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The Propagation of Ultra-high Energy Cosmic Rays

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Abstract. Extra-galactic Cosmic Rays propagate through a variety of radiation and magnetic fields and interact in various ways. An analysis is given of the expected spectra and mass compositions at Earth for a variety of assumptions as to the characteristics of the particles on production.

1 Introduction

The observation of giant extensive air showers (GEAS) which are believed to be initiated by the cosmic ray particles of energies of about 10^{20}eV is one of the most intriguing puzzles since 1965, when two famous papers by Greisen and Zatzepin and Kuzmin appeared predicting the existence in the universal cosmic ray proton energy spectrum of a sharp cut-off at about 5×10^{19}eV. Studies of the ultra high energy cosmic ray (UHECR) anisotropy suggest that the sources of particles at such high energies are indeed universal, e.g. they are distributed almost uniformly over large distances. To solve this paradox a number of more or less advanced hypotheses have been proposed. One of them, one of the less exotic ones (in the sense of not-requiring any extra, new physics) is that the UHECR particles are not protons, but heavier nuclei. It was discussed some time ago in (Tkaczyk *et al.*, 1999), and the idea returned to recently ((Stecker, 1998), (Anchordoqui *et al.*, 2000)) after years of considering iron (the heaviest reasonable possible element) and other nuclei as too fragile to survive the journey through the infrared background (IRB).

In this paper we want to verify (again) this point taking into account the most recent results concerning fragmentation cross sections as well as the determinations of IRB, indicating the importance of appropriate depiction of the propagation (transport) effects in the irregular intergalactic magnetic fields.

2 Energy loss processes

The UHECR domain is quite rich in physical processes involved in energy losses. Starting with protons of relatively low energies, about 10^{18}eV, the e^+e^- pair creation on cosmic microwave background (CMB) photons starts to play a role, which reaches a maximum of importance slightly below 10^{19}eV. The main GZK process of energy loss is due to Δ resonance excitation (and its subsequent decay dissipating energy, eventually to low energy γ's) on CMB photons. The energy losses of heavier nuclei relative to electron-positron pair creation are Z^2 stronger, but due to the different rest mass, thus Lorentz factor, the respective total nucleus energy should be A times higher than that of proton. The same scaling in energy scale ought to be applied for the Δ resonance creation (but without Z^2 enhancement). This makes the GZK mechanism for heavy nuclei not important, however, for completeness, it was taken into account in the present calculations. The dominating process for nuclei is the photodisintegration on background photons. The significant rise of the fragmentation cross section just at the energies of our present interest is due to the existence of the giant dipole resonance. Its excitation energy is close to 20 MeV for (almost) all interesting heavy nuclei. This is about one order of magnitude below the Δ resonance excitation energy, thus, if the collisions only with CMB photons are considered, the threshold energy for nuclear disintegration is of order of $A/10$ higher than the proton GZK cut-off energy. The review of the whole situation is presented in Fig.1.

To compare the e^+e^-, Δ resonance creation by nucleons and the disintegration of heavy nuclei the cross sections have to be convoluted, not only with the photon energy spectrum, but also with the inelasticity of the respective process. In Fig.1 the inverse average length for 1% energy loss is shown. The pair production cross sections used in the present calculations are obtained with exact numerical integration of the general equations to be found in QED handbooks (that are almost 70 years old (Bethe and Heitler, 1934)) and are very close to the values given by Blumenthal (1970) in his widely

