Ultra-High Energy Cosmic Rays: A Recap of the Discussions at the European Cosmic Ray Symposium 2014

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Abstract. This contribution summarizes the talks, posters, and discussions of the ECRS 2014, held in Kiel, Germany - related to the research field of ultra-high energy cosmic rays (UHECR). Here, the definition of UHECR is cosmic rays with an energy above approximately 0.1 EeV, i.e. $10^{17}$ eV, and the corresponding sessions were named HECR-II. Recent experimental results, like the identified heavy knee in the cosmic ray energy spectrum or the hotspot in the arrival direction of cosmic rays with highest energy, will be shown and discussed in relation to the need and requirements of future experimental efforts.

1. Introduction

The spectrum of primary cosmic rays covers a large energy range from a few GeV to above 100 EeV, where the flux decreases very fast with a factor $\approx 1000$ per decade of energy. In first order the spectrum can be described by power laws, where three evident features define slight changes of the index of these power laws (see Fig. 1): the knee, the ankle, and the final flux suppression. Whereas at lower energies the measurements are performed in a direct way with compact detectors in space or at high-flying balloons, primary cosmic rays above energies of about 100 TeV have to be investigated by observations of extensive air showers (EAS) [1]. EAS are generated when high-energy cosmic particles enter the atmosphere. Forward-boosted secondary particles as well as emitted light during the development of the EAS in various frequency ranges form the detectable products. Using large-area ground-based detector installations for registering various components of the EAS, the direction, the energy, and the mass of the primaries are estimated. The variety of possible EAS observation techniques is displayed in Figure 2.

By such indirect studies of the primary cosmic rays a steepening of the power-law spectrum at around 35 PeV, known as the knee, has been identified. At higher energies around 3-5 EeV appears to be a further change of the spectral index, called the ankle. Finally, in the energy region above ca. 50 EeV, a cut-off like feature of the cosmic ray spectrum is observed.

Many theoretical models (often also contradictory ideas) exist to describe the origin of the observed features, but for none of them a convincing explanation exists, in particular concerning the details. The gross picture explains cosmic rays as follows: Galactic sources, in particular Supernova Remnants, accelerate fully ionized nuclei to a maximum energy corresponding to the knee-energy. However, the acceleration is more effective for nuclei of higher charge, therefore,
Figure 1. The all-particle spectrum of cosmic rays as measured by various experiments (adapted from [2]).

for iron nuclei this maximum energy is expected at around 100 PeV. The transition to cosmic rays of extra-galactic origin occurs at energies where the galactic component vanishes and the ankle could be the signature of this transition.

Cosmic rays of highest energy will interact with the cosmic microwave background leading to a maximum energy at Earth for extra-galactic sources (Greisen- Zatsepin-Kuz’min, or short GZK cut-off) which is predicted for energies were the third structure is observed, but that could also mark the maximum energy of acceleration of extra-galactic sources.

Any explanation of the features of the cosmic-ray spectrum needs sufficiently detailed knowledge of its shape and of the variation of the mass composition of cosmic rays. In addition, anisotropy studies at various scales, energy ranges, and primary mass groups are needed to solve the puzzle of the origin of UHECR. But, it might be that even that will not help in understanding the astrophysics of the high-energy cosmos. Here, the most promising ansatz for the future is the multi-messenger particle astronomy, i.e. combining information from measurements of many observables from the same sources to understand the acceleration and propagation processes in detail. The information from high-energy cosmic rays, gamma rays, and neutrinos, at best paired with multi-wavelength electromagnetic observations, and even, in far future, of gravitational waves have to be combined in experiment and theory.
In this contribution discussions are focused on the part of the energy spectrum above the energy region of the knee, experimentally investigated by the observation of extensive air showers\(^1\).

2. Experimental Status: Approaching the Ankle
A decade ago, the KASCADE experiment [3] has shown that the knee feature is due to a distinct break in the intensity in the light component of cosmic rays (Z < 6), only, where the difference in the energies of the knee features of protons and Helium nuclei is in agreement with the assumption of a rigidity (charge) dependent knee [4]. Compared to the knee energy, the range \(10^{16} - 10^{18}\) eV stayed somehow unexplored until recently, though the study of primary energy spectrum and mass composition in this energy range is of crucial importance for understanding origin and propagation of cosmic rays, as here the transition from galactic to extra-galactic origin of cosmic

\(^1\) Naturally, not all current topics of the field were presented at the conference, and even not all contributions given are covered by this review, which is based on a few very personal impressions. I apologize for the incompleteness and not paying attention to detail, but hope to touch some aspects of interest for a more general readership.
Figure 3. Left panel: The all-particle, cosmic-ray energy spectrum by three different experiments (KASCADE-Grande [10]; Tunka-133 [13]; IceTop [14]). Right panel: All-particle, light-mass enriched, and heavy-mass enriched energy spectra from KASCADE-Grande. One all-particle and the heavy enriched spectra is from one analysis, the other all-particle and the light primary spectrum result from a larger data set with higher energy threshold (from [6]).

rays is expected.

