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On the propagation of the highest energy cosmic ray nuclei

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ABSTRACT: We study the propagation of ultra-high energy cosmic ray nuclei through the background of cosmic microwave and intergalactic infrared photons, using recent re-estimates for the density of the last ones. We perform a detailed Monte Carlo simulation to follow the disintegration histories of nuclei starting as Fe and reaching the Earth from extragalactic sources. We obtain the maximum energies of the arriving nuclear fragments as well as the mass composition as a function of the distance traveled. Cosmic rays with energies in excess of 2×10^{20} eV cannot originate from Fe nuclei produced in sources beyond 10 Mpc.

KEYWORDS: High Energy Cosmic Rays, Electromagnetic Processes and Properties.

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Contents

1. Introduction

The cosmic ray (CR) spectrum is known to extend up to energies beyond 10^{20} eV, with the highest energy air showers observed having energies of 2–3$\times 10^{20}$ eV. The origin and nature of these ultra-high energy (UHE) events are one of the pressing unsolved problems defying us today. The CR spectrum has the overall shape of a leg, and is well fitted by power laws, whose index increases (spectrum steepening) for energies above the 'knee' ($E \sim 3\times 10^{15}$ eV), flattening again above the 'ankle' (at $E \sim 5\times 10^{18}$ eV). The CR composition becomes heavier for increasing energies around the knee, and the CR are probably mostly of galactic origin up to the ankle. Approaching the ankle, the CR composition seems to become lighter again, and the increasing rigidity of CRs does not allow anymore their confinement into the Galaxy. Hence, CR fluxes are most probably of extragalactic origin above the ankle. There have been studies suggesting that the arrival direction of the highest energy events may be indicating that their origin lies in the local supercluster, but they are not conclusive. The small anisotropies observed may also be compatible with a cosmological origin of the highest energy events.

The big difficulty which appears is that CR protons with $E \gtrsim 5 \times 10^{19}$ eV, i.e. relativistic γ factors $\gtrsim 5 \times 10^{10}$, are not able to propagate more than ~ 100 Mpc due to their energy losses by photopion production off the cosmic microwave background (CMB) photons, giving rise to the well known GZK cutoff [1]. At energies 2×10^{20} eV their mean free path is already only 30 Mpc. Heavy nuclei with smaller γ factors, but comparable energies, also get attenuated but mainly by photodisintegrations off the intergalactic infrared (IR) background and off CMB photons, as well as by pair creation losses to a lesser extent [2, 3, 4, 5, 6, 7].

A detailed study of the propagation of UHECR Fe nuclei, including all the relevant energy loss mechanisms, was performed more than twenty years ago by Puget, Stecker and Bredekamp [5]. However, the estimates of the density of IR photons employed then were about an order of magnitude larger than the new empirically based estimates

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obtained using the measured emissivity of IRAS galaxies [8]. In the light of the lower IR background densities inferred recently, it was suggested that UHECR nuclei may propagate much longer distances unattenuated [9], so that the events with energies 2–3×10^{20} eV could have possibly originated as Fe nuclei produced at distances up to 100 Mpc, and hence in particular in the whole local supercluster.[1] However, as we showed in a recent letter [10], at energies larger than 10^{20} eV it is photodisintegration off CMB photons (and not off IR ones) which dominates the opacity for Fe disintegration. This implies that the maximum energies with which the surviving fragments can reach the Earth are not significantly changed (for distances below a few hundred Mpc) with the new estimates of the IR density. In particular, for sources at distances of 100 Mpc the maximum energies of the surviving fragments do not exceed $\sim 10^{20}$ eV, and can arrive to 2×10^{20} eV only for distances below 10 Mpc.

The aim of the present paper is to re-evaluate in detail the propagation of heavy nuclei, following the photodisintegration histories by means of a Monte Carlo which includes all relevant processes, much in the spirit of the original Puget et al. paper [5]. From this we can establish all the effects resulting from the new estimates of the IR background density. In particular, we obtain the final mass composition and energy as a function of the distance to the source, as well as the possible fluctuations in these quantities which may arise from the particular way in which the photodisintegration takes place in each case. We also study the effects of pair creation losses, which turn out to be important in some cases for the determination of the final mass composition.