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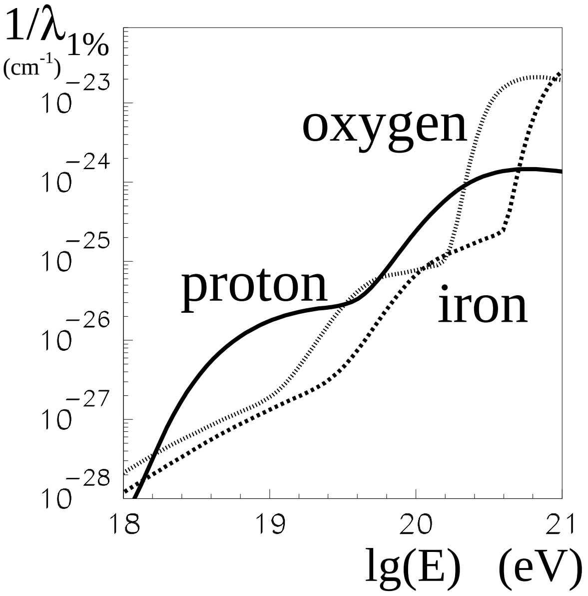

Fig. 1. Inverse mean length for 1% energy loss for iron, nitrogen and protons on extragalactic background photons.

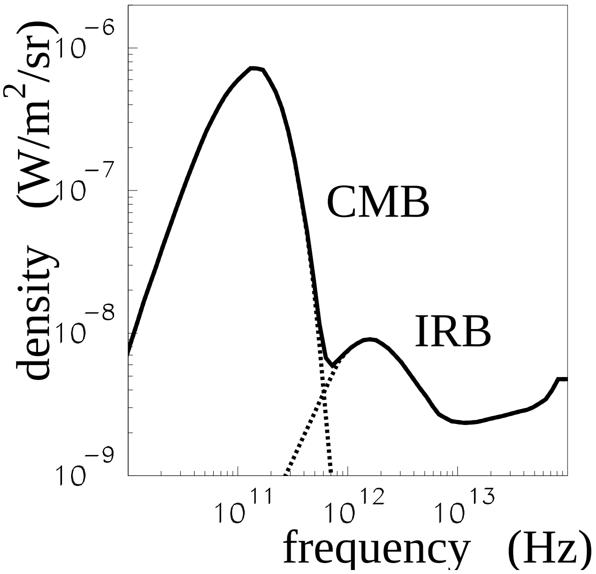

Fig. 2. The intergalactic photon power spectrum used in the calculations.

used paper. The GZK process was introduced based on measured inelastic photon-proton cross sections given in (Armstrong *et al.*, 1972). For fragmentation of nuclei we used the parametrization given by (Stecker and Salamon, 1999). The CMB was assumed of temperature 2.7 K and for higher energy photons we take the spectrum obtained by Malkan and Stecker (1998) (the one labeled there ”best estimate” intergalactic IRB). The form of the photon energy flux density spectrum is shown in Fig.2.

3 Application to cosmic ray spectra

With the calculated energy losses it is easy to obtain the energy spectrum of UHECR traversing certain distances in the extragalactic photon field from the source assuming a production spectrum. For simplicity we used the simple power-law with index of -2.3. As will be shown this choice is quite satisfactory. Results of such calculations are shown in Fig.3. The presented curves are shifted vertically to be better seen. They illustrate the well known and expected behaviour of propagated cosmic ray spectra - the famous GZK cut-off and very abrupt reduction of iron flux due to disintegration.

However the spectra from Fig.3 cannot be simply compared with the measured ones. The important change of the transport processes through the intergalactic space is likely present just in the energy range of our present interest. It is the result of the existence of irregular magnetic fields. The proton Larmor radius in the field of 10 nGs is 110 kpc $\times \left(E/10^{18}\mathrm{eV}\right)$ and this is comparable with the size scale of these irregularities (of order of 100 kpc) for a proton energy of about 10^{18}eV. For the discussion of the values adopted see (Wibig and Wolfendale, 2001) and (Siegl *et al.*, 1999) and references therein. Thus the typical diffusion undoubtfully present below 10^{18}eV changes to rectilinear propagation for energies at the end of the measured spectra. Details of the magnetic field structures are of course unknown. One way forward is to use some theoretical based spectrum of turbulences, as e.g. the Kolmogorov one (Siegl *et al.*, 1999). Another way is to assume some simplified picture of intergalactic space to obtain some approximate results leaving the more detail studies for the future, when our knowledge on magnetic fields as well as on UHECR sources will grow. We used this second possibility, assuming that the irregular field of strength 10 nGs changes randomly its direction in the ferromagnetic domain fashion with the domain size fixed at 100 kpc. We expected that general conclusions should be valid for more sophisticated models (as, e.g., (Siegl *et al.*, 1999)).

