Suggestions for Identifying the Primary of Post-GZK Air Showers

José BORDES  
jose.m.bordes@uv.es  
Departament Fisica Teorica, Universitat de Valencia,  
calle Dr. Moliner 50, E-46100 Burjassot (Valencia), Spain

CHAN Hong-Mo  
chanhm@v2.rl.ac.uk  
Rutherford Appleton Laboratory,  
Chilton, Didcot, Oxon, OX11 0QX, United Kingdom

TSOU Sheung Tsun  
tsou@maths.ox.ac.uk  
Mathematical Institute, University of Oxford,  
24-29 St. Giles’, Oxford, OX1 3LB, United Kingdom

Abstract

A procedure is suggested for systematically narrowing the choice of possible primaries for (UHECR) air showers with energies beyond the Greisen-Zatsepin-Kuz’mín cut-off of $4 \times 10^{19}$ eV.
The continued observation in the last few years of ever more air showers with energies beyond the Greisen-Zatsepin-Kuz’min (GZK) cutoff has further increased the credibility of these events and the urgency for answering the question of their likely origin. Since protons and other atomic nuclei, the primaries of lower energy air showers, are thought not to survive journeys longer than 50 Mpc through the cosmic microwave background with energies greater than $4 \times 10^{19}$ eV, it follows that the primary of any shower observed with energy above that cutoff has either to originate within a 50 Mpc radius or else to be some particle other than a proton or an atomic nucleus. In either case, it signifies new physics since, as of today, we know neither of any likely astrophysical sources capable of emitting such energetic particles within a distance of 50 Mpc nor of any particle capable of surviving a long journey through the 2.7 K microwave background and yet produce such an energetic air shower on collision with an air nucleus.

Obviously, one ingredient of first importance for resolving the mystery of post-GZK air showers is the identity of the primary particle producing them. The purpose of this paper is to suggest a possible procedure, from the theoretical point of view at least, for systematically narrowing the choice of possible candidates with the aim of eventually zeroing in on the actual identity of the post-GZK primary. We believe that this will go a long way towards explaining the effect and open a window into a new area of physics which may as yet be entirely unconceived.

A first question to ask is whether the primary particle responsible for post-GZK air showers is or is not the proton or an atomic nucleus. If it is, then the explanation for post-GZK air showers would seem to lie, by the reasoning above, in finding some hitherto unsuspected nearby source either in the form of novel celestial bodies capable of producing cosmic rays of such high energies, or else, as also suggested, from the decay of ultra-massive particles or from the annihilation of relic neutrinos left over from the Big Bang. At our present level of understanding, this seems the only conclusion we could draw unless we are willing to consider more drastic modifications of the basic laws of physics, such as the intriguing suggestion of a violation of Lorentz invariance at ultra high energies, so that the GZK-cutoff is itself invalidated. On the other hand, if the primary particle of post-GZK air showers is not the proton or an atomic nucleus, but some other particle coming from a distant source, then the explanation would seem to lie in the realm of new particle physics beyond the current Standard Model, either in terms of a new interaction of some known particle (such as a new strong interaction for neutrinos at high energy as we ourselves advocate.
The first question we pose ourselves, therefore, is whether one can devise some means for distinguishing the proton or an atomic nucleus from some other particle as the primary of post-GZK air showers. (We shall assume for the sake of economy that, if not the proton or an atomic nucleus, then it is only one other type of particles acting as primaries for post-GZK air showers, which is reasonable given that it is already hard enough to find just any particle to suit the purpose.) Our proposal is the following, the idea for which has already been alluded to in an earlier paper [10]. The penetrating power of a particle through the atmosphere is determined by its cross section with air nuclei, which cross section is itself a characteristic of the particle. Now, air showers at energies shortly below the GZK cutoff are thought to be mostly protons, which has a cross section with air nuclei equivalent to a flux attenuation constant of around 60gm/cm² implying an average penetration depth of about 25 km. If air showers above the GZK cutoff are also produced by protons as primaries, then the penetration depth should remain similar. On the other hand, if the primaries for post-GZK air showers are some different particles, which have no reason to have the same cross section as protons with air nuclei, then the average penetration depth would show a near discontinuous change as the energy crosses the GZK cutoff.

