Ultra-high energy cosmic rays and new physics

Subir Sarkar

Department of Physics, University of Oxford,
1 Keble Road, Oxford OX1 3NP, UK
E-mail: s.sarkar@physics.ox.ac.uk

Cosmic rays with energies beyond the Greisen-Zatsepin-Kuzmin ‘cutoff’ at \(\sim 4 \times 10^{10}\) GeV pose a conundrum, the solution of which requires either drastic revision of our astrophysical understanding, or new physics beyond the Standard Model. Nucleons of such energies must originate within the local supercluster in order to avoid excessive energy losses through photopion production on the cosmic microwave background. However they do not point back towards possible nearby sources, e.g. the active galaxy Cen A or M87 in the Virgo cluster, so such an astrophysical origin requires intergalactic magnetic fields to be a hundred times stronger than previously believed, in order to isotropise their arrival directions. Alternatively the primaries may be high energy neutrinos, say from distant gamma-ray bursts, which annihilate on the local relic background neutrinos to create “Z-bursts”. A related possibility is that the primary neutrinos may initiate the observed air showers directly if their interaction cross-sections are boosted to hadronic strength through non-perturbative physics such as TeV-scale quantum gravity. Or the primaries may instead be new strongly interacting neutral particles with a longer mean free path than nucleons, coming perhaps from distant BL-Lac objects or FR-II radio galaxies. Yet another possibility is that Lorentz invariance is violated at high energies thus suppressing the energy loss processes altogether. The idea that has perhaps been studied in most detail is that such cosmic rays originate from the decays of massive relic particles (“wimpzillas”) clustered as dark matter in the galactic halo. All these hypotheses will soon be critically tested by the Pierre Auger Observatory, presently under construction in Argentina, and by proposed satellite experiments such as EUSO.

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1 Introduction

In 1962, Linsley [1] detected a cosmic ray air shower at the pioneering Volcano Ranch array with an estimated energy exceeding $10^{11} \text{GeV}$. The significance of this event became clear only some years later, following the serendipitous discovery of the universal 2.7 K cosmic microwave background (CMB), when Greisen and, independently, Zatsepin and Kuzmin [2] noted that cosmic ray nucleons with energies exceeding $E_{\text{GZK}} \sim 4 \times 10^{10} \text{GeV}$ would suffer severe energy losses through scattering on the CMB photons due to excitation of the $\Delta (1232)$ resonance with a cross-section of $\sim 400 \mu\text{b}$. Consequently their typical range should decrease rapidly above this energy, leading to a ‘GZK cutoff’ in the energy spectrum if the sources are cosmologically distant. Conversely the absence of such a cutoff in the spectrum (which is approximated by a power-law $dN/dE \propto E^{-3}$ at lower energies) would imply that the sources are nearby, within the local supercluster.

Plausible astrophysical sources for such ultra-high energy cosmic rays (UHECRs) were discussed by Hillas [8] who noted that simply to contain charged particles long enough for them to be accelerated to such high energies required sufficiently large magnetic fields and/or spatial volumes such as could plausibly be achieved only in a few specific sites such as the extended lobes of giant radio galaxies or active galactic nuclei. Moreover particles of such energies should be undeflected by the weak intergalactic magnetic fields, so should point back to their sources. Thus there was the exciting prospect that further such observations would clarify the long-standing question of the origin of cosmic rays. Indeed UHECRs continued to be observed with other detectors, notably at Haverah Park [9] and Yakutsk [10]. However, perhaps because of the theoretical prejudice that the sources of UHECRs must be cosmologically distant, as well as concerns regarding uncertainties in the energy measurements, these observations appear not to have been taken seriously [11]. As late as 1993 it was stated that the GZK cutoff is indeed present in the data, confirming the expectation that the sources of UHECRs are distant FR-II radio galaxies [12].