Now, at the ECRS 2014, three experiments presented results for the all-particle energy spectrum, at least. I discuss in the following the spectra of cosmic rays in the range from $10^{16}$ to $10^{18}$ eV obtained by KASCADE-Grande [5, 6], Tunka-133 [7, 8], and IceTop [9]. Despite the overall power-law behavior of the all-particle spectrum (see Fig. 3), there are some structures observed, which do not allow to describe the spectrum with a single slope index. Of course, these structures are smaller than the well-known knee or ankle features, but statistically significant, found by KASCADE-Grande and confirmed by Tunka-133 and IceTop. There is a clear evidence that just above $10^{16}$ eV the spectrum shows a concavity, i.e. a hardening of the spectrum appears. Another feature, also seen by all three experiments, is a small break at around $10^{17}$ eV, which appears at KASCADE-Grande at a little lower energy than for the other two experiments. Applying a second power law a statistically significant change of the index is similarly obtained at all three experiments.

KASCADE-Grande has shown that the spectral form does not depend on the hadronic interaction model in use [15]. This is not true for the absolute flux, where a difference of 15-20% can appear. As KASCADE-Grande measures the total number of electrons and muons, separately, these differences are related to the absolute normalization of the energy scale by the various models. IceTop has reported results on the basis of SIBYLL and QGSJet, but found the difference very small, which is probably owed to the observation level close to the shower maximum. Tunka-133’s measurements are based on a calorimetric method$^2$; i.e. the energy calibration is seen as less dependent from the hadronic interaction model (for a more detailed discussion see [16]).

The main difference of the three spectra is the absolute normalization to the energy scale, which moves the found structures slightly in energy and by that also in the absolute flux. But the spectra agree nicely within the given systematic uncertainties. The normalizations depend

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2 Whereas imaging fluorescence or Cherenkov telescopes can resolve the shower development in the atmosphere directly, Cherenkov arrays like Tunka-133 need to analyse the lateral or time distribution of the light to reconstruct the composition sensitive shower maximum.
Figure 4. All-particle energy spectra of the low energy extensions of the Telescope Array (left, [17]), and the Pierre Auger Observatory (right, [18]).

on the calibration (hadronic interaction model) as well as on the treatment of including the a-priori unknown elemental composition. Despite the fact that the three experiments use different observation techniques, are located at different observation levels, and use different hadronic interaction models to interpret their data, the agreement within 20% of the total flux is surprisingly good. On one hand this confirms the structures found so far, but on the other hand it also confirms the high quality of the data taken by these modern experiments and also the validity of the hadronic interaction models (at least for this energy range and for the observables measured).

At the present conference, Sven Schoo also discussed the recent results of KASCADE-Grande on the investigations of the elemental composition, where the goal is the reconstruction of individual mass group spectra [6]. Structures observed in these individual spectra provide stronger constraints to astrophysical models of origin and propagation of high-energy cosmic rays than the all-particle spectrum or a mean logarithmic mass. The evolution of the mass parameter as a function of energy keeps track of the evolution of the composition, and allows an event-by-event separation between light, medium and heavy primaries, at least. The application of this methodical approach to shower selection and separation in various mass groups is performed and cross-checked in different ways, where the right panel of Figure 3 shows the main results: The reconstructed spectrum of the electron-poor events, i.e. the spectrum of heavy primaries, shows a distinct knee-like feature at about $8 \cdot 10^{16}$ eV [11]. Hence, the selection of heavy primaries enhances the knee-like feature that is already present in the all-particle spectrum. In addition, an ankle-like feature was found in the spectrum of the electron-rich events, e.g. light elements of the primary cosmic rays, at an energy of $10^{17.08 \pm 0.08}$ eV [12]. This feature can be interpreted as a first experimental hint for an early appearance of an extra-galactic, light mass cosmic-ray component.

Both large observatories, the Telescope Array and the Pierre Auger Observatory have been setup with a denser array on a small part of its total area, called TALE and Auger Infill, respectively. First all-particle spectra have been presented by these installations at the conference [17, 18] displayed in Figure 4. In case of TALE, a reconstruction of the fluorescence telescope data is applied, which takes into account also the measured Cherenkov light which leads to a significantly lower energy threshold. The shown preliminary spectrum confirms the beforehand found spectral features below the ankle.

Denis Allard examined the energy range of the transition and the experimental results from a theoretical point of view [19]. He concluded that the observed light composition ankle at 100 PeV indeed could be the signature of an early appearance of cosmic rays of extra-galactic origin.
Figure 5. Scenarios to explain the flux and shape of the cosmic-ray energy spectrum at the highest energies measured by the Auger observatory (from [19]). Left: the (GZK-)propagation model, where the cosmic rays are accelerated to the indicated very high energy of and the spectral shape arise from propagation effects; Right: the maximum acceleration model, where the cut-off starts with primary protons at an energy of $E_{\text{max}} = 10^{18.4}\text{eV}$ and the flux of the other primaries cut according to their charge at $E = Z \cdot E_{\text{max}}$.

This is also in agreement with a scenario where the spectrum at the highest energies and the flux suppression (see next chapter) is explained by reaching the maximum acceleration power at the source regions. For a conclusive explanation, however, more experimental data is required at all energies of UHECR. The planned LHAASO experiment [20] at lower energies as well as the TALE and Auger Infill installations will contribute to set more constraints on the theoretical models.