Explicitly, the probability for a primary particle to penetrate to a depth \( r \) at an angle \( \theta \) to the zenith and effecting a collision there to produce an air shower is easily shown to be [10]:

\[
F(r, \theta) = K(\sigma) \rho(h(r, \theta)) f(r, \theta),
\]

where \( K(\sigma) \) is the flux attenuation constant:

\[
K(\sigma) = (N/A)\sigma,
\]

with \( N \) being the Avogadro number, \( A \) the atomic number of the air nucleus, and \( \sigma \) the incident particle-air nucleus cross section. The function \( f(r, \theta) \) is the attenuated flux at the point \( (r, \theta) \):

\[
f(r, \theta) = f_{inc} \exp \left\{ K(\sigma) \int_\infty^r dr' \rho(h(r', \theta)) \right\},
\]

\(^1\)There has been a claim in the literature [14] that particle physics explanations for post-GZK showers in general do not work. We believe this claim to be ill-founded for reasons given in [13, 14].
and \( \rho(h) \) is the air density at height \( h \) in cm above sea-level, which can be roughly parametrized as [10]:

\[
\rho(h) = 1.2 \times \exp(-h/h_0) \times 10^{-3} \text{ gm/cm}^3, \tag{4}
\]

where:

\[
h_0 \sim 7.5 \times 10^5 \text{ cm}, \tag{5}
\]

and \( h \) is given in terms of \( r, \theta \) and the radius of the earth \( R \) as:

\[
h(r, \theta) = \sqrt{R^2 + 2rR \cos \theta + r^2} - R. \tag{6}
\]

With these formulae, it is easy to evaluate the average penetration depth at any incident angle \( \theta \) for any given value of the primary particle cross section \( \sigma \) with air nuclei. In Figure 4, this average penetration depth \( \bar{r}_1(\theta) \) so calculated is plotted as a function of \( \theta \) for various cross sections \( \sigma \) of the primary particle with air nuclei. One sees that \( \bar{r}_1 \) is quite sensitive to \( \sigma \). For example, for \( \theta = 0 \), one obtains for the benchmark value of \( K = 60 \text{ gm/cm}^2 \) appropriate for protons, a value for \( \bar{r}_1 \) of 25.1 km, but for a particle with half that cross section, an \( \bar{r}_1 \) of only 19.8 km, a drop by about 6 km. Hence, if the primary for post-GZK showers is a particle with only half the cross section of the proton, our arguments above suggest that \( \bar{r}_1(\theta) \) for any \( \theta \) as a function of the primary energy would show a sudden drop of that order as it crosses the GZK threshold.

However, given the scarcity of post-GZK events, it looks likely that for many years to come, one will not have collected enough events to evaluate \( \bar{r}_1 \) as a function of energy for a fixed value of the zenith angle \( \theta \). Fortunately, the dependence of \( \bar{r}_1 \) on \( \theta \) is rather trivial and can be readily integrated out, as follows. Define for any shower with primary vertex (i.e. point of first interaction) at \( r, \theta \) an equivalent vertical height \( h_1 \) as follows:

\[
\int_{h_1}^{\infty} dh \rho(h) = \int_{r}^{r'} dr' \rho(h(r', \theta)), \tag{7}
\]

namely the height at which a vertical primary would have traversed the same amount of air as the actual particle incident at the angle \( \theta \) has traversed by the time it reaches the point \( r, \theta \). By definition, we have of course:

\[
\frac{dr}{dh_1} = \frac{\rho(h_1)}{\rho(h(r, \theta))}, \tag{8}
\]
Figure 1: Average penetration depth $\bar{r}_1$ as a function of the incident zenith angle $\theta$ for varying cross sections of the primary.
so that if we define an average equivalent vertical height $\bar{h}_{eq}$ as:

$$\bar{h}_{eq} = \int_0^\infty dr' h_1 (r', \theta) F(r', \theta) / \int_0^\infty dr' F(r', \theta),$$

we have easily:

$$\bar{h}_{eq} = \int_{r'=0}^\infty dh'_{eq} h'_1 F(h'_{eq}, 0) / \int_{r'=0}^\infty dh' F(h', 0).$$

