Correlation of the Highest Energy Cosmic Rays with the Supergalactic Plane

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We examine the anisotropy of the arrival directions of twenty seven ultra high energy cosmic rays detected by the Pierre Auger Collaboration. We confirm the anisotropy of the arrival directions of these events and find a significant correlation with the updated definition of the supergalactic plane at distances up to 70 Mpc. A Monte Carlo calculation of isotropic event arrival direction distribution suggests a chance probability for isotropic event arrival direction distribution of $2-6\times10^{-4}$.

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The identification of the sources of the ultrahigh energy cosmic rays (UHECR), the highest energy nuclei in the Universe, is one of the most important goals of the high energy astrophysics. It is difficult to even imagine how nature can manage to accelerate these particles to energies exceeding by orders of magnitude what we can do in man made accelerators. Since these nuclei of energy approaching $10^{20}$ eV do not strongly deflected in the galactic magnetic fields, one expects them to come from directions coincidental with their sources if extragalactic magnetic fields are not very strong. Source identification would not only prove that cosmic ray astronomy is possible, but also contain information about the magnetic and photon fields in the source direction that can not be extracted in any other way. The first step in this direction was made less than a year ago.

The Auger Collaboration reported a correlation of their 27 highest energy events ($E > 5.7\times10^{19}$ eV (57 EeV) with active galactic nuclei (AGN) at redshifts $z$ less than 0.017 [1] from the Vèron-Cetty and Vèron catalog [2] (V-C). Twenty out of 27 events are within 3.1° of individual AGN, while for isotropic arrival distribution one expects on average 5 coincidences. Five of the non-correlating events come from less than 12° galactic latitude which may be understood as larger deflections in the galactic magnetic field. Most of the correlating events are visibly at relatively small angles from Cen A. It is surprising that there are no events coming from the direction of the Virgo cluster, that includes a large number of powerful galaxies in addition to M87, as stated in Ref. [3].

Several papers among them Refs. [4, 5, 6, 7] were submitted during the last three months that discussed the type of the correlating sources, their luminosity and distance, as well as made correlations with different other types of sources and attempted to explain the large number of UHECR around Cen A and the lack of events close to the Virgo cluster. All sources discussed, be them AGN from the V-C or Swift BAT catalogs or spiral galaxies, do tend not to be distributed isotropically and contribute to the definition of the Supergalactic Plane (SGP) - the plane of weight of nearby galaxies [8]. Many of the Auger events thus come from directions close to the SGP. There are, however, eight UHECR, five of which correlate with AGN, at supergalactic latitude higher than 40°.

A report on the correlation of the then existing statistics of UHECR of energy above $4\times10^{19}$ eV was published in 1995 [4]. The data set consisted mostly of events detected by the Haverah Park detector with the addition of events detected by AGASA, Yakutsk and Volcano Ranch air shower arrays. The anisotropy of that data set was studied by a comparison of the average and RMS supergalactic latitudes $|\theta_{\text{SGP}}|$ of the experimental events to that of an isotropic Monte Carlo sample. The significance of the correlation was at the 3σ level. Later on, when the AGASA detector dominated the world’s statistics [10], the significance of the correlation decreased.

After the list of the energies and arrival direction of the 27 events was published in a more detailed second paper [11] it became possible to study the statistical significance of the possible correlation of the Auger events with the Supergalactic Plane. The arrival directions of these events are superimposed on the SGP in Fig. 1. The extended Cen A radio lobe, almost parallel to SGP, and the Virgo cluster (with 11 of its most powerful galaxies plotted) are outlined. We attempted to calculate the probability for such a correlation by a Monte Carlo sim-

FIG. 1: The 27 Auger events are superimposed in galactic coordinates in a sinusoidal projection on the supergalactic plane in the definition of Ref. [12]. The shaded area shows $|\theta_{\text{SGP}}| < 10°$. The gray squares show the positions of V-C AGN that have galactic latitude more than 12°.
ulation. We injected 100,000 sets of 27 events each using the equal field of view areas published by the Auger Collaboration [11].

Because of the large number of UHECR at large supergalactic latitude we decided a posteriori to count the events that come from directions close to SGP. We chose $|b_{SGP}|$ less than 10° and 15°. Two arbitrary bands with a difference of 5° were chosen because the average magnitude of the scattering angle in the galactic magnetic field is of that size. Since the number of experimentally detected events is small we chose to test two bands in order not to be deceived by random coincidences. Nine and 13 events fall in these two bands. The probability of random coincidences, based on the isotropically distributed Monte Carlo sample, is 0.024 and 0.008 respectively, corresponding to 2.0 and 2.4 $\sigma$.

Until now we dealt with the original definition [12] of the supergalactic plane by de Vaucouleurs. This definition was studied in 2000 by Lahav et al. in terms of redshift [13] on the basis of the Optical Redshift Survey (ORS) (8457 galaxies, 98\% with redshift). Since ORS had a zone of avoidance of |b| < 20° it was complemented with IRAS galaxies in order to describe better the intersection of SGP with the galactic plane. This study introduces correction to the definition of SGP for different distances from 0 to 80 Mpc. The one that is most suitable for analysis of the Auger events is for distances up to 70 Mpc, i.e. almost identical to the redshift of 0.017. The corrected shape of the SGP is plotted in Fig. 1. Although the corrected SGP does not look very different from the original one in galactic coordinates the SGP North Pole direction is at the original $b_{SGP} = 65°$. The same degree of rotation defines the SGP updated to distances of 80 Mpc.

