Heavy Cosmic Ray Nuclei from Extragalactic Sources above ”The Ankle”

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***Abstract*— A very recent observation by the Auger Observatory group [1] presents evidence for cosmic rays above 5.6×10^{19} eV - (56 EeV) being ’predominantly protons’ from Active Galactic Nuclei. If, as would be expected, the particles above the ankle at about 2 EeV are almost all of extragalactic (EG) origin then it follows that the characteristics of the nuclear interactions of such particles would need to be very different from conventional expectation – a result that follows from the measured positions of ’shower maximum’ at somewhat lower energies where mass measurements using conventional nuclear interaction models indicate $\langle \ln A\rangle \simeq 2.5$.**

In our own analysis we study to what extent the Auger results could, indeed, give such a mean value for $\langle \ln A\rangle$ rather than a much smaller one. We conclude that they can, and the need for a dramatic change in the nuclear physics disappears.

I. INTRODUCTION

The impressive results from the Auger Observatory are shown in Figure 1, where we have indicated the energy ranking by the size of the ‘circles’. It is evident that, as the authors [1] point out, the distribution is not isotropic and, furthermore, their analysis shows that the arrival directions of many are correlated with AGN out to about 70 Mpc.

Our own analysis, to be described, is an alternative in that it considers the possibility that half of the detected particles may have come from just 3 ‘nearby’ sources. If this is true then, adopting a particular model for the magnetic field in the intergalactic medium (IGM), it is possible to estimate roughly what the mean mass ($\langle \ln A\rangle$) might be. Alternatively, we can ask the question, assuming the conventional mean mass, $\langle \ln A\rangle \simeq 2.5$, is the magnetic field ‘reasonable’, bearing in mind the uncertainties in its derivation. In fact, concerning the latter remark, it is not essential to assume the presence of the 3 ‘sources’ but simply to examine if ‘medium nuclei’ are allowed by the data.

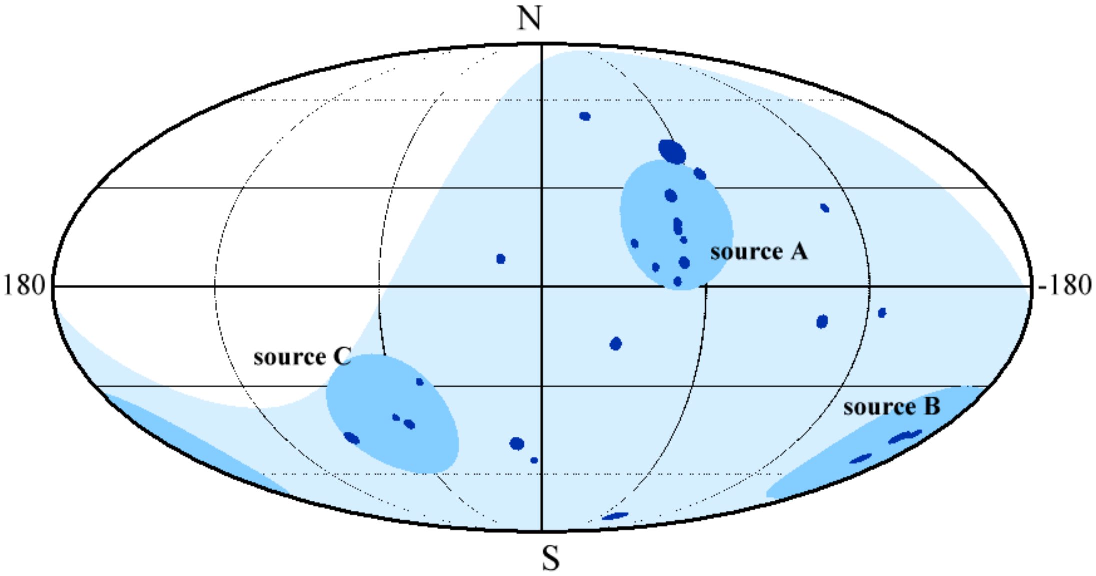

Fig.1 Auger source map showing possible ’sources’ A, B and C [1]. The energy threshold is 57 EeV.

We start by discussing the role of the ankle in the spectrum (i.e. the sharp change of slope at $\sim$ 3 EeV) insofar as it is germane to the argument, the relevance of previous searches for ‘discrete’ sources and the problem with nuclear physics.

