that the deflection in a single field cell is considerably less than 1 rad and the particle crosses several field cells during its way to the earth. Then for protons arriving with small total deflection angles $\beta \simeq 2{\cdot}7\, KE_{19}^{-1}\, D^{1/2}$ deg and $\delta \simeq 1800\, K^2 E_{19}^{-2} D^2 \simeq 250\beta^2 D$ yr. By fixing the energy and either β or δ, the scattering constant can be expressed as a function of D. In figure 2 these functions are plotted for $E_{19} = 3$ and $\beta = 5°$, $\delta = 10^6$ yr and 10 yr. Close directional correlations with objects active on the timescale of 10^6 years might be observed for K and D values in regions 3 and 4. In 4 the time delays are so short that the association of cosmic ray particles with recently observed explosions (eg supernovae) might be observed. In region 2, the angular deflections or time delays prevent the detection of close directional correlations. Finally region 1 is beyond the 'diffusion horizon' and particles from such sources cannot reach us because their velocities of diffusion towards us are counterbalanced by the recessional velocity due to the Hubble expansion.

A further 'propagation effect' is the decrease of flux with distance. Assuming that the angular deflections are small, the flux should decrease at least as fast as D^{-2}. Since we have no firm identification for the sources of the observed ultra-high-energy cosmic rays the source intensities cannot be estimated. One might ask, however, about the minimum source intensities needed to give rise to a detectable effect. The physical plausibility of the resulting intensities (or energy outputs) is useful in deciding whether some marginally significant statistical results should be taken seriously.

The detected flux of cosmic rays above 10^{19} eV is a few particles per 10 km^2 sr yr, with a considerable uncertainty mainly due to the difficulties in the estimation of the primary energy (Bell *et al* 1973, Edge *et al* 1973). The total detection area–time product providing the present world statistics is of the order of 300 km^2 yr (Bell *et al* 1973). In order to give a marked excess above the background we estimate that a typical source should contribute definitely more than 1 particle per 10 km^2 per 10 yr (perpendicular to the line of sight), even if there are several sources of similar intensity in the sample. Accepting this as a lower limit and taking the typical particle energy as 2×10^{19} eV, the total rate of energy production in the form of particles above 10^{19} eV is $10^{38} D^2$ erg s^{-1}; where D (Mpc) is the distance of the source. It is of course difficult to imagine a source in which most cosmic rays are accelerated to ultra-high energies. It is much more likely that the total energy output in the form of relativistic particles should be at least 10^4 times higher than the above estimates corresponding to a power spectrum with a differential exponent $\gamma = 2{\cdot}4$. In figure 3 these energy requirements

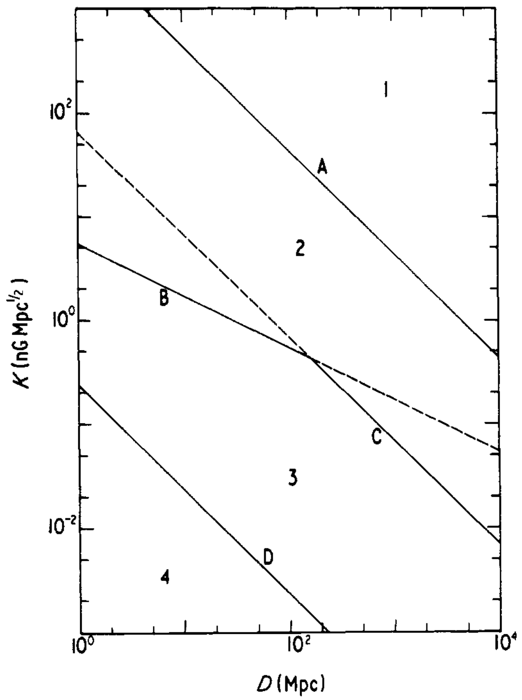

Figure 2. The intergalactic propagation of 3×10^{19} eV protons for various values of the source distance D and of the unknown scattering parameter K. The four regions separated by solid lines correspond to largely different observable features; for 1 the particles are mostly swept away by the combined effect of diffusion and expansion; for 2 they can reach the earth but the large angular deflections or time delays prevent an identification with optically observed active objects; for 3 such identifications could be made for long-lived intensive sources but not for recently observed explosions (such as SN); finally, for 4 the time delays are short enough for detecting such coincidences. A, diffusion horizon; B, deflection = 5°; C: time delay = 10^6 yr; D: time delay = 10 yr.

are compared with the measured luminosities of a few particularly active objects. These luminosities refer to some limited regions of the electromagnetic spectrum but it is unlikely that the total rate of energy production in the objects should be more than two orders of magnitude higher than these estimates.