The process of particle transport in such magnetic fields cannot be treated analytically and was simulated exactly using a 3-dim Monte Carlo code with all the discussed above energy loss processes including not “on average” but also exactly with Monte Carlo reproduced fluctuations of the actual interaction paths lengths.

The diffusion effects, on one side, an increase of the propagation time (photon density traversed), but, on the other, on the possibility of crossing the detection surface many times by the same UHECR particle before it escapes (propagation time exceeds the age of the Universe). The first leads to a reduction, the second to an enlargement of the observed flux, but these correct the simple picture from Fig.3 in the way shown in Fig.4 where fluxes of properly transported UHECR over the same distances from the sources as in Fig.3 are presented.

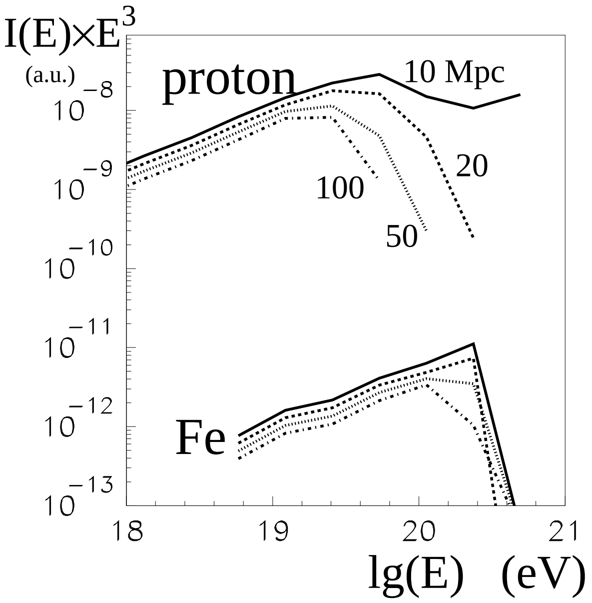

Fig. 3. The cosmic ray energy spectrum expected after traversing 10, 20, 50 and 100 Mpc (lines from the top) for protons (four upper curves) and iron nuclei (lower) of the EG photon background. Source spectrum is power-law with index -2.3. No magnetic field.

When the propagation is pure diffusion (below 10^{19}eV for iron or 26 times less for protons) it is almost impossible for CR particles to reach a distance bigger than about 20 Mpc from the source within the Hubble time. In the intermediate region, when the transport changes more and more to rectilinear (10^{19}–10^{20}eV for iron) the flux is higher than the respective flux from Fig.3 (for smaller distances in the case of iron, because for distances as large as 100 Mpc the increase of the path length act to diminish the flux). The increase is significant, it could reach two orders of magnitude as is seen in Fig.4.

4 Comparison with the best estimate of the primary spectrum

The spectra of UHECR have been measured for quite a long time by many experiments each of them having its own special methodology developed for a particular detection technique determining an estimated event energy uncertainty (and possible systematic biases). Spectra published by different groups were analyzed and combined by us in Wibig and Wolfendale (2001) using the well established “ankle” feature seen more or less clearly above 10^{18}eV in each data set. Eventually we show that the data can be consistently described by one, well established “world average” UHECR spectrum. It is shown in Fig.5. The results of our calculations are shown in Fig.5 as a solid curve. It was obtained assuming that sources of UHECR are distributed uniformly in the Universe and emit iron and oxygen nuclei (in equal portions) with energies given by a power-law spectrum with an index of -2.3.

