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

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Abstract: A recent observation by the Auger Observatory group presents evidence for cosmic rays above 5.6×10^{19} eV -(56 EeV) being 'predominantly protons' coming from Active Galactic Nuclei. If, as would be expected, the particles above the ankle at about 2 EeV are almost all of Extragalactic 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 $\langle \ln A\rangle \simeq 2.5$. Such a claim is rather dramatic.

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.

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1. INTRODUCTION

The impressive results from the Auger Observatory are shown in Fig. (**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, further more, their analysis shows that the arrival directions of many are correlated with AGN out to about70Mpc.

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 'near by' 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.

We start by discussing the role of the ankle in the spectrum (i.e. the sharp change of slope at $\sim 3EeV$) 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 2EeV (e.g. [4]). There have been claims for Extragalactic (EG) 'signals' from specific sources (e.g. [5]) but, apart for rather strong 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 results, based on an exposure (area times time) exceeding the sum total of the world's data, have recently appeared ([1]). Fig. (**1**) shows the results and it is evident that there is 'clumpiness' in the arrival directions as already mentioned. The exposure of the PAO is not uniform, and the Northern part of the sky is not visible at all as shown in the Fig. (**1**).

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, if they had higher masses (and thus higher charges).

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 ultrahigh energy particles (the depth of maximum question 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?'

2. THE ANKLE

As remarked already, and referred to by us in several publications (e.g. [8]) we consider that this feature marks the transition from a mainly Galactic (G-) to a mainly Extragalactic 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 (e.g. [8]) and these are strengthened from observation of the Auger energy spectrum reportedin [7]. The ankle is so sharp as to make its explanation in terms of EG-p quite untenable.

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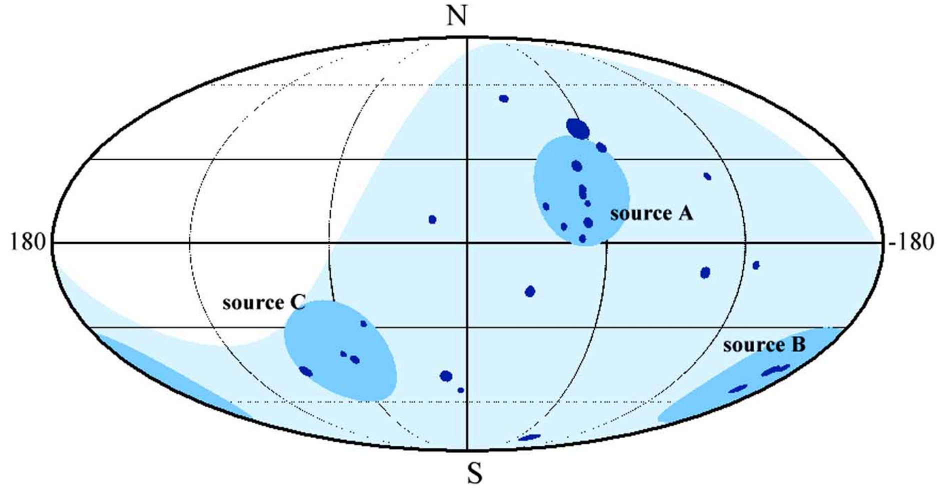

Fig. (1). Auger source map ([1]) showing the possible 'sources' A, B and C identified by us. The energy threshold is 56 EeV. The exposure of the Pierre Auger Observatory is not uniform, lightly marked region of the sky shows the PAO visible part of the sky.

The situation can be seen by reference to Fig. (**2**). A two-component spectrum with the Galactic and Extragalactic spectra crossing sharply, as in Fig. (**2a**), clearly gives a sharp ankle. The EG-protons alone, spectrum (Fig. **2b**) has too smooth a transition; in fact, various factors would make the transition smoother still for such a model. Fig. (**2c**) refers to one of our variants ([8]); specifically, the 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 of 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. Infact, the prediction shown in Fig. (**2c**), which is for protons alone, would need to be displaced

