The Origin of Cosmic Rays of the highest energies

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***Abstract*. An observation by the Auger Observatory group presents evidence for cosmic rays above 5.6$\times$ 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 $\ell 13 \approx$ 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 $< \ell$nA$>$ rather than a much smaller one. We conclude that they can, and the need for a dramatic change in the nuclear physics disappears.**

***Keywords*: ultra high-energy cosmic rays, intergalactic medium, cosmic ray propagation, anisotropy**

I. Introduction

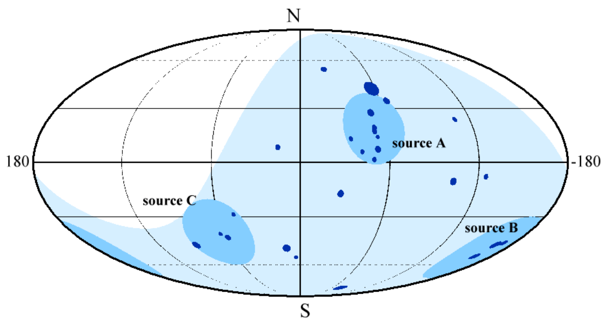

Fig. 1. Auger source map ([1]) showing the possible 'sources' A, B and C identified by us. The energy threshold is 57 EeV.

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.

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 2 EeV (e.g. [4]). There have been claims for 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.

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 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 (e.g. [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 (e.g. [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.

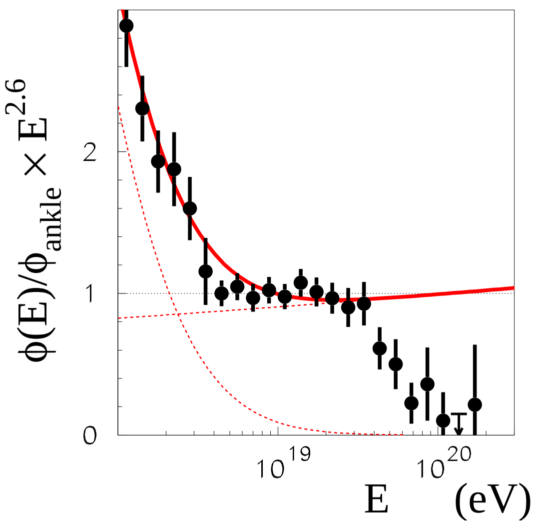

Fig. 2. The Auger energy spectrum in comparison with our model prediction ([8]). The attenuation by the CMB is not shown.

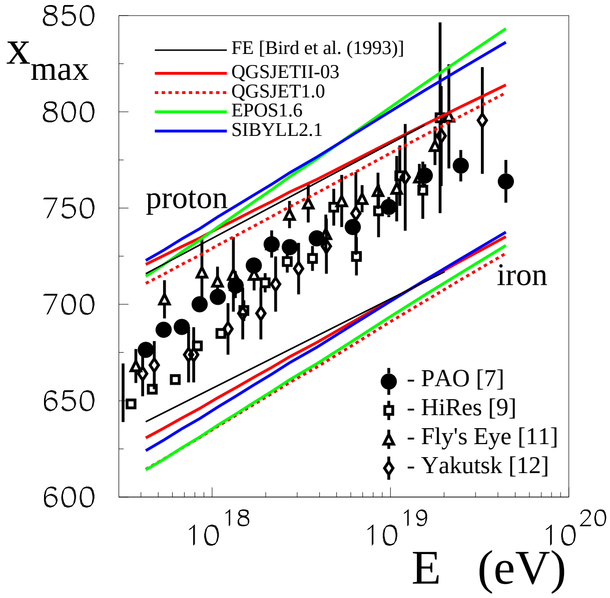

Fig. 3. Depth of shower maximum versus energy measured by different experiments compared with different model predictions.

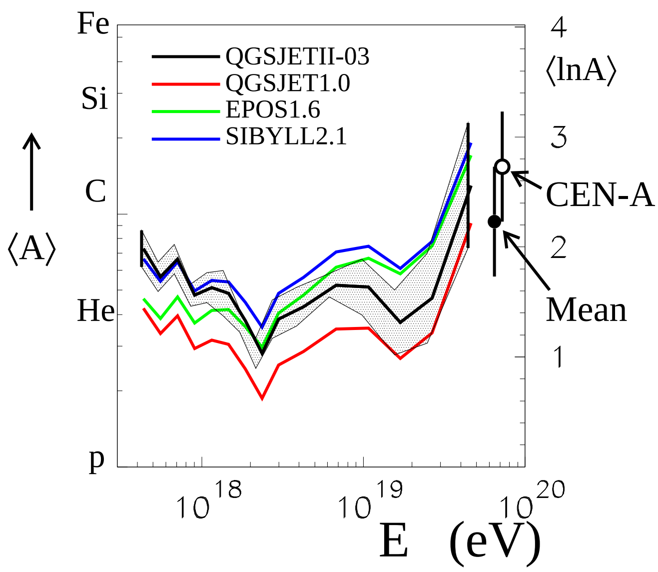

Fig. 4. $\langle \ln A \rangle$ vs energy from our analysis of the Auger results and different models. Most other $X_{\max}$ values from Figure 3 would give higher mean masses.

