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Ultra High Energy Cosmic Rays: A Short Review

Roberto Aloisio

INAF - Osservatorio Astrofisico Arcetri, largo E. Fermi 5, I-50125 Firenze (Italy)
INFN - Laboratori Nazionali Gran Sasso, ss 17bis km 18+910, I-67100 L'Aquila (Italy)

Abstract

We will review the main physical aspects of Ultra High Energy Cosmic Rays. We will discuss in particular their propagation through astrophysical backgrounds, focusing on the latest experimental observations of HiRes, Telescope Array and Auger. We will also review the issue of the transition between galactic and extra-galactic cosmic rays.

Keywords: Cosmic Rays Theory, Cosmic Rays Observations, Particles Astrophysics, Astrophysical Backgrounds

1. Introduction

Ultra High Energy Cosmic Rays (UHECR) are the most energetic particles observed in Nature, with energies up to few$\times 10^{20}$ eV. As any other observation of Cosmic Rays (CR), UHECR are characterized by three basic observables: spectrum, chemical composition and anisotropy. In this short review we will mainly discuss the first two observables neglecting the discussion about a possible anisotropy in the arrival directions of UHECR.

The behavior of the UHECR spectrum is mainly conditioned by the interaction of such particles with the intervening astrophysical backgrounds and by the cosmological evolution of the Universe. In the energy range $E \simeq 10^{18} \div 10^{19}$ eV the propagation of UHE particles is extended over cosmological distances with a typical path length of the order of Gpc. Therefore one should also take into account the adiabatic energy losses suffered by particles because of the cosmological expansion of the Universe.

The background affecting the propagation of UHE protons is only the Cosmic Microwave Background (CMB). There are two spectral signatures that can be firmly related to the propagation of protons through this background: pair-production dip [1], which is a rather faint feature caused by the pair production process:

$$p + \gamma_{CMB} \rightarrow e^+ + e^- + p \qquad (1)$$

and a sharp steepening of the spectrum caused by the pion photo-production:

$$p + \gamma_{CMB} \rightarrow \pi + p \qquad (2)$$

called Greisen-Zatsepin-Kuzmin (GZK) cut-off [2].

In the case of UHE nuclei the situation changes because, apart from CMB, also the Extragalactic Background Light (EBL) becomes relevant. The interaction processes that condition the propagation of UHE nuclei are pair production, that involves only the CMB background [4], and photo-disintegration. The latter is the process in which a nucleus of atomic mass number A because of the interaction with CMB and EBL looses one or more nucleons:

$$A + \gamma_{CMB,EBL} \rightarrow (A - nN) + nN \qquad (3)$$

the most relevant process is the one nucleon emission ($n = 1$) as discussed in [4].The photo-disintegration of nuclei, together with the pair production process, produces a steepening in the observed spectrum. The exact position and behavior of the flux suppression depends on the nuclei species as well as on the details of the cosmological evolution of the EBL which, differently from CMB, is not known analytically being model dependent [5]. In general the nuclei flux steepening is not as sharp as the GZK and it is placed at lower energies respect to the GZK energy scale [4].

The GZK cutoff is the most spectacular feature in the UHECR spectrum. However one must remember that it is defined only for UHE protons interacting with the CMB filed. The cutoff energy position is roughly fixed by the energy where the pair-production (Eq. (1)) and the photo-pion production (Eq. (2)) energy losses become equal, namely at $E_{GZK} \simeq 50$ EeV [3]. The shape of the GZK flux suppression could also be model-depend: it depends on a possible local over-density or deficit of sources and can be mimicked by low enough values of the maximum energy that sources can provide. In contrast, the pair-production dip is practically model-independent mainly because protons contributing to this energy range arrive from sources lying at cosmological distances.