2. The propagation of heavy nuclei

As we said before, CR with energies above the ankle are most probably extragalactic. This means that in their journey they may be attenuated by the interactions with the photon background. This background consists essentially of the microwave photons of the 2.7°K cosmic background radiation and, at larger energies, of the intergalactic background of IR photons emitted by galaxies. The background of optical radiation turns out to be of no relevance for UHECR propagation.

Although the CMB density is well known, the intergalactic IR one cannot be measured directly and has to be estimated from the observation of the spatial distribution, IR spectra and emissivity of the galaxies which are sources for this IR emission. This was done recently by Malkan and Stecker [8], who obtained a result which is about an order of magnitude smaller than previous estimates. We will then adopt for the spectral density of the IR background

$$\frac{\mathrm{d}n}{\mathrm{d}\epsilon} = 1.1 \times 10^{-4} \left(\frac{\epsilon}{\mathrm{eV}}\right)^{-2.5} \ \mathrm{cm}^{-3}\mathrm{eV}^{-1} \qquad (2.1)$$

[1] It has to be stressed that Fe nuclei are good candidates for UHECRs, due to their high abundance in supernova environments and their large value of Z, which enhances the energy achievable in the acceleration process.

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for photon energies ϵ in the range between 2×10^{-3} eV and 0.8 eV. This is a factor of 10 smaller than the "high infrared (HIR)" density adopted in ref. [5], and is in the upper range of the recent estimates. In order to quantify the possible effects of an optical intergalactic background, we just modeled this last with a Planckian distribution with $T = 5000°$K and a dilution factor of 1.2×10^{-15}, as in [5].

UHECR nuclei propagating through these photon backgrounds will loose energy mainly by two processes:

i) photopair production, which has a threshold corresponding to photon energies in the rest frame of the nucleus of $2m_e c^2 \simeq 1$ MeV. This process was studied in detail by Blumenthal [11], and the main contribution arises from interactions with CMB photons. We used for the energy loss rate the expressions given in ref. [12].

ii) photodisintegration losses, for which the rate of emission of i nucleons from a nucleus of mass A (with cross section $\sigma_{A,i}$) is given by

$$R_{A,i} = \frac{1}{2\gamma^2} \int_0^\infty \frac{\mathrm{d}\epsilon}{\epsilon^2} \frac{\mathrm{d}n}{\mathrm{d}\epsilon} \int_0^{2\gamma\epsilon} \mathrm{d}\epsilon' \epsilon' \sigma_{A,i}(\epsilon') \,, \tag{2.2}$$

where γ is the relativistic factor of the nucleus, ϵ the photon energy in the observer's system and ϵ' its energy in the rest frame of the CR nucleus.

The cross sections for photodisintegration $\sigma_{A,i}(\epsilon')$ contain essentially two regimes. At $\epsilon' < 30$ MeV there is the domain of the giant resonance and the disintegration proceeds mainly by the emission of one or two nucleons. At higher energies, the cross section is dominated by multi-nucleon emission for heavy nuclei and is approximately flat up to $\epsilon' \sim 150$ MeV. We fitted the various $\sigma_{A,i}$ with the parameters in Table I and II of ref. [5]. A useful quantity to estimate the energy loss rate by photodisintegration is given by the effective rate

$$R_{eff,A} = \frac{\mathrm{d}A}{\mathrm{d}t} = \sum_i i R_{A,i} \,. \tag{2.3}$$

Since neglecting pair creation processes one has that photodisintegrations alone lead to $E^{-1}\mathrm{d}E/\mathrm{d}t = A^{-1}\mathrm{d}A/\mathrm{d}t$, the energy loss time for photodisintegration is then $A/R_{eff,A}$. The different contributions to this quantity are plotted in fig. 1. We show separately the contributions to the disintegration from CMB, IR and optical photons for Fe nuclei, together with the total one (solid line) and the photopair creation energy loss rate.[2]

It is apparent that the optical background has no relevant effect, that the IR one dominates the photodisintegration processes below 10^{20} eV and the CMB dominates above 10^{20} eV. The pair creation rate is relevant for Fe energies 4×10^{19} eV–2×10^{20} eV (i.e. γ factors ~ 1–4×10^9), for which the typical CMB photon energy in the rest frame of the nucleus is above threshold (> 1 MeV) but still well below the peak of the giant resonance ($\sim$ 10–20 MeV). The effect of pair creation losses is to reduce the γ factor of the nucleus, obviously leaving A unchanged.