The breakthrough came the same year with the detection of an event of energy $(3.2 \pm 0.9) \times 10^{11} \text{GeV}$ by the innovative Fly’s Eye detector in Utah, which measured the fluorescence from the excited $N_2$ molecules in the atmospheric shower and was thus able to reliably determine the energy [13]. Moreover the shower was seen to have its maximum at an atmospheric depth of $815^{+45}_{-35} \text{ g cm}^{-2}$, consistent with a proton primary, but significantly less than the expected value of $1075 \text{ g cm}^{-2}$ for a photon primary [14]. Subsequently the Akeno Giant Air Shower Array (AGASA) has detected a large number of air showers with energies exceeding $E_{\text{GZK}}$ [17].

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*Recent detailed calculations [3] indicate that the typical range of a nucleon drops below $\sim 100 \text{ Mpc}$ above $10^{11} \text{ GeV}$. For heavy nuclei the dominant energy loss process is photodissociation; above $10^{11} \text{ GeV}$ this happens through scattering on the CMB and the typical range is even smaller than for nucleons [3]. For photon primaries the dominant opacity above $E_{\text{GZK}}$ is due to pair production on the (poorly known [8]) extragalactic radio background; the mean free path is estimated to be $\sim 1 - 5 \text{ Mpc}$ at $10^{11} \text{ GeV}$ [7].

†Further observations by Fly’s Eye [3] as well as its successor HiRES [16] indicated a gradual increase in the depth of maximum with energy, suggesting a change in composition from heavy nuclei to nucleons.
In fact the possible existence of such high energy cosmic rays had already been mooted a decade earlier by particle physicists \[18\] as a likely signature of Grand Unified Theories (GUTs). In particular, Hill \[19\] had proposed that relic topological defects such as magnetic monopoles created during GUT symmetry breaking in the early universe may have formed metastable bound states which would occasionally annihilate at the present epoch, thus releasing high energy quark and gluon jets which would hadronise to release cosmic rays of energy up to the GUT scale. Subsequently the development of superstring theory had led to independently motivated suggestions for the existence of massive relic particles associated with the ‘hidden sector’ of supersymmetry breaking; the lightest such state, having only gravitational interactions, would be metastable, thus a natural candidate for the dark matter \[20\]. Indeed just before the Fly’s Eye event was announced, detailed studies had been undertaken of the observational signatures of such particles \[21\], focussing on the possibility of detecting high energy neutrinos from their slow decays \[22\]. (Moreover, the possibility that weakly interacting neutral particles such as neutrinos may acquire large interaction cross-sections through new physics had been discussed in the context of the detection of anomalous air showers from the X-ray binary Cygnus X-3 \[23\].)

In recent years several other speculative ideas have been put forward for the possible origin of post-GZK UHECRs and some of them have been studied in sufficient detail as to allow clear experimental tests. The data set has also grown allowing some possibilities to be ruled out altogether and severe constraints to be put on others. This is an opportune time to assess the situation, particularly since the giant Pierre Auger Observatory \[24\], under construction in Argentina, has recently seen “first light” and is expected to increase the world statistics of UHECRs by ten-fold within a few years.

2 Observational Status

The AGASA experiment has provided most of the data on UHECRs in recent years. In their 2000 review, Nagano and Watson \[11\] had noted that the measurements were consistent at the level of ±15% in energy (or ±45% in flux) with older data from Haverah Park, Yakutsk and Fly’s Eye. After making various necessary corrections, these authors had combined all the data to obtain the ‘standard’ differential energy spectrum:

\[
J(E) = C \left( \frac{E}{6.3 \times 10^9 \text{GeV}} \right)^{3.20\pm0.05}, \quad \text{for} \quad 4 \times 10^8 \text{GeV} < E < 6.3 \times 10^9 \text{GeV} \quad (1)
\]

\[
J(E) = C \left( \frac{E}{6.3 \times 10^9 \text{GeV}} \right)^{2.75\pm0.20}, \quad \text{for} \quad 6.3 \times 10^9 \text{GeV} < E < 4 \times 10^{10} \text{GeV},
\]

where \(C = (9.23 \pm 0.65) \times 10^{-33} \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{eV}^{-1}\). Although the spectral shape at higher energies was uncertain, there was no evidence of the GZK cutoff up to \(\sim 3 \times 10^{11} \text{GeV}\). Preliminary data in 1999 from the HiRes air fluorescence detector \[25\], the successor to Fly’s Eye, had 7 events above \(10^{11} \text{GeV}\), in conformity with this spectrum.