From the experimental point of view the situation is far from being clear with different experiments claiming contradictory results. The HiRes and, nowadays, the Telescope Array (TA) experiments show a proton dominated composition till the highest energies with a clear observation of the proton pair-production dip and GZK cut-off [6]. Chemical composition observed by HiRes and TA is coherent with such picture showing a pure proton dominated spectrum starting from energies $E \simeq 10^{18}$ eV till the highest energies. The experimental picture changes taking into account the Auger observations. The spectrum observed by Auger shows a behavior not clearly understood in terms of the proton pair-production dip and GZK cut-off [7]. This spectral behavior could be a signal of a substantial nuclei pollution in the spectrum, which is confirmed by the Auger observations on chemical composition that show a progressively heavy composition toward the highest energies, this tendency starts already at $E \gtrsim 4 \times 10^{18}$ eV [7]. In this short review we will discuss the main issues in the physics of UHECR presenting a twofold discussion from both experimental as well as theoretical point of view. The paper is organized as follows: in section 2 we will mainly discuss the two observable features connected with protons propagation, i.e. dip and GZK cut-off, presenting a comparison with HiRes and TA data, in section 3 we will focus on the Auger observations of spectrum and chemical composition, discussing the consequences of a nuclei dominated spectrum, in section 4 we will discuss the physics of the transition between galactic and extra-galactic CR, finally conclusions will take place in section 5.

2. HiRes and TA data: dip and GZK cut-off

The dip is a quite faint feature that arises in the spectrum of UHE protons in the energy range 2×10^{18} eV $\div 5 \times 10^{19}$ eV due to the pair production process; it is a unique imprint of the interaction of protons with the CMB background. The dip behavior is more pronounced when analyzed in terms of the modification factor $\eta(E) = J_p(E)/j_p^{umm}(E)$ [1], defined as the ratio of proton spectrum divided by the so-called unmodified spectrum, where only adiabatic energy losses (expansion of the Universe) are taken into account.

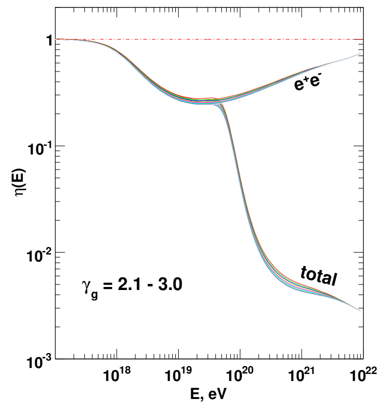

Figure 1: Modification factor for different values of γ_g (see text).

In this paper we will always assume a power law injection spectrum for UHECR, namely $Q(E_g) \propto E_g^{-\gamma_g}$ being E_g the UHECR generation energy eventually bounded from above by the maximum attainable energy at the source E_g^{max}. A useful characteristic of the modification factor is its universality, it depends very weekly on the injection power law index and on various physical phenomena that can be included in the calculation [1]. In figure 1 we plot $\eta(E)$ for different values of γ_g (as labelled); it can be seen that if one includes in the calculation of J_p only adiabatic energy losses then, by definition, $\eta(E) = 1$ (dash dotted line). When e^+e^- production is additionally included one obtains $\eta(E)$ as labelled in figure 1, this behavior corresponds to the pair-production dip. Finally, if all channels of energy losses are taken into account $\eta(E)$ shows also the GZK suppression, curve labelled 'total'. The only "critical" assumption at the very base of the dip behavior is the proton dominated spectrum, already a nuclei pollution at the level of 15% will spoil the behavior of figure 1.

Modification factor is a very useful tool to study the effect of the CMB radiation field on the propagation of UHE protons and can be compared with observations simply dividing the observed spectra by the unmodified spectrum $J_p^{umm}(E) \propto E^{-\gamma_g}$. In figures 2,3 we compare the modification factor with the observations of HiRes and TA [6]. This comparison involves only two free

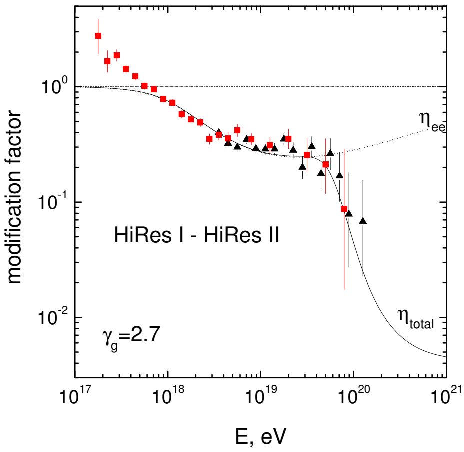

Figure 2: The pair production dip compared with the HiRes experimental data [6], this experiment confirms the pair-production dip with good accuracy ($\chi^2/d.o.f. \simeq 1.0 \div 1.2$).

