The Future of Ultra High Energy Cosmic Rays

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Contrary to earlier expectations, several cosmic ray events with energies above $10^{20}$ eV have been reported by a number of ultra-high energy cosmic ray observatories. According to the AGASA experiment, the flux of such events is well above the predicted Greisen-Zatsepin-Kuzmin cutoff due to the pion production of extragalactic cosmic ray protons off the cosmic microwave background. In addition to the relatively high flux of events, the isotropic distribution of arrival directions and an indication of small scale clustering strongly challenge all models proposed to resolve this puzzle. We discuss how the GZK cutoff is modified by the local distribution of galaxies and how astrophysical proton sources with soft injection spectra are ruled out by AGASA data. Sources with hard injection spectrum are barely allowed by the observed spectrum. If the most recent claims by AGASA that the highest energy events are due to clustered nuclei are confirmed, the most plausible explanation are astrophysical sources with very hard spectra such as extragalactic unipolar inductors. In addition, extragalactic magnetic fields need to be well below the current nano-Gauss upper limits. Alternatively, if the primaries are not nuclei, the need for new physics explanations is paramount. We present an overview of the theoretical proposals along with their most general signatures to be tested by upcoming experiments.

1. Introduction

The future of ultra high energy cosmic ray physics looks extremely promising. The present state of observations is particularly puzzling and the necessary experiments to resolve these puzzles will be operating in the very near future. The puzzles begin with the lack of the predicted Greisen-Zatsepin-Kuzmin (GZK) cutoff. Contrary to earlier expectations, cosmic rays with energies above $10^{20}$ eV have been detected by a number of experiments (for a review see and for a more recent update see ).

If these particles are protons, they are likely to originate in extragalactic sources, since at these high energies the Galactic magnetic field cannot confine protons in the Galaxy. However, extragalactic protons with energies above a few times $10^{19}$ eV can produce pions through interactions with the cosmic microwave background (CMB) and consequently lose significant amounts of energy as they traverse intergalactic distances. Thus, in addition to the extraordinary energy requirements for astrophysical sources to accelerate protons to $>10^{20}$ eV, the photopion threshold reaction suppresses the observable flux above $\sim 10^{20}$ eV. These conditions were expected to cause a natural high-energy limit to the cosmic ray spectrum known as the GZK cutoff.

As shown by the most recent compilation of the AGASA data, the spectrum of cosmic rays does not end at the expected GZK cutoff. The significant flux observed above $10^{20}$ eV together with a nearly isotropic distribution of event arrival directions challenges astrophysically based explanations as well as new physics alternatives (see and references therein). In addition, the reported small scale clustering tends to rule out most scenarios.

This challenging state of affairs is stimulating both for theoretical investigations as well as experimental efforts. The explanation may hide in the experimental arena such as an over estimate of the flux at the highest energies. This explanation has been proposed by the HiRes collab-
oration based on an analysis of their monocular data [9]. Even if this were the case, events above the GZK cutoff are also observed by HiRes. The Mono HiRes data looks more like the GZK feature, as discussed in the next section, followed by indications of new sources at energies above the feature. Events past $10^{20}$ eV pose theoretical challenges which will be explained in the future by either astrophysically novel sources or new fundamental physics.

2. The GZK Feature

Ultra-high energy cosmic rays (UHECRs) propagating from extragalactic sources to Earth suffer a number of losses in their interaction with cosmic backgrounds. These include pair production, photopion production, and adiabatic losses due to the universe’s expansion. The adiabatic and pair production losses change the spectrum continuously, while the pion production process has a threshold given by the pion mass, i.e., protons need to be at ultra-high energies to be able to produce a pion off CMB photons. A careful calculation would show that the GZK cutoff is not an absolute end to the cosmic ray spectrum but it generates a clear feature around $5 \times 10^{19}$ eV set by the pion mass threshold. The spectrum recovers at energies above this feature and the local distribution of sources can significantly affect the agreement between predicted and observed spectra (see [10,11]).

To see this effect more clearly, we developed a numerical code that can calculate the UHECR spectrum for a given input spectrum (assumed to be a power law at the source with spectral index $\gamma$, $J(E) \propto E^{-\gamma}$), a given spatial distribution of sources, and a choice for redshift evolution of sources [11]. Some results from this study are shown in Figs. 1,2,4 and 8.