At the International Cosmic Ray Conference in Hamburg in August 2001, AGASA reported 17 events above \(10^{11} \text{GeV}\) with a total exposure of \(\sim 6 \times 10^{16} \text{m}^2 \text{st}\) (the data
set having been enlarged by accepting showers inclined by as much as 60° to the vertical), consistent with their earlier data [26]. On the basis of more detailed comparison with simulations, the energy estimates were raised (by 20% at 10^{11} \text{ GeV}) relative to previously quoted results. As shown in Fig. 1, the flux at \( E > E_{\text{GZK}} \) is considerably above the expectation for an uniformly distributed population of cosmologically distant sources (with a power-law injection spectrum chosen to match data at lower energies).

\[ J(E) \sim E^\alpha \text{ eV}^{-1} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \]

\[ \text{Energy [eV]} \]

Figure 1: The AGASA spectrum compared with the expectation for the GZK-processed flux from cosmologically distant sources [26].

However HIRES, with a similar exposure in the mono mode, reported only 2 events above 10^{11} \text{ GeV} [27], instead of the \( \sim 20 \) events expected on the basis of the above standard spectrum (1). In stereo mode, with about 20% of this exposure, only 1 event was seen. As seen in Fig. 2, there is a clear discrepancy with the AGASA data. The resolution of this may have to do with a possible underestimate of the efficiency of atmospheric fluorescence emission at longer wavelengths (more relevant for higher energies due to Rayleigh scattering) as suggested by a recent measurement [28]. This may have caused HiRes to underestimate the energies (and overestimate the exposure) although the magnitude of such corrections cannot yet be precisely quantified [29]. It is also the case that the beginning of the ‘ankle’ in the spectrum is a factor of \( \sim 2 \) lower in the fluorescence detector data than in the air shower detector data. The Auger Observatory [24] employs both types of detectors so should be soon able to resolve these discrepancies and establish a consistent energy scale. However it should be emphasised that although the energy spectrum (1) may require revision, the existence of UHECRs above \( E_{\text{GZK}} \) is not in doubt!
New results have also been presented by AGASA on the angular distribution of events on the sky \cite{30}. In accordance with earlier data, there is no evidence for any large-scale anisotropy for the 59 observed showers (having zenith angles < 45°) with energies above $E_{\text{GZK}}$. As seen in Fig. 3, there is no observed correlation with the galactic plane (such as is seen at lower energies around $\sim 10^9$ GeV by both Fly’s Eye and AGASA \cite{31}), or with the super-galactic plane (as had been claimed earlier, particularly in the Haverah park data \cite{32}). However a number of ‘clusters’ — defined as a grouping of 2 or more events within (approximately the experimental angular resolution of) 2.5° — are seen; the chance probability that these result from an isotropic distribution is estimated by Monte Carlo to be 0.05% for the 5 observed doublets and 1.66% for the 1 observed triplet \cite{30}. Assuming that all observed events above $4 \times 10^{10}$ GeV come from one particular class of source, the number of such sources is estimated assuming Poisson statistics to be $220^{+207}_{-100}$. It is also found that the cosmic rays contributing to the clusters have a hard energy spectrum with a differential spectral index of $-1.8$. If these are assumed to come from a separate source population then the total number of observed sources is limited to be less than 427 \cite{30}. However it has been pointed out that the data set used to make the initial claim for clustering ought not to be used in the actual analysis; moreover the directions of the most energetic events observed by previous experiments do not line up with any of the 6 ‘clusters’ \cite{29}. Thus the indication for compact sources is exciting but still needs confirmation with increased statistics, as will be provided by Auger.
Finally, with regard to the composition of UHECRs, new data has muddled the picture suggested earlier by Fly’s Eye and HiRes [15, 16] of a change from heavy nucleus (“iron”) domination at $3 \times 10^8 \text{GeV}$ to nucleon domination at $10^{10} \text{GeV}$. The muon content of the AGASA showers implies a mixed composition over $\sim 10^9 - 10^{10} \text{GeV}$ [33] and a new analysis of Haverah Park data also indicates that nucleons make up no more than 34% of the flux in the range $(0.3 - 2) \times 10^9 \text{GeV}$ [34]. As seen in Fig. 4, the conclusions are quite sensitive to the choice of the interaction model used [35] hence the matter cannot be considered to be definitively settled as yet. However it would appear that a bound of $< 50\%$ can be set on the photon component at $E > E_{\text{GZK}}$ from analysis of horizontal showers at Haverah Park, independently of the interaction model [34]. A similar limit is obtained by AGASA on the basis that photon-initiated showers tend to be muon-poor [36]. This is potentially a powerful discriminant between models of the origin of UHECRs. Unfortunately the propagation of photons at these energies is uncertain since the dominant opacity (towards $\gamma \gamma$ pair production) is determined by the low frequency radio background which is poorly measured — the last experimental attempt was in 1970 [4]. Subsequently model-dependent estimates have been made which suggest a mean free path at $10^{11} \text{GeV}$ of a few Mpc [4]. Hence even if photons are absent in the UHECRs observed at Earth this does not exclude the possibility that they were emitted by the sources, especially if the mean free path turns out to be even smaller.
Figure 4: Variation of the depth of shower maximum with energy in different experiments, compared to expectations in various hadronic interaction models [36].