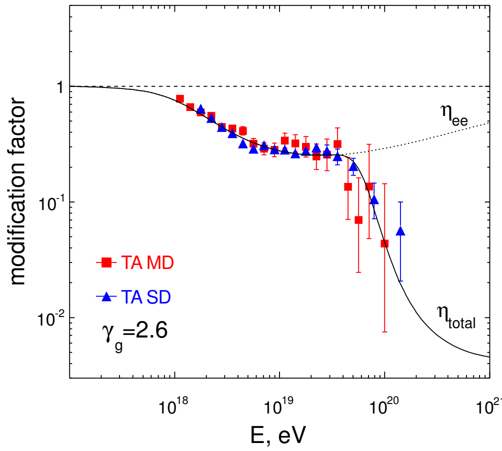

Figure 3: The pair production dip compared with the TA experimental data [6].

parameters: the power law index at injection γ_g and the total emissivity of UHE protons sources.

The fit of HiRes and TA data to the pair-production dip is quite good with a $\chi^2/d.o.f \simeq 1$ and a best fit value of $\gamma_g \simeq 2.7$ for HiRes and $\gamma_g = 2.6$ for TA. From figures 2,3 one can notice that the modification factor observed by HiRes exceeds the theoretical one around EeV energies; since by definition $\eta(E) \leqslant 1$ this excess signals the appearance of a new component of CR at $E < 1$ EeV. This component can be nothing else but the galactic cosmic rays. Therefore the dip model for UHECR implies a transition from galactic to extra-galactic CR at $E \lesssim 1$ EeV, we will come back to this in section 4.

The experimental observations of HiRes and TA show a strong evidence of the GZK cut-off in the spectra, while Auger data, that we will discuss in the next session, seem less compatible with the expected GZK behavior of the spectra. In general all experiments show a flux suppression at the highest energies, nevertheless to ascribe it to the process of photo-pion production of protons on the CMB field (i.e. GZK suppression) one must prove that: (i) the energy scale of the cut-off and its shape correspond to the theoretical predictions, (ii) the observed chemical composition is strongly dominated by protons.

The integral spectrum of protons $J_p(>E)$ has a power law behavior at low energy. Increasing the energy, because of the photo-pion production process, $J_p(>E)$ shows an abrupt suppression (i.e. GZK cut-off). The energy scale at which this suppression arises can be evaluated as the energy at which the integral flux is reduced by half of its low energy value. This energy scale $E_{1/2}$ can be computed with extreme accuracy and it is found to be practically model independent [3], its theoretical prediction is $E_{1/2} = 10^{19.72}$ eV $\simeq 52.5$ EeV [3].

The HiRes and TA observations show a proton dominated spectrum at all energies $E > 10^{18}$ eV [6], moreover the HiRes collaboration measured $E_{1/2}$ obtaining a value in a pretty good agreement with theoretical expectations, namely $E_{1/2}^{HiRes} = 10^{19.73\pm0.07}$ eV. These experimental evidences show a coherent picture of a proton dominated flux that exhibits the expected features: pair-production dip and photo-pion production suppression (GZK).

3. Auger data: heavy nuclei

The spectrum observed by the Pierre Auger experiment, shown by filled squares in figure 4, differs from the HiRes and TA spectra, shown by triangles and circles. On the other hand, as discussed in the previous section, the HiRes/TA data are well fitted by the pair-production dip, shown as continuos line in figure 4.