It has long been suggested that the cosmic ray particles above the ankle are extragalactic (e.g. [2], [3]); indeed, some believe that the transition starts at an even lower energy than 2 EeV (e.g. [4]). There have been many claims for EG ’signals’ from specific sources (e.g. [5]) but, apart for rather strong

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evidence for particles from the VIRGO cluster (the centre of the supercluster in which we are situated) the results have been conflicting. There were thus high expectations for the results from the very large Auger Observatory and such result, based on an exposure (area times time) exceeding the sum total of the world's data have recently appeared [1]. Figure 1 shows the results and it is evident that there is 'clumpiness' in the arrival directions as already mentioned.

The Auger conclusion that the primaries are 'predominantly protons' is based on the contention that the deflections in the intergalactic medium (IGM) and the Galaxy would nullify the coincidences for heavier nuclei.

Although not stated, the need for a change in the nuclear physics would appear to follow from examination of the world's data (and their own e.g. [6], [7]) on the depth of shower maximum, which indicate $\langle \ln A \rangle \sim 1.5 \pm 0.5$ at 10 EeV and $\sim 2.5 \pm 0.5$ at 40 EeV, the highest energy point plotted in the Auger results. With the conventional nuclear physics model, protons ($\langle \ln A \rangle = 0$) are ruled out for the particles above 56 EeV. If true, this result would arguably be more important than the demonstration that AGN are responsible for the ultra high energy particles (the depth of maximum problem is considered in more detail, later).

This, then is the problem addressed here: Are 'medium nuclei' ($\langle \ln A \rangle = 2 \div 3$) ruled out?

II. THE ANKLE

As remarked already, and referred to by us in several publications (eg. [8]) we consider that this feature marks the transition from a mainly Galactic (G -) to a mainly Extragalactic (EG -) origin. Some others have it as a property of EG protons and a demonstration that this is the case would clearly support the Auger contention. We have made many arguments against the EG protons/ankle hypothesis (eg. [8]) and these are strengthened from observation of the Auger energy spectrum reported in [7]. The ankle is so sharp as to make its explanation in terms of E - p quite untenable.

The situation can be seen by reference to Figure 2. A two component spectrum with the spectra Galactic (G -) and Extragalactic (EG -) crossing sharply, as in Figure 2a, clearly gives a sharp ankle. The EG protons alone, spectrum (Figure 2b) has too smooth a transition; in fact, various factors would make the transition smoother still for such a model [8]. Figure 2c refers to one of our variants [8]; specifically, origin of ultra high energy cosmic rays (UHECR) in quasars. It is our contention that the actual form of the spectrum can be used to define the best fit spatial distribution of the sources as a function or red shift $Q(z)$ see [8]. The rather sharp fall in the Auger spectrum at about 40 Eev has relevance here, as will be discussed in more detail elsewhere. At present a possibility is that heavy nuclei are involved,indeed,this is the basis of our following arguments. In fact the prediction shown,which is for protons alone, would need to be displaced downwards to allow for 'heavy' nuclei at energies below 20 EeV,too.

