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Experimental results: an update

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Abstract

This article is a summary of experimental results from highest energy cosmic ray measurements, focusing on data and analyses that became available after 1999. ***To cite this article: R. Engel, H. Klages, C. R. Physique 5 (2004).***

Résumé

Revue des résultats expérimentaux récents. Cet article présente un résumé des résultats obtenus dans le domaine de l'observation des rayons cosmiques les plus énergétiques, en insistant tout particulièrement sur les données et analyses postérieures à 1999. ***Pour citer cet article : R. Engel, H. Klages, C. R. Physique 5 (2004).***

Keywords: Energy spectrum; Anisotropies; Angular correlations; Mass composition

Mots-clés : Spectre d'énergie ; Anisotropies ; Corrélations angulaires ; Identification des primaires

1. Introduction

There are numerous articles available in the literature that review the observational and theoretical status and progress in the field of highest energy cosmic ray research, for example [1–15]. One of the most complete experimental reviews is the work of Nagano and Watson [4] that gives a comprehensive overview of all experiments and their results [4], including some discussion of the implications. We shall use this review as a baseline of our discussion of new data and re-analyses of old data that became available since then. For completeness we include in this article some older results but we will not discuss the different experimental configurations and measurement techniques. Most of the experiments are covered in detail in [4], namely AGASA [16], Fly's Eye [17], Haverah Park [18,19], SUGAR [20,21], Volcano Ranch [22], and Yakutsk [23,24]. The only new experiment that went into operation and has published data is the High Resolution Fly's Eye (HiRes). A description of the HiRes prototype detector that took data in coincidence with MIA can be found in [25]. The complete setup of HiRes with HiRes I and HiRes II as fluorescence detectors is discussed in [26,27].

In 1999 all observations indicated a power-law-like continuation of the ultra-high energy cosmic ray flux to energies well exceeding the GZK cutoff. AGASA had reported 6 events above 10^{20} eV [28] and first, preliminary data of the new HiRes Fly's Eye detector [29] supported this result with 7 events. In addition, Haverah Park had observed 4 events above 10^{20} eV [4,19].[1]

Since 1999 the Haverah Park data were re-analyzed using CORSIKA [30] with QGSJET [31,32] as a modern hadronic interaction model for shower simulations [33]. The energy assignment was revised by about −30%, moving all observed events with zenith angle less than 45° below 10^{20} eV. Similarly a detailed study of the atmospheric properties at the HiRes detector site

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[1] A complete list of candidate events at $E > 10^{20}$ eV is given in [4].

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lead to an adjustment of the correction for light absorption. The latest HiRes data set contains only 10 events above $10^{19.8}$ eV with about 26 expected according to the AGASA observation [34].

The currently accumulated experimental information on cosmic rays does not give a consistent picture of the cosmic ray flux at the highest energies. However, there is evidence for post-GZK cutoff events. At the time of writing this article the list of detected events with energy nominally reconstructed to be above 10^{20} eV, passing the quality cuts of the experiments, is the following: AGASA: 11 [35], HiRes I (mono): 2 [34,36], Yakutsk: 1 [37], Fly's Eye (mono) 1 [38], Haverah Park: 1 [39] and Volcano Ranch: 1 [22].

The situation is similarly unclear with respect to the arrival direction distribution. Several experiments observe a slight excess of cosmic rays coming from the direction of the Galactic center region at about 10^{18} eV [40–42], however, the exact direction and the characteristics of this excess differ from experiment to experiment. At higher energy the arrival directions seem to become more isotropic again [43].

AGASA reported a clustering of UHE cosmic rays with energies above $10^{19.5}$ eV on small angular scales [44–46]. The events of the Yakutsk array show clustering even at lower energy, $E > 10^{17}$ eV [47]. HiRes data in stereo mode do not confirm any indication of clustering so far [48] which might be related to the different energy range and the lower statistics of the data set.

There are a number of new results regarding the composition and fraction of gamma-rays at very high energy (for a recent review, see [49]). Again, different measurements are not giving a coherent picture. New data from HiRes [27,50,51] on the mean depth of the shower maximum suggest a change to a light composition at much lower energy (below 10^{18} eV) than previous measurements [52–55]. Using the QGSJET model for interpreting the data the measurements of Haverah Park and Volcano Ranch were recently re-analyzed [56,57], both favouring a mixed composition with a significant contribution from heavy elements (iron).

Last but not least a number of observations made at the Yakutsk array indicate a change of the basic properties of air showers at energies $E > 10^{18.5}$ eV [58,59]. There is an ongoing debate whether such changes could be related to the discrepancies between AGASA and Yakutsk data and to which extent they might be caused by the detection techniques of the Yakutsk experiment [60,61].

Due to the limited statistics of UHE cosmic rays collected so far, most of the aforementioned discrepancies between different results are not of contradictory character in a strict sense. In addition, interpretation of the measurements depends to a large degree on extensive air shower simulations and models of hadronic interactions used for them (for example, [62–66]). Shortcomings in these simulations will most likely cause systematic differences between results derived from detectors employing different measurement techniques or analyses based on different simulation models. In this sense this review has to be understood as merely a summary of available results. We shall not attempt to argue in favour of one of the experiments or data sets.

The structure of the article is as follows. In Section 2 the currently available data of highest energy cosmic ray fluxes are compared. Systematic features in the energy spectrum are discussed and the question of compatibility of the data with the existence of a GZK cutoff is addressed. In Section 3 we summarize new results on studies of the arrival direction distribution and in Section 4 a compilation of recent composition measurements is presented. In Section 5 we give conclusions and an outlook, briefly describing some of the very promising detector projects planned or currently under construction.

2. Cosmic ray flux

Fig. 1 shows a compilation of cosmic ray flux measurements at very high energy. The presentation as $dN/d\ln E$ closely corresponds to the method of measurement: counting events falling into bins in $\ln E$. In most cases the error bars indicate the statistical uncertainty only. The shaded area, representing the results of the recent reanalysis of the Haverah Park data [33], incorporates some systematic effects as it is obtained by assuming extreme compositions, either fully iron or proton dominated. An experimental systematic error of the shower energy of the form $E' = (1 + f)E$ corresponds in this plot merely to a horizontal shift of the data by $\ln(1 + f)$.

