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Ultra high energy cosmic rays above 10^{11} GeV: Hints to new physics beyond Standard Model

PIJUSHPANI BHATTACHARJEE
Indian Institute of Astrophysics, Koramangala, Bangalore 560 034, India

Abstract. The observed cosmic ray events above 10^{11} GeV are difficult to explain within the context of known physics of propagation of known particles in the Universe and within the standard acceleration mechanisms that are likely to operate in powerful astrophysical objects. Several ideas of possible new physics beyond the Standard Model have been suggested in order to explain these events. The major suggestions are summarized here.

Keywords. Ultra high energy cosmic rays; physics beyond standard model.

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1. Introduction

The origin of the observed cosmic ray (CR) events above $10^{20}\,\mathrm{eV}$ — the so-called extremely high energy (EHE) CR — remains a mystery. Altogether, there are now more than 20 recorded EHECR events above $10^{20}\,\mathrm{eV}$, the highest energy event detected so far being at energy $\sim 3\times 10^{20}\,\mathrm{eV}$. The existence of the EHECR events at the detected flux level is difficult to explain. For a recent review of the relevant issues and the current status of the subject, see, e.g., [1] which also contains an extensive list of references to original literature and to earlier reviews; another recent review is [2]. For reviews of the observational aspects, see, e.g. ref. [3].

The energies and nature of the primary EHECR particles are inferred from the properties of the 'extensive air showers' (EAS) they initiate as they enter and pass through the Earth's atmosphere. Because of the relatively small number of EHECR events detected so far, the nature of the primary EHECR particles is not known with certainty. The current data are consistent with EHECR primaries being mainly protons, although photon primaries cannot be ruled out at this time. The flux of EHECR at $\sim 10^{20}\,\mathrm{eV}$ is $\lesssim 1\,\mathrm{particle/km^2/century}$ which exemplifies the difficulty in detecting these events and necessitates construction of detectors with large area coverage such as the Auger [4], HiRes [5], telescope array [6], and the proposed OWL [7] detectors. The present data, while not sufficient to measure the spectrum of the EHECR accurately, already give indications of a spectrum above $10^{20}\,\mathrm{eV}$ that is significantly harder than the one below it, probably signifying a new component of the spectrum above $10^{20}\,\mathrm{eV}$ different in origin than the one below it.

The basic problems encountered in explaining the origin of EHECR are the following:

First, it is extremely difficult [8] to accelerate particles to energies above 10^{20} eV even in the most powerful known astrophysical objects by means of the standard acceleration mechanisms.

Second, nucleons of energy above $\sim 6 \times 10^{19}$ eV from sources at distances $\gtrsim 60$ Mpc would lose energy drastically (by roughly one-fifth of its energy in each interaction) due to Greisen–Zatsepin–Kuzmin (GZK) effect [9], i.e., photo-pion production off the cosmic microwave background (CMB) photons, the mean free path for the process at energies above 10^{20} eV being roughly energy independent and ~ 6 Mpc. Similarly, heavier nuclei would be photo-dissociated in the CMB and infrared (IR) background within similar distances, while photons would be absorbed due to e^+e^- pair production off the radio background photons within distances of few tens of Mpc. Thus, the sources of the EHECR particles, if they are 'standard' particles such as nucleons, nuclei and/or photons, must be within ~ 60 Mpc from earth. At the same time, since at EHECR energies, the trajectories of protons or nuclei are not deflected significantly by the intergalactic and galactic magnetic fields, the arrival directions of the events should point back to their sources in the sky. However, no suitable powerful astrophysical objects capable of accelerating particles to energies above 10^{20} eV are found within ~ 100 Mpc along the known arrival directions of the events. Indeed, the distribution of the EHECR events is consistent with isotropy in contrast to the highly inhomogeneous and anisotropic distribution of luminous matter within 100 Mpc.