3. Experimental Status: The Highest Energies

Mainly two experiments contribute presently to the investigation of cosmic rays of the highest energies, i.e. above the ankle. These are the Pierre Auger Observatory ([21], and references therein) located in Argentina viewing the Southern Hemisphere of the sky, and the Telescope Array ([22], and references therein) in Utah, US sensitive to the Northern Sky. Both experiments detect air showers by the hybrid technique, i.e. by an array of particle detectors operating 24 hours per day plus fluorescence telescopes, where a calorimetric measurement of the EAS (therefore reaching a good composition sensitivity) is possible, paid by the price of a significantly reduced duty cycle as this technique can only be performed in clear, moonless nights.

The reported [17, 23] all-particle energy spectra of both experiments are displayed in Figures 1 and 4. Both experiments have observed a clear flux suppression at an energy of $\approx 5 \cdot 10^{19}\text{eV}$. Where the absolute flux agrees at both experiments at energies below and around the ankle, the Telescope Array reports a systematically higher flux at the highest energies compared to the Pierre Auger Observatory. Taking into account the statistical and systematic uncertainties of both experiments, however, the difference is still possible by instrumental effects. But, the interesting question is now why such a difference is not visible at lower energies when it is based on systematic uncertainties. As both experiments use similar techniques of detection, the question is allowed if the reason can be due to the fact that the observation happens at different hemispheres of the Earth?

The most important question, however, is related to the origin of the flux suppression. It
The distribution is created by using an oversampling of 20 degree. Included are 72 events from 5 years of data taking. The observed hotspot is located south of the supergalactic plane with a significance of more than five sigma (by Li-Ma calculation). From [17].

could be either due to the predicted and expected GZK-effect [24, 25] or by exceeding the maximum energy of acceleration processes at the sources of the cosmic rays. For the latter case a dependence on the charge Z of the maximum energy for the individual primary masses is expected. Also a mixture of both scenarios is possible.

The measured all-particle spectrum is explainable by both scenarios (Fig. 5) [19, 23, 26], or to be more precise, both scenarios are not perfectly in agreement with the data, despite the large uncertainties still present in the measurements. To answer the question of the true scenario a detailed determination of the elemental composition of the cosmic rays is needed. Unfortunately, this is hampered at the highest energies by the low duty cycle of the mass sensitive fluorescence measurements. No new results on composition could be presented at this conference. But, there are methodical improvements to extract composition information also from the surface detectors to overcome the low duty cycle of the fluorescence measurements, presented by Ruben Conceicao [27], e.g.. Further constraints on the composition could be obtained by determining limits of (or detect) primary photons and neutrinos at energies around $10^{18}$ eV. The concept is based on the fact that protons interacting with the cosmic microwave background generate those gammas and neutrinos (so-called GZK particles). Hence, such limits will constrain the content of primary protons on the total flux at the energy range of the flux suppression. The limits could be improved over the last years, but the necessary sensitivity is not yet reached to additionally constrain the models.

An independent access to the data is the study of the arrival directions of the measured cosmic rays. At the conference an interesting hotspot was discussed observed by the Telescope Array for events above the flux suppression energy (Fig. 6). After six years of data taking a large-area hotspot is visible with a significance of meanwhile more than five sigma [17]. This is of high interest, as at the highest energies it is expected that the deflection of the cosmic rays (at least of the singly-charged protons) is small so that the source can be observed directly.

3 The Greisen-Zatsepin-Kuz’mint limit (GZK limit) is a theoretical upper limit on the energy of cosmic rays coming from distant sources. The limit is set by slowing-interactions of cosmic ray protons (photo-pion production) with the microwave background radiation over long distances. For primary iron nuclei a similar effect (photodissociation at giant dipole resonances) is expected to start at roughly the same energy.
However, as there is no clear counterpart of a possible source behind this hotspot the origin is presently neither confirmed nor understood.

In summary, despite the large progress in the detection of UHECR and its connected achievements in the analysis of the data the mystery of the origin of the UHECR is not yet solved. The most urgent problems and challenges for the community can be listed as

- Explaining the results (theory): None of the existing theories is able to explain all the measurements, where this can also be reasoned in the statistical accuracy and quality of the data.
- Statistics at highest energies: Still the statistical accuracy is far too small for detailed analyses at the highest energies.
- Better composition measurements: to decide on the astrophysical origin of the flux suppression the elemental composition has to be determined as accurately as possible.
- Understanding of the air showers: any reconstruction and interpretation of the air-shower measurements relies on the understanding of the shower development in the atmosphere.
- Particle physics with UHECR: Studying the hadronic interaction processes via air-shower observables helps to improve the simulations as well as gives complementary information to accelerator experiments (at a much higher interaction energy).
- What is the best detection technique to reach these goals?
- Multi-messenger particle astronomy: The answer to the big question ‘What is the origin of cosmic rays?’ can probably only be solved by combining the information of many messengers sent by the sources, i.e. high energy gammas, neutrinos, and cosmic rays.
- And finally: understanding the source, acceleration and propagation of cosmic rays (theory).

