

Ultra high energy cosmic rays: A review

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Abstract

We present the main results on the energy spectrum and composition of the highest energy cosmic rays of energy exceeding 10^{18} eV obtained by the High Resolution Fly's Eye and the Southern Auger Observatory. The current results are somewhat contradictory and raise interesting questions about the origin and character of these particles.

1 Introduction

There is not an exact definition which cosmic rays should be called of ultrahigh energy. Generally the term is applied to those cosmic rays that we think are not accelerated in our Galaxy, i.e. are of extragalactic origin. This definition is certainly model dependent, but it always includes cosmic rays of energy above 10^{19} eV. Showers generated by such high energy cosmic rays were first detected by the Vulcano Ranch air shower array in New Mexico, U.S.A. [1]. The first cosmic ray of energy 10^{20} eV, and possibly higher, was also detected by the same array [2]. In this article we will call all particles of energy above 10^{18} eV ultrahigh energy cosmic rays, abbreviated to UHECR.

At the time (1963) this did not cause any surprize: all physicists expected that the cosmic ray spectrum will go forever to higher and higher energies and the only reason we do not see such particles is that their flux is very low. It was only after the discovery of the microwave background that Greisen [3] in U.S. and Zatsepin & Kuzmin [4] in the Soviet Union predicted the end

of the cosmic ray spectrum because of the cosmic rays interactions with the microwave background. This feature is now called the *GZK* feature or cutoff.

In order to give the reader an impression of how big these showers are we show in Fig. 1 the shower profile (number of particles as a function of the atmospheric depth) of the highest energy cosmic ray shower detected by the Fly's Eye experiment [5]. The energy estimate for this shower is 3×10^{20} eV and the number of shower electrons at the shower maximum development (N_{max}) is more than 2×10^{11} . The energy estimate of such showers consists of an integration on the shower profile times the average electron energy.

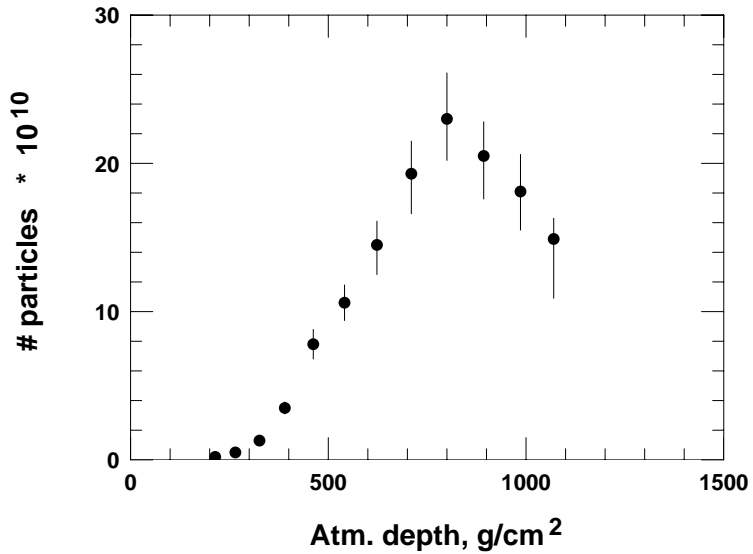


Figure 1: Shower profile of the highest energy shower (3×10^{20} eV) detected by the Fly's Eye experiment.

The next figure shows the state of our knowledge of the energy spectrum of the UHECR before the current generation of experiments, HiRes and Auger. One of the data sets shown in Fig. 2, Agasa, attracts the attention since it does include more than 10 events of energy above 10^{20} eV [6]. At the time Agasa was the biggest (100 sq. km.) air shower array. Since we do not expect UHECR of this energy to be able to propagate from their sources to us, this result called for UHECR production models different from acceleration at astrophysical objects. As a result tens of exotic models explaining the existence of these particles as a result of ultraheavy *X*-particles decay appeared in the literature. The UHECRs in such models are most likely to be either γ -rays or neutrinos because most of the decay products have to

be mesons rather than nucleons.

