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Cluster analysis of extremely high energy cosmic rays in the northern sky

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Abstract

The arrival directions of extremely high energy cosmic rays (EHECR) above 4×10^{19} eV, observed by four surface array experiments in the northern hemisphere, are examined for coincidences from similar directions in the sky. The total number of cosmic rays is 92. A significant number of double coincidences (doublet) and triple coincidences (triplet) is observed on the supergalactic plane within the experimental angular resolution. The chance probability of such multiplets from a uniform distribution is less than 1% if we consider a restricted region within $\pm 10°$ of the supergalactic plane. Though there is still a possibility of chance coincidence, the present results on small angle clustering along the supergalactic plane may be important in interpreting EHECR enigma. An independent set of data is required to check our claims. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

It is well known that extremely high energy cosmic rays (EHECR) are subject to photopion production by interactions with primordial photons on traversal through intergalactic space, attenuating their energies down to 4×10^{19} eV (40 EeV) if their sources are distributed uniformly over cosmological distances. In this case the arrival directions of the highest energy cosmic rays around 40 EeV are expected to be almost isotropic and some of them above 40 EeV may be correlated to the topological structure of nearby galaxies since there is a good chance that the sample comes from less than 100 Mpc and that if protons, the deflections in the intergalactic magnetic field may be expected to be small. If powerful radio galaxies are sources of EHECR's, a correlation of their arrival directions on the sky with the supergalactic (SG) plane might be expected, as suggested by Biermann and Stanev [1], since extragalactic radio sources concentrate towards the SG plane and this concentration extends to at least $z \sim$

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0.02, based on the MRC Catalog measured at Molonglo covering the declination band between 18.5° and −18.5° [2]. In 1995 Stanev et al. [3] studied the arrival direction of cosmic rays with energies greater than 40 EeV and found that they exhibit a good correlation with the direction of the SG plane. The magnitude of the observed excess is $2.5 \sim 2.8\sigma$, in terms of Gaussian probabilities. They used 42 events of the world data published at that time with 27 events being from the Haverah Park experiment.

The AGASA group claimed [4] that three doublets of showers with angular separation of less than 2.5° (consistent with the experimental resolution) are observed among the 36 events above 40 EeV, corresponding to a chance probability of 2.9% from a uniform distribution, but noted that a significant fraction of EHECR's are uniformly distributed over the observable sky. Two of three doublets are observed within 2.0° of the SG plane. Adding the AGASA data up to August, 1998 and reevaluating the energies and arrival directions of all AGASA events, Takeda et al. [5] found one triplet and three doublets in a total of 47 events. The chance probability is smaller than 1% and the significance increased with the increased data set. It is interesting to note that the centroids of the triplet and one of the doublets are 0.7 and 0.9 degrees off the SG plane, respectively.

In the northern hemisphere, four surface array experiments at Volcano Ranch (VR), Haverah Park (HP), Yakutsk (YK) and Akeno (AG) have been operational so far and, with 81 events above 40 EeV, we have reported in Ref. [6] that a significant number of doublets and triplet are observed around the SG plane with a chance probability less than 1% supporting the AGASA result.

It is important now to examine whether the significance of such a clustering of EHECR's in the sky in correlation with the SG plane increases or not when using the world data set which includes the new published AGASA data. If clusters along the SG plane are real, source models which do not relate to the SG plane may find difficulty in explaining the observations.

In this report we examine the arrival direction distribution of the events so far published by the four experiments in the northern hemisphere. While we report rather low probabilities of various occurrences we emphasize that we regard these claims as charting the way for the analysis of future, independent data sets rather than as providing conclusive evidence of anisotropy.

2. Analysis and results

The experimental data reported by VR [10], HP [3], YK [9] and AG [5] are used in the following analysis. The Fly's Eye events have differing error ellipses, event by event [6], which makes the estimation of the chance probability complicated and the exposure in right ascension of the Fly's Eye instrument is less uniform than that of the ground arrays. Hence they are not included in the present analysis.

Experimental details for the four experiments and conditions for the present analysis are summarized in Table 1. Only extensive air showers (EAS) with zenith angles within 45° are used in the present analysis to select EAS of good quality in energy and arrival direction determination. The arrival directions are determined by the arrival time of the shower front at different detectors, resulting in the estimated

Table 1
Experimental sites and number of events above 40 EeV.