In principle, a local overdensity of sources can decrease the gap between observed and detected events above the GZK cutoff. This effect can easily be understood: photopion energy losses limit the maximum distance at which sources can contribute at the highest energies to a few tens of Mpc, while cosmic rays below the pion production threshold come from much larger volumes. A local overdensity will increase the observed flux at the highest energies relative to the lower energy flux. If the UHECR source distribution is proportional to that given by the galaxy distribution, the observed local overdensity is not high enough to explain the data [11]. We reached that conclusion using the source distribution as given by the CfA and PSCz galaxy redshift surveys (PSCz results are shown in Figs. 1 and 2). The local density is only about a factor of two above the mean which is not enough to bridge the gap, although a priori UHECR sources may cluster differently from luminous matter (see, e.g., [12]).

In order to explain the highest energy events with extragalactic protons, a more profitable avenue is to study the effect of the spectral index. In Fig. 1, we set the input spectral index $\gamma = 3$ such that the events below $10^{19.5}$ eV also fit the predicted flux. If the highest energy events are confirmed by larger experiments, the evidence points...
Figure 2. Simulated fluxes for the AGASA statistics of 728 events above $10^{19}$ eV, and $\gamma = 2.1$, using a homogeneous source distribution with $z_{\text{max}} = 0.1$ (\ hatch), the PSCz distribution with $z_{\text{max}} = 0.1$ (horizontal \ hatch), and a homogeneous source distribution with $z_{\text{max}} = 1$ (\ hatch).

Towards a new source with a spectrum harder than $J(E) \propto E^{-3}$. Given earlier AGASA data as of ref. [13] with 728 events above $10^{19}$ eV, Fig. 2 shows how a spectral index $\gamma = 2.1$ can more easily fit the data at the highest energies. Fig. 2 shows both the mean and the fluctuations around the mean flux for the data set in [13]. As more events are observed, such as in the Auger Project [4], the fluctuations about the mean decrease as shown in Fig. 8. In Fig. 3, we show the mean behavior of the GZK feature for different input spectra assuming a homogeneous distribution of sources. As the spectral index decreases, the agreement with the observations improves. In sum, sources of UHECRs distributed as ordinary galaxies are marginally consistent with present spectral data and, for hard injection spectra, the GZK cutoff is not really a cutoff but a feature in the high-energy cosmic ray spectrum.

The transition from the lower energy ($\sim 10^{19}$ eV) region of the UHECR spectrum to the higher energy region ($\sim 10^{20}$ eV) can be made smoother if the sources have a redshift evolution. In Fig. 4, we show the effect of a source luminosity evolution for sources with luminosity $\propto (1 + z)^m$. If the source luminosity increases with redshift $z$, ($m > 0$), the flux of UHECRs at energies below the GZK cutoff will increase relative to the flux above the cutoff. This effect changes the shape of the spectrum, broadening the transition region.

In addition to the presence of events past the GZK cutoff, there has been no clear counterparts identified in the arrival direction of the highest energy events. If these events are protons or photons, these observations should be astronomical, i.e., their arrival directions should be the angular position of sources. At these high energies the Galactic and extragalactic magnetic fields should not affect proton orbits significantly so that even protons would point back to their sources within a few degrees. Protons at $10^{20}$ eV propagate mainly in straight lines as they traverse the Galaxy since their gyroradii are $\sim 100$ kpc in $\mu$G fields which is typical in the Galactic disk. Extragalactic fields are expected to be $\ll \mu$G, and induce at most $\sim 1^\circ$ deviation from the source [15]. Even if the Local Supercluster has relatively strong fields,
the highest energy events are expected to deviate at most $\sim 10^\circ$ [16,17]. At present, no correlations between arrival directions and plausible optical counterparts such as sources in the Galactic plane, the Local Group, or the Local Supercluster have been clearly identified. Ultra high energy cosmic ray data are consistent with an isotropic distribution of sources in sharp contrast to the anisotropic distribution of light within 50 Mpc from Earth.

In addition to the overall isotropic distribution of arrival directions, the AGASA data shows evidence of a small scale clustering of events. The number of observed double and triple events seems much higher than expected for a random distribution [4]. These clusters do not correlate with any known nearby galaxy population and give most models the hardest hurdle to overcome. The only positive cross correlation found thus far is between the UHECR clusters and very distant BL Lacertae objects [18]. These highly active galaxies are likely to be prime accelerators, but their location is too far from Earth to avoid a GZK cutoff to the spectrum. This positive cross correlation has inspired new physics proposals [19] that make use of new neutral particles [20] that need to be very long lived to be able to traverse cosmological distances. A more radical option would be the breaking of Lorentz invariance that may render the neutron stable [21]. Both possibilities give future experiments the perfect carrot.