In the framework of the dip model, taking into account the systematic errors in energy determination, one can try to shift the Auger energy scale having the dip behavior as reference. This procedure, proposed in [1], is based on the fact that the energy position of the pair-production dip is rigidly fixed by the interaction of protons with the CMB radiation field, so that it can be used as a "standard candle". This approach is based on a single hypothesis: a pure proton composition of UHECR.

Shifting accordingly to the dip "standard candle" the energy scale of the Auger data one has the result shown in figure 5. Where the Auger data have been shifted

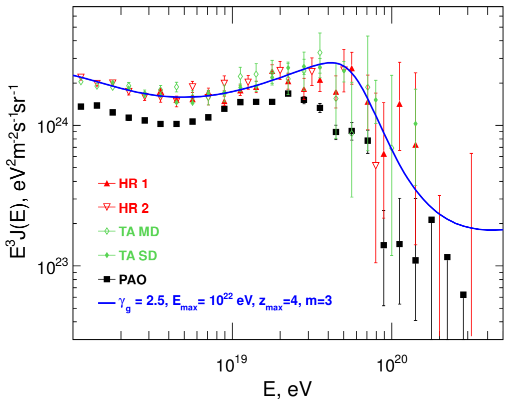

Figure 4: Spectrum of UHECR as observed by HiRes, TA and Auger experiments (as labeled). Continuos line is the best fit of HiRes/TA with a pure proton composition (dip model)

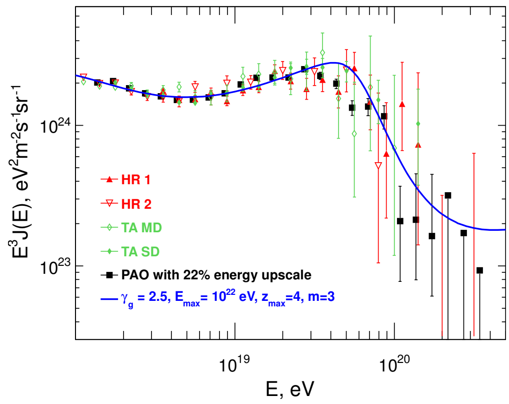

Figure 5: The same as in 4 with the Auger spectrum shifted in energy as $E \rightarrow k_{cal}E$ with $k_{cal} = 1.22$.

according to $E \rightarrow k_{cal}E$ with $k_{cal} = 1.22$, allowed by the systematic error claimed by the Auger collaboration [7].

After the energy shift, the apparent coincidence of the Auger and HiRes/TA data is mainly related to the low energy part of the spectra (see figure 5), while at the highest energies statistical uncertainties are too large to distinguish among spectra. Nevertheless, while HiRes and TA data are compatible with the GZK steepening the Auger data, which at energies around 50 EeV still show low statistical errors, are not compatible with the behavior expected from the photo-pion production process of protons on the CMB field.

Even playing with the different parameters involved in the computation (i.e. injection power law index γ_g, sources cosmological evolution, maximum acceleration energy, local over-density of sources, etc.) one could not reconcile the Auger spectrum behavior with the GZK expectation. Being the GZK steepening a clear signal of a proton dominated spectrum, the Auger spectrum is coherent with the chemical composition measured by this experiment at the highest energies which is quite incompatible with a pure proton composition. Auger data on chemical composition show a steady behavior that, starting already from energies around 3 EeV, moves from a light (proton) to an heavier composition reaching an almost pure Iron composition at energies around 30 EeV [7]. These observations based on the Auger Fluorescence Detector (FD) are further straightened by the observations of the Auger Surface Detector (SD), namely the shower muon content and the signal rise time in the Cherenkov tanks [8].

The early steepening observed in the Auger spectrum can be easily explained in terms of nuclei propagation. Nevertheless, even assuming a rich chemical composition with different nuclei species injected at the source it is not easy to obtain a good explanation of both spectrum and chemical composition observed by Auger. A wide class of mixed composition models [9], while showing a good description of the spectrum, fail to fit the mass composition observed by Auger. Most of these models assume a mass composition similar to the one observed at galactic scales, therefore enhanced in protons, and the resulting mass composition starts to become heavier only at energies $E > 50$ EeV [9] where photo-pion production substantially depletes the proton component.