4.2. Extragalactic supernovae

Supernova (SN) explosions, the most violent phenomena occurring in stars, have long been considered as obvious candidates for producing cosmic rays. While Galactic SN probably do give some (and perhaps even a dominant) contribution to the local flux at moderate energies, it is very much in doubt whether there is a sufficiently high production rate above 10^{19} eV for extragalactic SN to give a noticeable local flux. According to a recent proposal of Colgate (1975) there might be such a possibility. In his model, cosmic rays are generated by the same type of source (tentatively identified with SN) throughout the whole energy spectrum, the contributions to the local flux being mostly Galactic except at the highest energies, where the extragalactic flux becomes predominant.

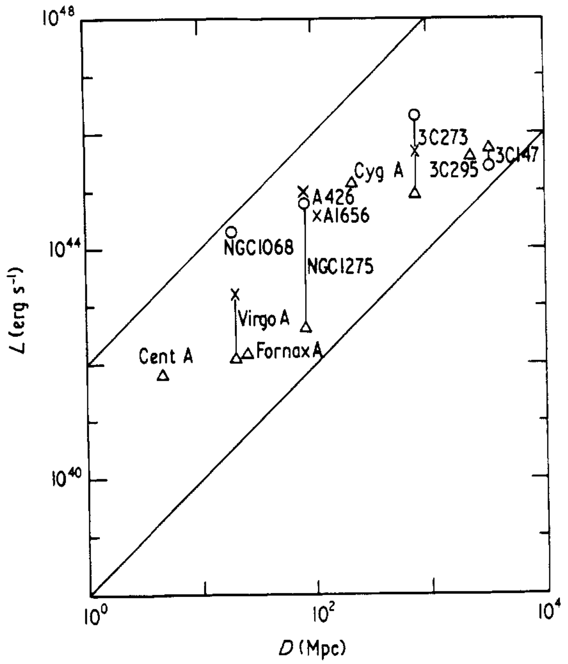

Figure 3. Luminosities and distances of some selected source candidates compared to minimum energy requirements. The lower line represents the minimum power output required in the form of particles with energies above 10^{19} eV in order to give rise to observable correlations. The upper line is the estimated minimum output required in cosmic rays of all energies. Luminosities are presented in the radio (△, 10^7–10^{11} Hz), x-ray (× , 2–10 keV) and optical (○) wavebands. The optical data given refer to non-thermal sources (Seyfert galaxies and quasars).

In the present search for correlations between SN and cosmic rays the SN data have been taken from 'The Master List of Supernovae Discovered since 1885' maintained by the Palomar group (Sargent *et al* 1974). The distances of the parent galaxies of the observed SN have been calculated from the corrected recessional velocity values of Sandage and Tammann (1975a, b, c) using a Hubble constant of $60\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The times of arrival and energies of the cosmic ray showers observed at Haverah Park (A A Watson, private communication) and at Volcano Ranch (J Linsley, private communication) have also been used in the course of the evaluation.