Compare this with:

$$\bar{h} = \int_{h'=0}^\infty dh' h' F(h', 0) / \int_{h'=0}^\infty dh' F(h', 0),$$

namely the average penetration depth of air showers coming down vertically. One sees that the two quantities differ only by the lower limits of the integrals, i.e. $h' = 0$ for the latter but $h'$ at $r' = 0$ for the former. However, given that the weight function $F(h, 0)$ is already very small by the time it reaches ground level, one can to a good approximation neglect this difference in the lower limits and put:

$$\bar{h}_{eq}(\theta) = \bar{h}.$$ 

In other words, the average equivalent vertical height for any incident angle is to a good approximation the same as the average height of air showers coming down vertically and independent of the incident angle. Thus, instead of evaluating the average penetration depth for each value of $\theta$, we can evaluate the equivalent vertical height $h_1$ averaged over all events of whatever incident angle $\theta$, and this will have the same near discontinuity at the GZK cut-off energy as for the average height of showers coming down vertically. As far as statistics is concerned, therefore, the present amount of data could already be enough for uncovering the phenomenon if post-GZK primaries are indeed particles other than the proton with a different cross section.

Of course, the GZK cut-off not being abrupt, and particle cross sections themselves being energy dependent, albeit only slowly, the expected near discontinuity in $\bar{h}_{eq}$ may possibly be masked and not be readily observable. To test this, we have calculated $\bar{h}_{eq}$ using the above formalism but under the following more realistic assumptions: (i) that the total cosmic ray spectrum, say $N$, is given by the fit of Bird et al.:

$$dJ/dE \sim (E/E_a)^{-\gamma_1} + (E/E_a)^{-\gamma_2},$$

where $E_a$ is the atmospheric cut-off.
with the recent best fit parameters \[18\]:

\[\gamma_1 = 3.16, \quad \gamma_2 = 2.78, \quad E_a = 10^{19.01} \text{ eV},\] (14)

(ii) that the proton spectrum \(N_p\) is cut-off by the GZK effect according to the calculation reported in \[18\], (iii) that the difference \(N_X = N - N_p\) is made up by a particle \(X\) having a cross section \(\sigma\) with air nuclei different from that of the proton, and (iv) that the cross sections \(\sigma_p\) and \(\sigma_X\) both rise slowly with energy as say \(\sim s^{0.08}\) as suggested by the fit of \[22\]. Then if \(\bar{h}_p\) is the average height of proton showers, and \(\bar{h}_X\) that of \(X\) showers, the average height \(\bar{h}\) of all showers observed would be

\[\bar{h} = \frac{\bar{h}_p N_p + \bar{h}_X N_X}{N} .\] (15)

The result is shown in Figure 2. One sees that in spite of some smoothing out, the near discontinuity remains markedly noticeable.

Since the test involves taking averages of penetration depths, it cannot of course distinguish primaries of air showers on an event by event basis. However, if experiments can locate the primary vertex of an air shower with some accuracy, the test seems sufficient to provide the answer to the question whether the primary for post-GZK air showers is or is not the proton. The crucial question then is whether an experiment can be devised to locate the primary vertex of an air shower with the required accuracy. This is an experimental question that we as theoreticians cannot presume to answer. Naively, however, it seems to us that among current designs it is the Fly’s Eye experiment \[17\], or its derivatives such as HiRes \[19\] and AUGER \[20\], capable of mapping the development profile of an air shower which will have the best chance. Although a shower will not presumably produce an observable light signal until some time after the first interaction, nevertheless, by studying the development profile of the shower in its initial stages with a simulation program which lays particular emphasis on reproducing these aspects, one should be able, we think, to locate the primary vertex with some confidence, hopefully to the accuracy of about a kilometer for our purpose.

Indeed, if our aim is not as yet to measure the actual cross section of the post-GZK primary, but only to ascertain whether it is or is not a proton, then what is really essential is not the actual location of the primary vertex but only whether there is or is not a near discontinuity in the energy dependence of \(\bar{h}_1\). In that case, any measurable property of air showers which depends sensitively on the height \(h_1\) of first interactions could in principle be
Figure 2: Average equivalent vertical height of air showers as a function of the primary energy across the GZK cut-off assuming post-GZK primaries of varying cross sections.
used instead of $h_1$ for the analysis, since it should also show a near discontinuity around the GZK cut-off so long as its functional dependence of $h_1$ is smooth. Possible examples are the equivalent vertical height at which light is first detected from the shower in a Fly’s Eye type detector [17], or else the height of showers as estimated from extrapolating muon tracks backwards in arrangements such as GRAND [21]. Whether such alternatives are at all feasible can be decided only by simulations of shower development folding in the experimental details, on which question we are incompetent to judge at this stage.