Experiment	Longitude	Latitude	Number of events	Zenith angle	Error in arrival determination
AGASA	138°30'E	38°47'N	47	$< 45°$	1.8°
Haverah Park	1°38'W	53°58'N	27	$< 45°$	3°
Yakutsk	129°24'E	61°42'N	12	$< 45°$	3°
Volcano Ranch	106°47'W	35°09'N	6	$< 45°$	(3°)
Total			92		

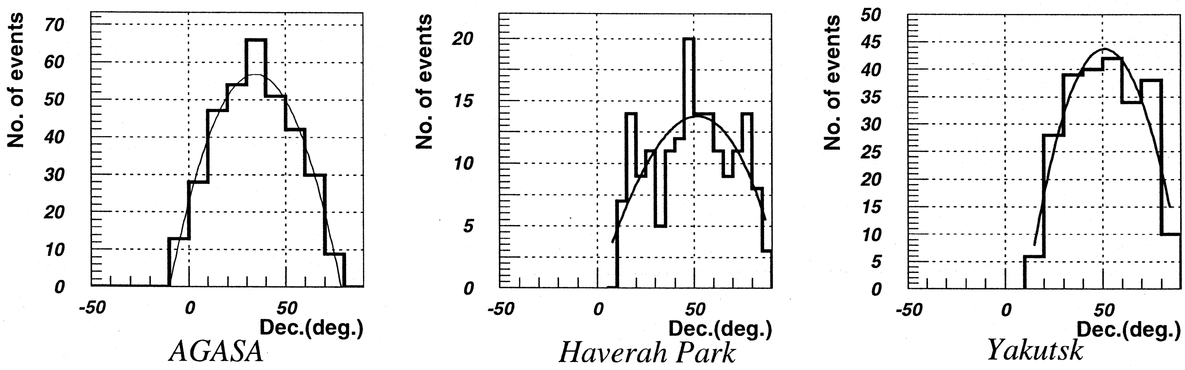

Fig. 1. Declination distribution of showers of energies above 10 EeV and zenith angles smaller than 45° of AG, YK and HP.

directional uncertainties evaluated by each experiment as listed in Table 1 for 40 EeV events.

The method of energy estimation is different in each experiment. In this report we use 92 extensive air showers whose energies are estimated to be above 40 EeV by each experiment and do not normalize the energy between experiments.

The observable sky is different for each experiment and is not uniform in declination. In the case of the ground array experiments listed in Table 1, the right ascension distribution is almost uniform. The declination distributions for observed events above 10 EeV is, however, different for each experiment as it depends upon the latitude of the array and detector type, as shown in Fig. 1. Since the triggering efficiency of each experiment becomes uniform over their array area above 10 EeV, the declination distribution of observed events above 40 EeV in each experiment is similar to that above 10 EeV.

2.1. Galactic and supergalactic latitude distribution

To study the general arrival direction distribution of 92 events, the latitude distribution in galactic (G) and SG coordinates are shown in Fig. 2. Solid lines show the sum of the expected distributions assuming a uniform incident arrival direction distribution for each experiment; a uniform distribution in right ascension and the observed declination distributions of Fig. 1 are used to obtain these curves. There are no statistically significant deviations from uniformity in G coordinates. In the SG coordinate system, there is some excess between 0° and 30°, but it is not statistically significant. Most EHECR's, then, are found to be uniformly distributed over the observable sky.

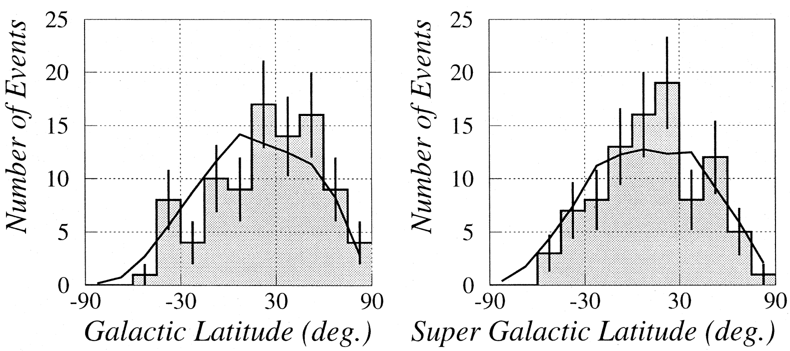

Fig. 2. Galactic (left) and supergalactic latitude (right) distribution of arrival directions of 92 cosmic rays from four ground array experiments. Energy thresholds are 40 EeV. Solid lines are the sum of expected distributions of each experiment for a uniform distribution.