In the following I will touch some progress in these challenges as far as reported at the conference.

4. Presented Theoretical Achievements

Only a few theoretical papers related to UHECR were discussed at this conference. There are still too many free parameters to develop a consistent theory of source, acceleration, and propagation of UHECRs describing all (partly also contradicting) observations. For example, it is still not fully excluded (even though implausible\(^4\)) that the entire cosmic ray spectrum is of galactic origin (see the contribution of Volkov et al. [28]). However, achievements were presented how to work with the available data for getting deeper insights. Two examples shall be given here:

Ptuskin [30] discussed a method to obtain the source spectrum of cosmic rays, i.e. the spectrum after acceleration but before propagation, by means of the measured spectrum on Earth. Taking into account different possible composition scenarios and by solving the inverse transport problem the source spectra are obtained. Interestingly, the relatively small differences in the measured spectra between Auger and TA lead to significantly different source spectra (see Fig. 7).

Alves Batista [31] studied the effect of magnetic fields to the propagation of UHECR and came to the conclusion that a much better understanding of both, the galactic and the extra-galactic magnetic fields as well as the general matter distribution in the Universe is needed for pursuing UHECR astronomy. The studies show that relatively small changes of the magnetic field and/or matter distribution alter the arrival pattern of UHECR on Earth significantly.

\(^4\) The model described in [28, 29] focuses on the possibility to accelerate particles within our Galaxy to \(10^{20}\) eV, but the main argument for an extra-galactic origin of the highest energies is the non-observation of significant anisotropies at \(10^{18}\) eV, which is ignored in this model.
5. Do we Understand the Measurements?

Both techniques applied to measure the EAS generated by UHECR, the fluorescence and the particle detection technique do still have large systematic uncertainties in calibrating the absolute energy and mass scale of the primary cosmic ray. Besides the intrinsic shower-to-shower fluctuations these are the main sources hampering a sufficient energy resolution of better than $\approx 15 - 20\%$.

Concerning the fluorescence detection technique, in the last decade, in particular by laboratory measurements, many efforts were done to understand the transmission of the light through the atmosphere, to control the temperature and pressure dependence of the fluorescence light yield and scattering, to understand effects of aerosols and ozone, and to study the absolute fluorescence yield. A nice and valuable summary of these efforts was given by Bianca Keilhauer [32]. In the conclusions she stated that obviously the understanding of fluorescence light emission and transmission is essential for the air-shower interpretation, but that meanwhile a consistent and comprehensive description of the fluorescence emission is available. However, the absolute scaling (fluorescence yield) is still the main unknown parameter and consequently the largest uncertainty at the interpretation and calibration of the air showers.

An interesting study was presented by Stefanie Falk [33], where the transmission of the light in the atmosphere was compared for telescopes located on Earth and in Space. Figure 8 shows that there are indeed large differences. For example, for a wavelength of 337 nm (a peak in the fluorescence emission spectrum) only 2% of the light is transmitted to the ground telescope, whereas, due to the less dense atmosphere, 50% of the light reaches the telescope in space. However, in space the absorption of the light by the ozone layer plays a non-negligible role and reduces the light by another 6-10% (not shown in Figure 8, but discussed in [33]).

For air-shower measurements with an array of particle detectors at ground, (a non-calorimetric detection), the interpretation depends heavily on the understanding of the air-shower development, i.e. on the reliability of the hadronic interaction models in use [34]. There

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5 Plans exist to install a sophisticated fluorescence telescope at the International Space Station observing the air-shower developments in the atmosphere from above. This project is called JEM-EUSO, see chapter 7 of this paper.
were a lot of improvements of the model descriptions in the last years based on both, multi-observable measurements of EAS (mainly by KASCADE) and by LHC results, and the latest generation of models agree well to each other as well as to a large extend also to the EAS measurements - at least at energies lower than $10^{17}$ eV. For the highest energies, however, still the interaction physics have to be extrapolated by three orders of magnitude, and also the important phase space for the EAS development (the extreme forward direction) is not really covered by accelerator experiments.

Concerning the latter, there exists the LHCf experiment at CERN, dedicated to measure the impact points and energy of neutral particles in the extreme forward direction. The measurements are already used to check the validity of the present hadronic interaction models [35]. Bongi also discussed in a more general way possible contributions of accelerator experiments to improve the simulation and therefore the reconstruction quality and the interpretation of extensive air-showers. Four topics were identified:

- Inelastic cross-section: Important for the first interaction, as it defines if the EAS starts early in the atmosphere or if it penetrates deep.
- Forward energy spectrum of secondaries: When the spectrum is soft, the shower has an early and rapid development.
- Inelasticity of the interactions: A large inelasticity would also hint to a rapid development of the shower.
- Nuclear interactions: Multiplicity and rapidity distributions of the secondary particles at all energies are an important ingredient to model the shower development.

The higher energy accessible by the next stages of the LHC will further improve the situation. In addition, an LHCf-like detector at RHIC or a Carbon or Nitrogen beam at LHC would significantly contribute to a better understanding of the EAS and by that finally help to solve the puzzle of the origin of high-energy cosmic rays.