3. Astrophysical Zevatrons

The puzzle presented by the observations of cosmic rays above $10^{20}$ eV have generated a number of proposals that can be divided into Astrophysical Zevatrons and New Physics models. Astrophysical Zevatrons are also referred to as bottom-up models and involve searching for acceleration sites in known astrophysical objects that can reach ZeV energies. New Physics proposals can be either hybrid or pure top-down models. First we discuss astrophysical Zevatrons in this section and new physics models in the next.

Cosmic rays can be accelerated in astrophysical plasmas when large-scale macroscopic motions, such as shocks, winds, and turbulent flows, are transferred to individual particles. The maximum energy of accelerated particles, $E_{\text{max}}$, can be estimated by requiring that the gyroradius of the particle be contained in the acceleration region: $E_{\text{max}} = Z e B L$, where $Z e$ is the charge of the particle, $B$ is the strength and $L$ the coherence length of the magnetic field embedded in the plasma. For $E_{\text{max}} \gtrsim 10^{20}$ eV and $Z \sim 1$, the only known astrophysical sources with reasonable $BL$ products are neutron stars, active galactic nuclei (AGNs), radio lobes of AGNs, and clusters of galaxies. Fig. 5 (known as a Hillas plot [22]) highlights the $B$ vs. $L$ for these objects.

Clusters of Galaxies: Cluster shocks, although very large, are not able to accelerate protons to energies above $\sim 10^{19}$ eV [23]. Propagation in the cluster also generates a GZK feature.

AGN Radio Lobes: Jets from the central black-hole of an active galaxy end at a termination shock where the interaction of the jet with the intergalactic medium forms radio lobes and ‘hot spots’. Of special interest are the most power-
Figure 5. $B$ vs. $L$, for $E_{\text{max}} = 10^{20}$ eV, $Z = 1$ (dashed line) and $Z = 26$ (solid line).

ful AGNs where shocks can accelerate particles to energies well above $\sim 10^{18}$ eV via the first-order Fermi mechanism [24]. A nearby specially powerful source may be able to reach energies past the cutoff and fit the observed spectrum [25]. However, extremely powerful AGNs with radio lobes and hot spots are rare and far apart and are unlikely to match the observed arrival direction distribution. If M87 is the primary source of UHECRs a concentration of events in the direction of M87 should be seen. The next known nearby source after M87 is NGC315 which is already too far at a distance of $\sim 80$ Mpc. Any unknown source between M87 and NGC315 would likely contribute a second hot spot, not the observed isotropic distribution. The very distant radio lobes will contribute a GZK cut spectrum which is also not observed.

The possibility of stronger Galactic and extragalactic magnetic fields may reduce the problem. In particular, a strong Galactic wind can significantly alter the paths of UHECRs such that the observed arrival directions of events above $10^{20}$ eV would trace back to the North Galactic Pole which is close to the Virgo cluster where M87 resides [27]. The proposed wind would focus most observed events within a very narrow energy range into the northern Galactic pole and render point source identification fruitless. Full sky coverage of future experiments will be a key discriminator of such proposals.

AGN - Central Regions: The powerful engines that give rise to the observed jets and radio lobes are located in the central regions of active galaxies and are powered by the accretion of matter onto supermassive black holes. The central engines might themselves be the UHECR accelerators [28]. The nuclei of generic active galaxies (not only the ones with radio lobes) can accelerate particles via a unipolar inductor not unlike the one operating in pulsars. In the case of AGNs, the magnetic field may be provided by the infalling matter and the spinning black hole horizon provides the imperfect conductor for the unipolar induction. This proposal has to face the debilitating losses that UHE charged particles face in the acceleration region due to the intense radiation field present in AGNs. In addition, the spatial distribution of objects implies a GZK cutoff of the observed spectrum. This limitation due to energy losses has led to the proposal that quasar remnants, supermassive black holes in centers of inactive galaxies, are more effective UHECR accelerators [29]. From Figure 1-3, these models can only succeed if the source spectrum is fairly hard ($\gamma < 2$).