Fig. 2 is a compilation of the integrated aperture of the experiments with data above 10^{19} eV for the fluxes shown in Fig. 1. About 1.5 times more events with $E > 10^{20}$ are expected in the HiRes I (mono) data set than AGASA has accumulated. Similarly the Yakutsk experiment is expected to have slightly more than a third of the statistics of HiRes I and about one half of that of AGASA. It is clear that the event statistics given in Section 1 does not agree with these relations.

It is usual to present the UHE cosmic ray flux multiplied by E^3 to enhance possible features in the energy spectrum, see Fig. 3. There is some ambiguity in converting the flux shown in Fig. 1 to $E^3 J(E)$: due to the steeply falling flux the mean energy of the events falling into a given bin is, in general, not equal to the middle of the bin. This effect becomes important

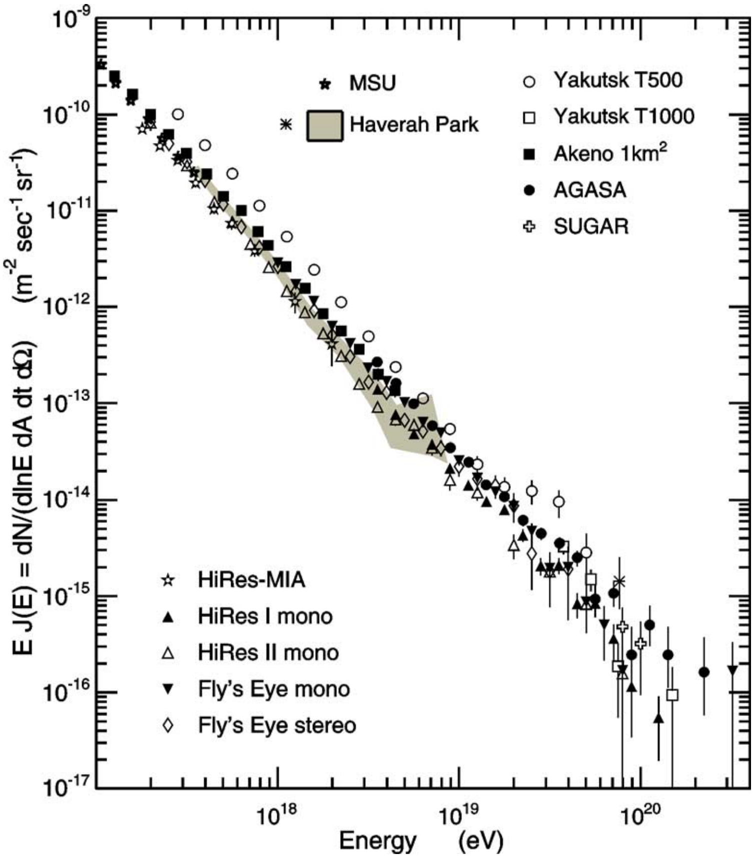

Fig. 1. Data compilation of cosmic ray flux measurements at very high energy. Shown are the data of AGASA [35,67], Akeno [68,69], Fly's Eye [52,70], Haverah Park [33], HiRes-MIA [50,71], HiRes Fly's Eye [26,34,72], MSU [73], SUGAR [74], and Yakutsk [75]. Yakutsk T500 (trigger 500) refers to the smaller subarray of the experiment with 500 m detector spacing and T1000 (trigger 1000) to the array with 1000 m detector distance. The data of the MSU array are included to show the connection of the high energy measurements to lower energy data covering the *knee* of the cosmic ray spectrum.

for large energy bin sizes and even more with very low statistics. Furthermore, in this presentation the energy resolution of the experiments corresponds not only to a horizontal shift anymore.[2]

Even in this presentation spectral features such as the *second knee* at about 10^{18} eV and the *ankle* [52] are hardly visible. There are a number of measurements that clearly show a dip-like structure in the cosmic ray flux at $E \approx 10^{18.5}$ eV, as shown in the left panel of Fig. 4. These measurements are all fluorescence yield based. Lowering the energy scale of the Fly's Eye stereo data by 20–30% would bring the measurements to almost perfect agreement. (We do not consider the Fly's Eye mono data because of an expected, significantly larger systematic uncertainty of the energy reconstruction.) On the other hand the data of the surface detectors show no sign of an *ankle* at a similar energy (right panel in Fig. 4). In the case of the Akeno and AGASA combination this might be related to the transition from one array to another one: the small array is not big enough to collect high statistics and the efficiency of the big array is not well known close to the trigger threshold. Furthermore the method of energy reconstruction is based on electron densities for Akeno and scintillator densities (i.e., electrons and muons) for AGASA data [67]. These problems do not exist for the Yakutsk data. In fact, both surface detector data sets indicate a dip at a much higher energy $\sim 10^{19}$ eV. In addition to this discrepancy concerning the *ankle* the flux obtained with surface detector measurements is higher than that from fluorescence data over the entire energy range. This might be an indication of a systematic difference in reconstructing the energy using ground array and fluorescence data, due most likely to the limited understanding of simulating giant air showers. Using different hadronic interaction models influences the shower characteristics

[2] To account for the experimental energy resolution one should increase the vertical error bars correspondingly and draw them at an inclined angle. We have not done this here to preserve the clarity of the plot.