[2]Looking at this and the following figures, it is important to keep in mind that 1 Mpc= 1.03×10^{14} s.

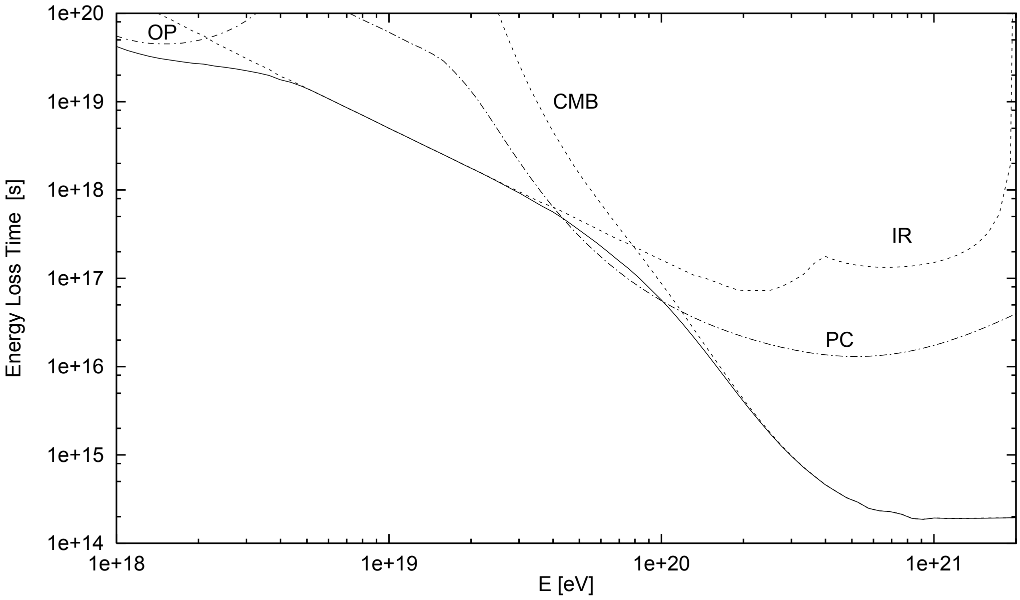

Figure 1: Effective energy loss time for Fe photodisintegration off microwave (CMB), infrared (IR) and optical (OP) photons, as well as the total one (solid line) and the pair creation (PC) energy loss time.

3. Results

Using the rates just discussed, we performed a Monte Carlo simulation in order to follow the possible disintegration histories of Fe nuclei. In figures 2 and 3 we plot the final mass (i.e. A) and energy E of the heaviest fragment surviving from the disintegration process. We show in these figures the results of simulations with initial values of the relativistic factor $\gamma_0 = 1 \times 10^{10}$, 4×10^9 and 1×10^9. The curves shown for each value of γ_0 correspond, in fig. 2, to the average value $\langle A \rangle$ from all the simulations (solid line) and the region (between the two dashed lines) including 95% of the simulations.[3] This gives a clear idea of the range of values which can result from fluctuations from the average behaviour.

To further understand the relevance of the different processes and the impact of the new determinations of the IR density, we also plot the results for $\langle A \rangle$ obtained in simulations which do not include pair creation processes (dotted lines) and also the results we would obtain (dot-dashed line) with an IR density a factor of ten larger (i.e. the HIR density of ref. [5]). Figure 3 is similar but for the final values of the energy.

From these figures we can draw the following conclusions:

i) For large initial energies ($E_0 > 2.5 \times 10^{20}$ eV, i.e. $\gamma_0 > 5 \times 10^9$), both the effects of the IR photons and of pair creation processes are of no relevance along the whole journey of the nucleus, and the energy losses are essentially due to photodisintegration off CMB photons alone.

[3]Only 2.5% of the simulations are below the lower curves and 2.5% are above the upper ones.