3 Conventional explanations

The lack of a GZK cutoff, which requires the sources to be relatively nearby, coupled with the isotropy, which implies a cosmologically distant population, pose severe problems for any astrophysical explanation of UHECRs [37]. For example, γ-ray bursts are isotropically distributed and may well have the necessary capability to accelerate protons to such high energies [38], but being cosmologically distant they cannot provide the events observed at $E > E_{\text{GZK}}$ [39]. Other possible sources such as active galactic nuclei may even be able to account for the post-GZK events if they are concentrated locally by a factor $\gtrsim 30$ [4]; however, the local supercluster is overdense by a factor of only $\sim 2$. There are some nearby active galaxies but even if they can accelerate UHECR these would need to be deflected through large angles (and isotropised) by the intergalactic magnetic field (IGMF) [40]; this requires the field strength to be $\sim 100$ times stronger than the upper limit of a few nG inferred from observational bounds on Faraday rotation in distant radio sources [41]. It has been proposed that the radio galaxy Cen A at 3.4 Mpc is the source of UHECRs [42]; however, detailed calculations [43] show that this requires an IGMF of $\sim 1 \mu$G to isotropise their directions and even so it would be difficult to account for the direction of the highest energy Fly’s Eye event. By backtracing the 13 most energetic events in a magnetic field modelled as originating from a ‘galactic wind’, the radio galaxy M87 in the Virgo cluster has also been implicated as the source [44]. The convergence of the backtraced events turns out however to be due to the assumed magnetic field geometry and cannot therefore be considered evidence for an unique source [45].
4 Models involving new physics

Given the problems of an astrophysical origin, it is natural to speculate that UHECRs are linked to physics beyond the Standard Model. Many novel suggestions have been made in this regard [46]. I shall focus on only those which have been investigated in sufficient detail so as to provide falsifiability criteria.