At the galactic energy scales, the mass composition becoming heavier with increasing energy appears as a natural consequence of the rigidity dependent scenario for particles acceleration. The maximum acceleration energy that a single specie can reach is proportional to the particles charge $E^Z_{max} = ZE^p_{max}$ and the contribution to the spectrum at these energies of particles with charge lower than Z is suppressed. The disappointing model for UHECR [13] was build exactly under such assumption on maximum energy. In [13] was demonstrated that to avoid a proton dominated spectrum at the highest energies one must assume that the maximum energy for protons is in the range $4 \div 10$ EeV. This conclusion remains valid for a large range of generation power law indexes $\gamma_g \simeq 2.0 \div 2.8$, nevertheless to achieve a good description of the observed UHECR spectrum in the disappointing model one should assume a quite flat injection spectrum with $\gamma_g = 2.0 \div 2.2$. This fact, as we will discuss in the next session, has important consequences on the transition between galactic and extra-galactic CR. In

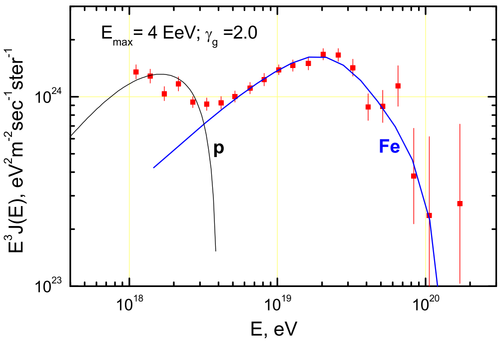

Figure 6: Energy spectrum in the two components model with proton and iron nuclei for a homogeneous distribution of sources with γ_g = 2.0 and E^p_{max} = 4 EeV.

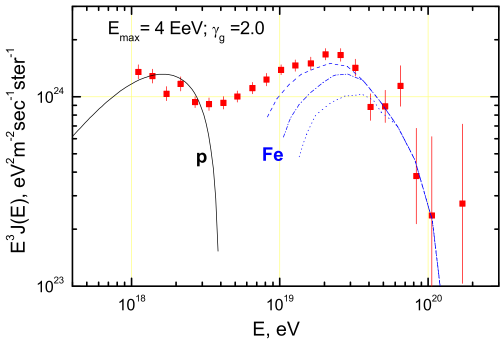

Figure 7: As in figure 6 with a diffusion cut-off, the gap is expected to be filled by intermediate mass nuclei.

figures 6,7 we plot two different implementations of the disappointing model: a simple two component model with protons and iron (figure 6), the same two components model with a diffusion cut-off in the iron spectrum due to the possible presence of a *nG* scale intergalactic magnetic field (figure 7). Note that the gap in the spectrum in figure 7 can be filled by the presence of secondary nuclei produced by the photo-disintegration of iron.

This model was called "disappointing" because it corresponds to a lack of many signatures predicted in the alternative case of a proton dominated scenario, such as the cosmogenic neutrino production and correlation with astrophysical sources. The disappointing model as presented here and in [13] is not complete because, while it reaches a good description of the observed Auger spectrum, it does not try to describe also the chemical composition observed at all energies.

The only successful theoretical attempt to fit at once spectrum and chemical composition of Auger was presented in [14] where it is assumed the presence of a very nearby source ($\simeq$ 70 Mpc) with a very flat generation spectrum ($\gamma_g \simeq 1.6$) injecting heavy nuclei only.

4. Galactic and extra-galactic cosmic rays

The different models aiming to describe UHECR observations have different consequences when applied to the transition from galactic to extra-galactic CR, therefore this theme of investigation has obtained an increasing interest in recent years. In general the physics of galactic CR is well understood in the framework of the standard model, which is based on the paradigm of Super Nova Remnant (SNR) as sources of galactic CR and Diffusive Shock Acceleration (DSA) as the mechanism of particles acceleration. In the standard model of galactic CR the observation of the knee at energy 2×10^{15} eV in the spectrum fixes the maximum energy of protons at the source and therefore, in a rigidity dependent scenario, the maximum energy for iron nuclei, the end of galactic CR, will be around energies 10^{17} eV.

