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Arrival Directions of Cosmic Rays above 40 EeV

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Abstract

The arrival directions of cosmic rays of nominal energy above $4 \times 10^{19}\mathrm{eV}$ detected by large arrays show two interesting departures from isotropy: (a) the only significant feature in supergalactic latitude is an improbable excess within 1° of the supergalactic plane, but largely at longitudes where there is no such concentration in galactic activity, and (b) two possibly significant close triplets, which produce this excess. No correlation is detected with directions in which extragalactic supernovae within 100 Mpc are numerous. Correlations with the distribution of galaxies will be presented at the conference. However, the 13 events above $10^{20}\mathrm{eV}$ notably prefer the half of the exposure-weighted sky closest to the galactic centre – possibly consistent with a galactic halo source – unlike events of lower energy.

1 Lack of association with regions of extragalactic supernovae:

In 1996, Uchihori et al. looked for evidence of clustering in the arrival directions of cosmic rays above 40 EeV ($4 \times 10^{19}\mathrm{eV}$), concluding that there was no convincing evidence of departure from isotropy. We adopt the same energy threshold in examining the larger data set now available. The data from the large arrays, AGASA, Haverah Park, Yakutsk and Volcano Ranch, are selected, as their analysis is mature and their sensitivity functions reasonably well understood. With the recent update (Takeda et al., 1999) of the AGASA data, there are 92 events nominally above $4 \times 10^{19}\mathrm{eV}$ (AGASA 47, Haverah Park 27, Yakutsk 12 and Volcano Ranch 6 – see Uchihori for sources), including 13 above $10^{20}\mathrm{eV}$. No attempt is made to re-align the energy scales, which may differ from each other by $\sim 15\%$.

There is no gross anisotropy, as shown in figure 1, which is a plot of the Northern sky, with the equatorial pole in the centre, and the (radial) declination scale adjusted – by becoming strongly compressed at low declinations – so that because of the differing sensitivities of each array at each declination, an isotropic cosmic ray flux would populate the circular diagram uniformly. This will be referred to as an equi-exposure plot. This lack of gross anisotropies is despite the facts that (a) deflections in the galactic domain should be small, as at the median energy of 52

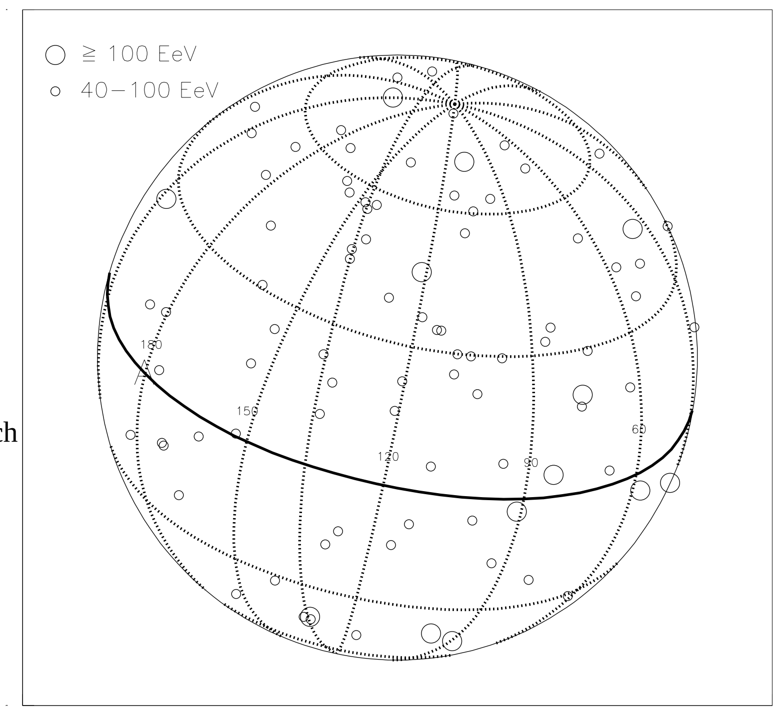

Figure 1: Equi-exposure plot of arrival directions of 92 UHE cosmic rays. The equatorial pole is in the centre of the circle, and lines of galactic latitude and longitude are shown (the latter numbered 60..150). The heavy line is the galactic plane, and an additional dotted line the supergalactic plane. Larger circles mark events above a quoted energy of $10^{20}\mathrm{eV}$.

EeV, the gyroradius of a proton would be greater than 56 kpc if exposed in the galactic halo to a magnetic field whose constant transverse component was less than 1 microgauss, and (b) above this energy photopion production on the microwave background incresingly limits the range of distance of sources which can contribute, and (c) within several hundred Mpc the local distribution of visible matter is highly anisotropic.