The search has been carried out in three stages. First, all those SN were included for which the recessional velocity of the parent galaxy was known and less than $2500\,\mathrm{km\,s^{-1}}$ (92 SN). The coincidence criteria included the proper time sequence (SN earlier) and an angular deviation of less than 5°. For the 89 shower directions ($E > 1{\cdot}5 \times 10^{19}$ eV) published by Linsley and Watson (1974) somewhat more coincidences have been found than statistically expected; furthermore, the average (and median) distance to the SN involved in the coincidences was lower than expected for random right ascensions of the showers. There was also some positive correlation between the time delay and D^2/E^2. Each of these effects pointed towards a genuine connection between SN and showers. None of these deviations is, however, statistically significant in itself, and the extension of the number of showers to 119 ($E > 10^{19}$ eV) has not strengthened the evidence either. The comparison of expected and observed numbers of coincidences given in table 1 shows in fact only a very slight excess. In the second stage the analysis was restricted to correlations with SN observed at high Galactic latitudes ($|b^{II}| > 45°$) and at smaller distances ($D < 16{\cdot}7$ Mpc corresponding to a limiting corrected recessional velocity of $1000\ \mathrm{km\ s^{-1}}$). This sample included only 22 SN, but most of the genuine effect is expected from this subset. A somewhat complicated evaluation using the methods of maximum likelihood has yielded the following significances: 4% for energies above $1{\cdot}5 \times 10^{19}$ eV and 10% for energies above 10^{19} eV. Finally in the third stage a very small sample of SN was looked at (11 SN satisfying the conditions $|b^{II}| > 45°$, $D < 10$ Mpc). The maximum likelihood significance was again similar to that found before (8%). Although the maximum likelihood method admittedly implies some arbitrariness in the construction of the likelihood function it has the advantage that one obtains some estimates for the unknown parameters, in our case for the 'intensity parameter' (the number or total energy of ultra-high-energy particles produced in a SN) and for the 'propagation parameter' K discussed in 4.1. Of course, these estimates are physically meaningful only if the effect is genuine and not merely a statistical fluctuation. According to these estimates the total energy produced in the form of particles with energies above 10^{19} eV should be about 3×10^{47} erg (ie 10^{40} particles with an average energy of approximately 2×10^{19} eV) with the propagation parameter of approximately $5 \times 10^{-2}\ \mathrm{nG\ Mpc^{1/2}}$. It is interesting to note that the local flux calculated from all extragalactic SN explosions in the universe would have the same order of magnitude as the observed flux if one accepts the above 'intensity parameter' for all SN.

The predominantly extragalactic SN origin of the highest-energy primaries encounters some difficulties however. One is a lack of any intensity enhancement around the Virgo cluster as reported in I. In fact the number of SN in that region shows a definite excess and thus an enhanced intensity would be expected even if the time delays are too long to associate the particles with individual SN explosions. There is a more important difficulty with the transition between the two energy regions, one where Galactic and the other where extragalactic SN give the main contribution. For straight-line propagation the time-averaged flux from the Galactic SN should be roughly two orders of magnitude higher than the extragalactic SN contribution. Now it might happen that at very high energies a 'preferential bending out' of the Galactic particles on the one hand and a fluctuation in time on the other, as proposed by Colgate, largely reduces the flux of Galactic origin. At somewhat lower energies, however, the much more intense Galactic flux should surely dominate the extragalactic one and a smooth power spectrum as observed would seem unlikely under such circumstances. It should also be noted that the energy required for the production of particles above 10^{19} eV is very high (3×10^{47} erg), and the production spectrum should be close to the flattest spectrum allowed by Colgate in order to have realistic values for the total energy of cosmic rays produced by a supernova. We feel that the statistical indications for excess coincidences found are much too weak to counterbalance these difficulties.

4.3. Strong extragalactic radio sources

Although very little is known about the production mechanism of ultra-high-energy cosmic rays, the best extragalactic source candidates appear to be the objects showing violent activity on the scale of whole galaxies. One class of such objects is characterized by very intense non-thermal radio emission, undoubtedly generated by the synchrotron radiation of relativistic electrons. In spite of their huge distances, the radio brightness of the strongest extragalactic sources is comparable with the brightest Galactic sources, and it might well happen that they are also efficient ultra-high-energy cosmic ray producers.

The search for coincidences was carried out by using an all-sky catalogue of strong radio sources at 408 MHz (Robertson 1973). The catalogue covers the whole sky except a $\pm 10°$ band around the Galactic plane and a few localized regions (the solid angle covered is 10·1 sr). The number of sources above the lower flux limit of 10 Jy is 160 (1 Jy = 10^{-26} W m^{-2} Hz^{-1}). In order to restrict the sample, we have raised the lower threshold to 50 Jy. It is interesting to note that the total flux of the 13 sources thus included in the analysis far exceeds that of the remaining 147 sources. The brightest extragalactic radio source, Cyg A, is not included in the sample because of its low Galactic latitude.