Back to the present air-shower measurements, tests of the hadronic interaction models are performed by analyzing multi-parameter observations. There are many hints that the muon

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**Figure 8.** Comparison of the transmission factor $T$ for Mie and Rayleigh scattering. The Mie attenuation length is assumed to 52.645 km in a homogeneous mixing layer below 3 km, taken from measurements of the Pierre Auger Observatory. The Rayleigh attenuation length is computed with respect to the US-StdA 76. The detector was placed (a) in 40 km distance at ground level, (b) at the ISS altitude 400 km above ground (from [33]), see text.
component in the air-showers are not well described, at least at higher energies. Two examples of such investigations were presented at the conference:

At the Pierre Auger Observatory [36] inclined showers (zenith angle larger than 60 degree) were studied as for them at observation level the muon component is dominant compared to the electromagnetic component. The primary energy is estimated by the total number of muons calibrated with a subsample of showers detected in hybrid mode, i.e. by the fluorescence measurements. In Figure 9, the determined muon numbers are compared to predictions of Monte Carlo simulations of different hadronic interaction models. Obviously, a significantly smaller muon number is predicted than measured. The effect increases with energy and is finally so large that even a pure iron composition (which is not expected at $10^{19}$ eV!) cannot explain the data. The conclusion is that all the hadronic interaction models currently in use show a muon deficit in their predictions, at least at the highest energies.

At KASCADE-Grande [37], i.e. at an energy two orders of magnitude lower, the muon component predicted by the models is tested by another method. The same method cannot be applied as KASCADE-Grande (i) with its thin scintillators is not as sensitive to inclined showers as large water Cherenkov detectors are, and (ii) an independent energy measurement is also not possible as only particle detectors are available. However, KASCADE-Grande provides 622 m$^2$ dedicated muon detectors and the method chosen here is to investigate the attenuation of the muon component in the atmosphere by studying the dependence of the muon number at fixed energy with the zenith angle. The resulting attenuation parameter $\Lambda$ is for the data significantly larger than for the predictions, independent of the choice of the hadronic interaction model (Fig. 9). This means less predicted than measured muons and therefore, is tendentially in agreement with the findings of the Auger Observatory. However, in an absolute scale it leads to a smaller effect in number of muons (at a factor 100 lower energy).

Summary of this chapter: Despite the problems in fixing the absolute scale in energy and
mass, the understanding of the process of the evolution of extensive air showers is improving by both, investigations of the multi-parameter air-shower measurements and reaching higher energies and better forward detectors at accelerator experiments. This allows us to be more confident in the observed spectral features of the cosmic ray flux as well as in tendencies (getting heavier or lighter) in the elemental composition in the entire energy range from PeV to at least EeV.

6. Is Radio Detection a Technique for the Future?

The above mentioned problems in detecting and interpreting EAS in terms of energy and mass of the primary, together with the high costs of instrumenting large areas, make the study of new detection techniques very plausible. Over the past decade, in particular, tremendous progress has been made in the field of the digital radio detection of cosmic ray air showers. Impressive results are achieved with experiments like LOPES [38, 39], AERA [40, 41], LOFAR [42, 43], and Tunka-Rex [44], which have been presented at the conference and which exploit the potential of the detection technique.

![Figure 10.](image)

**Figure 10.** Left panel: Comparison of measurements and simulations for one air shower. Shown is the integrated radio pulse power for simulation (blue squares) and LOFAR measurements (red circles) as a function of distance to shower axis (from [43]). Several hundreds of antennas participated in the measurement of this individual EAS. Right panel: Distribution of the measured value of the \(a\) parameter, where the solid line indicates the 68% confidence interval around the mean value of the parameter; the dashed line shows the value of \(a = 0\). The parameter \(a\) is defining the part of the radial polarized signal in the EAS, i.e. gives the fraction of the signal stemming from the Askaryan effect [41].

In parallel to the experimental activities, simulation codes and analysis strategies have been developed to get knowledge about the sensitivity of the radio technique to primary direction, mass, and energy of UHECR. In addition, a clue is now available how the accuracies compare to the standard techniques, like fluorescence or particle detection. At all experiments and based on this meanwhile solid understanding of the underlying radio emission physics, analyses have been devised to reliably extract the geometry, energy, and even depth of shower maximum of air showers measured with radio antennas.
Figure 11. Left panel: Measurements of different experiments of the mean atmospheric depth of the shower maximum vs. energy. The results for LOPES are based on two independent methods [46]. The indicated number of events per bin deviate between both methods due to different quality cuts. Right panel: Correlation between the radio field strength at 100 m normalized by the sine of the geomagnetic angle and the energy reconstructed with the air-Cherenkov measurements of Tunka-133. The uncertainties of the electrical field are from the LDF fit, the uncertainties of the Tunka-133 energy reconstruction is estimated to 15%. The few outliers are probably events measured during thunderstorm conditions. As the bulk of the events are at lower energies, the inlay shows for all events the scatter between the energy reconstructed by Cherenkov and radio [44].

