On the interpretation of the cosmic-ray anisotropy at ultra-high energies

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Abstract

A natural interpretation of the correlation between nearby Active Galactic Nuclei (AGN) and the highest-energy cosmic rays observed recently by the Pierre Auger Collaboration is that the sources of the cosmic rays are either AGN or other objects with a similar spatial distribution (the “AGN hypothesis”). We question this interpretation. We calculate the expected distribution of the arrival directions of cosmic rays under the AGN hypothesis and argue that it is not supported by the data, one of manifestations of the discrepancy being the deficit of events from the direction of the Virgo supercluster. We briefly discuss possible alternative explanations including the origin of a significant part of the observed events from Cen A.

1 Introduction

The Pierre Auger Collaboration reported a remarkable correlation \cite{1} between the arrival directions of ultra-high-energy cosmic rays (UHECR) and positions of nearby Active Galactic Nuclei (AGN). The correlation was found by scanning over the maximum angular separation, the minimum event energy and the maximum AGN redshift, see Refs. \cite{2,3,4} for the details of the method. The best signal was found at the angle of 3.1° for the cosmic-ray set consisting of 15 events with reconstructed energies $E > 5.6 \times 10^{19}$ eV and for the set of 472 AGN obtained by imposing the cut on the redshift, $z \leq 0.018$, in the catalog \cite{5}. The correlation was tested with the independent set consisting of 13 events, with the parameters fixed \textit{a priori} from the first data set. The probability that the correlation has occurred by chance is $1.7 \times 10^{-3}$ as derived from the independent set. The conclusion was made
that there exists anisotropy of arrival directions which is consistent with the hypothesis that most of the cosmic rays reaching the Earth in that energy range are protons from nearby astrophysical sources, either AGN or other objects with a similar spatial distribution. We refer to the latter proposition as the “AGN hypothesis” in what follows.

Crucial ingredients of the AGN hypothesis are i) nearly rectilinear propagation of UHECR and ii) a large number of sources distributed similarly to AGN, i.e., tracing the distribution of matter in the Universe [6]. The second point deserves a comment. One may estimate the number of sources contributing to the flux from the statistics of clustering at small angles [7]. Counting events separated by less than $6^\circ$ as a doublet and adopting the (unrealistic) assumption of equal flux on the Earth from all sources, Ref. [8] estimates the lower limit on the number of sources as 61; a more fair assumption of equal cosmic-ray luminosity of the sources raises the estimate to 252. Account of possible distribution of sources in luminosity would further increase the estimate of their number. The AGN hypothesis thus implies the existence of at least a few hundred sources in the nearby Universe.

In this paper we show that, given the data presented in Refs. [1, 8], the AGN hypothesis is unlikely, and that there exist alternative interpretations of the observed correlation. We should stress that we question neither the fact nor the derived significance of the correlation. However, by itself, the observed correlation of UHECR with AGN implies only that the space distribution of UHECR at highest energies is not uniform. The question of what are actual sources of UHECR requires further study. Here we make an attempt in this direction. A brief account of our results has been reported in our comment [9] to the Pierre Auger publication.

2 Testing the AGN hypothesis

Let us consider the AGN hypothesis and see what kind of spatial distribution of cosmic-ray flux it predicts. This flux depends on several factors [1]: distances to AGN, their luminosities and their spatial distribution. The distance effect is accounted for by weighting each source with the $1/r^2$ suppression factor, $r$ being the distance to the source. The distribution of AGN in the cosmic-ray luminosities is not known. However, for a large group of sources in a given region of the sky (e.g., a rich cluster of galaxies) the effect of this distribution averages away. Therefore, in the case when the cosmic-ray flux is associated with the large-scale structure as in the AGN hypothesis, one may consider the sources as having the same

\footnote{First two factors are not accounted for in the method of positional correlations used in Refs. [1, 8].}
luminosities equal to the average source luminosity, provided this average source luminosity is space-independent.

The space distribution of sources (which, under the AGN hypothesis, are assumed to trace visible matter) in the nearby Universe is very inhomogeneous. The role of local inhomogeneities is enhanced by the cosmic-ray attenuation that cuts off the (uniform) flux coming from distant sources. The AGN hypothesis implies, therefore, strongly anisotropic flux at highest energies, with major local structures such as the Centaurus and Virgo superclusters providing sizeable contributions [10].

Fig. 1 shows the UHECR events used in the analysis of Ref. [1] together with the expected flux of cosmic rays simulated assuming the AGN hypothesis (see figure caption for notations). One may identify the Virgo and Centaurus superclusters. The expected numbers of events from these two structures are nearly equal. It is seen in Fig. 1 that there is a deficit of observed events from Virgo as well as from other local structures, except the Centaurus supercluster. This suggests that the AGN hypothesis proposed in Ref. [1] may be disfavored by the data.