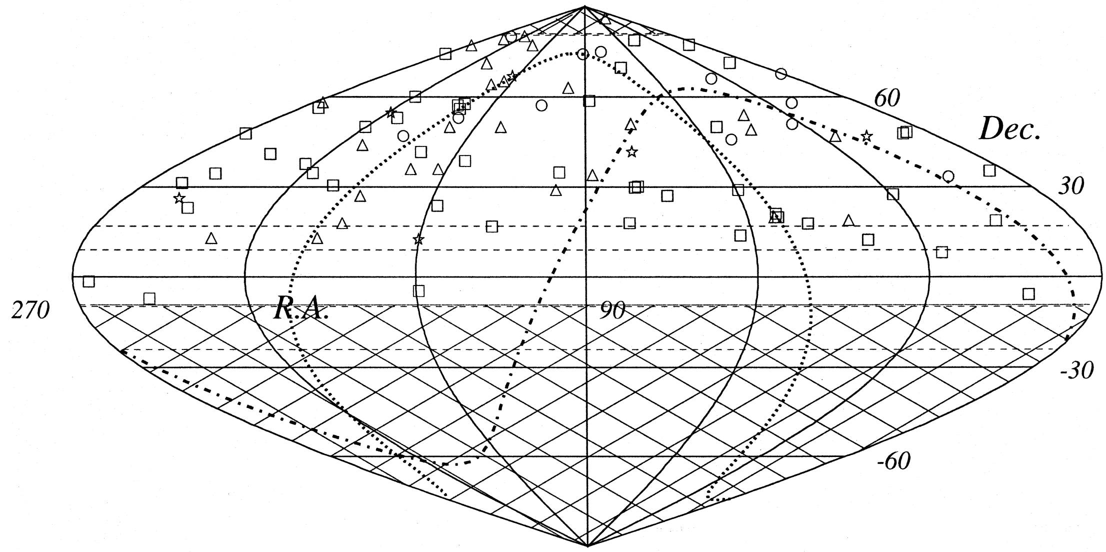

Fig. 3. Sky map of 92 events above 40EeV in equatorial coordinates. Squares – AGASA, Triangles – Haverah Park, Circles – Yakutsk and Stars – Volcano Ranch. The region of sky observable in each experiment is shown by dashed lines from the top YK, HP, AG and VR. The hatched region at the pole is invisible sky by AG and VR. The dot dash curve is the galactic plane and the dotted curve is the supergalactic plane.

2.2. Clustering of arrival directions of showers

In Figs. 3 and 4, the arrival directions of each event from the four arrays are plotted in equatorial and galactic coordinates, respectively. Some coincidences of events coming from similar direction are apparent. In the following we estimate the chance probability of such coincidences arising from a uni-

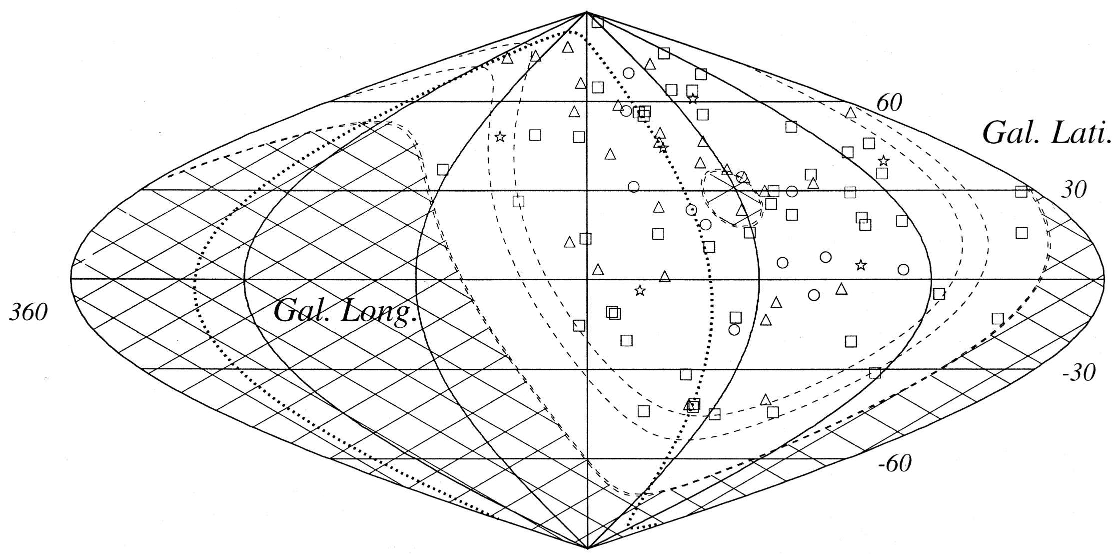

Fig. 4. Sky map of 92 events above 40EeV in galactic coordinates. The symbols are the same as used in Fig. 3. The hatched region centered around $l = 120°$ and $b = 30°$ is the blind spot for AG and VR.