The LOFAR core instrument, built as low frequency astronomical radio antenna array in the Netherlands, is equipped with a small scintillator array enabling to trigger and record air showers with a huge number of antennas per single event. By this (Fig. 10) the irregular shape and the asymmetries of the footprint of the radio signal on ground as expected by the detailed emission simulations is proofed experimentally [43]. The irregular footprints stem from various effects of the radio emission, like the interfering of the two dominant emission mechanisms, geomagnetic effect and Askaryan emission with different polarizations, the geometry of the impinging shower (mainly relative to the Earth’s magnetic field), or the used frequency band for detection.

The Auger Engineering Radio Array AERA, covering the largest area and highest energies in radio hybrid experiments could proof the emission mechanisms via detailed polarization measurements. As mentioned before, two radio emission mechanisms, the geomagnetic and the Askaryan effects, are going to contribute mainly to the radio signal from air showers. The electric field induced by the geomagnetic effect points to the direction of \( \vec{v} \times \vec{B} \), where \( \vec{v} \) is a scalar vector describing the direction of air showers and \( \vec{B} \) is the geomagnetic field. Whereas the electric field induced by the Askaryan effect has a radial direction pointing towards the core of the showers [45]. For individual showers (Fig. 10) AERA could determine the contribution of the Askaryan mechanisms to the total signal in terms of the \( a \) parameter (see figure caption). In average this is approximately 14% [41].

By the improved understanding of the radio signal first analyses of the primary UHECR parameters, like energy and mass are possible now. Figure 11 shows two examples, where the LOPES experiment applied two different methods (using the lateral distribution of the radio signal, and the shape of the wavefront, respectively) to determine the shower maximum [46]. This is the first measurement of the shower maximum by the radio detection technique. This is very promising for the future, despite the fact that at LOPES the systematic uncertainties are very large due to the human-made noise at the industrial environment of KASCADE-Grande. Tunka-Rex, a radio array measuring in coincidence with the Tunka Cherenkov array, has shown...
a first correlation of the radio estimated energy with the energy determined by the Cherenkov light emission. It shows that an energy resolution of better than 15% can be reached with the radio technique.

The very promising achievements for an application of the radio detection technique in future experiments, however, are accompanied by the cognition of some intrinsic limitations of the radio detection technique. In my view, for the present status of the radio detection technique following statements can be made:

- Radio measurements provide a calorimetric energy measurement of the electromagnetic component of the air shower with nearly 100% duty cycle (except thunderstorm periods).
- Having small experimental uncertainties (i.e. a radio quiet environment) the energy resolution achievable with radio detectors should be better than 10%.
- Radio emission gives information complementary to particle detectors as the pure electromagnetic component is selected. Self-trigger is possible, but difficult due to human made transient signals faking the radio EAS signal. All reconstructions are easier if the geometry of the EAS is known.
- The mass of the primary cosmic rays can be measured with the radio technique via the geometrical distance to the main emission region in the shower, which is closely correlated with the depth of the shower maximum. The distance to the shower maximum leaves an imprint in several observables, like lateral signal pattern, shape of the shower wavefront, or the frequency spectrum of the signal. The resolution achievable, however still needs experimental verification.
- The angular resolution is expected to be better than 0.5 degree for sophisticated and large arrays.
- The radio signal pattern and the detection threshold depends heavily on the geometry of the EAS, but is due to the exact knowledge of the emission mechanisms under control, and the dependencies on the atmospheric parameters are negligible (compared to the fluorescence light measurements).
- Radio detectors can be built cost effective, but this depends on two main aspects, the cost of an individual radio detector station and the needed density of these sensors. It is clear that antennas and digital electronics can certainly be built at much lower prices than those of particle detectors. The difficulty for a cheap radio detector arises, however, when the needed spacing of the detectors is considered.
- A big disadvantage of the radio technique lies in the relatively small footprint of the detectable signal (in terms of the ratio of signal-to-(galactic)noise) for vertically arriving air showers. This footprint, however, increases drastically when more inclined events are measured.
- Still studies have to be continued to make the technique a cost-effective, high sensitive instrument for a large-scale stand-alone or hybrid application of the radio detection technique. This concerns the R&D on the optimization of the radio stations themselves as well as on the reconstruction techniques. An encouraging ansatz is the study of a local hybrid measurement of the radio signal with a water-Cherenkov particle detector together with the corresponding single signal analysis.

7. Go for Highest Energies - with Larger Statistics and Better Mass Sensitivity
Still, cosmic rays of the highest energies of the wide spanning cosmic ray energy spectrum is the one least explored, which is natural as the flux of such particles reaching our Earth is extremely low. Though, it is the most interesting region as the origin is unknown and there is even no
convincing theory explaining the acceleration to such high energies. Correspondingly, many and partly exotic explanations exist in literature. As an experimental physicist, I will not go to all these speculations, but will discuss the present and planned efforts to solve the long-standing mystery of the $10^{20}$ eV cosmic particles.