To quantify this statement we took the sample of AGN used in the analysis of Ref. [1]. According to the catalog classification [5], the sample consists of 457 AGN, 14 quasars and one probable BL Lac object, Cen A. We removed from the sample 3 objects with \( z = 0 \) classified as stars in the database [12]. We then calculated the space distribution of the expected cosmic-ray flux, weighting each source with the factor \( 1/r^2 \).

Fig. 2 shows the expected number of events within a given angular distance from the center of the Virgo supercluster vs. the observed one. The observed and expected distributions of events are inconsistent. According to the Kuiper test, the probability that the observed and simulated events are drawn from the same distribution is \( 2 \times 10^{-4} \). The main origin of inconsistency is clear: out of 27 events, \( \sim 6 \) are expected to come from Virgo under the AGN hypothesis while none is observed. The probability of this is \( 10^{-3} \), in agreement with the Kuiper test.

Similar results are obtained in tests which do not use the Virgo supercluster as a reference point. Comparing the Galactic longitudes of observed and expected cosmic rays we find that the probability that the two samples are drawn from the same distribution is 2% according to the Kuiper test, while for the Galactic latitude the corresponding probability is \( 10^{-4} \). Analogous tests for the Supergalactic longitude and latitude give the probabilities of 7% and \( 10^{-4} \), respectively.

The results do not change qualitatively when the catalog of AGN is replaced by a complete
Figure 1: Hammer projection of the celestial sphere in supergalactic coordinates with crosses at the positions of nearby AGN from the sample used in the correlation analysis of Ref. [1]. The color saturation of a given cross indicates the expected cosmic-ray flux with the account of the exposure of the Pierre Auger Observatory (PAO) and the $1/r^2$ suppression, $r$ being the distance to the source. Open circles represent 27 highest-energy cosmic rays detected by PAO. Shading shows the expected cosmic-ray flux from sources that follow the local matter distribution (for details see Ref. [1]), smoothed at the angular scale of $3.1^\circ$ and convoluted with the PAO exposure (darker regions correspond to higher cosmic-ray flux). Blue lines cut out the region with Galactic latitude $|b| < 15^\circ$ where the latter flux cannot be determined because of incompleteness of the source catalog. The positions of the Centaurus (Cen) and Virgo (Vir) superclusters are indicated.
Figure 2: Number of events in the circle of radius $\theta$ (in degrees) centered on the Virgo cluster as determined in [12]: gray, expected number of events assuming the AGN hypothesis; black, events actually observed, Ref. [1]. The side panel zooms on the region around Virgo.
sample of galaxies within the sphere of radius 270 Mpc \[1\]. Thus, our conclusions do not depend crucially on specific properties of the AGN catalog used in Refs. \[1, 8\] (in particular on its incompleteness), and apply equally to any class of sources as long as they are distributed similarly to the visible matter. Given the strongest disagreement at the level of \(10^{-4}\) and the number of various tests performed, we conclude that the AGN hypothesis is disfavored at the confidence level of at least 99%.

To demonstrate that our conclusions are insensitive to the assumption of equal cosmic-ray luminosity of sources, we performed the same tests assuming that at the Earth the cosmic-ray flux produced by an AGN is proportional to its flux in visible light (derived from \(V\)-band magnitudes listed in the catalog \[5\]). No additional \(1/r^2\) suppression is needed in this case. This change in assumptions did not change the result qualitatively. This is expected, as the number of AGN in the direction of the Centaurus and Virgo superclusters is large (several dozens), and the effect of the distribution in luminosity averages away.

3 Alternative explanations: Cen A?

If, as it is suggested by the above arguments, the highest-energy cosmic rays observed by the Pierre Auger Observatory do not come from sources that follow the local matter distribution, how can one explain the observed correlations with AGN? One possible explanation could be the existence of a nearby bright source which happens to be in the direction to the Centaurus supercluster where the density of background AGN is larger than in average. Events produced by such a source and deflected by magnetic fields would overlap with the background AGN more often than the uniformly distributed events, thus creating a correlation signal with AGN. This spurious signal would increase with the accumulation of statistics. Contrary to the AGN hypothesis, this explanation would imply one or at most a few sources in the nearby Universe and relatively large deflections, due to either strong magnetic fields or to the presence of heavy nuclei in the flux. Interestingly, in that case the properties of the highest-energy cosmic rays may appear different in the Southern and Northern hemispheres.