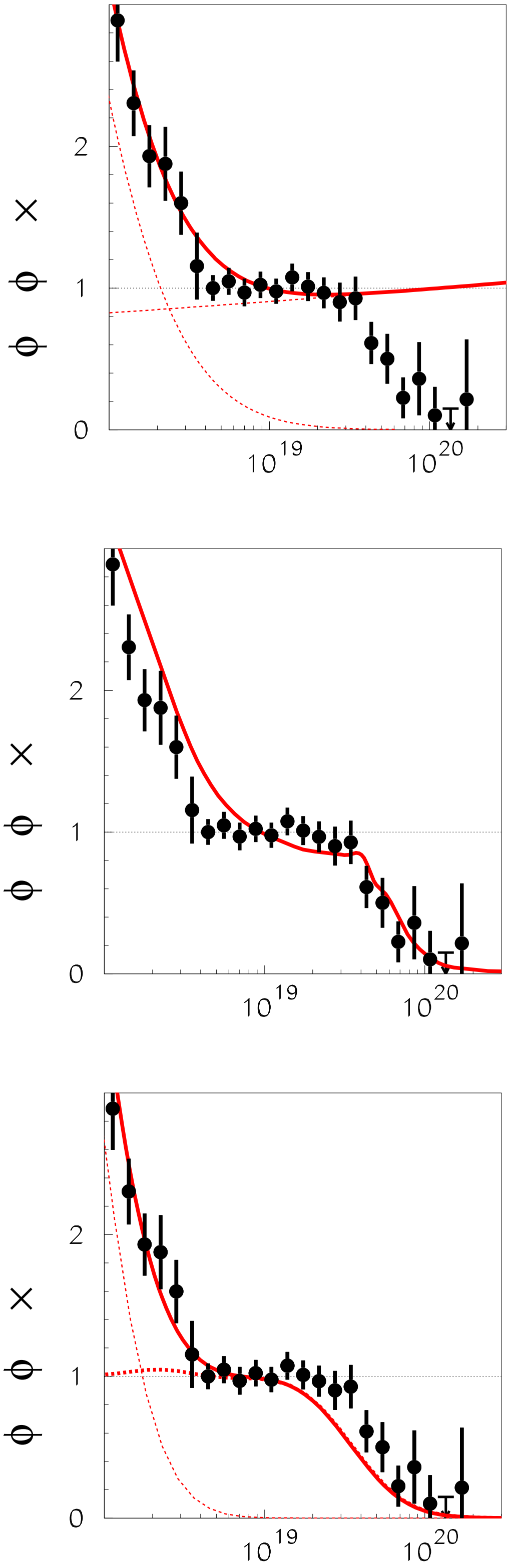

Fig. 2. The Auger energy spectrum [7] in comparison with various predictions
a. Our model fit [8] where the Galactic (G -) and Extragalactic (EG -) spectra are simple power laws;
b. Comparison with EG protons only model of [4];
c. Comparison with our Q2 model for protons [8];
The shortage above 10 EeV would be covered by heavier nuclei.

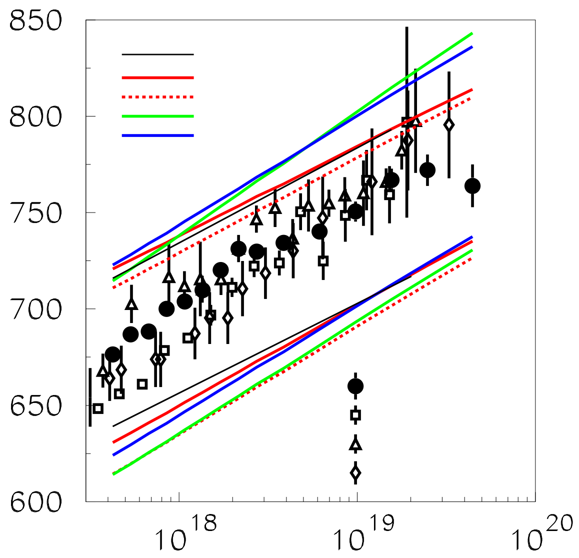

Fig. 3. Depth of shower maximum versus energy measured by different experiments compared with different model predictions.

III. The Depth of Shower Maximum

Measurements over many years have shown that the depth of maximum increases with increasing energy and its value is roughly mid way between expectation for 'all protons' and 'all iron' for essentially all the nuclear models to date. With their superior statistics and analysis, the Auger work [7] has shown that there is structure in the energy dependence, with a feature near the ankle energy. Figure 3 shows the results and Figure 4 shows the resulting $\langle \ln A \rangle$ from our analysis. It is interesting to note that the HiRes EAS array shows a similar feature: an $X\max$ change close to the ankle [9]. A relevant matter to consider now is the expected mass composition *before* the ankle. This cannot be anywhere near mainly 'protonic' because of the lack of the large anisotropies favouring the Galactic Plane that would occur for protons, as shown by us in a previous detailed analysis [10]. Thus, the nuclear physics models should not be too inaccurate here. Were the particles to be mainly protonic only above the ankle, the change in nuclear physics model would need to take place over half a decade of energy, at most, and we consider this to be unphysical.

At this stage, it can be remarked that, in fact, the Auger $X\max$ results would give too high an anisotropy at 1EeV,where the particles are of Galactic origin because of the significant flux of very light particles. The lower $X\max$ values measured by most others would not [10].