Third, our galaxy is too small in size to contain and accelerate particles to EHECR energies by means of any gradual acceleration mechanism. Moreover, no anisotropy associated with the galactic disk, as would be expected if the EHECR particles were accelerated in galactic sources, is seen. Thus, within the standard acceleration scenario, the sources of the EHECR particles are widely believed to be extragalactic. On the other hand, the GZK effect implies that the CR spectrum above $\sim 6 \times 10^{19}$ eV should have a 'GZK cutoff' somewhere in the energy region of $\sim 10^{20}$ eV if the EHECR particles are nucleons, nuclei or photons (or electrons/positrons) and if the extragalactic sources of these particles are uniformly distributed in the Universe. Thus, the apparent absence of the GZK cutoff, as indicated by the significant number of detected events above 10^{20} eV, is indeed a puzzle.

Several suggestions have been made with the aim of 'solving' the above problems. Most of these proposals involve some kind of new physics beyond the Standard Model (SM) in one form or another. These suggestions generally fall into two broad classes. In one class are proposals which attempt to *evade* the GZK distance limit by postulating new physics. Among these are suggestions involving small violation of Lorentz invariance, supersymmetry, a small neutrino mass, new interactions of neutrinos with matter, and so on (see below). The other class of proposals addresses the problem of energetics itself by doing away with the question of acceleration of particles: the EHECR particles are hypothesized to arise simply from decay of some supermassive particles (of mass $> 10^{21}$ eV) originating from fundamental processes in the early Universe. This class of proposals generally goes by the name of 'top-down' scenario as opposed to the 'bottom-up' scenario in which particles are accelerated from lower energies to the requisite EHECR energies. In some models of the top-down scenario, the relevant massive particles may be decaying at large cosmological distances beyond the GZK limit in which case some GZK limit evading mechanism may also have to be invoked.

2. Ways to avoid the GZK distance limit

2.1 *Violation of Lorentz invariance*

It has been pointed out by a number of authors [10,11] that the GZK effect may be eliminated altogether by allowing violation of Lorentz invariance (VLI) by a tiny amount that is consistent with all current experiments. There are several (often inequivalent) ways of formulating and parametrizing the VLI. In essentially all of these formulations, there is a universal 'preferred frame', usually identified with the frame in which the CMB is isotropic. In this frame, one can write down a translationally and rotationally invariant, but manifestly Lorentz non-invariant, 'Standard Model' Lagrangian, and study the consequences. Without going into details, I mention here, for illustrative purpose, only one particular parametrization of VLI (following [11]) that directly leads to avoidance of the GZK effect for EHECR nucleons. In this particular parametrization, the maximum attainable speed is different for different particles, with the energy-momentum relation for the particle a of rest mass m_a being $E_a^2 = m_a^2 c_a^4 + \vec{p}_a^2 c_a^2$, where c_a is the limiting speed for the particle a. Now, the dominant contribution to the GZK effect results from the photoproduction of the first pion-nucleon resonance $\Delta(1232)$ in the interaction of nucleons with the CMB photons: $p + \gamma_{\rm CMB} \rightarrow \Delta(1232) \rightarrow N + \pi$. For this reaction to proceed, one must have [11], in presence of VLI,

$$2\epsilon + m_p^2/2E \geq (c_\Delta - c_p)E + m_\Delta^2/2E\,,$$

where E and ϵ are the energies of the proton and a CMB photon, respectively. Thus, for $(c_\Delta - c_p) > 2\epsilon^2/(m_\Delta^2 - m_p^2) \simeq 1.7 \times 10^{-25}(\epsilon/2.4 \times 10^{-4}\,{\rm eV})^2$, the above reaction cannot take place, and hence there is no GZK effect. There are several other fascinating effects of allowing a small VLI, some of which are relevant for the question of origin and propagation of EHECR, and the resulting constraints on VLI parameters from cosmic ray observations are often more stringent than the corresponding laboratory limits; for more details, see [11].