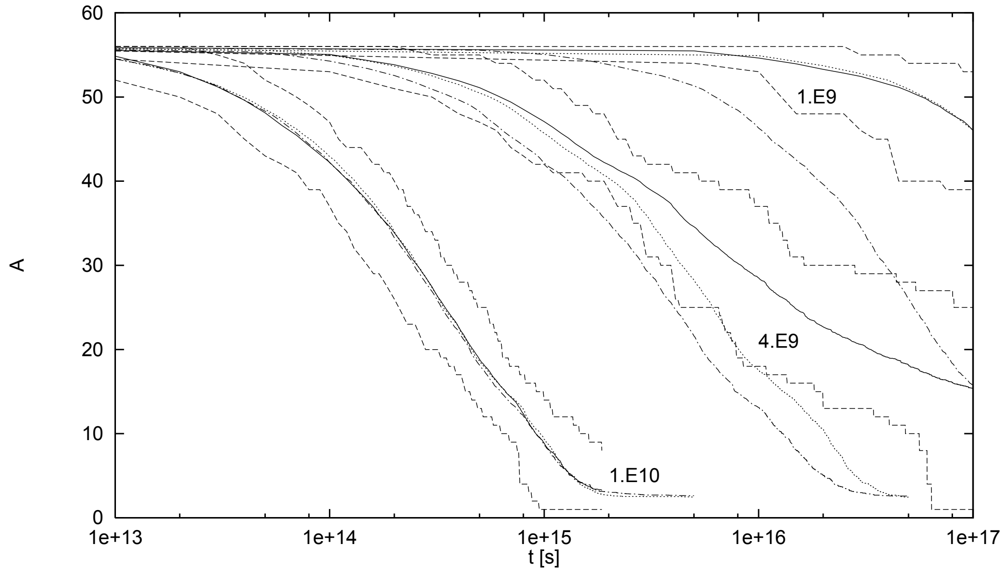

Figure 2: Evolution of the mass number A of the heaviest fragment surviving photodisintegration vs. travel time t. The initial γ factors considered are 1×10^{10} (1.E10 curve), 4×10^{9} (4.E9 curve) and 1×10^{9} (1.E9).

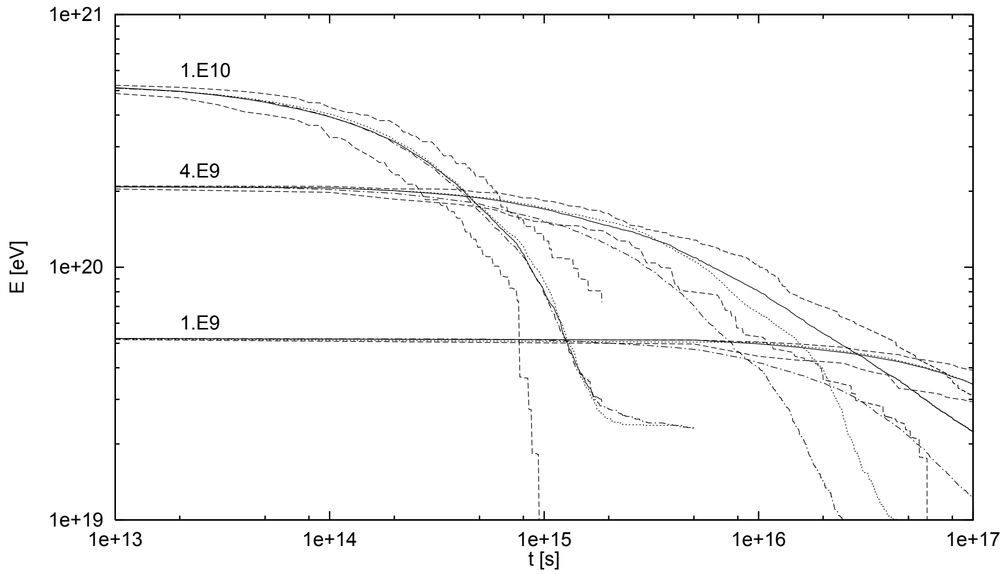

Figure 3: Similar as fig. 2 but for the final energy E vs. t.

ii) At $\gamma_0 < 5 \times 10^9$ the pair creation losses start to be relevant, reducing the value of γ significantly as the nucleus propagates distances $O(100$ Mpc$)$. The effect is maximum for $\gamma_0 \simeq 4 \times 10^9$ but becomes small again for $\gamma_0 \lesssim 1 \times 10^9$, for which appreciable effects only appear for cosmological distances ($> 10^3$ Mpc), as can be simply understood from fig. 1. The effect of neglecting pair creation losses translates into keeping $\gamma = \gamma_0$ constant during the propagation, and this enhances the photodisintegration rates and then reduces $\langle A \rangle$ more rapidly.