4.1 Z-bursts

Since at least one species of relic neutrinos must have a mass of \( \sim 0.1 \text{ eV} \), it is an attractive possibility to suppose that these provide a target for ultra-high energy neutrinos from distant sources to annihilate on. This would create “Z-bursts” with an energy of \( \frac{m_Z^2}{2m_\nu} \sim 4 \times 10^{12} (m_\nu/1 \text{ eV})^{-1} \text{ GeV} \), i.e. in just the right energy range to be a source for UHECRs [47]. The energy spectrum of the nucleons and \( \gamma \)-rays resulting from \( Z \) decays is well measured at LEP so a detailed comparison can be made with the data [48]. In fact a good match to the energy spectrum is obtained for a relic neutrino mass of \( 0.26^{+0.2}_{-0.14} \text{ eV} \); however the required ultra-high energy flux is rather large, taking into account that such light relic neutrinos cannot have a overdensity within the GZK distance of more than a factor of \( \sim 2 \) [48]. Although there are no direct experimental limits at such energies, any reasonable extrapolation to somewhat lower energies would violate the limits obtained recently by AMANDA. Moreover it is not clear how such high energy neutrinos would be created in the hypothetical cosmic sources — usually this would require the acceleration of even higher energy nucleons! (In principle, high energy neutrinos may be produced through the decays of super-massive relic particles [49] but such decays ought to also produce UHECRs directly as we discuss below, making this mechanism of less interest.) An alternative solution is to increase the local density of relic neutrinos by postulating that they are degenerate [50]; however this is increasingly constrained by failure to observed the associated ‘late ISW effect’ in the angular power spectrum of the CMB, as discussed by Hannestad at this meeting [51].

4.2 Strongly interacting neutrinos

Neutrinos with electroweak interactions cannot initiate the observed airshowers but, as has been speculated for some time [23], they may be become strongly interacting through new interactions. This possibility has been recently revived with the realisation that the string scale may in principle be as low as the TeV scale if there are new dimensions in Nature. However as discussed by Plüümacher at this meeting, the increase in cross-section through (t-channel) exchange of Kaluza-Klein gravitons is inadequate to account for the characteristics of the observed events [52]. A string-theoretic calculation in which the string amplitude is approximated as a sum over s-channel resonances (leptoquarks) also comes to a negative conclusion [53].
4.3 New neutral primaries

The GZK cutoff would be higher if the primary particle is a new stable hadron which is heavier than a nucleon. For example it might be a bound state of a light gluino if that is the lightest supersymmetric particle [54] or perhaps a H-dibaryon [55]. The air showers that would be initiated by such a particle (“uhecron”) have been studied in detail [56] and comparison with data limits the primary mass to be $\lesssim 50 \text{ GeV}$. The experimental constraints on new stable hadrons are already quite stringent [57] and it is likely that such a particle can soon be found or excluded. The interactions needed to produce such particles in distant sources must also produce neutrinos and $\gamma$-rays and the latter should be detectable, e.g. by Čerenkov telescopes such as VERITAS, MAGIC and HESS [46].

4.4 Violation of Lorentz invariance

It has been noted that a small modification of the relation between momentum and energy in special relativity may undo the GZK cutoff [58]. In particular this may happen for a deformed dispersion relation $c^2 p^2 = E^2 (1 + E/M_P) + \ldots$, motivated by considerations of quantum gravity at the Planck scale [59]. However this needs further examination in a quantum gravitational framework before definite conclusions can be drawn since, e.g., energy might be conserved only in a statistical sense [60].

4.5 Decaying supermassive dark matter

As mentioned earlier, the possible existence of relic metastable massive particles whose decays can create high energy cosmic rays and neutrinos had been discussed [18, 20, 21, 22] before the famous Fly’s Eye event [13] which focussed attention on the enigma of UHECRs. Subsequently this idea was revived [61] and it was further pointed out that such particles, being cold dark matter, would naturally have a overdensity by a factor of $\sim 10^4$ in the halo of our Galaxy [62, 63]. Hence if their slow decays generate UHECRs, all propagation effects will be unimportant (except possibly for photons) in determining the observed spectrum and composition, and, moreover, there should be a detectable anisotropy [64] in the arrival directions, given our asymmetric position in the Galaxy. In order to account for the highest energy events with the observed rates, the particle mass should exceed $m_X \gtrsim 10^{12} \text{ GeV}$ while its lifetime is determined to be $\tau_X \sim 3 \times 10^9 \zeta_X t_0$, where $t_0 \sim 10^{10} \text{ yr}$ is the age of the universe and $\zeta_X$ is the fraction of the halo dark matter density in the form of such particles [65]. This is in accordance with the theoretical expectation for ‘cryptons’ [20]. Moreover, as discussed by Kolb at this meeting, it is plausible that such particles (“wimpzillas”) were created with a cosmologically interesting abundance through the changing gravitational field at the end of inflation [66].