Rather than compare this with the distribution of mostly tiny galaxies on the sky, we plot in Figure 2 the distribution of recorded extragalactic supernovae (NED catalog), which probably traces the distribution of most powerful energy sources, and as they are of nearly uniform absolute magnitude, their brightness reflects their distance and roughly matches the expected flux of any other radiation (such as u.h.e. cosmic rays) whose deflections had not greatly masked the source directions. The plot uses the same co-ordinates as figure 1, for comparison. The size of symbol relates to the estimated SN peak magnitude, assuming that magnitude 7 corresponds to 1 Mpc (i.e. M=-18), the largest symbols being for $\mathrm{m} < 12$ (< 10 Mpc), with 2.5-magnitude bands thereafter. From the numbers, recording is clearly becoming increasingly inefficient beyond 10 Mpc, though the median distance is about 50 Mpc. For a comparison of these two distributions, the cosmic ray dataset is reduced to 70 by ignoring events which arrive within 16° of the galactic plane, the "zone of avoidance" where extragalactic objects are greatly dimmed. Weighting each catalogued supernova by its brightness, normalized to 1 for a supernova of peak apparent magnitude 7, corresponding to an absolute magnitude -18 placed at 1 Mpc (but truncating the four brightest SNae to magnitude 11.0 to avoid undue emphasis on a few nearby individuals), the total supernova signal within 2.5, 5 and 10 degrees of each observed cosmic ray arrival direction can be found. The averages are 0.010, 0.030 and 0.15 respectively for the reduced dataset of 70 real events. From 3400 simulated sets of 70 events (with avoidance zone) the supernova signals within these same radii are 0.010 (0.007), 0.037 (0.015) and 0.14 (0.03) respectively (the figures in brackets being the standard deviations), showing absolutely no preference of the real cosmic rays to favour directions of astrophysically active regions.

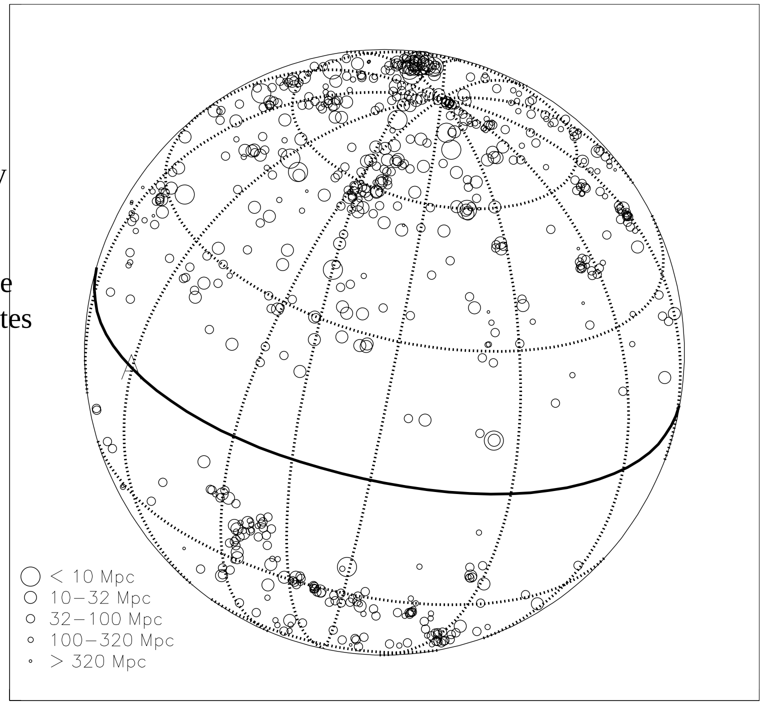

Figure 2: The same for extragalactic supernovae, out to about 200 Mpc. The larger circles indicate the supernovae of greater apparent brightness, hence closer, the distance being estimated from peak brightness.

In earlier data sets, two possible directional features had attracted comment: (a) a preference for lower supergalactic latitudes (Stanev et al., 1995), and (b) the existence of a few pairs of events, and one triplet, within the small separation of 2.5°. These two questions are examined first.

2 Supergalactic latitude

A slight preference for low supergalactic latitudes in the present dataset appears to be due to a remarkable concentration within 1° of the supergalactic plane, seen when the events are tabulated in 2° bands: there are 8 events in the central band ($-1^\circ..1^\circ$), compared with an average number of 1.73 per band averaged over the 6 latitude bands on either side of this. The chance probability of seeing at least 8 events in this particular band is about 5×10^{-4}. When the wider distribution in supergalactic latitude is plotted, with this apparent central excess allowed for, it matches that obtained by sampling from uniform density on the equi-exposure plot. The table below gives the numbers observed in 10-degree bands of supergalactic latitude, and the average number expected from the sky exposure to a flux which is uniform except for an enhancement at latitudes within 1° of the supergalactic plane, such that there are 8 events in that band, and a total of 92 events overall.

SG-Lat (mid-band):	-45	-35	-25	-15	-5	+5	+15	+25	+35	+45	+55	+65
Observed:	2	6	3	8	12	12	9	12	6	9	6	5
Expected:	3.1	4.7	6.2	7.5	11.7	12.1	9.0	8.5	7.8	6.7	5.2	3.8

This concentration on the supergalactic plane is related to the small clusters, discussed below, but it is astronomically surprising. A northerly group of showers, near galactic latitude 55°, is close to a dense cluster of galaxies and supernovae, but below a galactic latitude $\sim +30^{\circ}$, these showers arrive from a range of supergalactic longitude where the plane structure is not seen (as though we are here looking outwards from the supergalactic centre). Is this low chance probability misleading, or has one to look for an invisible agent? Perhaps this is some manifestation of the underlying structure of the initial plate, which determined the formation of galaxies there – perhaps a laminar magnetic field resulting from the original compression of matter into this plate. It is hard to imagine an adequate accelerator acting where matter has not concentrated into spinning luminous structures, and though one might imagine a regular magnetic field that has been wound up in the Virgo cluster region by a general rotation, so that charged particles accelerated in major clusters are focussed out along these distant field lines, and somewhat displaced from the cluster, it seems unlikely that the beam would end up so closely aligned.