2.2 *Supersymmetric particles as EHECR primaries*

Certain supersymmetric particles have been suggested as possible candidates for the EHECR primaries [12]. The particular scenario of ref. [12] involves a light and stable (or at least quasi-stable, with lifetime long compared to the strong interaction time scale) gluino with a mass between 0.1 and 1 GeV [13]. The suggested primary EHECR candidate is the lightest gluino-containing baryonic bound state, $uds\tilde{g}$, denoted S^0, which could be long-lived or stable. The kinematical threshold for $S^0 + \gamma_{\rm CMB} \rightarrow S^0 + \pi$ 'GZK' interaction would be higher than that for nucleons by a factor $\sim\; m_{S^0}/m_N$, where m_{S^0} and m_N are the masses of S^0 and the nucleon, respectively. Furthermore, the cross section for $\gamma_{\rm CMB} - S^0$ interaction would peak at an energy higher by a factor $(m_{S^0}/m_N)(m_* - m_{S^0})/(m_\Delta - m_N)$ where m_* is the mass of the lowest lying resonance of the S^0. It is expected that $(m_* - m_{S^0})/(m_\Delta - m_N) \gtrsim 2$. As a result of this and a somewhat smaller interaction cross section of S^0 with photons, the effective GZK threshold is higher by factors of a few, and sources of events above $10^{19.5}$ eV could be 15–30 times further away, than for the case of nucleons. The existence of the EHECR events was, therefore, proposed as a signal of SUSY [12]. Indeed, Farrar and Biermann [14] reported a possible correlation between the arrival direction of the five highest energy CR events and compact radio quasars at redshifts between 0.3 and 2.2, as might be expected if these quasars were sources of massive neutral particles. However, with the present data the interpretation of such evidence for a correlation remains somewhat subjective at the present time [15].

There are arguments against a light quasi-stable gluino [16], mainly based on constraints on the abundance of anomalous heavy isotopes of hydrogen and oxygen which could be formed as bound states of these nuclei and the gluino. However, the case of a light quasi-stable gluino does not seem to be settled yet. For a summary of accelerator constraints on scenarios with light gluinos, see ref. [17].

A specific difficulty of this scenario is the fact that, of course, the neutral S^0 cannot be accelerated, but rather has to be produced as a secondary of an accelerated proton interacting with the ambient matter. As a consequence, protons must be accelerated to at least 10^{21} eV at the source in order for the secondary S^0 particles to explain the EHECR events. Furthermore, secondary production would also include neutrinos and especially γ-rays, leading to γ-ray fluxes from powerful discrete acceleration sources that may be detectable by some of the proposed and up-coming γ-ray detectors. Such observations would, in turn, imply constraints on the required branching ratio of proton interactions into the S^0 which, very roughly, should be larger than ~ 0.01.

A further constraint on new, massive strongly interacting particles in general comes from the character of the air showers created by them. The observed EHECR air showers are consistent with nucleon primaries and limits the possible primary rest mass to less than $\simeq 50$ GeV [18]. With the statistics expected from upcoming experiments such as the Pierre Auger Project, this upper limit is likely to be lowered down to $\simeq 10$ GeV.

2.3 *Massive neutrino and 'Z-burst'*

If the neutrino has a small mass $m_\nu \sim 1\,\mathrm{eV}$, and if there are sources capable of producing neutrinos of sufficiently high energy ($\gtrsim 10^{22}\,\mathrm{eV}$), then interaction of those neutrinos with the cosmic thermal relic background neutrinos (ν_b) can excite the Z boson resonance, $\nu + \bar{\nu}_b \to Z$, at the EHE neutrino energy $E_{\nu,\mathrm{res}} = (M_Z^2/2m_\nu) \simeq 4 \times 10^{21}(\,\mathrm{eV}/m_\nu)\,\mathrm{eV}$. The decay of the Z into $q\bar{q}$ and the subsequent hadronization of the quarks would produce mainly pions and a small number of nucleons, with the pions further decaying into photons and neutrinos. It has been suggested [19] that the resulting EHE nucleons and photons from the decay of the Z bosons produced *within the GZK distance limit of* $\sim 60\,\mathrm{Mpc}$ *from Earth* could be candidates for the observed EHECR events. In this 'Z-burst' scenario, since the final decay products of the Z are dominated by photons and neutrinos, the EHECR events are predicted to be mainly photons (like in the top–down scenario in general; see below) rather than nucleons.