One can now count how many UHECR are in the 10° and 15° band with the new definition of the supergalactic plane. The numbers are 13 and 15 events respectively. The probability to have so many events drops to $1.6 \times 10^{-4}$ ($6.0 \times 10^{-4}$) for distances from the supergalactic plane of 10°(15°). The correlation of the Auger events with the updated definition of the SGP within 70 Mpc is indeed much more significant - the probabilities above correspond to 3.6(3.2)$\sigma$.

The average supergalactic latitude of the Auger events does not change much - from 26.7° with the classical definition to 22.5° with the new one. The RMS supergalactic latitude of the experimental events is 32° compared to 38.9° for a Monte Carlo sample of 100,000 uniformly distributed event samples in the Auger field of view. None of these results has high statistical significance. It is interesting to note that the 308 AGN from the V-C catalog within redshift of 0.017 and with galactic latitude more than 12° do not correlate better with the new definition of SGP - the average supergalactic latitude is 24.9° compared to 22.8° for the classical definition.

Meanwhile we had the report of the HiRes Collaboration [14] that does not see correlation of their 13 highest energy events with AGN. Because of the difference of the energy assignments of the two experiment the HiRes Collaboration has roughly adjusted the number of events to correspond to the experimental exposure. We plot the HiRes events [15] with dots in Fig. 2. Only two of 13 events are within 3.1° of an AGN from the same catalog. The chance probability for isotropic arrival direction distribution quoted in Ref. [14] is 82%. The field of view of HiRes is, of course, different from that of Auger, and since it is not presented in Ref. [14] we cannot estimate the possible correlation with SGP. As could be seen in Fig. 2, 3(5) events are within 10°(15°) of the supergalactic plane. There are, however, two pairs of events from Auger and HiRes that are very close to each other - at angular distances of 0.5° and 4°. The probability of these coincidences also cannot be estimated.

Since a degree of correlation with the supergalactic plane was found both in the Auger and the old data sets it is worth examining the two samples. The most difficult decision is to use approximately the same event energy threshold, since both data sets were shown to be sensitive to it and the energy assignments of all experiments are different. The correlations in the old data set appeared at energy above $4 \times 10^{19}$ eV. One should have in mind that Northern hemisphere detectors look mostly in the direction of the galactic anti-center, thus the scattering in the galactic magnetic fields [16] should be smaller.

We approached the selection of old events using the exposure of the old experiments. Agasa [10, 17] has the exposure of 1,400 km$^2$.sr.yr. Comparing to the exposure of Auger (9,000 km$^2$.sr.yr) we chose the four highest energy Agasa events. From Yakutsk [18] (850 km$^2$.sr.yr, A.A. Ivanov, private communication) we chose the 3 highest energy events and from Haverah Park [19] (250 km$^2$.sr.yr, A.A. Watson, private communication) we took one event. The arrival directions of these eight events are shown in Fig. 2. Once again, it is difficult to judge the importance of the correlation because of the choice of events and the uncertain field of view of the
three experiments but 1 event out of 8 is within 10° and 5 are within 15° of the updated SGP. Only 3 events are within 15° from the classical definition of SGP. Although we are not able to estimate the significance of this correlation, it obviously becomes somewhat stronger.

In conclusion, we studied the correlation of the 27 highest energy events detected by the Pierre Auger experiment with the supergalactic plane. We find 1-2% significance of the Auger events with the classical definition of SGP. The correlation is much stronger (2-6×10⁻⁴ chance probability for isotropic arrival direction distribution) of the 27 Auger events with the updated definition [13] of SGP within 70 Mpc.

Five of 13 HiRes events are within 15° of the updated SGP, while 5 out of 8 events from Agasa, Yakutsk and Haverah Park are at similar supergalactic latitude. Because of the lack of knowledge about the HiRes field of view and the uncertainty in our choice of events from three other experiments we cannot estimate correctly the significance of these correlations. It is obvious, though, that the flux of UHECR does not appear to be isotropic - a total of 17 (25) out of 48 events are within supergalactic latitude of 10° (15°). A degree of correlation with the SGP is expected as all suggested sources of UHECR should correlate with the local large scale structure.

It is possible that the five experiments examined here may see events coming from the same sources. There are three possible event pairs to Auger events - two from HiRes and one with Agasa. There is also a possible triple that includes two HiRes and one Yakutsk events. As far as Auger data is concerned, the largest event concentration is around the nearby radio galaxy Centaurus A. One can imagine that one third of the 27 Auger events are accelerated at this object and are spread along the SGP by low level organized extragalactic magnetic fields [20].

While performing this study we have not contributed to the identification of the sources of UHECR. We have only studied the isotropy of the arrival directions of these particles and have confirmed that the arrival directions of the Auger event sample are not isotropic using a different analysis procedure. The significance of the anisotropy of other event samples can only be studied after their fields of view are defined as well as that of the Auger Collaboration.

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