Search for Nuclei Sources in the Ultra-High Energy Cosmic Ray Data

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Abstract: We present a new method to search for heavy nuclei sources, on top of background, in the Ultra-High Energy Cosmic Ray data \cite{1}. We apply it to the 69 events with energies $E \geq 55$ TeV published by the Pierre Auger Collaboration. We find a set of events for which the method reconstructs the source near the Virgo galaxy cluster. The probability to have a comparable set of events in some background is $\sim 0.7\%$. The reconstructed source is located at $\sim 8.5$ degrees from the active galaxy M87. The probability to reconstruct the source at less than 10 degrees from M87 for data already containing a comparable set of events is $\sim 0.4\%$. This may be a hint at the Virgo galaxy cluster as an ultra-high energy heavy nuclei source \cite{2,1}. We discuss the capability of current and near future experiments to test this possibility. Such a scenario gives a self-consistent description of the Auger anisotropy and composition data at the highest energies.

Keywords: Ultra-High Energy Cosmic Rays, Galactic Magnetic Field

1 Introduction

The Pierre Auger Observatory measurements of the Ultra-High Energy Cosmic Ray (UHECR) composition are compatible with a shift towards heavy nuclei, above $\sim 10^{19}$ eV \cite{3}. The analysis of the muon data from the Yakutsk EAS Array also hint at a significant fraction of heavy nuclei at the highest energies \cite{4}. On the contrary, both HiRes measurements \cite{5} and preliminary results of Telescope Array \cite{6} are still consistent with a proton composition.

Both for protons and iron nuclei, UHECR sources must be located in the local Universe, within $r \leq 150$ Mpc for energies $E > 6 \times 10^{19}$ eV. They should lie within the Large Scale Structure (LSS) of galaxy distribution.

Until now, methods to look for sources have been proposed for proton or light nuclei primaries \cite{7,8}. We present here a new method to search for UHE heavy nuclei sources. In most regions of the sky, one cannot detect heavy nuclei sources without a better knowledge of the Galactic Magnetic Field (GMF) than currently available \cite{9,10,11}. Nonetheless, we show that in some favourable cases, one may construct an algorithm to detect some of such sources with the present knowledge of the GMF.

We apply this method to the 69 Auger events published in Ref. \cite{12}. We detect a set of events for which the associated reconstructed source lies near Virgo. The Virgo cluster is in principle a good candidate for containing one or several UHECR source(s). The probability to have a comparable set of events in some background and reconstruct the source in any direction of the sky is $\sim 7 \times 10^{-3}$. If such a set of events already exists in the data, the probability to reconstruct the source at less than 10$^\circ$ from M87 is $\sim 4 \times 10^{-3}$. The possibility that the detected feature is the heavy nuclei image of Virgo would be compatible with both the Auger composition and anisotropy at the highest energies. However, the present statistics do not allow us to conclude firmly. We discuss the ability of current and near future experiments to confirm or rule out this possibility.

We present the method in Section 2. In Section 3, we analyse the Auger data of Ref. \cite{12} and report the noteworthy feature. Section 4 presents a discussion of the results.

2 Method

For UHE proton sources, events are expected to be deflected on the sky from the sources as $1/E$ \cite{7,8}. For heavy nuclei primaries, images of sources located in most regions of the sky would have more complicated shapes, even at the highest energies \cite{13,14,15,9,10,11}. We find that in some GMF models and some regions of the sky, sources of nuclei of charge $Z$ can still have at least one of their images above $\sim 55$ TeV which roughly looks like a proton source image enlarged by a factor $\sim Z$ \cite{1}. Such images can be detected without a better knowledge of the GMF than currently available. The following method is optimized to look for such favourable heavy nuclei source images in the data.