Neutron Stars: Neutron star not only have the ability to confine $10^{20}$ eV protons, the rotation energy of young neutron stars is more than sufficient to match the observed UHECR fluxes [30]. However, ambient magnetic and radiation fields induce significant losses inside a neutron star’s light cylinder. However, the plasma that expands beyond the light cylinder is free from the main loss processes and may be accelerated to ultra high energies. In particular, newly formed, rapidly rotating neutron stars may accelerate iron nuclei to UHEs through relativistic MHD winds beyond their light cylinders [31]. This mechanism naturally leads to very hard injection spectra ($\gamma \simeq 1$). In this case, UHECRs originate mostly in the Galaxy and the arrival directions require that the primaries be heavier nuclei. Depending on the structure of Galactic magnetic
fields, the trajectories of iron nuclei from Galactic neutron stars can be consistent with the observed arrival directions of the highest energy events (see, e.g., [32,33]). This proposal should be constrained once the primary composition is clearly determined.

**Gamma-Ray Bursts:** Transient high energy phenomena such as gamma-ray bursts (GRBs) may also be a source of ultra-high energies protons [34,35]. In addition to both phenomena having unknown origins, GRBs and UHECRs have other similarities that may argue for a common source. Like UHECRs, GRBs are distributed isotropically in the sky, and the average rate of $\gamma$-ray energy emitted by GRBs is comparable to the energy generation rate of UHECRs of energy $>10^{19}$ eV in a redshift independent cosmological distribution of sources. However, recent GRB counterpart identifications argue for a strong cosmological evolution for GRBs. The distribution of UHECR arrival directions and arrival times argues against the GRB–UHECR common origin. Events past the GZK cutoff require that only GRBs from $\lesssim50$ Mpc contribute. Since less than about one burst is expected to have occurred within this region over a period of 100 yr, the unique source would appear as a concentration of UHECR events in a small part of the sky. In addition, the signal would be very narrow in energy $\Delta E/E \sim 1$. Again, a strong intergalactic magnetic field can ease the arrival direction difficulty dispersing the events of a single burst but also decreasing the flux below the observed level.

4. **New Physics Models**

The UHECR puzzle has inspired a number of different models that involve physics beyond the standard model of particle physics. New Physics proposals can be top-down models or a hybrid of astrophysical Zevatrons with new particles. Top-down models involve the decay of very high mass relics that could have formed in the early universe.

The most economical among hybrid proposals involves a familiar extension of the standard model, namely, neutrino masses. If some flavor of neutrinos have mass ($\sim 0.1$ eV), the relic neutrino background is a target for extremely high energy neutrinos to interact and generate other particles through the Z-pole [38,39]. This proposal requires very luminous sources of extremely high energy neutrinos throughout the universe. Neutrino energies need to be $\gtrsim10^{21}$ eV which implies primary protons in the source with energies $\gtrsim10^{22}$ eV. The decay products of the Z-pole interaction are dominated by photons, which gives a clear test to this proposal. In addition, the neutrino background only clusters on large scales, so the arrival direction for events should be mostly isotropic. Preserving a small scale clustering may be another challenge to this proposal.

If none of the astrophysical scenarios or the hybrid new physics models are able to explain present and future UHECR data, the alternative is to consider top-down models. The idea behind these models is that relics of the very early universe, topological defects (TDs) or superheavy relic (SHR) particles, produced after or at the end of inflation, can decay today and generate UHECRs. Defects, such as cosmic strings, domain walls, and magnetic monopoles, can be generated through the Kibble mechanism as symmetries are broken with the expansion and cooling of the universe. Topologically stable defects can survive to the present and decompose into their constituent fields as they collapse, annihilate, or reach critical current in the case of superconducting cosmic strings [38,39]. The decay products, superheavy gauge and higgs bosons, decay into jets of hadrons, mostly pions. Pions in the jets subsequently decay into $\gamma$-rays, electrons, and neutrinos. Only a few percent of the hadrons are expected to be nucleons. Typical features of these scenarios are a predominant release of $\gamma$-rays and neutrinos and a QCD fragmentation spectrum which is considerably harder than the case of Zevatron shock acceleration.