Note that for massless neutrinos, the required EHE neutrino energy would be much higher: $E_{\nu,\mathrm{res}}(m_\nu = 0) \simeq 8 \times 10^{15}(4.8 \times 10^{-4}\,\mathrm{eV}/\epsilon_{\nu,b})\,\mathrm{GeV}$, where $\epsilon_{\nu,b} \simeq 3T_\nu$ is the typical energy of the relic neutrino, $T_\nu \simeq 1.9$ K $\approx 1.6 \times 10^{-4}\,\mathrm{eV}$ being the effective temperature of the relic neutrino background.

Detailed numerical calculations have shown [20] that, in the Z-burst scenario, the most significant contribution to the EHECR could come from the Z bosons produced off the massive neutrinos clustered in the local supercluster. There are, however, constraints on the scenario from the associated γ-ray production and the flux of diffuse γ-rays measured by EGRET. More details on these and other constraints on the Z-burst scenario can be found in refs [20–22]. It has also been pointed out [23] that a degenerate relic neutrino background with a finite neutrino chemical potential (implying an asymmetry between ν and $\bar{\nu}$), produced, for example, through neutrino oscillation in the early Universe, would increase the neutrino annihilation and thus Z boson production probability.

If the EHECR events are indeed due to this Z-burst mechanism, then it offers the exciting possibility of 'detecting' the thermal relic (massive) neutrino background by looking for certain characteristic signatures in the EHECR spectrum, especially in the EHE neutrino spectrum, if the latter is measured by future experiments. It is to be noted, however, that for $m_\nu \simeq 0.07$ eV, the value suggested by the super-Kamiokande experiment [24], sources are required to produce neutrinos at least up to $10^{22}\,\mathrm{eV}$ for the Z-burst mechanism to work. Such high energies are rather difficult to obtain within conventional bottom–up models but are easily obtained in top–down models (see below). For more details see [1].

2.4 *New neutrino interactions*

The only particle in the SM that can propagate unattenuated with energies above $10^{20}\,\mathrm{eV}$ from sources at distances $\gg 100\,\mathrm{Mpc}$ is neutrino; however, in the SM, the probability of neutrinos initiating the observed EHECR air-shower events is at least a factor of $\sim 10^{-6}$ smaller than the corresponding probability in the case of nucleons, nuclei or photons. To overcome this problem, it has been suggested that the neutrino–nucleon interaction cross section could be enhanced significantly at centre-of-mass (CM) energies higher than the electroweak scale or above about a PeV in the nucleon rest frame by new physics beyond SM. The enhanced νN cross section, if it reaches $\sim$100–200 mb, could then allow neutrinos themselves to directly initiate the air showers responsible for the EHECR events. Most of these suggestions violate the unitarity of cross section [25]. However, two major unitarity-respecting possibilities have been suggested.

In one of these schemes, there is a broken local SU(3) 'generation symmetry' dual to the SU(3) colour symmetry. In this scheme, neutrinos can have effectively strong interaction with quarks and, in addition, neutrinos can interact coherently with all partons in the nucleon, resulting in an effective cross section comparable to the geometrical nucleon cross section [26]. However, the massive neutral gauge bosons of the broken generation symmetry would also mediate flavor changing neutral current (FCNC) processes, and experimental bounds on these processes indicate that the scale of any such new interaction must be above $\sim 100\,\mathrm{TeV}$.