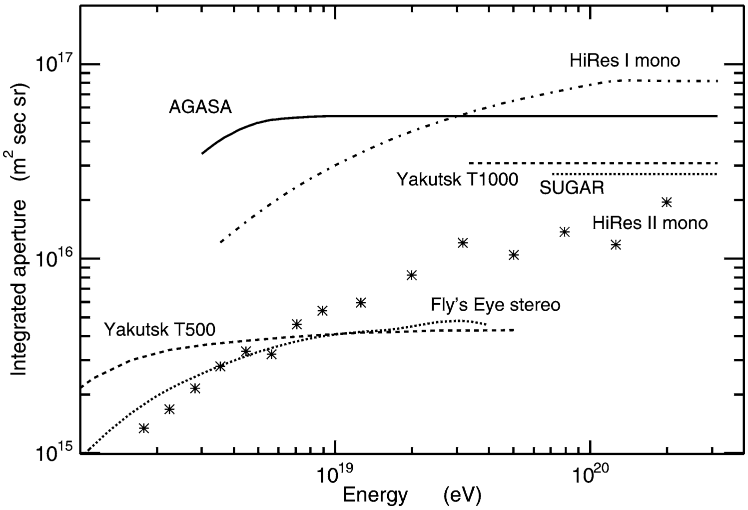

Fig. 2. Integrated aperture of different high energy detectors corresponding to the data shown in Fig. 1. The AGASA aperture refers to all EAS data with $\theta < 45^\circ$ up to May 2003. The two HiRes detectors have different data acquisition periods: HiRes I from June 1997 to February 2003 [72] and HiRes II from December 1999 to September 2001 [26,36]. The integrated aperture of the Yakutsk array includes data taken from September 1974 to June 2001 for T1000, and September 1979 till June 2001 for T500 [76]. The exposure shown for SUGAR is based on the reanalysis of the 5 highest energy events reported in [74] and corresponds to 11 years of operation. The Fly's Eye exposure in stereo mode is taken from [70]. The integrated aperture of the data set used in [33] to derive the Haverah Park flux shown in Fig. 1 is 7.39×10^{12} m^2 s sr.

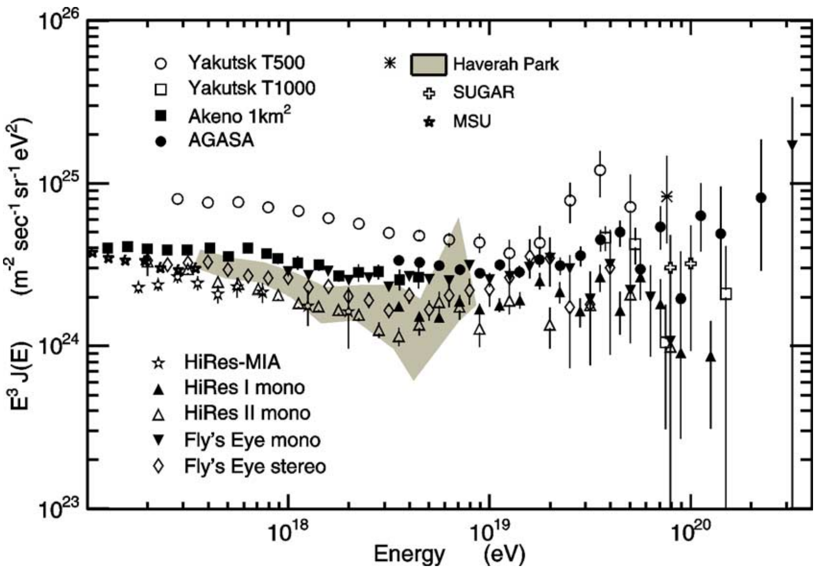

Fig. 3. Comparison of flux measurements scaled by E^3. (For references to the data see Fig. 1.)

at observation level significantly [62–64,77]. Only a hybrid experiment, employing both measurement methods, can investigate such possible discrepancies in an almost model-independent way.

To investigate the compatibility of the various measurements, the systematic error in the assignment of the energy is most important for surface detector arrays, as is the uncertainty in the energy-dependent effective aperture for fluorescence detectors. Here we only briefly discuss the two experiments with the largest integrated aperture, AGASA and HiRes.

The AGASA collaboration has recently studied the systematic error of the energy assignment in great detail [67]. They find a total systematic uncertainty of the energy assignment of about $\pm 18\%$. This estimate includes a 9% contribution characterizing various detector aspects. The main sources of uncertainty are related to shower phenomenology and the simulation of the relation of $S(600)$ to the primary particle energy. The previously applied conversion formula [78]

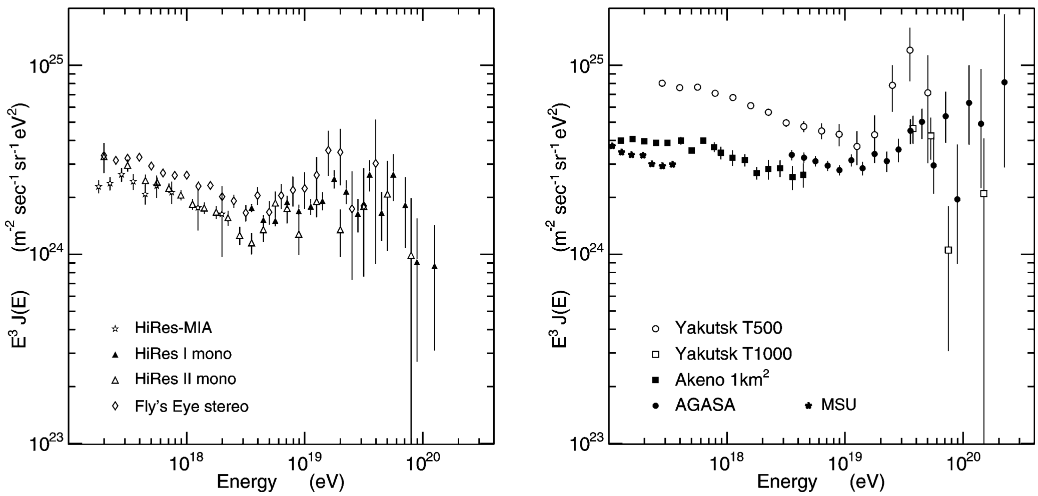

Fig. 4. Cosmic ray flux scaled by E^3. The left panel shows measurements clearly indicating the position of the *ankle* at about 3×10^{18} eV. The other data are given in the right panel. The Haverah Park data also confirms the *ankle* at about 3×10^{18} eV but with marginal statistical significance. (For references to the data see Fig. 1.)