3 Small-scale clustering:

The table below shows the number of clusters of various sizes, within a radius of 2.5° (selected by the observers as representing the smallest reasonable radius in view of experimental accuracy and of magnetic deflections in the Galaxy), or 5°. A cluster is defined as any chain of arrival directions linked by separations within the specified limit, rather than a group within a circle drawn around the centroid. The numbers of clusters have also been counted in several thousand simulated distributions, formed by uniform sampling of 92 events from the exposure map, but requiring that there are 8 events in the band within 1° of the supergalactic plane.

	Real	Simulated	Real	Simulated
Separation:	$< 2.5^{\circ}$	$< 2.5^{\circ}$	$< 5.0^{\circ}$	$< 5.0^{\circ}$
Multiplicity				
2	4	4.3	5	10
3	2	0.33	4	2.3
4	0	0.04	0	0.7
5	0	0.00	1	0.2
> 5	0	0	0	0.1

The number of close (2.5°) double events is thus as expected, but there is a probability of only 0.4% of observing more than 1 cluster larger than a doublet, whereas 2 triplets are seen. So one or both these triplets may be physical associations. Only one event in these triplets is more than 1° from the supergalactic plane. Opening up the selected separation to 5° does not greatly increase the number of clusters, as might be expected if many point sources were blurred by a few degrees by magnetic effects. The expected number of pairs is seen, and there is one quintuplet (which includes one close triplet) – not remarkable as one expects on average 0.3 groups of this size or larger. Had the cosmic ray sources been mapped by the supernovae, as considered in Section 1 one would have expected 16 pairs within 2.5° and 44 within 5°, rather than 8 and 18 in the actual dataset (reduced from 9 and 20 in the table above).

4 Events above 10^{20} eV:

The events having at least $10^{20}\mathrm{eV}$ estimated energy were also examined separately. Although the sample of 13 is necessarily small, these appear to have a different distribution on the sky. The equal-exposure sky-map has been divided into two equal halves, at the median value for the following three co-ordinates, and the numbers of cosmic rays lying below and above the median are tabulated – (1) magnitude of galactic latitude, $|b_{gal}|$, (2) magnitude of supergalactic latitude, $|b_{Super-gal}|$, (3) distance from galactic centre, $D_{Gal.Cen.}$. (The numbers within and beyond the expected median should be equal for isotropic radiation.)

The median value expected from the exposure sensitivity – uniform population of the maps in figures 1 and 2, modified by overpopulation of the band within 1° of the supergalactic plane – is denoted by median A in the table (and median B gives the median expected without the supergalactic-plane overpopulation).

measure :	median A	median B	No. within	No. beyond
$\geq 10^{20}$eV				
$\|b_{gal}\|$	28.2	27.6	6	7
$\|b_{Super-gal}\|$	23.0	26.0	4	9
$D_{Gal.Cen.}$	113.6	111.1	11	2
Below 10^{20}eV				
$\|b_{gal}\|$	28.2	27.6	31	48
$\|b_{Super-gal}\|$	23.0	26.0	42	37
$D_{Gal.Cen.}$	113.6	111.1	39	40

The probability of having an imbalance at least as great as 11/2 in favour of the half of the "observable sky" closest to the galactic centre is 1% (a result unchanged without overpopulation of the supergalactic plane). This is quite different from the distribution of events below $10^{20}\mathrm{eV}$. The true energy of the particles may perhaps be 15-20% lower than this, so the nominal $10^{20}\mathrm{eV}$ threshold may be selecting approximately those particles which are severely curtailed by the G-Z-K cutoff. These particles cannot have come from hundreds of Mpc distance, and this asymmetry on the sky, if confirmed in larger samples, and especially in the Auger observations from the southern hemisphere (which can see well the galactic centre), suggests a source in the galactic halo.

At present, favoured models for a galactic halo source involve decay of supermassive particles forming a part of the dark matter, but these should produce a very large proportion of photons amongst the most energetic cosmic rays, which seems at present to conflict with the penetration of these showers in the atmosphere.

5 Conclusions:

The events nominally above $10^{20}\mathrm{eV}$ are effectively those which are not expected if sources are fairly uniformly distributed in the universe, because of the GZK cut-off. Hence the apparent change to a distribution around the galaxy – whilst not established by the present small statistics – would be quite in keeping with a widely distributed source within the galactic halo. The possible two physical triplets appear to belong to a different, non-halo, distribution, and they raise doubts about an explanation of the isotropy of the 40-100 EeV particles that involves large magnetic deflections.

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