Table 2
Combined space angle resolution from angular resolution of each experiment.

Combination	Resolution (degrees)
AG-AG	2.5
AG-YK, AG-HP, AG-VR	3.5
HP-HP, YK-YK, VR-VR	4.2
HP-YK, HP-VR, YK-VR	4.2

Table 3
Probability of observing doublets and triplets with 1 000 000 simulated data sets. Each triplet is counted as three doublets.

Space angle	Doublet		Triplet	
	observed number	probability	observed number	probability
< 3.0°	12	1.5%	2	1.4%
< 4.0°	14	13.4%	2	8.3%
< 5.0°	20	15.9%	3	11.8%

form incident arrival direction distribution. An estimate of the space angle scatter due to errors in the arrival direction determination is obtained by quadrature addition of the uncertainties of Table 2 and ranges from $2.5^\circ \sim 4.2^\circ$, depending on the relevant combination of experimental uncertainties. Since 80% of all events are from AGASA and Haverah Park, it is sufficient to examine clusters within $3^\circ \sim 4^\circ$ for combined data set.

The number of triplets and doublets within space angles of 3°, 4° and 5° are listed in Table 3. In counting doublets in this table, each triplet is also decomposed into 3 doublets corresponding to the possible pair combinations with differing space angle separations. So there are actually 2 triplets and 6 independent doublets within a space angle 3°, but the 2 triplets are also counted as 6 doublets, making a total of 12 doublets as listed in the table. To estimate the probability of obtaining such clusters by chance from a uniform distribution, we simulated the same number of events from each experiment. 1 000 000 data sets, each comprising 92 showers, were simulated under the following assumptions:

1. The declination distributions of AG, HP and YK events are approximated by smooth functions as shown by the solid lines in Fig. 1. The AG declination distribution is used to simulate the VR data set.

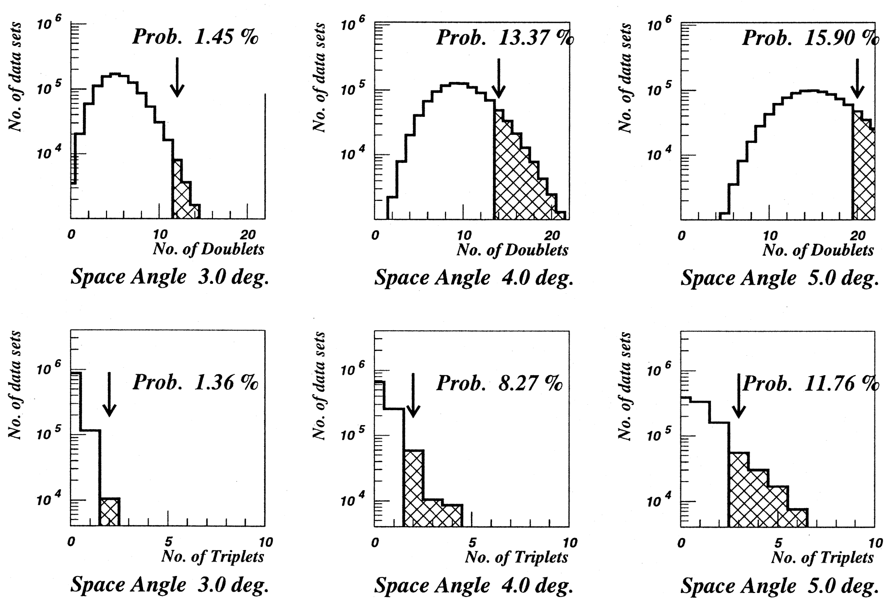

Fig. 5. Frequency distribution of the number of doublets in 1 000 000 simulated data sets within several space angles. The arrow mark shows the observed number of doublets. Chance probability of the observed number of doublets is calculated by summing the number of data sets in the hatched region.