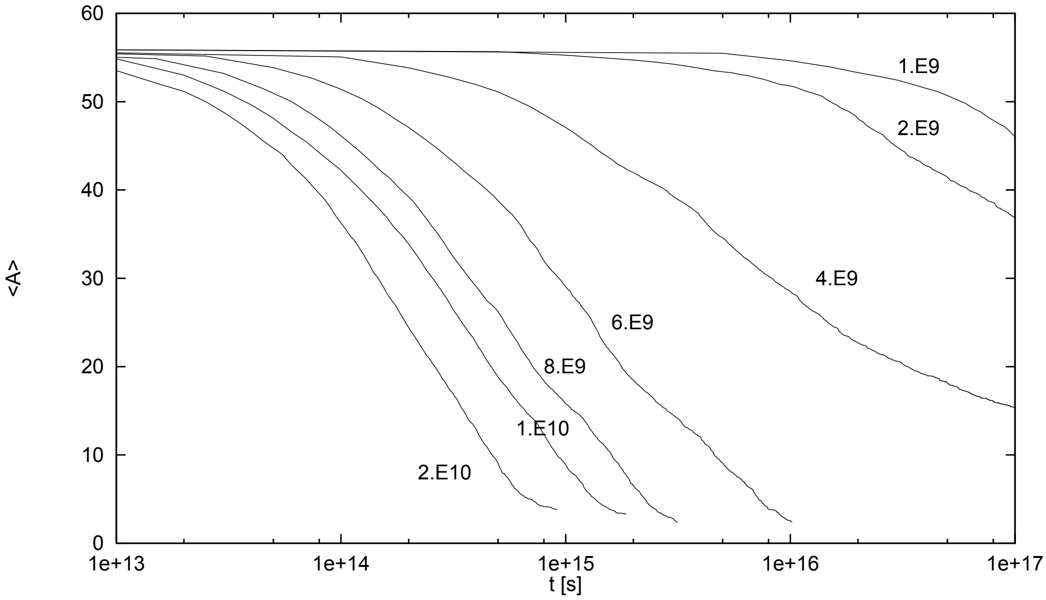

Figure 4: $\langle A \rangle$ vs. t for more sample values of γ_0.

iii) Also for $\gamma_0 < 5 \times 10^9$ the reduction in the IR density adopted has sizeable effects. In this respect point *ii*) is relevant, since pair creation losses shift the values of γ towards a domain where IR photons become increasingly important with respect to CMB ones. With the new values of the IR density the effects of photodisintegrations become small already for $\gamma_0 \simeq 1 \times 10^9$ if we consider propagation distances below 10^3 Mpc (i.e. for $t < 10^{17}$ s).

iv) The effects of neglecting pair creation losses are less pronounced in fig. 3. For instance, for $\gamma_0 = 4 \times 10^9$ the average energies with and without pair creation processes are similar up to $t \simeq 10^{16}$ s while the $\langle A \rangle$ values differ sizeably already for $t \simeq 3 \times 10^{15}$ s. This is due to a partial cancellation between the effects of the evolution of γ and of A in the values of the final energy ($E = m_p \gamma A$), since neglecting pair creation losses does not allow γ to decrease but makes instead A to drop faster.[4]

v) The effects of fluctuations due to different photodisintegration histories are not negligible. They give a spread in A (and E) of the order of 10% (considering the 95% probability range) for $\langle A \rangle \simeq 40$ but relatively larger for smaller $\langle A \rangle$, since variations $\Delta A \sim 10$–15 at a given time t can appear between different simulations.

In figures 4 and 5 we plot more sample values of $\langle A \rangle$ and $\langle E \rangle$, for values of $\gamma_0 = 2 \times 10^{10}$, 1×10^{10} and $(8,\ 6,\ 4,\ 2,\ 1) \times 10^9$. Looking at fig. 5 it is easy to infer the maximum energies which can be obtained from Fe nuclei injected at any fixed distance d. In particular, for $d = 100$ Mpc ($t = 10^{16}$ s) the maximum average energy is $E_{max} \simeq 8 \times 10^{19}$ eV and originates from $\gamma_0 \simeq 2$–4×10^9. Comparing with fig. 4 we see that these maximum energy events would correspond to fragments with masses $A(E_{max}) \simeq 30$–50, i.e. a rather heavy composition.