In figures 8,9 we plot together the fluxes of galactic and extra-galactic CR assuming the two different models dip (figure 8) and disappointing (figure 9) for UHECR and using the flux of galactic CR as computed in [10], that takes into account the scale distribution of SNR in the galaxy. The experimental data of figures 8,9 are those of HiRes [6] and Auger [7] on the UHECR side and, on the galactic side, the data of all particles spectrum of Kascade [11] and an average of the fluxes measured by different experiments as presented in [12].

The matching of galactic and extragalactic fluxes in the case of the dip model (figure 8) gives a very good description of the experimental data, reproducing in an extremely accurate way the spectra observations in the intermediate energetic regime where the transition is supposed to stand. The case of the disappointing model gives a less accurate description of the experimental data (figure 9) with a slightly suppression of the theoretical flux in the transition region not seen experimentally. The less good agreement with experimental data obtained, in the transition region, with the disappointing model respect to the dip model is a direct consequence of two important facts: (i) the quite flat power law injection index (γ_g = 2.0) of the disappointing model, (ii) the quite low maximum energy associated to iron nuclei ($E^{Fe}_{max} \simeq 10^{17}$ eV) in the standard model of galactic CR. These two facts produce a lacking of particles in the transition region not seen experimentally, to avoid such circumstance one should assume a larger maximum energy for galactic iron. Only in this way in-fact it is pos-

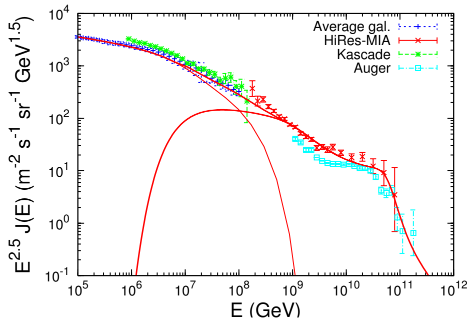

Figure 8: Transition from galactic to extra-galactic CR in the case of the dip model, with $E_{max} = 10^{21}$ eV and $\gamma_g = 2.7$. Galactic CR flux is taken from [10], experimental data are from HiRes [6], Auger [7], Kascade [11] and the average over different experimental results as in [12].

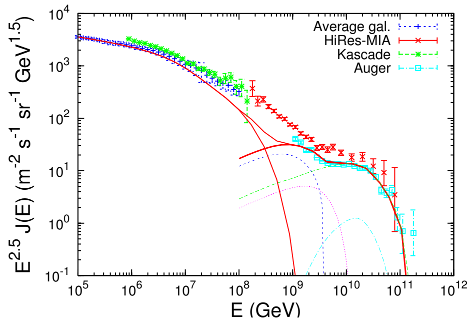

Figure 9: Transition from galactic to extra-galactic CR in the case of the disappointing model assuming a mixture of protons, He and Fe nuclei at the source with $E^p_{max} = 4 \times 10^{18}$ eV and $\gamma_g = 2.0$. Galactic CR flux as in figure 8.

sible to fill the gap in the transition region making the theoretical spectrum compatible with observations.

Let us conclude this section emphasizing the importance of the study of the transition between galactic and extra-galactic CR. In general, the transition is the superposition of the low energy tail of UHECR with the high energy tail of galactic CR and it is supposed to stand in the energy range $0.1 \div 10$ EeV. As discussed above the informations obtained at these energies on galactic CR involve the maximum acceleration energy of particles and their chemical composition. Therefore, assuming the standard model of galactic CR, the study of the transition can unveil the whole picture of the origin of galactic CR. Moreover, the low energy tail of UHECR can give key informations on the (possible) existence of the pair-production dip and on the propagation of UHECR in intergalactic magnetic fields [15]. Therefore, the experimental studies in the transition region are of paramount importance in this field of research, with the mass composition measurements being probably the most important task [15].