Of the 13 sources, 11 are radio galaxies and two are quasars. The nearest (and brightest) object included is the radio galaxy Cen A, which is only a few megaparsecs away. It is interesting to note that this galaxy has very recently been claimed to be the first identified source of high-energy ($E > 3 \times 10^{11}$ eV) γ rays (Grindlay *et al* 1975). There are two other sources within the Local Supercluster (M87 in the Virgo cluster and Fornax A). The farthest identified radio galaxy, 3C295 is also included (recessional velocity 138 000 km s^{-1}).

According to table 1, the number of cosmic ray coincidences is less than expected both for the 5° and 10° circles. Both coincidences at 5° are with 3C295, while at 10° there are 3 coincidences with 3C295 and one with M87. No coincidence has been observed with Cen A, the 'best' source candidate.

4.4. Extragalactic x-ray sources

This class of objects is more heterogeneous than that of the bright radio sources, and also the set of identifications with optical objects is much less complete. In the search for coincidences a representative sample of x-ray sources published by Rowan-Robinson and Fabian (1975) has been adopted. The sample contains those 39 'extragalactic' ($|b^{\mathrm{II}}| > 10°$) sources which fall in the zone of complete coverage of the Abell catalogue of clusters of galaxies and have fluxes higher than 3 counts s^{-1} as measured by the Uhuru satellite. This threshold corresponds to an energy flux of about 5×10^{-11} erg cm^{-2} s^{-1} in the 2–10 keV x-ray interval. Out of the 39 sources only 17 are more or less reliably identified, most of them with Abell clusters. The identifications also include the radio galaxy M87, the Seyfert galaxy NGC 4151 and the quasar 3C273.

The x-ray spectrum of cluster sources is not known well enough to decide whether the radiation is generated by the Compton scattering of relativistic electrons on the 2·7 K background or by thermal bremsstrahlung in a hot gas filling the clusters. While in the first case the presence of relativistic particles gives some justification for our search, the thermal bremsstrahlung interpretation gives no direct indication for violent acceleration processes. The results of the search (table 1) show no cosmic ray excess in the vicinity of the sources.

4.5. Galaxies with Seyfert or Seyfert-like spectra

The objects known as Seyfert galaxies are defined by combination of spectral and morphological criteria. The spectral features (broad high-excitation lines and an enhanced continuum) give evidence of fast gas motions and other violent processes, similar to those occurring on even larger scales in quasars.

The search for coincidences has been based on a catalogue compiled by Vorontsov-Vel'yaminov and Ivanišević (1974), which includes not only typical Seyferts but also various transitional objects intermediate between Seyfert galaxies and other types. Out of the 95 galaxies listed those 32 have been selected which are within a distance of 100 Mpc (ie $cz < 6000\,\mathrm{km\,s^{-1}}$). There is not much indication for an excess cosmic ray intensity around these sources.

4.6. Quasars

Quasars are characterized by a stellar appearance (ie very small angular diameter), broad emission lines, strong ultraviolet and infrared continua, and, what is more important, by large redshifts. The quasars can be subdivided into those which are radio sources (now generally termed QSS) and those which have similar optical properties but are radio quiet (QSO). If the redshifts are cosmological the radio luminosities of QSS are comparable with the most luminous radio galaxies. It is estimated that the QSS group comprises only a few per cent of all quasars. Some quasars are variable on short time scales, indicating small spatial extensions of either the quasars themselves or of some bright constituents emitting a substantial part of the radiation.

There is still some controversy about the origin of the redshifts of quasars. Although the consensus of opinion is now clearly in favour of an interpretation in terms of recessional velocities due to the Hubble expansion, some authors are still in favour of much smaller distances (for a recent account of the controversy see Field *et al* 1973). Accepting the majority view, quasars are intrinsically extremely luminous objects and this luminosity is due to very violent, strongly non-thermal processes. In such circumstances very efficient particle acceleration can be expected, but the reduction of the flux due to propagation effects makes the possibilities of detection very doubtful.