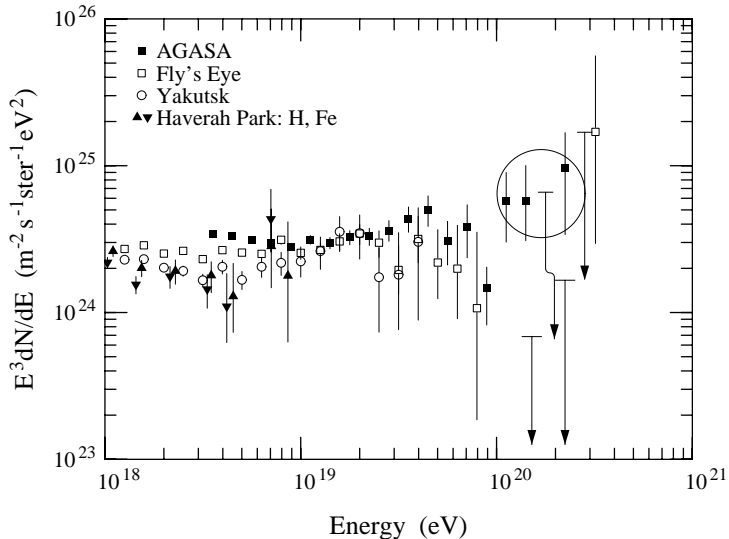


Figure 2: UHECR spectrum as determined before the current generation of experiments, HiRes and Auger.

Whatever the origin of the UHECR, acceleration at astrophysical objects or X -particle decay it is important to note that the energy spectrum detected at Earth is not the same as the acceleration and production spectrum is a result of the UHECR energy loss in propagation from their sources to us. We can use the detected energy spectrum and cosmic rays propagation calculations to study what the production spectrum is. Although all interaction properties are well known, propagation calculations still have to make simplifying assumptions:

- All sources have identical acceleration/production spectra, and
- Sources are isotropically distributed in the Universe.

2 UHECR energy spectrum

In this section we will discuss the contemporary measurements of the UHECR energy spectrum that were done by the High Resolution Fly's Eye (HiRes) detector and the Southern Auger Observatory. The HiRes experiment consists of two fluorescent telescopes, HiRes 1 and 2. Fluorescent light is emitted by the air Nitrogen atoms excited by the ionization of the shower particles. The light emission is isotropic and the yield at sea level is 4 UV

photons per one meter of electron track. This yield depends on the air density and temperature but 4 photons per meter of track is good enough for a simple idea for the photon fluxes at the telescope. HiRes 1 looks at elevations between 3 and 17° above the horizon, while HiRes 2 doubles the field of view up to elevation of 31°. The telescopes work both individually or in stereo mode. Stereoscopic detection makes the shower analysis much more accurate. The energy estimate couples the integral of the shower profile and the average electron energy.

The Southern Auger Observatory is a hybrid detector consisting of a huge air shower array of total area 3,000 km² and 24 fluorescent telescopes that observe the air above it. The detectors of the surface array (SD) are water Cherenkov tanks that register the Cherenkov light of the shower particles that hit the tank. Each water Cherenkov tank has a surface area of 10 m² and a depth of 1.2 m and is viewed by 3 photomultiplier tubes. The fluorescent telescopes are organized in 4 stations that occasionally can observe the fluorescent light in stereo. The surface array is fully efficient above shower energy of 3×10¹⁸ eV. The energy estimate of the surface array is obtained by the correlation of the shower signal at 1000 m from the shower axis, S_{1000} to the fluorescent signals in events detected by both detectors. The lower energy part of the spectrum is measured by hybrid events, where at least one of the surface detectors triggered in coincidence with the fluorescent telescope.

Fig. 3 shows the cosmic ray spectrum as measured by HiRes and Auger. The independent analyses of HiRes 1 and 2 [7] are shown with black and grey points while the stereo analysis [8] is shown with empty circles. The Auger surface array spectrum [9] is shown with black squares and the hybrid measurement [10] is shown with empty squares. Since the surface detector has much higher statistics the hybrid data are only important for energies below 10¹⁹ eV.