As earlier mentioned, at these high energies, in addition to the low statistical accuracy, the existing measurements disagree in their flux by a surprisingly large amount (see Fig. 1). The origin of the differences is not understood and several causes may play a role, e.g.:

(i) Statistical fluctuations and experimental systematic uncertainties.
(ii) It could lie in the fact that the energy reconstruction is limited by our current theoretical understanding of extensive air showers (EAS) [34]. The relevant energies as well as partly the kinematic features of the hadronic interactions at all energies are not well measured by accelerators, so that extrapolations are used in simulating the EAS leading to different EAS interpretations in terms of the primary energy and mass.
(iii) It could be that the two main experiments at the highest energies (Pierre Auger Observatory [21] and Telescope Array [22]) are located at different hemispheres and therefore, look at different regions of the sky. The standard picture is that the UHECR stem from astronomically nearby ($< 100$ Mpc) Active Galactic Nuclei, where we know that the distributions of those AGNs are not uniform over the sky [47].

![Figure 12](image-url)

**Figure 12.** Left: Pierre Auger upgrade prototype of a scintillator detector on top of the water-Cherenkov detector. In the back an access tower to an AMIGA underground muon detector is seen [36]. Right: layout of the planned Telescope Array extension TAx4 [26].

It is obvious, that in future one needs (for the highest energies)

- higher statistics
- better mass composition sensitivity
- observation of the full sky
- multi-messenger information (UHECR, UHE-$\gamma$, UHE-$\nu$)
- all of these with small experimental and systematic uncertainties!

...to finally solve the puzzle of the origin of the highest energy cosmic rays.

The Pierre Auger Collaboration is presently preparing an upgrade of the Observatory to address the optimization of the primary particle identification [23, 36]. To improve the
composition measurement at the highest energies, the Auger Collaboration proposes to enhance
the electron-muon separation capabilities of the existing surface detector stations by adding
4 m$^2$ scintillation detectors on top of each water Čerenkov detector (Fig. 12). In addition,
the data readout of the enhanced surface detector stations will be facilitated by replacing the
current readout electronics by modern state-of-the-art electronics providing three times faster
sampling, a significantly enhanced dynamic range, and enabling enhanced trigger and monitoring
capabilities. Further on, a sophisticated underground muon detector array (AMIGA) at a smaller
area of the observatory shall be built. With this upgraded observatory following physics program
is envisaged [36, 48]:

- measure a factor of 10 in statistics for composition determination (as then possible by the
data of the surface detectors measured with 100% duty cycle)
- decision if the flux suppression is due to the GZK effect or due to maximum acceleration,
or a combination of both
- by selecting protons perform particle astronomy, e.g. in terms of composition enhanced
anisotropy studies.
- study hadronic interactions at an interaction energy of $\sqrt{s} > 70$ TeV
- discover or limit ultra-high energy cosmogenic neutrino fluxes
- discover or limit ultra-high energy GZK induced gamma-ray fluxes
- clarify the science questions and the measurement techniques for the next generation
UHECR experiment

The last item includes the plans that the Observatory is further used for developing new tech-
nologies in detecting high-energy cosmic rays, e.g. the radio detection techniques or applying
improved photon sensors using semiconductor based detectors (SiPM). SiPMs are less sensitive
for damages by bright light and could therefore enhance the duty cycle of the fluorescence mea-
surements.

Preparations for the upgrade have been started and the plan is to finalize it in 2017.

The Telescope Array is planning to extend the sensitive area by a factor of 4 (Fig. 12). The
larger area with a sparse distribution of particle detectors aims for considerably increasing the
statistics of the highest energies, mainly to verify and establish the above mentioned hotspot [26].

A totally different concept to reach higher statistics is to observe the fluorescence light of
extensive air showers from space [49, 50]. The Extreme Universe Space Observatory (EUSO)
(Fig. 13) at the Japanese Module (JEM) of the International Space Station (ISS) is the most
prominent space mission devoted to the scientific research of EECR [51]. The main goal is the
exploration of the Universe through the detection of the extreme energy cosmic rays and
neutrinos by looking downward from the ISS to detect the fluorescence light of extensive air-
showers that they generate in the Earth’s atmosphere. The main scientific objective is astronomy
and astrophysics through the particle channel. This requires to identify the sources of cosmic
rays by the reconstruction of the arrival direction and energy spectra with a high collecting
power, beyond any other previous or planned experiment so far. The JEM-EUSO instrument
consists of the telescope, the focal surface, a monitoring system for the atmospheric conditions,
and a calibration system. In addition, there will be support and calibration systems on ground
as well as at the ISS.

One big advantage of JEM-EUSO will be the uniform full sky coverage due to the ISS orbit.
JEM-EUSO will be the first experiment to be able to take data of EECRs for both hemispheres

The JEM-EUSO collaboration invented the term EECR, Extreme Energy Cosmic Rays, to emphasize the focus
of the mission to the primary energies above the flux suppression.
to build a full sky map. This together with the huge exposure (up to a factor 10 compared to the Pierre Auger Observatory) to be reached will lead to anisotropy studies and identification of sources and source regions of high-energy cosmic rays which is not possible with ground-based observatories. JEM-EUSO will have a large observation area in nadir mode and even a roughly ten times bigger one in tilt mode, which is not yet fully explored, but the design enables the option to tilt the entire instrument at the ISS to have a larger coverage on ground.