IV. THE ARRIVAL DIRECTIONS

A. CEN–A

Returning to Figure 1, together with the Auger authors, we are impressed by the signal from Centaurus-A (CEN-A), a long favoured source with its double jet, high power and flat radio spectrum. The Auger workers allocate 2 of the nearby particles to it but we would argue that the 8 particles within 20° of CEN-A could well be due to it. Arguments in favour of the increased number of particles [7] having come from CEN-A can be listed:

i. We often find elliptical patterns as a result of propagation characteristics. Indeed, the median ratio of maximum to minimum extent is ~ 6.
ii. The radio source has a long jet in the direction of the longer axis.
iii. It is true that there is an excess of AGN in the general region 'above' (i.e. at higher latitudes than) CEN-A and thus there should, perhaps, be contributors to the cosmic ray flux from some of them but there are other regions with many AGN but no detected high energy cosmic rays.

The case for more 'nearby' sources on the basis of clustering of arrival directions is not strong but we have tentatively identified 2, denoted B and C in Figure 1. it is necessary to point out, however, that the argument to be advanced does not depend crucially on the legitimacy of B and C.

Although there is an excess above chance of coincidences with AGN in general the statistics will be made worse when the CEN-A events are removed. It is instructive to make an estimate of how many particles might have been expected to be seen by Auger from VIRGO. Including the difference in collection efficiency, a factor ~ 2.5, we would expect to see, for a single CEN-A source at the distance of VIRGO, about 0.3 events,therefore there are less than a few CEN–A type galaxies amongst several thousand galaxies, and probably ~ 10 AGN

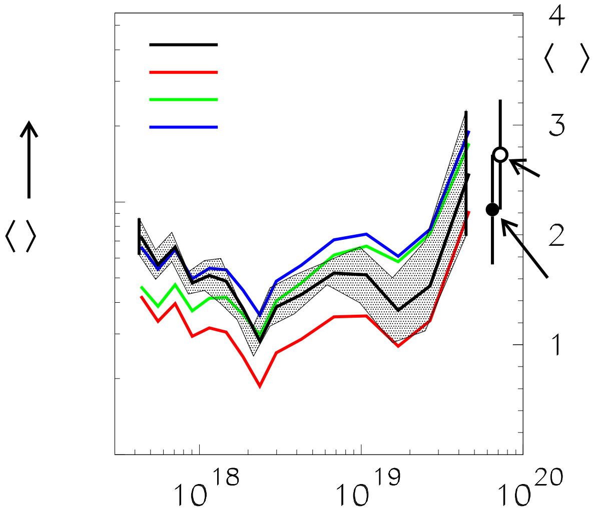

Fig. 4. $\langle \ln A \rangle$ vs energy from our analysis of the Auger results and different models. Most other $X_{\max}$ values from Figure 3 would give higher mean masses.

in that cluster. Were all AGN like CEN-A we would expect to see ~ 3 events here. This, not unexpected, variability of output in CR amongst AGN of different types coupled with the lower detection efficiency of distant AGN and not to mention their time variability tends to give problems for an analysis in which coincidences are sought between a non homogeneous set of AGN and UHECR. In fact, there was a prior likelihood of large radio galaxies rather than AGN in general being likely sources or UHECR for two reasons:

a. the likely detection of M87,(see Figure 1) a radio galaxy with a pronounced jet in the Northern hemisphere, [3] and,
b. the obvious need for a type of source with large linear dimensions and, preferably radio spectra with small exponent indicating, for electrons at least, flat energy spectra.

It is necessary to see if there is further support for the argument that radio galaxies may be important sources of UHECR. Those giving the highest radio fluxes at earth are, in order of increasing distance from earth:

- CEN-A (NGC 5128) at 4.9 Mpc
- VIRGO A (NGC 4486, M87) at 16.8 Mpc
- and FORNAX (NGC 1316, ARP 154) at 16.9 Mpc

Thus, the last mentioned may be relevant in the UHECR search.

B. 'Source B'

In the list just given, the first two have been mentioned already. FORNAX itself is seen to be not far from the 'Source B' but probably too far to be physically associated. However, it is in the FORNAX cluster and this has galaxies extending across to l, b: 200°, $-40°$. Most notable is that of the radio sources with flat radio spectra (associated with elliptical galaxies), [13] the flattest, with exponents ~0 and 0.1, are near to Source B. They are NGC 1052 and NGC 1407 at l, b, distance: 182°, 58°; 17.8 Mpc and 209°, $-50°$, 21.6 Mpc.