The first conclusion from Fig. 3 is that both experiments confirm the GZK cutoff. After energy of about 4×10¹⁹ eV the cosmic ray spectrum steepens and there are very few events above that energy. Note that the measured spectrum is multiplied by E^3 which makes the small differences in the energy calibration look significantly bigger. There are, though, some differences that steer the interpretations of the energy spectra towards different models. The Auger energy spectrum is fitted to $E^{-2.6}$ behaviour over an order of magnitude above 3×10¹⁸ eV, while the HiRes spectrum is somewhat steeper. The same is true for the exact position of the GZK cutoff, where the experimental statistics is low.

In spite of the similarity of the two spectra they allow quite different

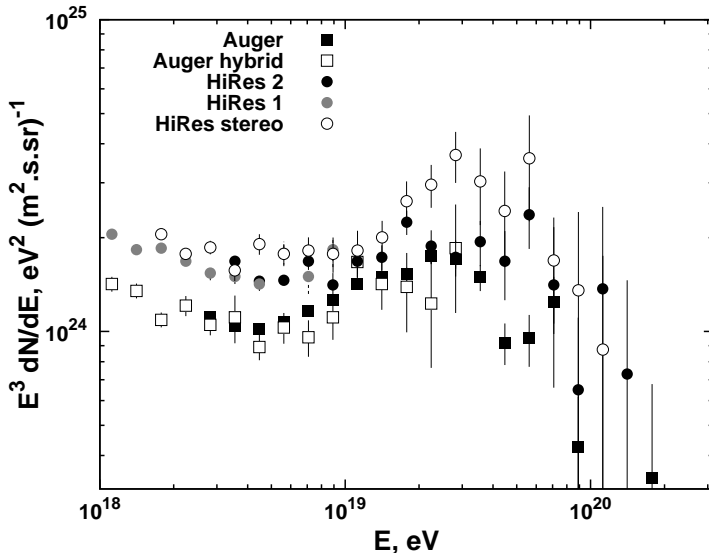


Figure 3: UHECR spectrum as measured by HiRes and Auger.

interpretations for the origine and type of UHECR. The HiRes spectrum is fully consistent with the model of Berezhinsky et al [?] which assumes a steep cosmic ray acceleration spectrum ($E^{-2.7}$) and a pure proton composition. There is no need for a cosmological evolution of the cosmic ray sources.

The interpretation of the Auger energy spectrum is much more complicated as it allows several different models. The first one is not dissimilar to that of Berezhinsky et al - pure proton composition, $E^{-2.55}$ acceleration spectrum and no cosmological distribution of the UHECR sources. The second proton composition model requires flatter $E^{-2.3}$ acceleration spectrum, a very strong (proportional to $(1+z)^5$) cosmological evolution of the sources. The third model is that of mixed composition, i.e. the same nuclei that exist in the galactic cosmic rays are accelerated at the powerful extragalactic sources. The acceleration spectra are relatively flat and the exact parameters depend on the composition of the accelerated cosmic rays.

3 Cosmic ray composition

The measurement of the cosmic ray composition at high energy depends on the parameters of the showers that different nuclei generate. At energy around 10^{15} - 10^{16} eV the main composition parameter is the ratio of muons to electrons in the shower. At higher energy such a measurement becomes

difficult since the muon counters are much more expensive and the main composition measurement is the depth of the shower maximum development X_{max} . Using a very simple analytic shower model Matthews [12] showed that

$$X_{max}^A = X_{max}^p - X_0 \ln A$$

where X_0 is the radiation length. Showers induced by heavy nuclei develop significantly faster than those of protons. The contemporary fluorescent detectors can measure X_{max} with an accuracy of about 20 g/cm² while the difference between the average X_{max} in proton and iron showers is about 100 g/cm².