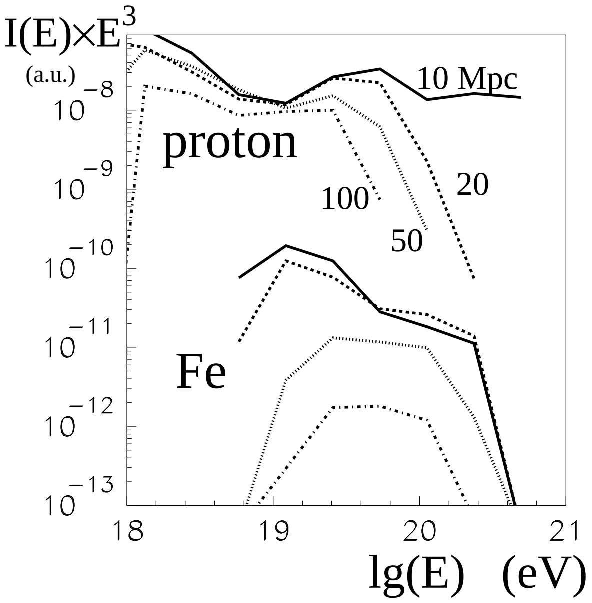

Fig. 4. The cosmic ray energy spectra expected for the source distance of 10, 20, 50 and 100 Mpc (description as in Fig.3) after propagation in random magnetic fields. Vertical shifts of production intensities are the same as in Fig.3.

For comparison the result of calculations by Takeda (1998) showing the GZK cut-off for universal proton production is given also as a dashed line. This sharp cut-off is not very sensitive to the production spectrum index. (Our results for protons with index of -2.3 are very close to that of Takeda with index of -3.0). Both lines are smeared out assuming a 15% experimental energy resolution. This is not very significant, however, the smoothed curve fits the data better.

5 Conclusions

It is clearly seen that the heavy nucleus hypothesis is able to explain the observed UHECR intensity above 10^{19}eV, shifting the cut-off energy by a factor of about five, a value that is just enough today. The existing statistics of Giant EAS do not allow us to confirm our model yet, but experiments planned and under construction could quite soon improve the statistics meaningfuly. Then two possibilities (at least) exist. If the cut-off is found where we propose in the present work, the heavy muclei hypothesis will gain strong support. If the UHECR spectrum follows the power law trend, the universality of source distribution ought to be in question. In the paper by Wibig and Wolfendale (2001) we present a possible solution which could be that the UHECR source is situated nearby, e.g. in the Virgo cluster. Such a hypothesis shifts the cut-off energy again by a factor of a few.

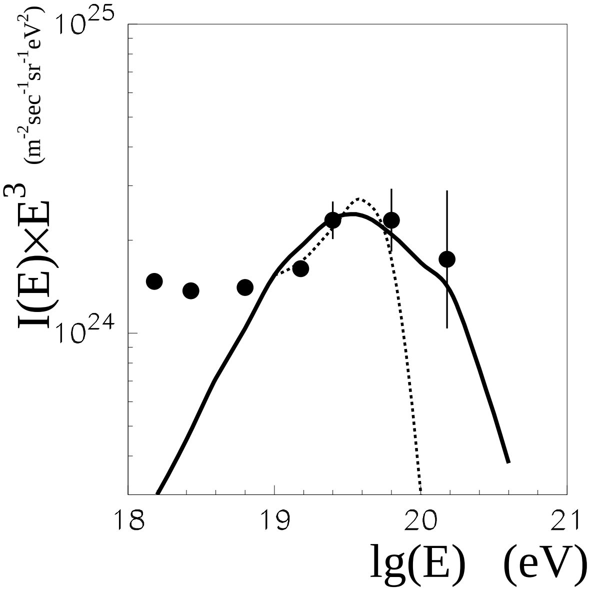

Fig. 5. The UHECR energy spectrum measured (point) compared with predictions for uniform source distribution and initial composition of 50% oxygen and 50% iron. Dashed curve shows GZK effect obtained by Takeda (1999) for universal proton flux.

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