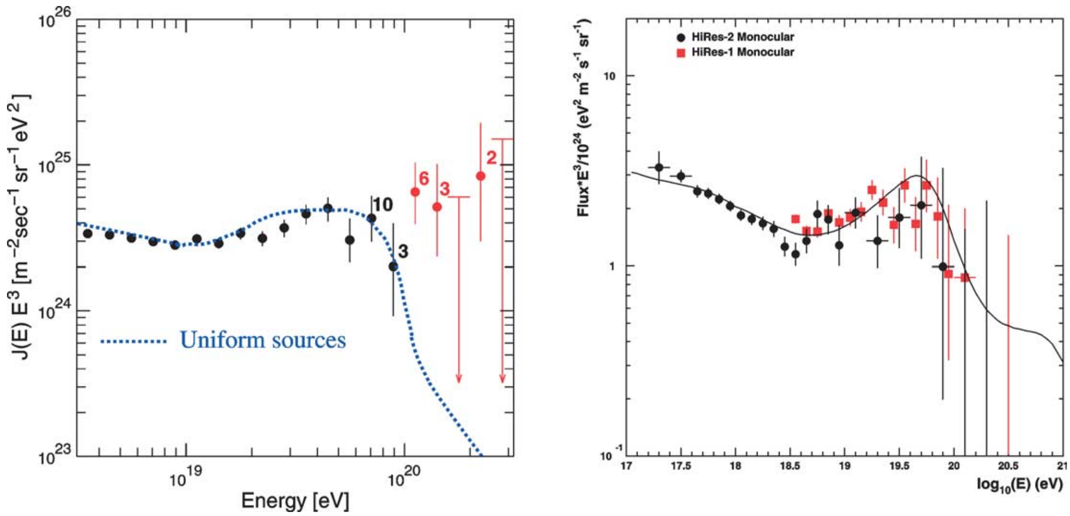

Fig. 5. Comparison of AGASA [28,35] and HiRes [34,82] data with GZK cutoff predictions, assuming an extragalactic cosmic ray flux of protons coming from uniformly distributed sources. The AGASA plot is from [83] and the HiRes plot from [36].

$$E = 2.03 \times 10^{17} \cdot S_0(600) \text{ eV} \tag{1}$$

with $S_0(600)$ being the scintillator signal in units of vertical equivalent muons, is revised upward by 10 to 12% by taking the altitude of the shower core positions and results of newer EAS simulations into account [67]. At the same time newly introduced corrections for the shower front structure and delayed particles lead to a shift of about the same size but opposite direction.

In case of the HiRes experiment the energy reconstruction is closely related to properties of the atmosphere which is serving as a calorimeter. At the same time, atmospheric properties also determine the aperture of the detector. The HiRes flux measurements (HiRes I and HiRes II mono) are found to have similar systematic uncertainties [26]. The main contributions to the systematic uncertainty of the flux are the absolute calibration of the detectors (±10%), the limited knowledge of the air fluorescence yield (±10%) [79] and atmospheric conditions. In addition the part of the primary energy that is not transferred to the electromagnetic shower component has to be corrected for (±5%) [80]. Adding quadratically all errors one obtains a total systematic uncertainty of 21% for the flux $J(E)$ [26]. The overall systematic uncertainty of the energy reconstruction only is given as ±17% in [72].

As discussed by many authors (see, for example, [81]), within the uncertainties given by the different experiments, their results are in agreement with each other at energies below $10^{19.5}$ eV. However, the measured fluxes at $E > 10^{20}$ eV are strikingly different: the AGASA data exhibits no sign of a GZK cutoff [28] whereas the HiRes measurements are compatible with a GZK cutoff as expected for a proton dominated flux and uniformly distributed sources [34,82], see Fig. 5.

Assuming uniformly distributed sources of UHE protons and treating the normalization of the expected energy spectrum as a free parameter AGASA expects to observe 1.8 events with 11 actually detected. This corresponds to a 4.5σ deviation from the GZK cutoff spectrum [35]. Other assumptions on the shape of the GZK proton spectrum lead to the prediction of 2.4 expected events [84,85], corresponding to a deviation of 3.9σ. In contrast, the HiRes spectrum can be well described by a model with GZK cutoff ($\chi^2/\mathrm{ndf} \sim 1.3$) [26]. A similarly good agreement between GZK model predictions and the Yakutsk data was shown by several authors (for example, [81,85]).

The discrepancy between the spectra of the two experiments with the highest exposure is, due to the low event statistics, of limited statistical significance. Adjusting the energy scales of the experiments within their published uncertainties results in a significance of the deviation between the two spectra of the order of 2σ [86,87]. Only the collection of a larger data sample will help to solve the question of the shape of the spectrum at energies above 10^{20} eV.

3. Arrival direction distribution

3.1. Large scale anisotropy

Analyzing the arrival directions of more than 10^5 showers above 10^{17} eV the AGASA Collaboration find an excess of showers coming from directions near the Galactic Center and the Cygnus region [40]. The significance of this excess is maximal if a 20° region near the Galactic Center is considered and reaches a statistical significance of 4.1σ. However, the excess region is at the angular acceptance limit of the AGASA array, which is at a declination of -24°, and the Galactic Center is outside the field of view. Close to the direction of the Galactic anti-Center a deficit of cosmic rays is seen at a level of 3.7σ. Expressed in terms of the amplitude of a harmonic analysis this corresponds to a 4% anisotropy in the energy region from $10^{17.5}$ to $10^{18.2}$ eV.

An analysis of SUGAR data [41] gives an independent confirmation of the excess of cosmic rays from the direction of the Galactic Center. Being located in the southern hemisphere, the Galactic Center is in the acceptance range of SUGAR. Whereas the AGASA excess seems to indicate an extended source, the SUGAR data suggest a point like source within the angular resolution of the array ($\Delta\theta \sim 3^\circ/\cos\theta$, where θ is the zenith angle). The direction of the point source location does not coincide with either the Galactic Center or the AGASA excess region but is closer to the latter one (see Fig. 6).