On the way to the full instrument ready for lunch to the ISS, several test or pathfinder experiments are needed and currently under development or in operation. A PDM (photon detection module with 2304 pixels, see Figure 13) can be seen as an independent unit, where one of those is used or will be used for most of the test experiments. These various test and pathfinder experiments presently under construction or in operation will provide more information and details on the capabilities of such a space instrument like JEM-EUSO:

- One PDM is used for EUSO-Balloon, serving as a demonstrator for technologies and methods featured in the space instrument. A first flight could be performed on August, 25, 2014 at Timmins, Canada. 5 hours of valuable data from the PDM, from the installed infrared camera, as well as Laser pulses send by a helicopter accompanying the full flight are presently being analysed. Further shorter flights are foreseen and a long duration flight at the Southpole is applied for.
- Also important information on the capabilities of the full instrument will be provided by EUSO-TA, which is a ground-based telescope formed by one PDM (identical to the PDM of EUSO-Balloon) and two Fresnel lenses. EUSO-TA is located at the Telescope Array site. The aims are to obtain an end-to-end calibration of the prototype telescope, and an inter-calibration with the fluorescence detector of TA.
- Currently, the collaboration considers a cooperation with the Russian project KLYPVE. KLYPVE [50] is a mirror based fluorescence telescope foreseen to be installed at the Russian segment of the ISS. The pathfinder of KLYPVE is TUS on board of the Russian Lomonosov (launch foreseen in 2015) satellite. Despite its smaller size, KLYPVE (or even TUS) could be the first experiment detecting EAS from space.
- Another project is Mini-EUSO, a small prototype experiment (one PDM and a two-25cm-diameter Fresnel-lens system) foreseen to operate inside the ISS for an observation of the UV
emission from the night-Earth through an UV-window. This instrument would map for the first time the Earth in UV, and could study atmospheric phenomena and bio-luminescence at Earth as well as meteors.

- The JEM-EUSO collaboration has also started to evaluate if SiPM can replace the heavy and expensive Multianode PMT’s presently in use. There is a fast commercial development of improved SiPM, where a comparable quantum efficiency to standard PMT’s is expected in near future.

JEM-EUSO is planned as a three to five year mission, where initially the launch was foreseen in 2017. Due to financial reasons this will not be possible. However, the JEM-EUSO collaboration continues the efforts to improve the baseline design and the capabilities and sensitivity of such an instrument with the aim to launch it to space at a later opportunity.

8. Final Goal: Multi-Messenger Particle Astronomy

There is the justified hope that in a decade from now a comprehensive study of the high-energy Universe will be possible by combining the data and the information of sophisticated experiments for all three particle channels: cosmic rays, neutrinos, and gamma rays (Fig. 14).

The present status (early 2015) of the most relevant experiments for such a multi-messenger particle astronomy is (see also [52]7):

- Gamma rays: MAGIC, VERITAS, and H.E.S.S. are already taking valuable data from many of the potential cosmic ray sources. The Cherenkov Telescope Array CTA [56] will be the next generation of this kind of experiments (TeV Imaging Cherenkov Telescope Arrays). Prototype telescopes in different sizes (sensitive to different energy ranges) are already existing, site selection and start of site preparation will happen in 2015.

- Neutrinos: IceCube [57] takes data and has detected first extra-terrestrial PeV neutrinos. An extension of IceCube (IceCube-Gen2) at the South Pole is under discussion and the pendants at the Northern Hemisphere (KM3NeT at the Mediterranean Sea [59, 60] and at a smaller scale GVD [58] at Lake Baikal in Siberia) have started the deployment of its first phase.

- Cosmic Rays: As discussed above, the Auger upgrade will be installed in the coming three years, Telescope Array plans to extend its sensitive area by a factor of four, and there is with the test experiments for JEM-EUSO a large progress for the first fluorescence telescope in Space.

However, there is still a long way to go. For example in UHECR studies, first the requirements of having more precise measurements with higher statistics have to be fulfilled before all information can be combined to perform particle astronomy!

Discussing the future in investigating the high-energy, non-thermal Universe I will not miss to affirm the need on combining all the data available in the various particle and wavelength channels. This will only be possible, if the data is publicly available with a short latency, which is meanwhile also a requirement of many funding agencies. A forerunner in this context is KCDC, the ‘KASCADE Cosmic-ray Data Centre’, a web portal, where data of astroparticle physics experiments is made available for the interested public [61]. In a first release, with KCDC [62] more than 160 million air showers are provided to the public. In addition, KCDC provides the conceptional design, how the data can be treated and processed so that they are also usable

7 For all three particle channels there are also other running or planned experiments, partly with different detection techniques, like HAWC [53], LHAASO, TAIGA/HiSCORE [54] for gamma rays; the virtual combination of all neutrino detectors (Global Neutrino Observatory, GNO) for high energy neutrinos [55], or LHAASO and IceTop for cosmic rays. Details about these experiments can be found in other contributions to this conference.
Most relevant (according to the opinion of the author) existing and future experiments for exploring the high-energy, non-thermal Universe. By a combination of all the information a multi-messenger particle astronomy is envisaged.

outside the community of experts in the research field. Detailed educational examples make a use also possible for high-school students and early stage researchers.

In summary, there is a lot of progress in the research field of ultra-high energy cosmic rays, and it makes sense to stay tuned waiting for achievements presented at international conferences in the coming years.

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