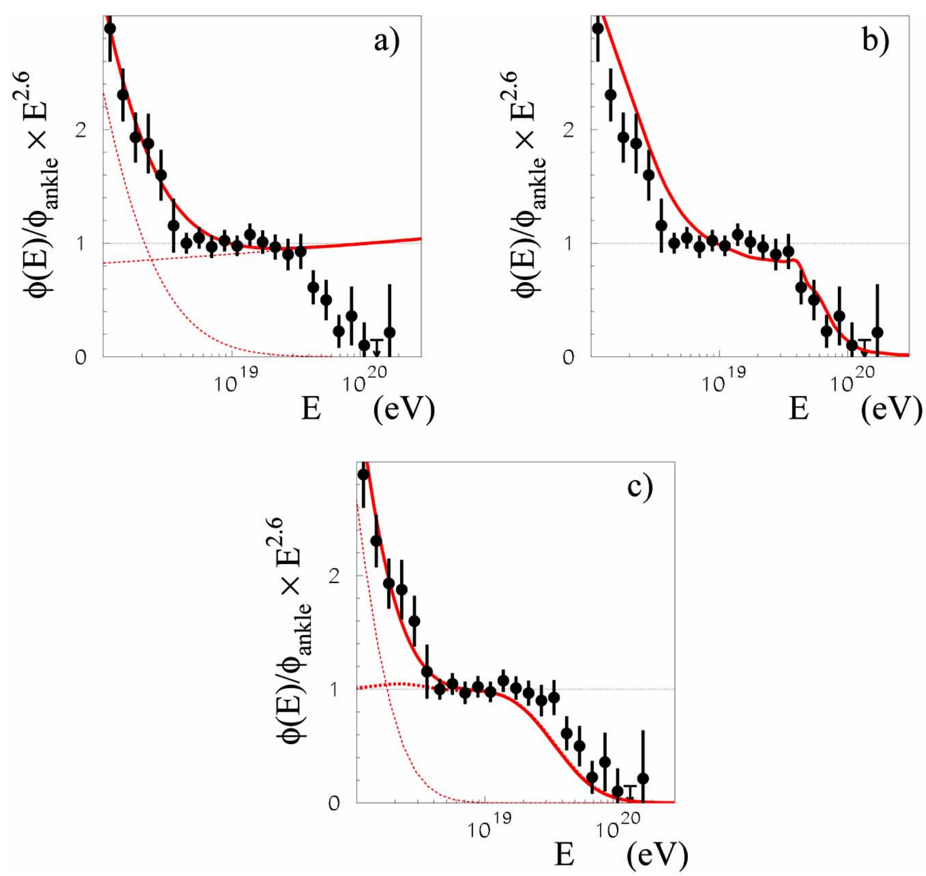

Fig. (2). The Auger energy spectrum ([7]) in comparison with various predictions
(**a**) Our model fit ([8]) where the Galactic (G -) and Extragalactic (EG -) spectra are simple power laws (no GZK cut-off for EG).
(**b**) Comparison with EG-protons only model of ([4]).
(**c**) Comparison with our Q2 model for protons ([8]). The shortage above 10 EeV would be covered by heavier nuclei (it is the sharpness of the ankle that is of concern here).

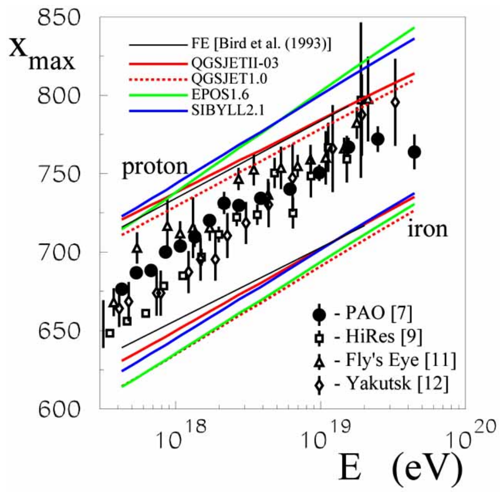

Fig. (3). Depth of shower maximum versus energy measured by different experiments compared with different model predictions.

down wards to allow for 'heavy' nuclei. The sum of the predictions for the different nuclei could easily fit the experimental points.

3. 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. Fig. (**3**) shows the results and Fig. (**4**) shows the resulting (lnA) from our analysis. It is interesting to note that the Hi-Res 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 and of Galactic origin. 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, if 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]).

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.

iv. Recently CEN-A has been identified by the H.E.S.S. Collaboration [14] as a source of high-energy (up to some TeV) gamma rays.

4. THE ARRIVAL DIRECTIONS

4.1. CEN–A

Returning to Fig. (**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 and, importantly, its comparatively nearby location see e.g. [13]. 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 favor of the increased number of particles having come from CEN–A can be considered:

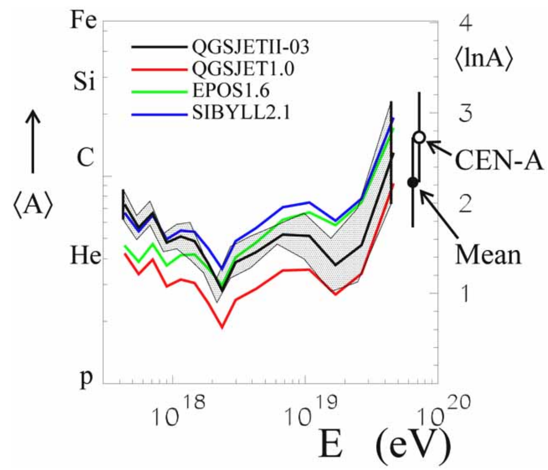

Fig. (4). (ln A)vs energy from our analysis of the Auger results and different models. Most other Xmax values from Fig. (**3**) would give higher mean masses.