We conclude that there are reasonable contenders for 'Source B'.

C. 'Source C'

The evidence for this 'cluster' of UHECR arrival directions being associated with a single known source is not strong. There are no obvious candidates. There are only a few 'normal' galaxies within 20 Mpc [14], [15] although there is a nearby galaxy within 5 Mpc. Presumably a source further away is responsible? A possibility is the cluster at ~ 30 Mpc [14] known as the 'Pisces-Austrinus spur' and this will be tentatively adopted. it must be said, however, that at this distance the number of other 'sources' which might have been expected to have been seen starts to grow.

D. Other Source Complications

Its well known that many AGN are time variable (and CEN-A is no exception). Thus, in view of transit time differences between UHECR and protons for very distant sources, the optical and UHECR sky may differ. It is interesting to note that nearby colliding galaxies (some of which go on to produce AGN) have not (yet) been seen (see [15] for previous work). In addition, to the different types of AGN their distances are clearly of great relevance; thus, catalogues are needed of putative claims for coincidences giving particle energies and AGN distances (and types). **It can be remarked at this stage that the term 'Active Galactive Nuclei' is perhaps a misnomer to describe the UHECR sources. Many of the large radio sources have ceased to have active nuclei by the time the radio jets are seen.**

V. THE CASE FOR, OR AGAINST, NON PROTONS

A. Acceleration Mechanisms

Starting with acceleration, there is an obvious advantage in accelerating high Z particles insofar as the commonly considered acceleration mechanisms operate, with a rapidly falling energy spectrum, to some maximum rigidity. Thus, provided there is an adequate pool of pre-accelerated nuclei, say up to iron, such non protons should be at an advantage. There is a similar situation in the tens of thousands of GeV region, where the mean mass increases with energy [16].

B. Angular deflections in the Galaxy

In [1] it is pointed out that the deflections in the Galactic magnetic field do not allow the incoming nuclei to maintain their common direction. This is true, but there are two points that should be made here:

a. For CEN-A the trajectories are very largely along the coherent magnetic field direction (the Sagittarius Arm).
b. Calculations by us for the random field, using the parameters of field strength and reversal length [17], [18], yield a median deflection of 0.72 degrees, again for CEN-A. Allowing a spread of arrival directions of 10° rms radius from CEN-A would allow a mean charge as high as 14 if there were no deflection in the IGM.

Turning to 'Source B' at $l \sim 190°$, $b \sim 60°$, the direction gives paths mainly in our weak 'spur'.

Finally, for 'Source C' at $l \sim 60°$, $b \sim 45°$, again the direction is along a spiral arm, specifically along the inter arm region between the Orion and Sagittarius arms where the magnetic field is lower, as well as being mainly ineffectual because of direction. Furthermore, the length of path through the irregular field is smaller than that for CEN-A (by a factor sin $\sin 19° / \sin 45° = 0.46$).

C. Angular deflections in the IGM

Uncertainty in the magnetic properties of the IGM is probably the biggest problem in the determination of the origin of the UHECR. In a simple model in which the field is characterised by a mean field B and a 'reversal legnth' L a number of authors have given the rms deflection, θ, for a source at a distance D. Our own analysis [15] gives $\theta(deg) = 510\, B\, \sqrt{LD}\, E^{-1}$ where B is in μGs, L and D are in Mpc and E, the particle energy, is in units of 100 EeV.

Other workers [19], [20] give relations within a factor 2 of the above (the difference relates to the meaning of 'B').

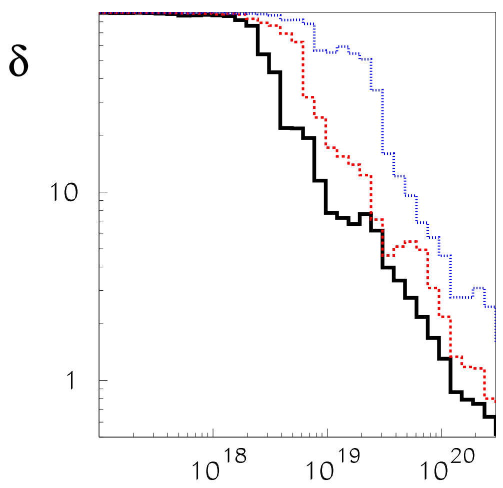

Fig. 5. Integral distribution of the root mean square angular deflection (δ - in degrees) for protons of energy greater than E from CEN–A (line labeled 5 Mpc) and the distributions for 15 Mpc and 100 Mpc distant sources for comparison. A universal mean field has been adopted [21]

Under the assumption of equipartition of the energy densities of UHECR and magnetic field a mean field of 2-3 nG is indicated. However, there will be big variations from region to region, most specifically in and near galaxy clusters. The VIRGO direction is a case in point; in [15] it is shown that for a source in VIRGO, the deflection could well be some three times the 'average' value.