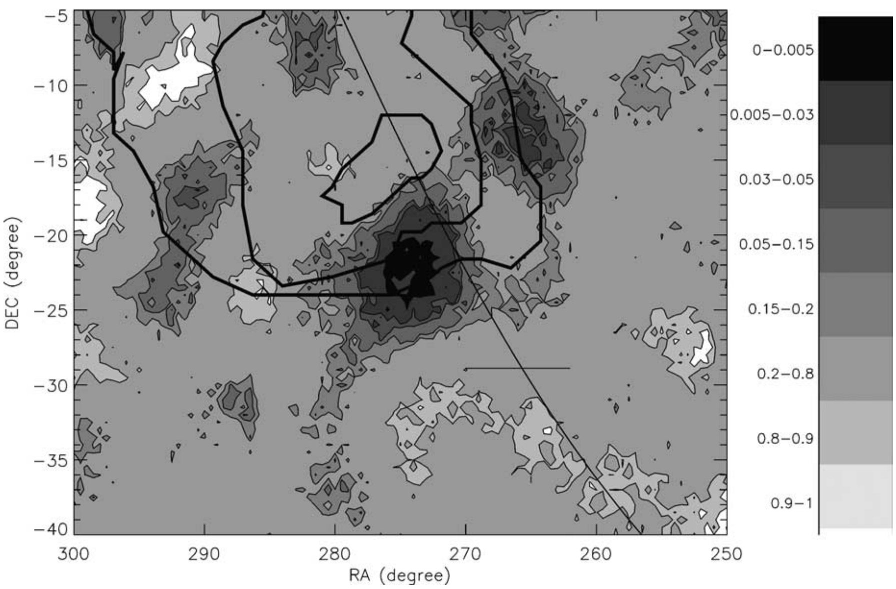

Fig. 6. Map showing the chance probability that the arrival directions observed by SUGAR [41] are compatible with an isotropic arrival distribution. The heavy lines mark the 2σ, 3σ and 4σ contours from the AGASA analysis [40] (from [41]).

An anisotropy study of Fly's Eye data also revealed a small but statistically significant excess of cosmic rays coming from the Galactic plane [42]. The chance probability of the correlation seen in the energy range from $10^{17.2}$ to $10^{18.5}$ eV is estimated to be less than 0.06%. The Haverah Park and Yakutsk arrays are located too far north to be able to see the excess regions of AGASA and SUGAR.

Below $10^{17.5}$ eV no significant anisotropy is found in the AGASA data [40]. This is in agreement with an analysis of more than 135,000 showers of the Yakutsk array with energies from 3×10^{16} to 3×10^{17} eV [88], which finds a dipole amplitude that is compatible with full isotropy.

At energies above $10^{18.5}$ eV the large scale structure of the arrival direction distribution appears, within the limited statistics of the AGASA array, isotropic [40]. This finding agrees with a recent study of the HiRes Collaboration, performing a global anisotropy search based on ~ 1500 events observed by HiRes I in monocular mode [43]. Showers with energies above $10^{18.5}$ eV were included in the analysis, whereas the energy-dependent aperture of HiRes (see Fig. 2) leads to a significantly higher mean shower energy than would be expected for a ground array measurement applying the same energy threshold. The HiRes data are compatible with an isotropic arrival direction distribution.

By combining data from arrays of the northern and southern hemispheres a full sky anisotropy study is reported in [89]. Considering in total 99 showers from AGASA and SUGAR with $E > 10^{19.6}$ no large scale anisotropy is found.

3.2. Small angle correlations

There is a very interesting small angle clustering reported by the AGASA Collaboration [44–46]. This small scale correlation could be a hint for point sources in our cosmological neighbourhood.

Fig. 7 shows the arrival direction distribution of cosmic rays above 4×10^{19} eV as observed by AGASA [45,46]. Although there is apparent overall isotropy, 5 doublets and 1 triplet are found within an angular separation of $\sim 2.5°$ [46] in the AGASA data collected through the end of 2000. The AGASA array has a shower reconstruction uncertainty of about 1.8°, slightly decreasing at high energy [45] in the relevant energy range. Adding quadratically the errors of two independent showers, one naturally expects a correlation signal to be most pronounced for separation angles smaller than $\sim 2.5°$. The chance probability of the small scale correlation found in the AGASA data is the subject of an ongoing discussion and different authors have obtained results ranging from less than 10^{-4} to 3×10^{-3}, see discussion in [135]. In [46] also the energy spectrum of correlated showers, having arrival direction differences of less than a few degrees, is investigated and found to be $\mathrm{d}N/\mathrm{d}E \sim E^{-1.8\pm0.5}$.

First studies of HiRes data did not confirm small scale clustering [90,48]. The HiRes I (mono) data set has higher statistics than that of AGASA, but it is characterized by a highly asymmetric angular resolution. Whereas the arrival direction can be determined very well orthogonal to the shower-detector plane, it is only poorly reconstructed within this plane, see [78] for more details. No significant small angle correlation is found and a limit of less than 4 doublets at 90% c.l. is derived [90]. The HiRes data set obtained in stereo mode has considerably lower statistics (compare Fig. 2). On the other hand the angular reconstruction has an uncertainty of less than 1°, making this data set particularly interesting. No significant clustering is seen for the more than 160 showers at $E > 10^{19}$ eV used in this analysis [48].

The authors of [91] included showers above 4×10^{19} eV from all four surface arrays of the northern hemisphere in their small scale correlation analysis. The combined data set is found to contain many clusters. However the statistical significance is

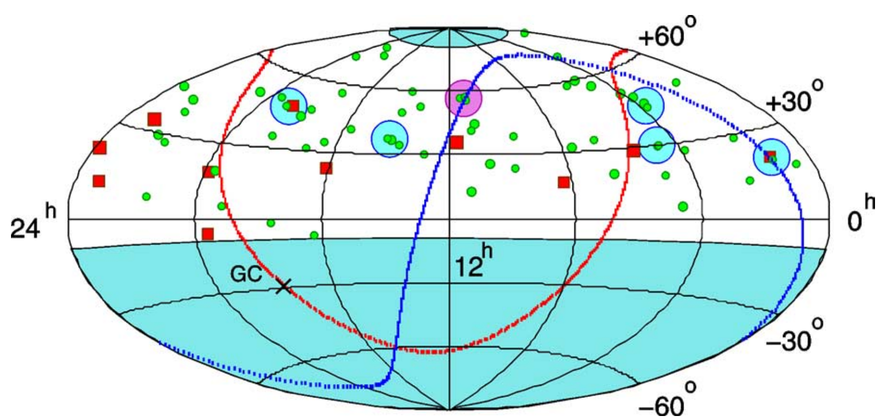

Fig. 7. Arrival direction distribution of cosmic rays with $E > 10^{19.4}$ eV. The small circles and squares are arrival directions of cosmic rays above $E > 10^{19.6}$ and 10^{20} eV, respectively. The big light circles mark doublets and the single big dark circle represents a triplet [45]. This plot is an updated version of the one shown in [45] which is available at [83].

low (∼ 10%). On the other hand, there are indications for a correlation with the supergalactic plane. Restricting the considered arrival directions to the range of ±10° off the supergalactic plane the chance probability for finding doublets and triplets decreases to the order of 1%.