The second possibility is that there may be a large increase in the number of degrees of freedom above the electroweak scale (see e.g. [27]). A specific implementation of this idea is realized in theories with n additional 'large' compact dimensions and a quantum gravity scale $M_{4+n} \sim \mathrm{TeV}$, a possibility that has recently received much attention in the literature [28], especially within the context of string theories. In these theories, the SM particles are confined to the usual $3+1$ dimensional space and only gravity propagates in the higher dimensional space. The typical size of the compact extra dimensions (assuming same for all the extra dimensions) R_n is related to the fundamental scale M_{4+n} through the relation $R_n \simeq M_{4+n}^{-1}(M_{\rm Pl}/M_{4+n})^{2/n}$, where $M_{\rm Pl} = 1.2 \times 10^{19}\,{\rm GeV}$ is the usual Planck energy. For $M_{4+n} \sim$ TeV, the $n = 1$ case is obviously ruled out, but higher n's are not. From a 4-dimensional point of view, the $4 + n$-dimensional graviton appears as an infinite tower of Kaluza–Klein (KK) excitations. The exchange of these KK modes, whose large number compensates for the weakness of the gravitational coupling, gives extra contribution to any 2-particle cross section that increases rapidly with energy. It has been suggested [27,29,30] that the resulting enhanced νN interaction cross section may make neutrinos responsible for the observed EHECR events. Constraints on this scenario from the existing data and projected data from future experiments are discussed in [31].

More recent detailed calculations [32] of the contribution of the KK modes to the enhanced νN cross section, however, show that the resulting cross section and the average energy transfer in each νN interaction are still too small to explain the observed vertical EHECR showers, although the new interaction could give rise to deeply penetrating showers or horizontal air showers which are so far unobserved but may be observed in future detectors such as the Auger.

There are also independent astrophysical constraints on M_{4+n} resulting from limiting the emission of KK gravitons into the extra dimensions. The strongest constraints in this regard come from nucleon–nucleon bremsstrahlung in type II supernovae [33], which give $M_6 \gtrsim 50\,{\rm TeV}$, $M_7 \gtrsim 4\,{\rm TeV}$, and $M_8 \gtrsim 1\,{\rm TeV}$, for $n = 2, 3, 4$, respectively. Thus, it is hoped, the up-coming large area EHECR detectors together with various astrophysical and cosmological constraints will be able to provide stringent constraints on these theories with large extra dimensions.

3. Ways to avoid the energy problem: The top–down scenario

As discussed lucidly by Hillas [8], there are hardly any astrophysical sources capable of accelerating particles to energies beyond $10^{20}\,{\rm eV}$. An alternative possibility is that the enormous energies of the EHECR particles are not due to any acceleration process; instead, they could arise simply from decay of very massive particles of mass $> 10^{20}\,{\rm eV}$. Two possible realizations of this top–down scenario have been suggested, both of which require physics beyond SM. Below we discuss them briefly; for detailed review and references to original literature, see ref. [1].

3.1 *EHECR from decays of metastable superheavy relic particles*

It has been suggested [34,35] that EHECR may be produced from the decay of some metastable superheavy relic particles (MSRPs) of mass $m_X \gtrsim 10^{12}\,{\rm GeV}$ and lifetime larger than or comparable to the age of the Universe. The long but finite lifetime of MSRPs could be due to slow decay of the MSRPs through non-perturbative instanton effects or through quantum gravity effects, for example. The MSRP 'X' particles would typically decay into quarks and leptons. The hadronization of the quarks produces a photon- and neutrino-dominated spectrum of particles with energy up to m_X. The EHECR are hypothesized to be mainly the photons from these MSRP decays.

There are no MSRP candidates within the SM. Possible candidates for MSRPs and their possible decay mechanisms giving them long lifetime have been discussed in the context of specific particle physics models beyond SM, in particular, superstring theory models, by a number of authors (see [1] for references). Several non-thermal mechanisms of production of MSRPs in the post-inflationary epoch in the early Universe have also been studied; see, e.g. ref. [36] for a review of these mechanisms. Under certain circumstances MSRPs can exist in the Universe with sufficient abundance so as to act as non-thermal superheavy dark matter.