Showers initiated by γ -rays or neutrinos have also development characteristics that are different from those of showers initiated by nuclei. Both HiRes [13] and Auger [14] were able to put limits on the fluxes of ultrahigh energy neutrinos. These limits were set on specific neutrino flavors but the limit the total neutrino flux since oscillations would led to $\nu_e : \nu_\mu : \nu_\tau$ ratio of approximately 1 : 1 : 1.

The Auger Observatory also put limits on the fraction of γ -rays in the total cosmic ray flux. The limits come from the fact that very high energy γ -ray showers develop significantly deeper in the atmosphere than proton showers do. Two different techniques were used again: hybrid showers between 10¹⁸ and 10¹⁹ eV [15] and surface detector [16] above that energy. The fraction of γ -rays in the cosmic ray flux above 2×10¹⁸ eV was limited to less than 4% and the fraction above 10¹⁹ eV to 2%. These limits almost eliminate the exotic models for UHECR production although it is still possible that highest energy particles, where the statistics is too low to set limits, are still γ -rays.

An important parameter in the study of the shower depth of maximum is the elongation rate D_{10} - the rate of change of X_{max} per a decade of energy. D_{10} is approximately $(1 - B)X_0 \ln 10$, where B is a parameter that depends on the hadronic interaction model. For different models D_{10} is between 50 and 60 g/cm² if the cosmic ray composition is constant. In case that the composition becomes lighter with energy D_{10} grows. If it becomes heavier D_{10} is lower. Fig. 4 shows the results on X_{max} energy dependence as measured by the HiRes and Auger together with the predictions of three different interaction models for proton and Fe showers.

The points labeled HiRes 05 show the first result with relatively small statistics published by HiRes in 2005 [17]. These points imply that the shower depth of maximum increases faster than any of the interaction models predict. This suggests that the cosmic ray composition becomes lighter

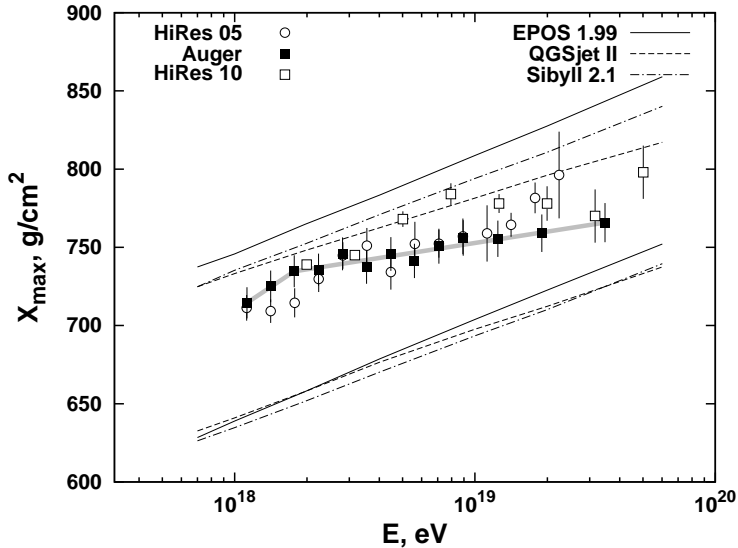


Figure 4: Depth of maximum as a function of the shower energy as measured by HiRes and Auger and the predictions of three different interaction models for proton and iron showers.

with energy, although it can be heavier than pure protons, especially if the EPOS 1.99 model is correct. The black squares show the X_{max} results of the Auger Observatory [18]. The general behavior is shown with the gray line. The three lowest energy points suggest D_{10} of 106 g/cm^2 with a large error bar. At higher energy the elongation rate becomes $24 \pm 3 \text{ g/cm}^2$. The interpretation in terms of cosmic ray composition should be that up to $3 \times 10^{18} \text{ eV}$ the cosmic ray composition becomes lighter and at higher energy it becomes heavier. The highest energy point at about $4 \times 10^{19} \text{ eV}$ is closer to iron than it is to protons in any of the interaction models. The open squares show the HiRes data set taken in stereo [19]. Some of these points are even higher than expected for Fe showers in the QGSJet II model. There is an obvious disagreement between the two experiments.