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 2, clearly gives a sharp ankle; indeed it gives the sharpest possible.

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 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 1 EeV,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 and, importantly, its comparatively nearby location. 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 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 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 ℓ15np, rather than AGN in generalℓ14np, 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:

TABLE I
MEDIAN EXPECTED DISPLACEMENTS (IN DEGREES) FOR PROTONS FROM THE SOURCES INDICATED. COMPARISON WITH OBSERVED DISPLACEMENTS GIVES AN ORDER OF MAGNITUDE ESTIMATE OF THE PARTICLE CHARGE, Z.

Source	d[1]	deflection[2]				Z
CEN–A	5	0.8-1.7	1.1	1.4-2.0	10	5.0-7.4
Source B	20	0.4-1.1	2.2	2.2-2.4	6	2.5-2.7
Source C	33	0.5-1.7	2.8	3.4-3.7	10	2.9-2.7

[1] - distance in Mpc
[2] - deflection in Galactic fields, in IGM, total deflection and observed median deflection

- 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.

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 Intergalactic Medium

Experimental knowledge of the large-scale magnetic fields which deflect extragalactic cosmic rays is rather scarce (see, for example, [17] and discussions given in [18] [19] and [20]). 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.

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. 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.

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 indicated on Figure 4.

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

VII. Conclusions

We conclude that it is probably not necessary to change the nuclear physics of high energy interactions at an 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 $X_{\max}$ - 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 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 I), for a mean deflection of 3° the mean Z would be about 6. The value of $\langle \ln A \rangle$ 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°, $+41.8^\circ$, ℓ lb top 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 ([22]) has demonstrated that the particles could be protons after all if the 30-year old model of 'Scale-breaking' ([23]), 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.

References

[1] J. Abraham *et al.*, Science **318** 938 (2007).
[2] A.A. Watson, QJL, R.Astro. Soc, **21**, 1 (1980).
[3] J. Szabelski, J. Wdowczyk, and A.W. Wolfendale, J. Phys. G. **12**, 1433 (1986).
[4] V.S. Berezinsky, and S.I. Grigorieva, Astron. Astrophys. **199**, 1, (1998).
[5] X. Chi, J. Wdowczyk and A.W. Wolfendale, J.Phys.G **18**, 1869 (1992).
[6] T. Wibig and A.W. Wolfendale, J. Phys. G **25**, 1099 (1999).
[7] A.A. Watson, Proc 30th ICRC (Merida) (2007).
[8] T. Wibig and A.W. Wolfendale, J. Phys. G **34**, 1891 (2007).
[9] T. Abu-Zayyard *et al.*, Phys. Rev. lett., **84**, 4276 (2000).
[10] T. Wibig and A.W. Wolfendale, J. Phys. G **25**, 2001 (1999).
[11] D.J. Bird, *et al.*, Ap. J., **424** 491 (1994).
[12] S. Knurenko, *et al.*, Proc. $17^{\rm th}$ ICRC (Hamburg) **1**, 177 (2001).
[13] E. Hummel *The Radio Continuum Structure of Bright Galaxies at 1.4 GHz*, PhD Thesis,
[14] Tully, R. B., *Nearby Galaxies Catalog*, C U P (1988).
[15] S.S. Al-Dargazelli *et al.*, J Phys G, **22**, 1825 (1996).
[16] S. Ogio, Proc.28th ICRC, **1**, 131 (2003).
[17] P.P. Kronberg, Rept. Prog. Phys. **57**, 325 (1994).
[18] D. Harari, S. Mollerach, E. Roulet, JHEP **0207**, 006 (2002).
[19] M. Bossa, S. Mollerach, and E. Roulet, J. Phys. G **29**, 1409 (2003).
[20] T. Wibig and A.W. Wolfendale, J. Phys. G **30**, 524 (2004).
[21] T. Wibig, Central European J. Phys. **2**, 277 (2004).
[22] T. Wibig, Proc. 21st ECRS, 7.0 (2008).
[23] J. Wdowczyk and A.W. Wolfendale, Nature **236**, 29 (1972); J. Phys. A **6** L48 (1973); Nature **306**, 347 (1983); J. Phys. G **10**, 257 (1984).