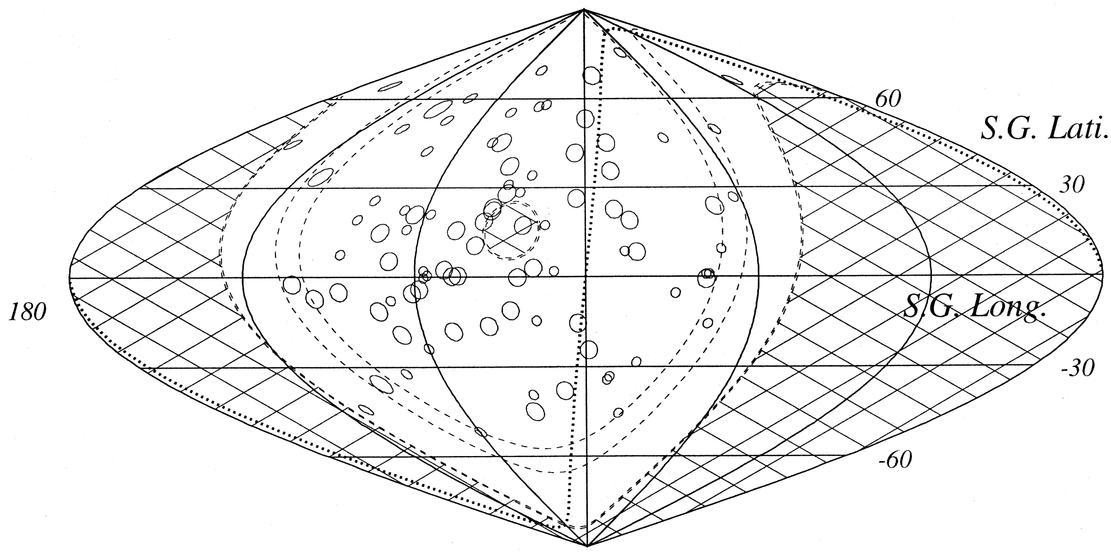

Fig. 6. Arrival directions with error circles of EHECR in supergalactic coordinates. The total number of events is 92.

2. A uniform distribution in right ascension with the observed declination distributions is assumed for all experiments.

In Fig. 5 the frequency distributions of the number of doublets found by simulation of 1 000 000 data sets within three different space angles separations are shown. The arrow shows the observed number of doublets. The chance probability of observing doublets is calculated as that fraction of the simulated data sets which have equal or more doublets than observed.

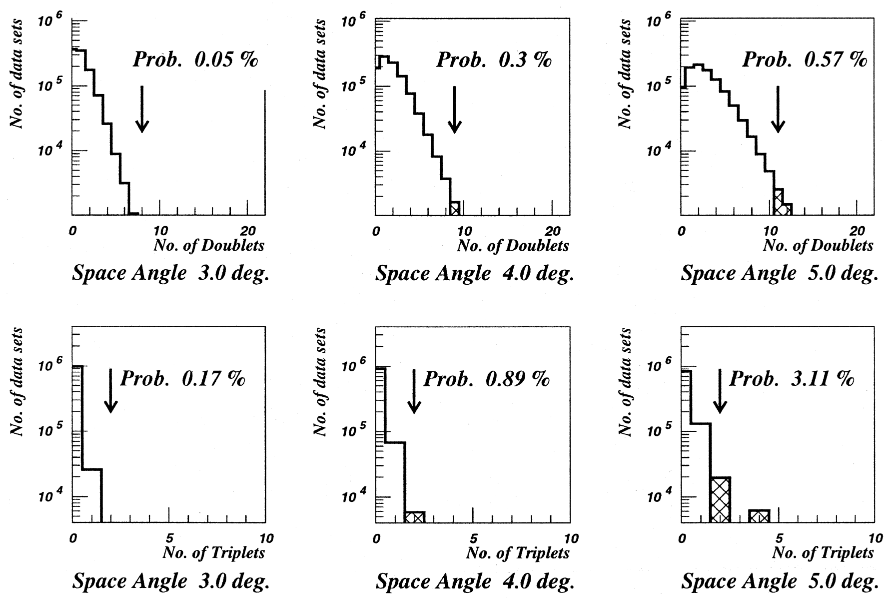

Fig. 7. Probability of observing doublets and triplets within 10° from the SG plane with 1 000 000 simulated data sets for 92 events.

Table 4
Probability of observing doublets and triplets within $\pm 10°$ from the SG plane for 92 events.