Studies of small angle correlations with the Yakutsk array are difficult because of the angular resolution of the shower axis reconstruction, which is about 4° [92]. Nevertheless, at much lower energy, clusters of the arrival directions of showers in the energy range $1.3{-}4 \times 10^{17}$ eV are found in [47]. The direction of these clusters seem to support a correlation with the supergalactic plane. Dividing the observed cosmic ray showers into isotropic and cluster components this correlation can be enhanced significantly [93].

There is a long history of searches for correlations with astrophysical point sources such as colliding galaxies and powerful radio galaxies. It appears almost impossible to assess unambiguously the chance probability of such correlations since highly incomplete catalogs of astrophysical objects necessarily have to be used in these analyses. We only want to mention the correlation with BL Lacertae, at a distance exceeding the GZK energy loss length, found in the AGASA and Yakutsk high energy data [94,95].

4. Cosmic ray composition and gamma-rays

4.1. Mass composition

The pioneering work of Fly's Eye [52] gave the first indications of a systematic change of the cosmic ray mass composition at high energy. Analyzing the mean depth of shower maximum, $\langle X_{\max}\rangle$, a change from an iron dominated composition at 10^{17} eV to a proton dominated composition at $10^{19.3}$ eV was found. An analysis entirely based on the mean $X_{\max}$ is strongly model dependent, see, for example, [55,62,66,96]. In Fig. 8 (left panel) a compilation of measurements of $\langle X_{\max}\rangle$ is shown together with model predictions. Adopting the QGSJET01 model [31,32,99] the conclusions of [52] still hold, though a mixed composition is expected at 10^{17} eV. On the other hand, on the basis of models like SIBYLL 2.1 [100–102] or DPMJET 2.55 [103] a much more moderate change of the composition is derived.

A more model independent way of searching for rapid changes from heavy to light elemental compositions is the analysis of the elongation rate [104,105], which is bound from above by that of electromagnetic showers (i.e., produced by primary gamma-rays), $\mathrm{d}\langle X_{\max}\rangle/\mathrm{d}\log E < \ln(10)X_0$. Here X_0 denotes the radiation length in air. The elongation rates of the Yakutsk and Fly's Eye measurements are close to the electromagnetic limit which means any model with scaling violations will predict a change to a lighter composition [55,106].

In the right panel of Fig. 8 we separately show the recent results obtained from HiRes-MIA [50,71] and HiRes stereo observation data [51]. In contrast to the old measurements of Fly's Eye [52] and Yakutsk [54] the HiRes data indicate a change from an iron-like to a proton dominated composition already at 10^{18} eV. The two independent measurements are consistent in the overlap region. The large elongation rate of the low-energy data of ∼ 93 g/cm^2 [71] can only be understood in terms of a

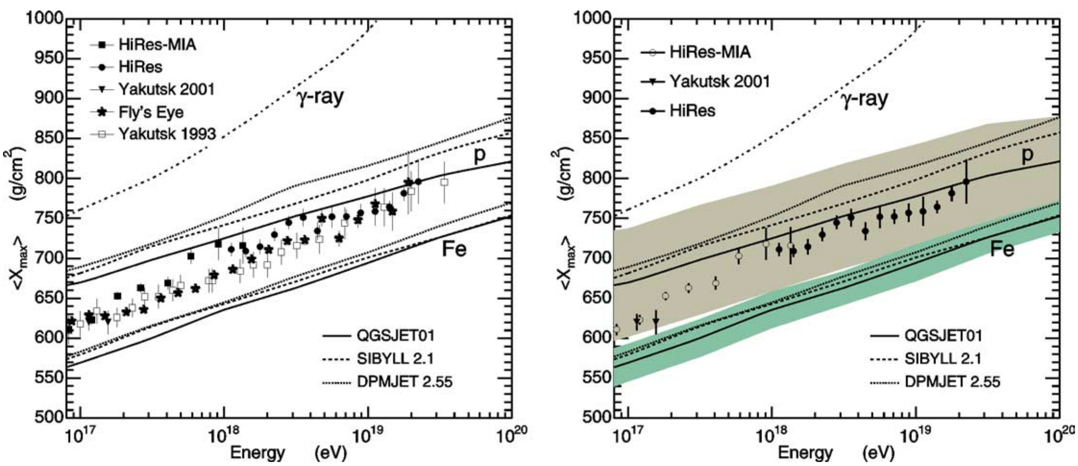

Fig. 8. Compilation of measurements of the mean $X_{\max}$ of very high energy air showers. The data are from Fly's Eye [52], HiRes-MIA [50], HiRes [51], and Yakutsk 1993 [54] and 2001 [97]. The model predictions are calculated with CORSIKA [30] and are taken from [96,98]. The right panel shows only measurements published after 1999. The QGSJET predictions on fluctuations of the depth of maximum of individual showers are indicated by the shaded (cross-hatched) area for proton (iron) primaries.