If the result of an analysis with $\bar{h}_1$ or any of its alternatives show a clear change in value at around the GZK threshold, then it can be taken as indication that post-GZK air showers are generated by some particle other than the proton. If the measurement is accurate enough, particularly in the case of $\bar{h}_1$, it would be possible even to estimate the value of the cross section of this new primary with air nuclei and use it as one ingredient for identifying the particle. On the other hand, if $\bar{h}_1$ remains perfectly smooth across the GZK threshold, showing no tendency at all for any sudden change, it can mean either it is still the proton which is responsible for post-GZK air showers or that these showers are generated by some particle with cross sections very similar to the proton, which is possible although it would be somewhat of a coincidence. In the latter case, therefore, one would be inclined to look for near galactic sources capable of producing protons of these ultra-high energies.

Suppose however that the result of the test is positive so that a new primary is indicated. The natural inference then would be that these particles come from distant sources for otherwise, if there are nearby sources capable of producing these new primaries with such high energy, there is no reason they cannot produce as well protons of such energies which will then give many more post-GZK proton showers in contradiction to the starting supposition. That being the case, the new primary must have presumably zero electric charge or otherwise it would have interacted with the 2.7 K microwave background and be degraded in energy. Furthermore, it was pointed out in [3] that out of the 60 or so post-GZK events with energy greater than $4 \times 10^{19}$eV detected by AGASA [1], there are 4 doublets and even 1 triplet of directional coincidences, with the members of each multiplet differing in incident direction by less than 2.5 degrees. The probability of these coincidences happening by chance was estimated to be less than 0.3 percent, which suggests that members of the same multiplet originate from the same source. If this effect is genuine, then it again favours zero charge for the new
primaries, for otherwise the members of a multiplet having different energies would have been deflected differently by the intergalactic magnetic fields and arrive on earth in quite different directions.

One is thus reduced to seeking a stable neutral particle which can survive a long journey through the microwave background but has yet a large enough cross section with air nuclei as to be capable of producing a shower in the earth’s atmosphere. As far as our present knowledge goes, of course, there is no such particle, which is the original source of the mystery. Faced with this dilemma, one can consider two possibilities: either that the post-GZK primary is an already known particle having acquired some new interaction at these ultra-high energies, or that it is an altogether new particle which has never been experimentally identified before. (Of course, it can also be that the post-GZK primary is both a new particle and one which has an unusual interaction only at ultra-high energies, but this possibility we shall tentatively discard as being uneconomical.) For the first alternative, there is only one candidate, namely the neutrino, which is neutral, stable, and has no difficulty traversing the microwave background over long distances with its energy intact. For the other alternative, the field is of course wide open.

The relative likelihood of these two alternatives can be contrasted if one accepts the directionally coincident multiplets of AGASA \cite{1} cited in the preceding paragraph as genuine and as meaning that each multiplet originate from the same source. Presumably, a source capable of generating particles of such energies as \(10^{20}\) eV should also generate many more particles of lower energies, unless the ultra-high energy particles are produced at source by a mechanisms which operate only at these energies. Hence, if the post-GZK primary is a new particle, with by assumption no unusual interaction operative only at ultra-high energy, then coming from the directions defined by the multiplets of \cite{1}, one expects many more showers at lower (pre-GZK) energies. Whereas, if the post-GZK primary is a particle (old or new) which acquires its strong interactions with nuclear matter only at ultra-high energies of order \(10^{20}\)eV, then no enhanced collimation of pre-GZK showers in the directions of the AGASA coincident multiplets need be expected, since in the first place, these primaries of lower energies would not be copiously produced by the source, and even if they were, they would not, on arrival one earth, be strongly interacting enough with air nuclei to produce air showers.

\footnote[2]{Note that a \(10^{20}\) eV neutrino colliding with a photon in the microwave background has a cm energy of only a few hundred MeV, far below the cm energy of a few hundred TeV for its collision with a nucleon in an air nucleus at which the new strong interaction is supposed to operate.}

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So far, to our knowledge, no unusual collimation of pre-GZK energy showers has been reported by experiment along the directions of the coincident multiplets observed by AGASA. We suggest that a search for the collimation effect be made. If the AGASA coincident multiplets are real, then the effect could be decisive between the two alternatives considered; collimation favours a new particle as post-GZK primary, while no collimation favours the neutrino alternative.