Space angle	Doublet		Triplet	
	observed number	probability	observed number	probability
< 3.0°	8	0.1%	2	0.2%
< 4.0°	9	0.3%	2	0.9%
< 5.0°	11	0.6%	2	3.1%

The chance probabilities of observing triplets or doublets within the three space angles separations are listed in Table 3. The probability is small only for clustering within 3°. The chance probabilities for clustering within 4° and 5° are larger than 10% and hence not statistically significant.

2.3. Correlation with the Supergalactic Plane

The arrival directions of EHECR of the four ground array experiments are plotted in the SG coordinate system in Fig. 6. Error circles are also shown; 1.8° in the case of AG, and 3.0° for HP, VR and YK.

Note that the two centroid of triplets are in a very narrow region (within 0.9°) about the SG plane. The SG plane and its thickness are not well defined. However, there are reports that radio source density along much of the SG latitude band within $\pm 10°$ is higher than the average surface density outside this band [2]. An estimate of the chance probabilities of obtaining this number of doublets within $\pm 10°$ from the SG plane is shown in Fig. 7. In this analysis, only the number of doublets within $\pm 10°$ region is counted and compared between observed data and simulated data, without taking into account doublets outside this region. In Table 4 the chance probabilities of doublets and triplets within $\pm 10°$ from the SG plane are listed. Whilst the choice of a cut at 10° about the SG plane is arbitrary, we note that the chance probabilities for doublets within all space angle separations, and for triplets within the two smaller space angle cuts, are intriguingly below 1%.

3. Discussion

As Fig. 2 indicates, there is about a 20% excess of events in the latitude band $0 \sim 30°$ about the SG plane. Though this excess is only a one σ effect, it may contribute to the apparently significant clustering estimated above, so we have also calculated the chance probability of multiplets, given a uniform distribution within this band but with a total event number excess of 20%. The result is listed in Table 5. As expected the statistical evidence for clustering is reduced somewhat (the chance probability is raised by approximately a factor 2), but for doublets within 4° the chance probability remains below 1%.

To examine the effect of the choice of coordinates, the analysis is repeated for the G coordinate system. There are no multiplets found, even for the largest space angles (within 5°) and within $\pm 10°$ of the G plane. The average number of doublets expected by chance is 2.8. The Poisson probability of observing no multiplets is thus 6%. Considering that the number of events within $\pm 10°$ of the G plane is about 30% less than that expected from uniformity (see Fig. 2), this probability is statistically reasonable.

The details of each event which are members of one of the clusters within 4° are listed in Table 6. Here one HP event is counted twice (doublet #5 and #8), since it forms a doublet with another HP event, and with a VR event. Clearly some, at least, of these multiplets must arise by chance. In an attempt to select genuinely coincident events from sources at limited distances, it may be better to only use events above a slightly higher energy threshold, to avoid the systematic differences in energy determination of each experiment. Selecting only events above 5×10^{19} eV, two triplets and one doublet (#7) remain, from a total number of 51 events. The chance probability of the triplet is now 1.1%, falling to 0.1% if we examine only the restricted region within $\pm 10°$ of the SG plane.

Table 5
Probability of observing doublets and triplets when an excess of 20% in the $0° \sim 30°$ range of SG latitude is assumed.

Space angle	Doublet		Triplet	
	observed number	probability	observed number	probability
< 3.0°	8	0.2%	2	0.3%
< 4.0°	9	0.8%	2	1.7%
< 5.0°	11	1.5%	2	5.4%

Table 6
Event lists of members of clusters within 4° from 4 surface experiments AGASA(AG), Haverah Park(HP), Volcano Ranch(VR) and Yakutsk(YK).