This disagreement carries over when the two experiments examined the width of the X_{max} distributions in each of the energy bins shown in Fig. 5. The width of these distributions also reflects the cosmic ray composition. The predictions for proton showers are of order 60 g/cm^2 while for Fe showers they are about 20 g/cm^2 . In the case of Auger the decrease of the rms values follow the average depth of maximum and both of them suggest a composition that becomes heavier with the increasing energy, In the case of

HiRes the best fit is a straight line. Note that the definitions of *width* are not identical. Auger uses directly the rms value of the distribution while HiRes gives the Gaussian width after the long tail of the distribution is cut off.

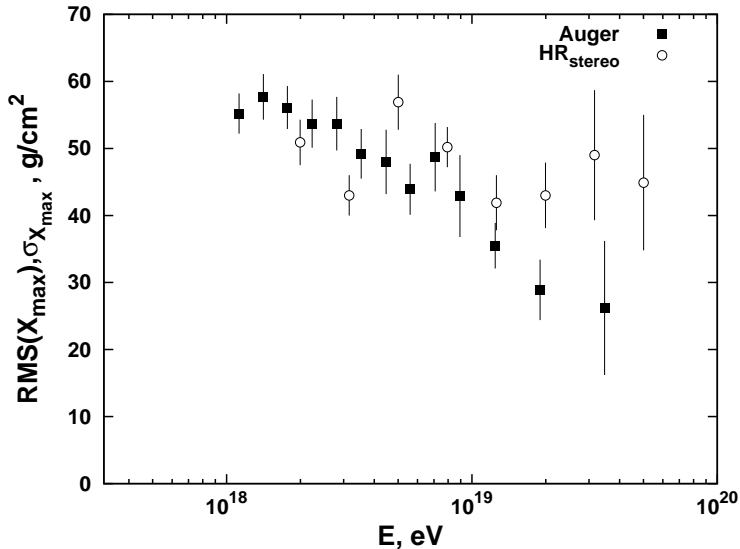


Figure 5: Width of the X_{max} distributions measured by Auger and HiRes.

One possibility for the disagreement is that HiRes and Auger select their event samples in different ways. The reason is that none of the fluorescent detectors observes the whole sky and only elevations up to 31° in the best case. The experiments want to be certain they do are not biased toward early or late developing showers and apply very different cuts to the data. Auger, for example only uses hybrid events which implies selecting showers relatively close to the fluorescent detector while HiRes does not use showers closer than 10 km to any of their telescopes.

4 Arrival directions of the highest energy cosmic rays

The idea is that UHECR do not scatter much in the galactic and extragalactic magnetic fields so they will cluster around their sources and thus reveal them. The Southern Auger Observatory is the biggest UHECR detector and has the highest chance to look for the sources of these particles. Early in

the game Auger made a trial scan, identified the procedure to follow and in 2007 they published a paper [20] on the correlation of their events of energy exceeding 57 EeV with the active galactic nuclei from the VCV [21] catalog at redshifts smaller than 0.018.

Out of 27 highest energy events 19 events came from directions not exceeding 3.1° from an AGN. Most of the events that did not correlate passed less than 12° from the galactic plane where the galactic magnetic field is the strongest. Accounting for the scans in particle energy, AGN distance, and distance from the AGNs the significance of the correlation was not huge, but still exceeding 3σ . These events and the AGNs with $|b| \leq 12^\circ$ are shown in Fig. 6.