One plausible candidate for the source projected onto the Centaurus supercluster is Cen A \[9\]. We would like to emphasize that Cen A is not located within the Centaurus supercluster: Cen A is at the distance of 3.5 Mpc from us, while the supercluster is at 45 Mpc. Cen A is a special object, different from the majority of AGN in the sample used in Ref. \[1\]. It is the closest Fanaroff-Riley type I (FR I) radio galaxy. FR I galaxies constitute
the parent population for BL Lac type objects, i.e., it is believed that if the angle between the jet of FR I galaxy and the line of sight is small, such an object appears for an observer as a BL Lac type object. Cen A possesses the spectral energy distribution typical for BL Lacs [13]. However, the value of the viewing angle $\theta$ of its jet is still controversial. For the parsec-scale jet, Ref. [14] found $\theta \sim 50^\circ - 80^\circ$, whereas Ref. [15] found indications for $\theta \sim 15^\circ$ for the 100 pc scale jet. Cen A is often called a hidden or misaligned BL Lac, and it is the only object classified as a BL Lac in the catalog [5] which enters the sample of Ref. [1]. We should mention also that there have been correlations found between BL Lacs and cosmic rays of lower energies in the Northern hemisphere [2, 16, 17, 18, 19], which are not supported, however, in the Southern hemisphere [20].

Being the nearest FR I radio galaxy, Cen A was suggested long ago as a source of some [21, 22] or even most [23, 24] of the observed cosmic rays of extreme energies. (See, however, Ref. [25] where a different interesting explanation of the Auger anisotropy is proposed and the acceleration power of Cen A is questioned.) After the deficit of events from Virgo in the Auger sample was argued to be a problem [9], the interest to the conjecture has been revived [26, 27]. Here, we support the plausibility of the Cen-A scenario by the following observations.

Firstly, the study of the chemical composition of the primary UHECR flux with the fluorescent detector of the Pierre Auger observatory [28] suggests that a significant fraction of primary particles are heavy, or at least intermediate-mass nuclei. The same conclusion has been recently made from the analysis of precise Yakutsk muon data [29]. This agrees with the expectation that heavier nuclei are generally accelerated to higher energies than protons, which may be crucial for Cen A [30] with its weak acceleration power. However, heavy composition contradicts the AGN hypothesis which assumes that most of the cosmic rays of highest energies are protons since the expected deflections of heavy nuclei in the Galactic magnetic field (GMF) are not compatible with the angular scale of the observed correlation. Indeed, the deflections in the $O(\mu G)$ regular component of the Galactic magnetic field can reach a few tens of degrees for heavy nuclei. Additionally, one expects deflections in the random component of the magnetic field which may be comparable to the deflection in the regular component [31].

Secondly, the outer radio lobes of Cen A extend for $\sim 10^\circ$ in the North–South direction (see, e.g., Ref. [32]). Since the lobes and hot spots are probable acceleration sites [33], a number of the observed events can be associated with Cen A even without large deflections (i.e. assuming that these events are protons).
Figure 3: The Monte-Carlo probability $P$ to have the observed number of events in a circle of a given radius around Cen A on the celestial sphere, out of the 27 events of the Auger sample. The values of $P$ are indicative only since their calculation accounts neither for the statistical penalty associated with the choice of angular scale nor for the bias in the sample.

Thirdly, there exists a correlation between the arrival directions of UHECR and the position of Cen A. The correlation test is similar to that performed in Refs. [1, 8] except the catalog of candidate sources now consists of only one object, Cen A. One finds (see Fig. 3) that, on average, for the isotropic distribution 1.5 events out of 27 are expected to fall within the circle of $20^\circ$ around Cen A, while 9 are observed. Out of $10^6$ Monte-Carlo tries this happened 11 times.

We see that the expected magnetic deflections of heavy nuclei and the size of the outer radio lobes are in a good agreement with the angular scale of the correlation signal around Cen A, thus supporting the hypothesis that Cen A may be a source of a sizable part of the UHECR events observed by PAO. A quantitative test of this or of any other conjecture requires the full PAO data. The published subset used in this analysis was obtained by tuning the cut on the minimal event energy in such a way as to maximize the AGN correlation signal,
and is therefore biased.

4 Conclusions

To summarize, the data presented in Refs. [1, 8] disfavor the hypothesis that most of the highest-energy cosmic rays come from a large number of nearby astrophysical sources, either AGN or other objects with a similar spatial distribution. Further doubts on this interpretation arise from the absence of the similar correlation in the Northern hemisphere, as one can find from the published AGASA data and as it has been recently found by the HiRes collaboration [34] (see, however, Ref. [35] for a possible signal in the Yakutsk data). The alternative explanation of the observed correlations could be, e.g., the existence of a bright source in the direction of the Centaurus supercluster, Cen A being a possible candidate. Both this and other interpretations could be tested with larger unbiased data sets.

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