The quasar data have been taken from a catalogue compiled by de Veny *et al* (1971) containing 202 objects. The majority of these are QSS, being optical identifications of radio sources in the Cambridge and Parkes catalogues, but some radio-quiet objects are included. Restricting the analysis to the 110 'nearby' quasars which have redshifts below 1, some excess coincidences have been found (table 1) although the effect is not significant. By taking the 55 nearest quasars only, the excess increases for the 5° circles ($1{\cdot}74\sigma$) but somewhat decreases for the 10° circles ($1{\cdot}51\sigma$). A subdivision into narrower redshift intervals shows that most of the excess is caused by quasars with redshifts between 0·3 and 0·4, and not by those with the smallest redshifts. This can be considered as an indication for a statistical origin of the excess.

As we have already mentioned, the cosmological origin of redshifts is not quite unanimously accepted. One of the main proponents of small quasar distances, Arp (1974) has compiled a list of 10 quasars suspected to be associated with the Local Group of galaxies. Interestingly enough, we have found 9 cosmic ray coincidences in 5° circles around these objects, while the expected number is 2·9. Such an excess has a fairly low probability (0·3 %).

5. Conclusions

The searches carried out in I and in the present paper give no firm evidence for the association of the arrival directions of ultra-high-energy cosmic rays with either the large-scale features of the Galaxy and of the Supercluster or with sets of individual source candidates. There are, however, some indications for positive effects which, if substantiated by future searches using improved cosmic ray data, might turn out to give much information both about the origin and composition of cosmic rays and about some important astrophysical parameters such as the magnitude and degree of irregularity of Galactic and intergalactic magnetic fields. Therefore at the present stage it seems best to keep an open mind about the presence of anisotropies, and to sketch some possible scenarios both for the case of 'no anisotropy' (ie for anisotropies below the present observational threshold) and for the cases of 'indicated anisotropies'.

The present observational limits on large-scale anisotropy above 10^{19} eV seem to exclude a Galactic origin for a predominantly proton composition, even if there is a substantial halo field around the Galaxy. A Galactic model with heavy primaries and halo, however, cannot be excluded, and this possibility deserves to be further studied both experimentally and theoretically. For an extragalactic origin there are virtually no restrictions on the composition. In the unlikely case of predominantly neutral primaries the sources should be at cosmological distances (ie a strong evolutionary effect must be invoked in order to get rid of nearby sources), otherwise there would probably be observable excesses in the close vicinity of some nearby sources. The same restriction applies to proton primaries if both the Galactic and intergalactic fields are so weak that the deflections are negligible and the time delays are less than the life times of sources. In that case however, the energy losses on the cosmological background radiation would reduce the flux and would make the energy requirements even more difficult to satisfy (figure 3). It seems more likely that the Galactic and/or extragalactic fields are strong enough to smooth out the small-scale anisotropies; in that case the search for small-scale coincidences would give no information even if the cosmic ray data improved considerably. Although the search for large-scale anisotropies would be somewhat more helpful the present observational limits cannot exclude any reasonable possibility.

We now turn to the positive indications. In order that a Galactic supernova remnant (or young pulsar) origin (see §3.1) of at least some of the observed particles should not contradict the large-scale features, one must assume that most primaries are heavies while the slight excess around SN remnants is caused by protons and neutrons, which are only a small fraction of the particles produced and therefore do not destroy the overall isotropy. Of course a Galactic halo is then also necessary for isotropizing the flux of heavy primaries. As for the extragalactic SN origin, the difficulties have been discussed in §4.2. From a purely statistical point of view, the best indication points to a quasar origin. If quasars are at cosmological distances, then the energies required in the form of particles with $E > 10^{19}$ eV would, however, be almost prohibitively high (see figure 3). Although the observed correlations might be somewhat easier to interpret in terms of a non-cosmological origin of redshifts, we feel that the statistical evidence (0·3% chance probability) is not yet strong enough to justify a definite suggestion in such an important and controversial field.

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Note added in proof. At the 14th International Conference on Cosmic Rays (Munich, August 1975) revised values were given for the arrival directions of the 20 air showers from the Yakutsk array included in the data of Krasilnikov *et al* (1974). These give a considerably smaller amplitude for the first harmonic of the RA distribution above $\delta = +30°$ that was discussed in I. We have repeated the present analysis with the revised directions and find that there are only insignificant changes to the observed and expected numbers of coincidences reported here. These affect none of our conclusions.

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