To proceed further, we think we shall have to rely more on particle physics than air shower physics in attempting to identify the post-GZK primary. The reason is that, once a shower is produced, its later development will depend only subtly on the primary interaction, and such subtleties are probably beyond the predictive power of present theories either of new particles or of new interactions. Each theory, however, which claims to offer an explanation for post-GZK air showers should in principle be able to make concrete predictions in particle physics tied to the post-GZK phenomenon, and these predictions can be subjected to tests by experiment. As example, rather than explore the wide open field of new particles as the post-GZK primary, we shall concentrate now on the neutrino alternative.

For the neutrino to act as post-GZK primary, it has to acquire at ultra-high energy a strong interaction. The simplest scenario in which this can happen is when neutrinos interact via the exchange of some heavy particle \([9, 10, 11]\). Then at energies much below the mass of the exchanged particle, the effect of its exchange will be suppressed, just as "weak" interaction used to be considered weak at energies much below the \(W\) mass. However, when energies becomes comparable to the mass of the exchanged particle, this suppression will no longer operate and the interaction strength will then be characterized just by the coupling constant, which can in principle be strong. Such a scenario arises naturally in schemes where generation is supposed to originate from a broken "horizontal" gauge symmetry, since any particle carrying the generation index, including in particular the neutrino, will then interact via the exchange of the gauge bosons associated with the horizontal symmetry. These bosons must have large masses or otherwise they will give flavour-changing neutral current (FCNC) effects violating existing experimental bounds. On the other hand, they cannot be too heavy if their exchange is to be responsible for the interaction giving rise post-GZK showers. Indeed, a rough upper bound on the mass of these bosons would be given by the cm energy of a \(10^{20}\) eV primary impinging on a stationary air nucleus or a nucleon within it, which is of order 500 TeV. Now an upper bound on the gauge boson mass corresponds in the present scenario to lower
bounds on FCNC effects such as rare decays (e.g. \( K_L \rightarrow e^\pm \mu^\mp \)) or \( \mu - e \) conversions (e.g. \( \mu^- Ti \rightarrow e^- Ti \)) measured at low energy, on which effects there are already very stringent empirical limits, which has thus to be satisfied for consistency. For the particular scheme that we ourselves suggested \([9, 10, 11]\), the predictions on FCNC effects along these lines are detailed and explicit, and they have been tested and found to survive all existing experimental bounds in all the cases studied \([15, 24, 25]\). One concludes then that the scheme remains for the moment a viable explanation for post-GZK air showers. But the predictions are in some cases rather close to the existing empirical limits so that experiment in the near future should reveal whether the scheme’s present viability will be maintained.

Demands could be made on other schemes for similar concrete and testable predictions in particle physics, which are tied to their proposed explanation of post-GZK air showers. The quality of these predictions and their ability to survive experimental tests could then be used as criterion to judge the relative merit and credibility of the schemes, whether with new particles or with new interactions for neutrinos.

For the latter category assuming new interactions for neutrinos, there is still one more important theoretical criterion that any scheme will have to satisfy. The exchange of heavy gauge bosons is not by any means the only scenario that one can imagine for giving a new strong interaction to neutrinos at ultra-high energy. For instance, \([23]\) assumes that space-time has hidden dimensions which give rise to heavy spin 2 bosons coupling to neutrino giving them thus strong interactions for neutrinos at ultra-high energy. However, as emphasized in \([10]\), for the neutrino to have a hadron-sized cross section with air nuclei so as to produce air showers a strong interaction by itself is not enough. It has to interact not just strongly but also coherently with the nucleus (or at least with the nucleons inside it). Interactions due to heavy particle exchange are short-ranged, and if the neutrino interact strongly but only incoherently at short range with the partons inside the nucleon, the nucleon will appear to the neutrino just as a collection of black dots representing the partons, each dot with a size typified by the interaction range, which will be far from enough to give the interaction a hadron-sized cross section. Thus, one further necessary criterion for judging the merit of proposed schemes with neutrinos as the primary of post-GZK air showers is whether they can explain a hadron-sized cross section for neutrinos. The particular scheme we suggested \([10, 11]\) based on what we call the Dualized Standard Model (DSM) \([26]\) contains just such a mechanism, albeit poorly understood as yet, for obtaining for neutrinos a hadron-sized cross section sufficient for
producing air showers.

Much need yet be done both experimentally and theoretically before one can expect to unravel the mystery of post-GZK air showers, but it appears from the above discussion that, with enough patience, it may not be such an impossible task.

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