Fig. 1 presents a sketch of the method. It starts selecting an event with energy $E_1 \geq 10^{20}$ eV, denoted by “1”. Then, an assumption on the UHECR deflection power $D$ of
the GMF [8] is made, and only events at angular distances
≤ R = D/(55 EeV) − D/E from 1 are considered here-
after. Events with energies E2, located at angular distances
≤ D/E2 − D/E from 1, are tested by decreasing energy
order. Let us take one of them, denoted “2” in Fig. 1. 1 and
2 define the central line of a sector shaped region, high-
lighted in grey in Fig. 1. The sector has an angular exten-
sion R and an opening angle Θ. Its vertex corresponds to
1. Let us define X’ as the angular distance to 1. If the
number of events in the sector and their correlation coef-
cient Corr(X’,1/E) are respectively larger or equal to N
and Cmin, there is detection. Otherwise, the next event 2
in the ordered list is tested, until there is either detection or
all events 2 have been tested without any detection. In case
of detection, the source is reconstructed along the axis de-
fined by 1 and the center of mass of all points in the sector
(red axis in Fig. 1), by fitting 1/E versus X’ as in Ref. [8].
This method has four free parameters: N, Cmin, D and Θ.
D and Θ respectively depend on the regular and turbulent
GMF contributions to UHECR deflections.

3 Application to the Auger data

We apply the method presented in Section 2 to the 69 Auger
events, with E ≥ 55 EeV, published in Ref. [12]. We scan
them over discretized sets of values for N, Cmin, D and
Θ, N = {4, 5, ..., 69}, Cmin ∈ {−1, −0.9, ..., 0.9}. Ac-
cording to the relative contributions to UHECR deflections
of the regular and turbulent GMF components found by
Ref. [16], Θ ∈ {10°, 20°, ..., 80°} should suffice. Ref. [17]
notes that deflection angles on the sky for 10^{20} eV pro-
tons are expected to be ≃ 1 − 2.5°. Therefore, as-
suming iron nuclei, we take D = (26°, 30°, 52°, 65°) ×
10^{20} eV. We confront the data with some random back-
ground, made of 69 events distributed on the sky accord-
ing to the Auger exposure. Their energies are distributed
within four bins: [55 EeV, 10^{19.8} eV], [10^{19.8}, 10^{19.9}] eV,
[10^{19.9}, 10^{20}] eV and above 10^{20} eV, according to the 69
events energies. No noteworthy dependence on the distri-
bution of energies within the bins was found. For the last
bin, we take a E^{−4.3} spectrum, following [18], and a max-
imum energy E_{max} = 10^{20.5} eV, because the attenuation
length of heavy nuclei rapidly becomes shorter than a few
Mpc above this energy [19]. We checked that assuming
lower values for E_{max} only increases the significance of the
signal detected below.

An interesting signal is found in the Auger data around
the event with energy E = 142 EeV, which is located at
 ≃ 34° from the center of Virgo. This event plays the role
of “1” in the method presented in Fig. 1. For the tested
ranges of parameters, the lowest probability to reproduce
the Auger data with the background is found for N = 13,
Cmin = 0.6, D = 39° × 10^{20} eV and Θ = 40°. In the
data, Corr(X’,1/E) ≃ 0.66. These 13 detected events are
plotted in Galactic coordinates and surrounded with magen-
ta circles in Fig. 2. The filled magenta boxes, red open
boxes, green open circles and blue crosses respectively cor-
respond to the arrival directions on the sky of Auger events
with energies E ≥ 10^{20} eV, 10^{19.9} eV ≤ E ≤ 10^{20} eV,
10^{19.8} eV ≤ E ≤ 10^{19.9} eV and E ≤ 10^{19.8} eV.