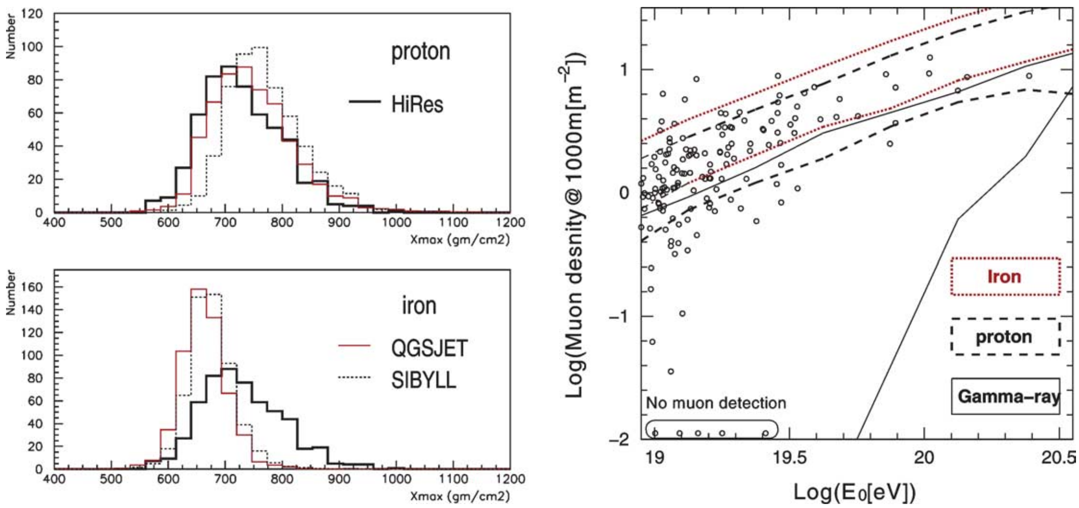

Fig. 9. Left panel: Distribution of $X_{\max}$ as measured by HiRes in stereo mode. The upper (lower) panel shows the data together with model predictions for proton (iron) induced showers (from [51]). Right panel: muon density at 1000m from the shower core. The shower measurements are shown together with lines enclosing the 1σ band of the expectation value for different primaries (from [109]).

change of composition. The muon density measured by MIA [107] indicates also a change from a heavy to light composition. However, the observed muon densities are higher or similar to the expectation for iron primaries and not compatible with medium or light nuclei. This discrepancy might be related to the hadronic interaction model QGSJET, on which the HiRes-MIA analysis is based. Using SIBYLL makes the inconsistency worse as it predicts fewer muons.

The model ambiguity of the interpretation of $\langle X_{\max}\rangle$ might be resolved to some degree by studying the measured distribution of $X_{\max}$ [53]. The fluctuations of proton induced showers are considerably larger than those of showers of heavy primaries, see shaded and hatched bands in Fig. 8 and [108] for more details. Fig. 9 (left panel) shows a comparison of the HiRes stereo observation data with predictions of the QGSJET01 and SIBYLL 2.1 models. Within the limited statistics, both models are compatible with the data if a mixture of different elements is assumed. Adopting a two-component composition using proton and iron as primary cosmic rays one gets 80% (70%) protons using QGSJET (SIBYLL) as reference scale [51].

Another method of studying the primary cosmic ray composition was recently applied to AGASA data in [109]. A higher muon density is expected in showers induced by heavy elements as compared to protons, see [108] for more details. Gamma-ray induced showers are characterized by the smallest number of muons. Similar to the depth of shower maximum, muon densities fluctuate considerably from shower to shower and the interpretation of the measurements depends strongly on the applied hadronic interaction model. The right panel of Fig. 9 shows the muon densities of AGASA showers with energies above 10^{19} eV. Comparing the data with model predictions from AIRES [110] and QGSJET01 the following limits on a two component composition are derived: less than 35% iron in the energy range 10^{19}–$10^{19.5}$ eV and less than 76% at higher energy (90% c.l.) [109]. These limits are compatible with the aforementioned new HiRes and old Fly's Eye results which are based on $X_{\max}$ measurements.[3]

A re-analysis of Haverah Park data was done in [56] to measure the cosmic ray composition. The authors employ the sensitivity of the steepness of the lateral particle distribution to the shower development height, which in turn depends on the depth of shower maximum, see [113] for more details. It was found that the predictions of CORSIKA with the QGSJET98 model give a good description of the data if a two-component composition with about (66 ± 2)% iron is used in the energy range from 2×10^{17} to 10^{18} eV. At higher energy (from 10^{18} to 2×10^{18} eV) indications are seen for a transition to a lighter composition. This is supported by the number of inclined showers with $E > 10^{19}$ eV that have triggered the Haverah Park array [39]. The data analyzed in [39] agree well with simulations assuming all primary particles are protons, though no mass composition study was done. On the other hand, a first study of the time structure of Haverah Park showers with zenith angles less than 45° gives some indication of an iron-dominated composition in the same energy range [114].

[3] A previous measurement with the Akeno instrument [111] in the energy range $10^{16.5}$–$10^{19.5}$ eV appeared to be in contradiction to the Fly's Eye composition interpretation [52], see also the analysis in [112]. We do not discuss these results here as they are based on old simulations.

Results from a re-analysis of Volcano Ranch data similar to the Haverah Park study became available recently [57,115]. Using ~ 370 showers in the energy range from 5×10^{17} to 10^{19} eV a fraction of $(75 \pm 5)\%$ iron is found for a two component composition and QGSJET01. Using the previous version of QGSJET increases the expected contribution of iron by about 14%.

There are strong indications for shortcomings in the shower simulations, due probably to limitations of modeling hadronic interactions. The mean $X_{\max}$ of the HiRes-MIA data is not consistent with the measured muon densities of the same events. The situation is similar for Haverah Park data: the conclusions on mass composition are different if the time structure of the shower front is used instead of the muon yield that determines the rate of inclined showers. Discrepancies of this type are also known from air shower studies at much lower energy (for example, see [116,66]). Every ultra high energy air shower contains many sub-showers of lower energy. Hence, in addition to accelerator measurements of hadronic multiparticle production [117,118], measurements and understanding of air shower data at lower energy are very important to tune and validate the used hadronic interaction models [119].

4.2. Gamma-ray limits

There are no indications of a substantial fraction of gamma-rays in the high energy cosmic ray flux.

The highest energy event of Fly's Eye ($E \sim 3.2 \times 10^{20}$ eV) [38] is most likely not of gamma-ray origin. Comparing the measured shower profile with Monte Carlo simulations shows that this event is well described by hadronic showers [120,121]. However, due to the large reconstruction uncertainty of the atmospheric depth of the shower profile, a photon cannot be excluded [121].