Cluster	Exp.	Date	log *E*	R.A.	Dec.	*l*	*b*	S.G.Lng.	S.G.Lat.
Triplet #1	HP	810105	19.99	20.00	20.00	132.70	−41.70	318.10	−0.79
	AG	931203	20.33	18.91	21.07	130.48	−41.44	318.11	0.89
	AG	951029	19.71	18.53	20.03	130.18	−42.51	317.02	0.93
Triplet #2	AG	920801	19.74	172.30	57.14	143.20	56.65	56.82	2.04
	AG	950126	19.89	168.65	57.58	145.53	55.10	55.51	0.51
	AG	980404	19.73	168.44	55.99	147.51	56.23	56.84	−0.37
Doublet #1	AG	910420	19.64	284.90	47.79	77.88	18.45	24.95	57.83
	AG	940706	20.03	281.36	48.32	77.58	20.86	29.35	57.26
Doublet #2	AG	860105	19.74	69.03	30.15	170.08	−11.50	350.38	−33.33
	AG	951115	19.69	70.39	29.85	171.09	−10.79	351.23	−34.31
Doublet #3	HP	860315	19.71	267.00	77.00	108.50	30.10	30.83	27.99
	AG	960513	19.68	269.05	74.12	105.11	29.79	31.09	30.94
Doublet #4	HP	720525	19.65	239.00	79.00	113.30	34.60	35.05	23.27
	YK	911201	19.62	235.40	79.80	114.60	34.60	34.88	22.22
Doublet #5	VR	610319	19.73	154.10	66.70	143.00	44.30	44.59	0.35
	HP	850313	19.62	157.00	65.00	143.60	46.30	46.63	0.24
Doublet #6	HP	661008	19.67	164.00	50.00	159.00	58.80	61.08	−5.53
	YK	750317	19.67	163.70	52.90	154.90	56.80	58.45	−4.16
Doublet #7	HP	740228	19.86	264.00	58.00	86.36	32.52	41.02	45.22
	AG	980330	19.84	259.16	56.32	84.39	35.17	45.44	45.35
Doublet #8	HP	760206	19.62	165.00	64.00	140.98	49.43	49.49	2.41
	HP	850313	19.62	157.00	65.00	143.60	46.30	46.63	0.24

The order of arrival times with respect to energy of the events in triplet #1 are not as expected from a recent, nearby bursting source where cosmic rays are accelerated in a short time [7]. According to simulations on the propagation of protons through both the intergalactic and Galactic magnetic fields by Medina Tanco [11], the extragalactic magnetic field must be much smaller than the present upper limit of 10^{-9} G to explain the present clustering within experimental angular resolution.

In the case of triplet #2, the direction is consistent with the Ursa-Major II cluster of galaxies which has 0.2° as apparent diameter. The magnetic field strength in this cluster of galaxies is possibly of the order of sub-μG, similar to that observed in the Coma cluster [12]. If so, each member of the triplet might be a gamma-ray, because protons may not be collimated within 2.5° and the mean distance of travel before decay for neutrons is 1 Mpc for 10^{20} eV. Since the cross section of pair creation by gamma-rays of this energy and the probability of bremsstrahlung of the resulting electrons are suppressed due to the LPM effect [14,15], the longitudinal development of a gamma-ray shower is greatly depressed and delayed. A ground array, therefore, might grossly underestimate the primary energy of such a shower if it is estimated by the local particle density around 600 m from the shower core [5,8]. However, if the geomagnetic field component normal to the arrival direction is large enough, electron–positron pair creation in the geomagnetic field occurs far from the earth and a cascade develops in the magnetosphere [16]. Therefore, in the northern hemisphere we might observe gamma-ray showers in the highest energy region mainly from a northerly direction [17]. The terrestrial arrival directions of the three members of triplet #2 are indeed from the north, which is at least consistent with this conjecture. However, it should be noted that the attenuation length of gamma-rays of energies above 4×10^{19} eV due to the interaction on radio photons is less than 10 Mpc [13] and hence a source distance limit also applies for gamma-rays.

If each member of the triplets are protons, coming from the same source, then the intervening magnetic field must be so weak that the particles are hardly deflected, or there is magnetic focusing in the magnetic field structure of the Local Supercluster as demonstrated by Lemoine et al. [18].

In Fig. 8, the directions of triplets (open squares) and doublets (open circles) are plotted on the CfA galaxy [19] distribution within 100 Mpc. There are no multiplets from the most crowded region (Virgo Cluster) and there seems no correlation with the density of nearby galaxies. In the following we look for any source candidate for the triplets #1 and #2, and the doublet #7.

The AG highest energy event and HP 10^{20} eV event are members of the triplet #1 and this triplet may be related to a nearby source. Mrk 359 ($l = 134.60°$, $b = -42.87°$) with $z = 0.017$ (68 Mpc assuming $H_0 = 75$ km/s/Mpc) is within 2.3° from the direction of the centroid of this triplet. This direction is also within 3 and 6 degrees of a clusterings of events with energies above 10^{19} eV claimed by Chi et al. ($l \simeq 133°$, $b \simeq -40°$) [20] and Efimov and Mikhailov (RA = 27°, Dec = 18° or $l = 143°$, $b = -42°$) [21]. Al-Dargazelli et al. [22] pointed that the colliding galaxy pair VV338 ($l = 138°$, $b = -34°$) (N672 and U1249) may be related to the clustering around the region $l = 135°$ and $b = -35°$, where they identified an apparent clustering above 10^{19} eV. Though VV338 is very close, 5.7 Mpc, the angular separation from triplet #1 is large (9.0°).