ZeV energies are not a challenge for top-down models since symmetry breaking scales at the end of inflation typically are $\gg 10^{21}$ eV. Fitting the observed flux of UHECRs is harder since the typical distances between TDs is the Horizon scale or several Gpc. The low flux hurts proposals based on ordinary and superconducting cosmic strings which are distributed through-
out space. Monopoles usually suffer the opposite problem, they would in general be too numerous. Inflation succeeds in diluting the number density of monopoles and makes them too rare for UHECR production. Once two symmetry breaking scales are invoked, a combination of horizon scales gives room to reasonable fluxes. This is the case of cosmic necklaces which are hybrid defects where each monopole is connected to two strings resembling beads on a cosmic string necklace. The UHECR flux which is ultimately generated by the annihilation of monopoles with antimonopoles trapped in the string. In these scenarios, protons dominate the flux in the lower energy side of the GZK cutoff while photons tend to dominate at higher energies depending on the radio background (see Fig. 6). If future data can settle the composition of UHECRs from 0.01 to 1 ZeV, these models can be well constrained. In addition to fitting the UHECR flux, topological defect models are constrained by limits from EGRET on the flux of photons from 10 MeV to 100 GeV.

Another interesting possibility is the proposal that UHECRs are produced by the decay of unstable superheavy relics that live much longer than the age of the universe. SHRs may be produced at the end of inflation by non-thermal effects such as a varying gravitational field, parametric resonances during preheating, instant preheating, or the decay of topological defects. These models need to invoke special symmetries to insure unusually long lifetimes for SHRs and that a sufficiently small percentage decays today producing UHECRs. As in the topological defects case, the decay of these relics also generates jets of hadrons. These particles behave like cold dark matter and could constitute a fair fraction of the halo of our Galaxy. Therefore, their halo decay products would not be limited by the GZK cutoff allowing for a large flux at UHEs (see Fig. 7). Similar signatures can occur if topological defects are microscopic, such as monopolonia and vortons, and decay in the Halo of our Galaxy. In both cases the composition of the primary would be a good discriminant since
the decay products are usually dominated by photons. In the case of SHR decays, the arrival direction distribution should be close to isotropic but show an asymmetry due to the position of the Earth in the Galactic Halo [41] and the clustering due to small scale dark matter inhomogeneities [43].

Figure 8. Simulated fluxes for the Auger projected statistics of 9075 events above $10^{19}$ eV, and $\gamma = 3$, using a homogeneous source distribution (\(\backslash\) hatches) and the PSCz distribution (\(\backslash\) hatches). The solid and dashed lines are the results of the analytical calculations for the same two cases. The dash-dotted and dash-dot-dot-dotted lines trace the mean simulated fluxes for the homogeneous and the PSCz cases.

5. Conclusion

Next generation experiments such as the Pierre Auger Project which is now under construction, the proposed Telescope Array, and the EUSO project and the OWL satellites will significantly improve the data at the extremely-high end of the cosmic ray spectrum. With these observatories a clear determination of the spectrum and spatial distribution of UHECR sources is within reach. In addition, the observations of UHE neutrinos in horizontal showers promises to open a new window into the workings of our Universe.

The lack of a GZK cutoff should become clear with Auger and most extragalactic Zevatrons may be ruled out. The observed spectrum will distinguish Zevatrons from new physics models by testing the hardness of the spectrum and the effect of propagation. Fig. 8 shows how clearly Auger will test the spectrum independent of their clustering properties. The cosmography of sources should also become clear and able to discriminate between plausible populations for UHECR sources. The correlation of arrival directions for events with energies above $10^{20}$ eV with some known structure such as the Galaxy, the Galactic halo, the Local Group or the Local Supercluster would be key in differentiating between different models. For instance, a correlation with the Galactic center and disk should become apparent at extremely high energies for the case of young neutron star winds, while a correlation with the large scale galaxy distribution should become clear for the case of quasar remnants. If SHRs are responsible for UHECR production, the arrival directions should correlate with the dark matter distribution and show the halo asymmetry. For these signatures to be tested, full sky coverage is essential. Finally, an excellent discriminator would be an unambiguous composition determination of the primaries. In general, Galactic disk models invoke iron nuclei to be consistent with the isotropic distribution, extragalactic Zevatrons tend to favor proton primaries, while photon primaries are more common for early universe relics.

The hybrid detector of the Auger Project should help settle the present disparity between HiRes and AGASA by cross calibrating the two techniques. It will also determine the composition by measuring the depth of shower maximum and the ground footprint of the same shower. AGASA seems to detect a hint of composition shifts at the highest energies. This would be quite a surprising development. In sum, the future looks very promising. The solution to the UHECR mystery as well as the birth of UHE neutrino astronomy is coming with the next generation of experiments which are under construction such as Auger or in
the planning stages such as the Telescope Array, EUSO, and OWL.

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