In what follows we use a model put forward by one of us [21] in which a Kolmogorov distribution is adopted for the scattering elements, with maximum and minimum linear dimensions of 0.01 to 2 Mpc and a mean field of 2 nG. The characteristics satisfy the condition from observation (referred to in [1] and elsewhere) that $\langle B_{\rm rms}\rangle\sqrt{L} < 10^{-9}$ G Mpc$^{1/2}$ where L is, as before, the effective field reversal length. It is appreciated that our scattering estimates are very imprecise but we regard them as the best available at the present time, particularly for the direction to CEN-A, which is far enough away from the enhanced field region approaching the VIRGO cluster.

Figure 5 shows the distribution of root mean square deflections for protons from 3 different distances and energy greater than E. The calculations were made by way of a Monte Carlo technique adopting the field model just described.

VI. APPLICATION TO THE UHECR MAP

Our method is to use the order of magnitude values of the median angular deviations from Figure 1, to give the expected median values of Z. Converting the mean value for the sources to an effective mass ($A = 2Z$) gives our estimated $\langle \ln A\rangle$. This is then shown on Figure 4.

The value for CEN-A, the best identified source, is seen to be $\langle Z\rangle = 6.3$ and $\langle \ln A\rangle$ follows as ~ 2.5. Taking the mean of all three gives $\langle Z\rangle$ = 3.8 and $\langle \ln A\rangle = 2.0$. It seems to us unlikely that for our assumptions about the magnetic fields and the clusters, the true value is outside these limits; certainly, $\langle \ln A\rangle$ = 0 appears not to be needed.

TABLE I

MEDIAN EXPECTED DISPLACEMENTS (IN DEGREES) FOR PROTONS FROM THE SOURCES INDICATED, AND THEIR 'TOTAL', I.E. ADDITION IN QUADRATURE. COMPARISON WITH OBSERVED DISPLACEMENTS GIVES AN ORDER OF MAGNITUDE ESTIMATE OF THE PARTICLE CHARGE, Z.

Source	Distance (Mpc)	Galaxy	IGM	Total	Median displacement observed	Z
CEN–A	5	0.7	1.1	1.3	10	7.7
Source B	20	0.46	2.2	2.2	6	2.7
Source C	33	0.48	2.8	2.8	10	3.6

VII. CONCLUSIONS

We conclude that it is probably not necessary to change the nuclear physics of high energy interactions at energy above 60 EeV, or so.

The way forward in the analysis of the Auger results is to endeavour to check the hypothesis that 'nearby' (within some 10s of Mpc) flat spectrum radio galaxies are responsible. Identification will clearly rely on examination of the allotted energies to events within clusters as a function of radial distance from the possible source. Individual $X_{\rm max}$ values need treating in the same manner.

A complication, affecting all searches, is the fact that the distant source may not be seen optically to be 'still on' when the particles arrive, [20]. Typical transit times of 10^5 years (over and above the light travel times) are not unlikely.

It remains to examine the situation if the Auger claim for coincidences with AGN is correct and, as is possible, the IGM fields are so low that the Extragalactic magnetic deflections are negligible. With the small Galactic deflections predicted in our analysis (e.g. Table 1), for a mean deflection of 3° the mean Z would be about 5. The value of $\langle \ln A\rangle$ follows as 2.3, a result in the region of that found in our own more complex analysis.

It should be remarked that we envisage a range of masses for the primary particles with some protons and some heavy nuclei, however, the fraction of the latter may well be very small in view of the small fraction of AGN not close to UHECR. Surprisingly, perhaps is the fact that the highest energy particle, at 148 EeV, from ℓ, b: $-57.2°$, $+41.8°$ which is unlikely to be deflected by more than $0.2°$ in the Galactic magnetic field (if a proton) is not associated with an AGN. It, at least, seems likely to be more massive than a proton.

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