5. Discussion and conclusions

We face nowadays the most serious disagreement in the observations of UHECR between the data of Auger and HiRes/TA. While Auger points toward an heavy composition at the highest energies, HiRes/TA shows a proton dominated composition at all energies.

The most self-consistent conclusions on the nature of UHECR are obtained at present by HiRes/TA: they observe a proton dominated chemical composition with a spectrum that shows both expected signatures of protons, i.e. the pair-production dip and the GZK cut-off. Moreover, in the HiRes data the GZK cut-off is also found in the integral spectrum with the expected value of the $E_{1/2}$ energy scale. The picture emerging from HiRes/TA data confirms the dip model [1] and places the transition between galactic and extra-galactic CR at energies around 10^{18} eV in very good agreement with galactic CR observations. The only discrepant feature of the HiRes/TA observations consists in the absolute lacking of any anisotropy signal, expected at the highest energies in the case of a pure proton composition.

The Auger data are quite different. Measurement of chemical composition shows a steadily increasing mass starting from energies around 3 EeV, observation recently confirmed by independent data on muon content in the showers [8]. The Auger chemical composition excludes the dip model and the observed high energy steepening as the GZK cut-off. At present there is no nuclei based model which explains simultaneously the Auger energy spectrum and chemical composition, apart from the model proposed in [14] based on an unlikely framework with a nearby source (70 Mpc) that injects only heavy nuclei with a very flat spectrum ($\gamma_g = 1.6$).

We can conclude that the key issue to distinguish among different models in UHECR physics is related to the measurement of chemical composition. The best method at present to determine the UHECR composition is given by the measure of the position of the maximum of the cascade developed in the atmosphere, i.e. the elongation curve $\langle X_{max} \rangle (E)$. In figure 10 we plot the elongation curve as observed by Auger [7] and in figure 11 the same quantity measured by HiRes [6]. The calculated reference values for proton and iron plotted in figures 10,11 are those computed in the framework of the QGSJET01 and QGSJET02 models [16].

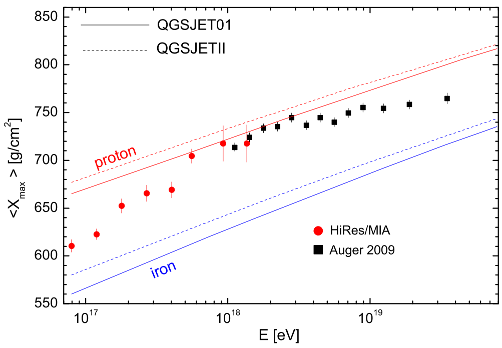

Figure 10: Elongation curve as measured by Auger [7]. The calculated reference values for proton and iron are those computed in the framework of the QGSJET1-2 model [16].

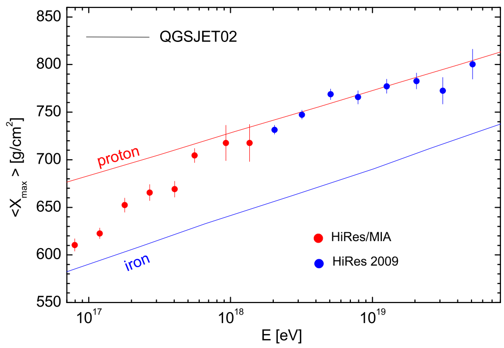

Figure 11: Elongation curve as measured by HiRes [6]. The calculated reference values for proton and iron are as in figure 10.

Unfortunately, the determination of chemical composition through $\langle X_{max}\rangle(E)$ suffers from many systematics due to the experimental approach and uncertainties in the interaction model. Systematic errors in the $\langle X_{max}\rangle$ measurements can be as large as $20 \div 25$ g/cm^2, to be compared with the difference of about 100 g/cm^2 between $\langle X_{max}\rangle$ of proton and iron. A better sensitivity to distinguish different nuclei is given by the width of the X_{max} distribution, i.e. $RMS(X_{max})$ [17].

We conclude stating that renewed experimental efforts are needed to reach a more reliable determination of the chemical composition of UHECR solving the apparent contradiction in the Auger and HiRes/TA data.

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