The spectra of the decay products is essentially determined by the physics of QCD fragmentation [65]. Recently several groups have undertaken calculations which improve on previous efforts [19, 62, 63] in being both better connected to laboratory data (available
upto LEP energies) and incorporating the possible effects of new physics e.g. supersymmetry at higher energies [67, 68, 69, 70, 71, 72]. As discussed by Toldra [73] at this meeting, an effective approach is to evolve the fragmentation functions measured at the $Z^0$ peak (for neutrinos, inferred using HERWIG) upto the scale of the decaying particle mass by solution of the DGLAP evolution equations. Similar results are obtained in two independent calculations [68, 72] and, as seen in Fig. 5, the evolved spectrum of nucleons is in good agreement with the ‘flat’ component (1) of cosmic rays at $E > E_{GZK}$. On the negative side, the decay photons, which have a similar spectral shape are more abundant by a factor of $\sim 2$, so this model (as well as the related one involving annihilations of wimpzillas [74]) would seem to be ruled out by the Haverah Park bound [34] on the photon component of UHECRs. However, as commented earlier, it is quite possible that such high energy photons are significantly attenuated in their passage through the low frequency radio background; this would in turn generate a background of low energy $\gamma$-rays and it is necessary to check that this does not exceed observational limits (work in progress).

![Figure 5: Fit to the UHECR spectrum beyond the ‘ankle’ with a decaying dark matter particle mass of $5 \times 10^{12}$ GeV (dashed line), including the effects of supersymmetry [72].](image)

Detailed calculations have also been made of the expected anisotropy, adopting different possible models of the dark matter halo (cusped, isothermal, triaxial and tilted) [75]. We find that the amplitude of the anisotropy is controlled by the extent of the halo, while the phase is controlled by its shape. As seen in Fig. 6, the amplitude of the first harmonic is $\sim 0.5$ for a cusped halo, but falls to $\sim 0.3$ for an isothermal halo, while the maximum is in the direction of the Galactic Centre, with deviations of up to $30^\circ$ possible for triaxial and tilted haloes. Contrary to a recent claim [76] the halo of M31 is not bright enough to provide conclusive evidence for this hypothesis. However another key signature of a
dark matter origin may be some ‘clustering’ of events since the halo CDM distribution is expected to be clumpy rather than being smooth [77]. Thus this model has several interesting observational signatures and can easily be falsified, e.g. if the UHECRs turn out to be heavy nuclei [78].

Figure 6: Contour plots (Hamer-Aitoff projections) of the UHECR sky for (a) cusped, (b) isothermal, (c) triaxial and (d) tilted models of the dark matter halo of our Galaxy. The effect of the halo of M31 is visible in the upper right of each plot [75].

5 Conclusions

After a long hiatus, high energy cosmic rays have again become very interesting for particle physicists looking for evidence of physics beyond the Standard Model. The source of the highest energy particles in Nature is an equally interesting enigma for astrophysicists. As Lemaître first suggested, the origin of such particles may even be linked to the early universe, although not quite as he imagined! Presently the data are tantalising but not sufficient in either quantity or quality to distinguish definitively between proposed models. The good news that this will soon be remedied by the Auger array [24] which should be complete by 2004 and is expected to detect $\sim 2000$ events above $E_{\text{GZK}}$ within 5 years. Moreover the ambitious space-based experiment EUSO [79], scheduled for a 3-year flight on the International Space Station in 2007, will provide another substantial increase in collecting power. This is an exciting time for cosmic ray physics and we look forward to the surprises that Nature has in store for us.
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