Since one cannot know a priori the best values for the four
free parameters of the method, one has to penalize over
all of them [1]. After penalization, the probability to find
an at least as significant feature in the background as the
feature detected in Fig. 2 is ≃ 6.6 × 10^{−3}. The source
associated with these 13 events (red cross in Fig. 2) is re-
constructed at ≃ 8.5° from M87, near the Virgo cluster
position (black disk). Even in case Virgo would only con-
tain one UHE heavy nuclei source, it would shine as an ex-
tended source on the sky because of magnetic fields inside
the cluster [20]. Moreover, due to the poor 1/E ordering
of events expected for heavy nuclei sources, the accuracy
on the position of the reconstructed source would not be

better than $\pm 10^\circ$. Therefore, the detected events are compatible with a common emission from Virgo. (Most of) the events in the “Cen A region” ($-60^\circ \leq l \leq -30^\circ$ and $0^\circ \leq b \leq 30^\circ$) and the 142 EeV event may be the heavy nuclei image of Virgo, deflected in the GMF. If one also adds the condition that the reconstructed source should be located at less than $10^\circ$ from M87, the above probability falls to $\approx 3 \times 10^{-5}$. One may argue that this detection can have been triggered by the overdensity of events in the “Cen A region” which may be due to another reason. In such a case, the relevant probability is the probability to reconstruct the source at less than $10^\circ$ from M87 in a data set already containing a feature as significant as the Auger feature. It is equal to $\approx 4 \times 10^{-3}$.

\section{Discussion}

We first cross-check the result of Section 3 with a “blind-like” analysis by dividing the Auger data set in two: The first 27 events and the $69 - 27 = 42$ newer ones. For the first set, we determine the “best sector” on the sky in which the significance of the signal is the largest [1], compared to some random background made of 27 events following Auger exposure and spectrum. This sector is highlighted in orange in Fig. 3. It contains 10 out of the 27 events - see upper panel. Then, the newer $69 - 27 = 42$ events are analysed with this sector. It contains 5 events out of 42, and $\text{Corr}(X',1/E) \approx 0.38$ - see lower panel. The probability to have in some background made of 42 events at least 5 events in this sector and $\text{Corr}(X',1/E) \geq 0.38$ is $\approx 2\%$. This value is compatible with the order of magnitude of the probability computed in the previous Section (0.4\%).

We suggest in Section 3 that the events in the Cen A region may be a hint at the heavy nuclei image of Virgo. Let us note that the anisotropy above 55 EeV in the Auger data is due to the overdensity of events in the Cen A region. By computing the 2, 3 and 4-point autocorrelation functions, defined as in Ref. [2], we find that the rest of the sky is currently still compatible with isotropy. We plot in Fig. 4 the probability that the signal in the data is a fluctuation of the background as a function of the angle (labels “69”). The 3 and 4-point autocorrelation functions have a minimum on the $\sim 20^\circ$ scale. If one removes the events in the $20^\circ$ region around Cen A (“no Cen A”), the minimum disappears.

Let us also point out that some GMF configurations are compatible with the possibility presented in Section 3. Fig. 5 shows the iron image, for $E = 60 - 140$ EeV, of the Virgo cluster in a reshaped version of existing GMF models, whose parameters are discussed in [1]. If one adds a turbulent component to this model, low energy events would be spread in the whole Cen A region. If Virgo would be confirmed in the future to be a heavy nuclei source, it would put strong constraints on the GMF. For instance, the 142 EeV event would give an estimate of UHECR deflections in the Galactic Northern halo, and the contribution of the turbulent GMF to deflections should be small because of the small spread of the image in the Cen A region. It would also bring constraints on the GMF strengths, extensions and geometries in the Galactic disk and halo [1]. This would put restrictions on the source(s), too. Due to their equal rigidities $E/Z$, $60 - 80$ EeV iron nuclei are deflected as $2 - 3$ EeV protons in cosmic magnetic fields. Thus, if UHECR sources accelerate both nuclei and protons and if the Cen A region events are heavy nuclei, one should have protons at $Z$ times lower energies, in the same region [21]. Since Auger data is compatible with isotropy.
UHECR data are however still needed to confirm or rule out this possibility.

In Section 4, we cross-checked this possibility with a “blind-like” analysis. We also pointed out that the anisotropy in the Auger data is due to the Cen A region events. We note that the next generation of UHECR experiments will be able to test the possibility presented here.

References