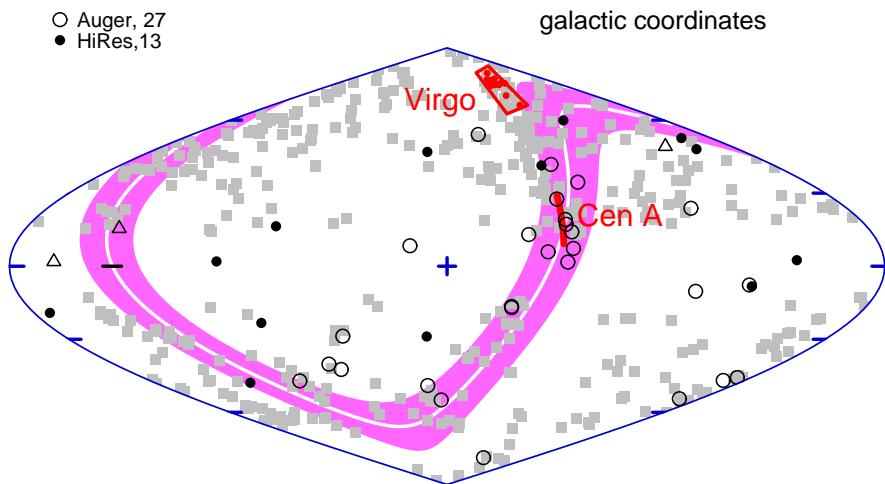


Figure 6: Correlation of the arrival directions of the Auger and HiRes highest energy events with the VCV catalog.

HiRes looked for correlation of their highest energy 13 events with the AGNs from the same catalog and did not see any correlation [22]. The fields of view of the two experiments do not coincide, but there is enough overlap to look for correlations of both data sets.

The Auger Observatory has more than doubled its statistics by the time of the International Cosmic Ray Conference in 2009. The level of correlation, however, decreased significantly to about 2σ [23]. Since the VCV catalog does not appear to be the best one to contain possible UHECR sources the collaboration attempted to correlate the arrival directions of their highest energy events with objects from different ones with similar results. Only

about 30% of UHECR seem to correlate with the directions of powerful extragalactic objects while the rest seem to come from an isotropic distribution. The exception is the direction of the nearby (less than 4 Mpc) radio galaxy Centaurus A around which several events are clustered.

There is obviously an internal contradiction between the idea of correlation of the arrival directions with extragalactic objects and that of heavy cosmic ray composition. If the highest energy events are indeed heavy nuclei they may scatter a lot and appear to come to us from isotropic directions. The question of UHECR astronomy can most likely be solved only with vastly increased statistics. Auger is now proposing a new, much larger Northern Observatory.

5 Summary

The main question raised by the results of the Agasa collaboration, the energy extent of the cosmic ray spectrum, is now solved. Both HiRes and Auger observe its end, the GZK cutoff. With a small change in the energy assignment, less than the systematic error of 20%, the two measured spectra will be fully consistent.

The results on the cosmic ray composition are much more contradictory. HiRes sees cosmic ray composition close to a purely proton one while Auger observes increasingly heavier composition above 3×10^{18} eV. The reasons for this disagreement are not obvious and it will take the two groups lots of work and collaboration to understand them. There maybe some help from the new hybrid experiment Telescope Array which combines scintillator counters with fluorescent telescopes.

The question about the sources of these particles is not yet solved. Less than 1/3 of the highest Auger events correlate in arrival direction with the possible sources from different catalogs. The solution will most likely require significant increase of the experimental statistics.

DISCUSSION

DANIELE FARGION Why we do not see UHECR events in Auger towards Virgo and why are no events toward Norma?

TODOR STANEV The answer of Auger is that after accounting for the exposure (1/3) and for the distance (1/25) they expect 75 times less events from Virgo for equal luminosity. There are models, including yours, that can explain the lack of events.

SERGIO PETRERA I have a comment on the HiRes spectrum - They show that their data are well fit by the model of Berezhinsky et al. They never published fits with other models, but mixed composition models can successfully fit data as well because of the many handles they have.

TODOR STANEV The HiRes group used an existing model to fit their spectrum. After it worked they did not present other fits.

FRANCESCO VISSANI Greisen, Zatsepin and Kuzmin put together their proposal *before* the data were known. Many of the models you discussed were proposed *after* the data were available, for instance the super-heavy decaying particle model. Don't you believe that this consideration already puts these theories in a different position?

TODOR STANEV You are correct. The GZK was the original model. Contemporary models are made to fit observations. It would be better to call them fits to data rather than models.

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