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 Fig. (**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.

The choice of 20° as such is dictated by the fact that taking annular rings round the centre of CEN-A, the density of particles falls off very rapidly beyond this angular distance. In fact, the choice of 20° as distinct from 15° or 25° is not crucial. The case for the same angle for 'sources' B and C is for consistency, but again, the value is not critical.

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 in that cluster. Were all AGN like CEN– Awe would expect to see ~ 3eventshere. 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 Fig. **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
- FORNAX (NGC 1316, ARP 154) at 16.9 Mpc

Thus, the last mentioned may be relevant in the UHECR search, although the high radio fluxes, of course, are not necessarily related to UHECR production.

4.2. '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), ([15]) 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'.

4.3. '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 ([16, 17]) although there is a nearby galaxy within 5 Mpc. Presumably a source further away is responsible? A possibility is the cluster at ~ 30 Mpc ([16]) 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.

4.4. 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 photons 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 [17] 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. The large radio sources have often ceased to have active nuclei by the time the radio jets are seen.

5. THE CASE FOR, OR AGAINST, NON PROTONS

5.1. Acceleration Mechanisms

Starting with acceleration, there is an obvious advantage in accelerating high -Z particles insofar as the commonly considered acceleration mechanisms, including any electromagnetic acceleration mechanisms of course, with a rapidly falling energy spectrum operates, 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 ([18]).

5.2. Angular Deflections in the Galactic Magnetic Field

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) and the deflections will therefore be small.

b. Calculations by us for the random field, using the parameters of field strength and reversal length ([19,20]), 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 ~ 190°, b ~−60°, the direction gives paths mainly in our weak 'spur'.

Finally, for 'Source C' at l ~ 60°, b ~−45°, 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 sin19°/45° =0.46).

We have performed new calculations of Galactic deflections, as follows. Firstly, the structure of the regular (as well as the irregular) field has to be assumed. The simple model of the Galactic disk field is a toroid aligned with the stellar spiral structure and the field changes its direction between nearby spiral arms. The field was chosen to be symmetric with respect to the Galactic Plane. The halo around the disk is filled with the field similar to that in the disk but diminishing slowly with the distance from the Galactic Plane on a scale of few kpc ([21, 22]), but it can be also the dipole field ([23]) as suggested by the dynamo mechanism. For the random component we have used the Kolmogorov turbulent field with a spectrum of turbulences ranging from 1 to 100 pc length scales. The field is normalized to have an average strength of 4μG at the Solar System position. Its strength is diminishing with height above the Galactic Plane and the distance from the Galactic Centre following the regular field model of [21,22].

Table 1. 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	0.4	2.2	2.2	6	2.7
Source C	33	1.7	2.8	3.3	10	3.1

Table 2. Median Deflection in the Galactic Magnetic Field of UHECR Coming from the Direction of our Three Sources Calculated for Different Models of the Galactic Magnetic Field

French and Osborne, 1976 Giller and Wolfendale 1993		Candia *et al*., 2002		Alvarez-Muniz and Stanev 2006		Harari *et al*. 1999	
source A	0.7◦	source A	0.6◦	source A	1.7◦	source A	0.7◦
source B	0.5◦	source B	0.7◦	source B	0.7◦	source B	0.4◦
source C	0.5◦	source C	1.8◦	source C	1.0◦	source C	1.7◦

It is important to note that such a field, when applied to the CR particles produced as iron nuclei in the Galactic Disk (uniformly), traps CR of energies below the ankle within the Galaxy, as suggested in our model of transition from Galactic to Extragalactic components at the ankle ([24]).

The median deflection in the Galactic field is shown in Table **2**. All three models and results described in ([19,20]) agree within 0.2-0.3 systematic error bands (except for single numbers for specific models).

We can not average the deflection for the three different models, because the interpretation of such a procedure is, by definition, questionable so we will use for further purposes as deflections for our sources A, B and C: 0.7,0.4 and 1.7 degrees respectively obtained for the model of [22].

5.3. Angular Deflections in the Intergalactic Medium

Experimental knowledge of the large-scale magnetic fields which deflect extragalactic cosmic rays is rather scarce (see, for example, [25] and discussions given in [26], [27] and [28]). These fields will have both regular and random components. The former can be, in principle, a relic of distant epochs (occasionally compressed and magnified or amplified by dynamo-like mechanisms). However, at present we have no evidence of the existence of such, so we neglect it.