Obviously, the flux of EHECR produced by this mechanism depends on the abundance as well as the lifetime of the MSRPs, neither of which is known with much confidence. An interesting aspect of this scenario is that, like the cold dark matter (CDM) particles, the MSRPs would gravitationally cluster, in particular, on the scale of the galactic halo (GH). The flux of EHECR photons and nucleons will, therefore, be dominated by the contribution of MSRP decay within the GH, which would naturally explain the *absence* of the GZK cutoff, since the size of the GH is much less than the GZK distance limit. Because of the general isotropic distribution of the MSRPs within the GH, the scenario also naturally explains the observed isotropy of the EHECR. There will, however, be a small anisotropy associated with the off-center location of the solar system in the GH, which will hopefully be detectable by the up-coming detector such as the Auger, providing an important test of the scenario.

Another important aspect of the top–down scenario in general, including the MSRP decay model as well as the topological defect model discussed in the next section, is that the spectrum of the EHECR particles is mainly determined by the spectrum of the hadronization products of the quarks from the decay of the massive X particles, which in turn is determined by QCD. The hadronization spectra of various particles turn out to be significantly harder than the generic particle spectra predicted in the bottom–up (shock acceleration) scenario. Thus, should the top–down scenario of EHECR origin be confirmed by future experiments, the measured spectra of the EHECR particles in those experiments would be a probe of QCD at energies well beyond those currently accessible in particle colliders.

3.2 *EHECR from collapse or annihilation of cosmic topological defects*

Cosmic topological defects (TDs) such as magnetic monopoles, cosmic strings, domain walls, and textures are predicted to form during symmetry breaking phase transitions in the early Universe (see [37] for a review). It has been suggested (see ref. [1] for references) that collapse or annihilation of some of these TDs in the present-day universe would produce superheavy 'X' particles (superheavy gauge bosons, Higgs bosons, fermions, etc., of the underlying spontaneously broken gauge theory) of mass m_X which can be as high as a typical grand unified theory (GUT) mass scale of $\sim 10^{16}\,\mathrm{GeV}$. The decay of these X particles to quarks and leptons and subsequent hadronization of the quarks could then be a source of EHECR particles extending in energy up to m_X.

Processes involving specific TDs, such as collapsing cosmic string loops, monopole–antimonopole annihilation, collapsing necklaces (closed loops of cosmic strings with monopole 'beads' on them), current-saturated superconducting cosmic string loops, vorton decay, and so on, have been studied in the literature. Again, a photon and neutrino dominated EHECR spectrum, determined mainly by QCD, is predicted, although the absolute flux is much more difficult to predict. Unlike the MSRP decay case, however, the TD scenario is significantly constrained by the measured flux of the diffuse γ-ray background in the several MeV to several GeV region, in addition to being constrained by the observed EHECR flux. This is because, in most TD models, the X particle production from TDs and their decay occur not only in the present epoch at small cosmological distances, but also at earlier epochs (or equivalently at large cosmological distances). While those X particles produced and decaying at small redshifts ($z \ll 1$) give rise to the observed EHECR, the (mainly electromagnetic) energy injected at ultra high energies at larger redshifts cascades down to lower energies (in the MeV–GeV region) in the present epoch due to the development of electromagnetic cascade on the background radiation fields.

In some TD models — as in the case of monopole–antimonopole annihilation through formation and subsequent collapse of metastable monopole–antimonopole bound states called monopolonia, or in the case of collapsing necklaces — the relevant TDs would be clustered in the GH, giving rise to predicted EHECR spectra having properties similar to those in the MSRP decay model discussed above.

Perhaps, the most important aspect of the top–down models in general is the predicted dominant EHE neutrino flux whose possible detection in the up-coming experiments would provide a clear signature of the top–down scenario. For more details on the top–down models, see ref. [1].

4. Conclusions

The solution of the EHECR enigma seems to require some kind of new physics beyond SM, either to solve the problem of energetics or to solve the problem of absence of sufficiently powerful identifiable astrophysical sources in the nearby universe. The up-coming and proposed future EHECR experiments have the potential to probe some forms of physics beyond SM suggested in this context.

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