Triplet #2 comprises three AG events of similar energies, $(5–8) \times 10^{19}$ eV, and is within 2.4° from the direction of the interacting galaxy, VV144 (Mkn40 or Arp151; $l = 147.03°$, $b = 58.54°$). This is a Seyfert galaxy with $z = 0.020$, corresponding to about 81 Mpc. Triplet #2 is on top of a maximum in the arrival direction probability simulated by Medina Tanco [11] for sources located between 20 and 50 Mpc. These simulations assume that the luminous matter in the nearby universe tracks the distribution of cosmic ray sources and modulates the intensity of IGMF.

In the direction of doublet #7, there are interacting galaxies VV101 ($l = 87.06°$, $b = 33.75°$, 100 Mpc) with a space angle separation of 1.3° and VV89 ($l = 88.14°$, $b = 35.51°$, 14.5 Mpc) with a separation of 2.7°.

From the above discussion, if the extragalactic magnetic field is much weaker than the present upper limit of 10^{-9}G, then triplets #1 and #2 and doublet #7 are possibly correlated with interacting galaxies, as pointed out by Al-Dargazelli et al. [22] Clearly, the next generation experiments are needed to confirm such an association.

Recently, Lemoine et al. [18] made extensive simulations of the propagation of protons in a large scale magnetic field of strength $\sim 0.05–0.5 \mu$G in the Local Supercluster. They found an 8–20% prob-

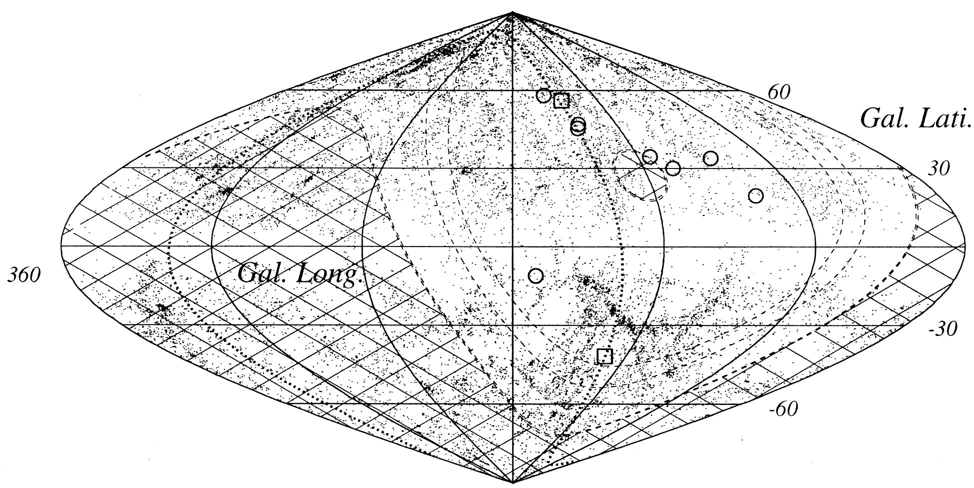

Fig. 8. The location of galaxies within 100 Mpc in G coordinates from the CfA 1995 catalogue and the clusters within 4°. The squares show triplets and the circles show doublets.

ability of detecting 5 doublets above 40 EeV in the AGASA data set of 47 events, due to magnetic focusing. It is important to examine what kind of conditions are required for the magnetic field configuration in the Local Supercluster to explain the present results of two triplets along the SG plane.

4. Conclusion

A number of collimated triplets and doublets within 4° (the approximate angular resolution of combined data set) are observed. The chance probability is of the order of 10% and is not statistically significant. However, the chance of observing triplets and doublets within $\pm 10°$ of the SG plane is less than 1%. It should be noted that the probability of observing the multiplets above 5×10^{19} eV is about 1% and it is less than 0.1% if attention is limited to within $\pm 10°$ of the SG plane. Though there is still a possibility of chance coincidence, we should pay more attention on the small angle clustering along the SG plane in the interpretation of EHECR enigma.

We expect detailed investigation with much better angular resolution and much higher statistics from future experiments. In particular we note that the probabilities given in this paper are 'a postiori' in that hints of clustering have been reported in earlier analysis and these data have been included here. There are insufficient events for an independent test of our observations. An independent set awaits new projects such as Hi-Res, Auger and Telescope Array.

Acknowledgements

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