The deeply penetrating muon component of inclined showers is used in an analysis of Haverah Park data in [39,122]. Using the primary cosmic ray flux parametrization of [4], less than 48% of the observed events above 10^{19} eV can be photons (95% c.l.). At energies above 4×10^{19} eV this limit is 50%.

Based on the analysis of muons observed in high energy showers at AGASA the following upper limits were derived in [109,123]: 34%, 59% and 63% for primary energies above 10^{19}, $10^{19.25}$ and $10^{19.5}$ eV, respectively (95% c.l.).

Combining the measurements of different experiments, the limits to the photon flux can be improved. A first estimate of the fraction of gamma-rays at $E > 10^{20}$ eV is discussed in [49]. Not more than 33% of the cosmic rays can be photons at 95% c.l. if one assumes that none of the 5 AGASA events above 10^{20} eV, for which a good muon measurement exists, is a photon.

5. Conclusions and outlook

Since 1999 many new measurements and analyses of data have increased our knowledge on ultra high energy cosmic rays. However, the main conclusions given in the review of Nagano and Watson [4] still apply.

- Cosmic rays with energies exceeding 10^{20} eV do exist. The energy dependence of their flux for $E > 10^{19.5}$ eV is still unknown because of the low event statistics and seemingly contradictory results of the AGASA and HiRes measurements.
- The arrival direction distribution of cosmic rays is, within the statistics of the measurements, isotropic even at the highest energies. There is only a small but statistically significant anisotropy at $\sim 10^{18}$ eV, where an enhancement of cosmic rays coming from the Galactic Center is seen. Indications of arrival direction multiplets exist, but the statistical significance of this small angle correlation is still very low.
- The mass composition of ultra high energy cosmic rays seems to become lighter with increasing energy. Measurements above 10^{19} eV favour a light composition, which appears to be proton dominated if QGSJET is used to interpret the data. However, all composition analyses show such a strong dependence on the hadronic interaction models used for shower simulation that a large fraction of heavy primaries cannot be excluded. Below 10^{18} eV the composition is probably heavier with a dominating contribution from iron. There are significant discrepancies between the different measurements and analyses in the range from 10^{18} to 10^{19} eV, which again might be due to problems of correctly simulating high energy air showers.
- There are no indications of a substantial fraction of ultra-high energy gamma-rays in the cosmic ray flux. Currently the limits on the gamma-ray flux are dominated by the low statistics of the observed showers.
- Experiments with larger collection area and new detection techniques are needed to significantly increase the statistics of the observed events. The combination of different detection techniques in single experiments will be the key to understanding systematic effects due to detection methods and our limited theoretical understanding of extensive air showers at ultra high energy. Uniform coverage of the northern and southern sky is mandatory for progressing in determining the arrival direction distribution and possible differences of the fluxes observed at the northern and southern hemisphere [124].
- Parallel to the experimental efforts of collecting many showers of ultra high energy more work is needed to improve our understanding of extensive air showers. In particular, the modeling of hadronic interactions over the entire energy range,

i.e., from the particle production threshold to the highest energies, is of prime importance for reliably interpreting cosmic ray data [65,119].

The near future will bring a large amount of new data on ultra high energy cosmic rays.

The HiRes Collaboration is planning to continue the operation of their detector system for several more years.

In 2003 the installation of the southern part of the Pierre Auger Observatory [125,126] has started in Argentina and data are already taken with both parts of this hybrid detector system. At the time of writing this article 6 of the 24 fluorescence telescopes and more than 200 of the 1600 ground array water Cherenkov detectors are operational. The Auger array covers already now an area of approximately four times the size of AGASA. At the end of 2004 the integrated aperture of the Auger array will come close to that of AGASA, allowing a first meaningful comparison of the results of these experiments. The full installation and commissioning of the southern Auger detector in Argentina is scheduled to be completed in early 2006. Then the Auger experiment will have an area of $3000\,\mathrm{km}^2$, collecting 3000 to 5000 events per year with energies above 10^{19} eV.

Due to hybrid operation about 10% of the Auger data will be of a new quality and systematic errors will be considerably reduced, especially in the energy assignment. Hybrid events will allow a much better calibration of the ground array of particle detectors with less dependence on high energy interaction models. Nearly 90% of the highest energy hybrid events will be detected in stereo mode, i.e., with two or more fluorescence telescopes.

To test the detector concepts, from 2001 to 2003 an engineering array with ~ 40 tanks and 2 fluorescence telescopes was operated [127,128]. During this time about 70 showers were detected in hybrid mode. A first analysis of this data set shows no systematic, significant discrepancy between the energy reconstructed from the fluorescence data and the measured lateral distribution [129].

It is planned to install a similar detector system (Auger North) in the U.S. after 2006. This will give the Auger Observatory nearly uniform full sky coverage and, together with a pointing accuracy better than 1° for energies above 10^{19} eV, allow critical correlation and anisotropy studies.

A new experiment is supposed to enter the field rather soon. The Japanese–U.S. Telescope Array (TA) [130,131] will be located in Millard County, Utah. Its installation is scheduled to start in 2004. Like the Auger experiment, TA is planned as a hybrid experiment employing fluorescence telescopes in 3 buildings positioned around the surface detectors. The ground array will consist of 576 scintillator detectors on a 1.2 km rectangular grid, with an effective area of about 9 times that of the AGASA experiment. An infill array is forseen to measure showers with a lower energy threshold than the Auger detector and will allow comparisons with old data sets in the energy region around 10^{18} eV.

A totally different approach is pursued by the Extreme Universe Space Observatory (EUSO) project [132–134]. The international EUSO Collaboration plans to install a fluorescence and Cherenkov detector system on the international space station ISS. The EUSO detector will view the light produced by extremely high energy air showers in the dark part of the atmosphere from a height of about 400 km. The instantaneous aperture can reach up to 3000 times that of AGASA due to a very large ($\pm 30^\circ$) field of view. This large aperture is expected to allow the measurement of more than 1000 events per year above the experimental threshold of $10^{19.5}$ eV. The installation of the detector on the ISS is planned for 2010 with 3 years of data taking.

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