The irregular component is present in intergalactic space, as it is in our Galaxy (and others). Its source can be ionized plasma emitted by galaxies and clusters of galaxies, some of which will have come from supernova remnants bursting out of the host galaxies. The escape of Galactic cosmic rays into the intergalactic medium (IGM) is a special case of this "process". Insofar as the energy density of cosmic rays in the IGM coming from escape from galaxies, is ~ 10^{-6} eV cm^{-3} (obtained by integrating the extragalactic flux of cosmic rays), the corresponding magnetic energy density will give an rms field of ~ 2×10^{-9} G (i.e. 2 nG) assuming equipartition. Another source of extragalactic magnetic field is from Active Galactic Nuclei and other near-cataclysmic events. The magnetic disturbances evolve in time in accordance with the conventional turbulence picture, transferring energy successively down to smaller scales where the energy is finally dissipated.

Turning to estimates of the magnitude of the cosmic ray deflections, in a simple model in which the field is characterised by a mean field B and a 'reversal length' L, a number of authors have given the rms deflection, θ, for a source at a distance D. Our own analysis ([17]) gives $\theta(deg)= 510\ B\ LDE^{-1}$ where B is in μG, L and D are in Mpc and E, the particle energy, is in units of 100 EeV.

Other workers ([30, 31]) give relations within a factor 2 of the above (the difference relates to the meaning of 'B').

Under the assumption of equipartition of the energy densities of UHECR and magnetic field a mean field of ~ 2 nG is indicated as already remarked. 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 [17] 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 ([32]) in which a Kolmogorov distribution is adopted for the scattering elements, with maximum and minimum linear dimensions of 2 and 0.01 Mpc and a mean field of 2 nG. The characteristics satisfy the condition from observation (referred to in [1] and elsewhere). that (Brms) $L< 10^{-9}$ $GMpc^{1/2}$ 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.

Fig. (**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.

6. APPLICATION TO THE UHECR MAP

Our method is to use the order of magnitude values of the median angular deviations from Fig. (**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 (ln A). This is then indicated on Fig. (**4**).

The value for CEN–A, the best identified source, is seen to be (Z)=7.7 and (ln$A$) follows as ~ 2.7. Taking the mean of all three gives (Z)=4.7 and (ln$A$)=2.2. It seems to us unlikely that for our assumptions about the magnetic fields and the clusters, the true value is outside these limits; certainly, (lnA)= 0 appears not to be needed.

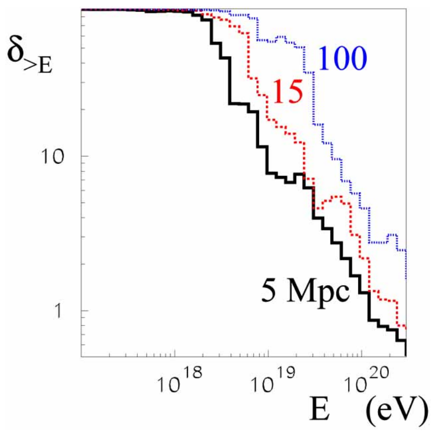

Fig. (5). Integral distribution of the root mean square angular deflection (δ -in degrees) for protons of energy greater than E from CEN–A (line labeled 5 Mpc) and the distributions for 15 Mpc and 100 Mpc distant sources for comparison. A universal mean field has been adopted ([32]).

It is interesting to consider CEN A and our derived mean mass in more detail. It was pointed outin [29] that the AGN and radio galaxies are 'widely thought of as regions of low metallicity' and thus it might thought that this object would not be a source of ultra-high energy heavy nuclei. However, the same authors refer to the role of galactic winds as accelerators and we consider such winds to be more efficient for heavy nuclei. However, this aspect will need further study.

7. CONCLUSIONS

We conclude that it is 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 an examination of the allotted energies to events within clusters as a function of radial distance from the possible source. Individual Xmax - 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, ([28]). 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 after all 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 (Table **1**), for a mean deflection of 3° the mean Z would be about 6. The value of (ln$A$) follows as 2.5, 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.

Finally, a stop-press remark can be made about the depth of maximum. One of us ([33]) has demonstrated that the particles could be protons after all if the 30-year old model of 'Scale-breaking' ([34]), which related to energies in the PeV region, is still valid at these much higher energies. Protons then 'look like heavy nuclei' from the standpoint of the depth of maximum observations.

The relevance of the very recent Auger work reported at the Lodz International Cosmic Ray Conference (July, 2009) needs to be considered [35]. Briefly, surprisingly few further coincidences of UHECR with AGN have been recorded and the mean mass is found to be increasing with energy into the region considered here. We are of the view that both results strengthen our arguments.

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