[4]This in particular shows that the inclusion of pair creation losses does not modify the maximum attainable energies computed in [10].

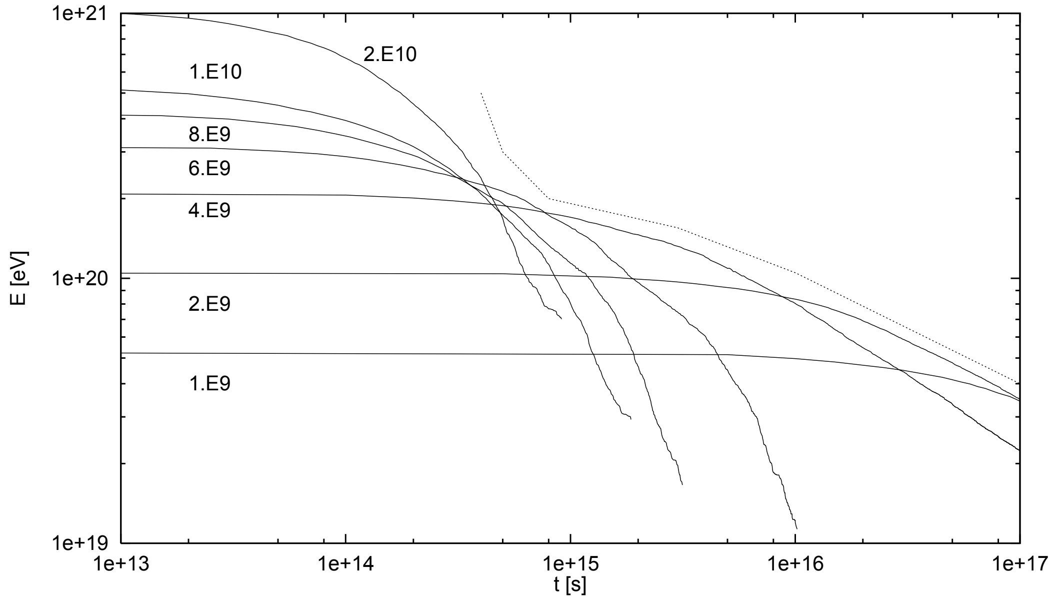

Figure 5: $\langle E \rangle$ vs. t for several sample values of γ_0. The dotted line indicates the upper boundaries of the 95% probability range obtained in the simulations.

Fluctuations from the average behaviour can only slightly increase the maximum attainable energies, and this is illustrated with the dashed line, which represents the upper boundary of the 95% CL ranges (i.e. 97.5% of the simulations are below this curve) for any initial value of γ_0.

For source distances $d = 10$ Mpc, average energies up to $E_{max} \simeq 2 \times 10^{20}$ eV can result, and an interesting pile-up effect is observed since a broad range of initial energies (with $\gamma_0 \sim 4$–8×10^9) lead to approximately the same final energy ($\sim E_{max}$). This can produce a bump in the spectrum from sources at these distances if indeed the highest energy events originate from heavy nuclei. Due to the spread in values of γ_0 at E_{max}, we see from a comparison with fig. 4 that there will also be a wide spread in the final composition, with $A(E_{max}) \simeq 10$–45. Events with energies 2–3×10^{20} eV may appear as low probability fluctuations from the mean behaviour if $d \simeq 5$–8 Mpc, having initially $\gamma_0 > 10^{10}$ and a low mass final composition ($A < 10$).

For smaller source distances ($d \sim$ few Mpc), events with $E \simeq 3 \times 10^{20}$ eV could be heavier nuclei with smaller initial energies ($\gamma_0 > 6 \times 10^9$).

For very large values of γ_0 ($\gamma_0 > 2 \times 10^{10}$), the heavy nuclei completely disintegrate in less than 10 Mpc, and the photopion production (not included here) becomes the main attenuation process for the secondary nucleons, which are then subject to the usual GZK cutoff.

In conclusion, the main implication of the lower values of the IR density recently estimated is to increase the mean free path of the heavy nuclei with initial γ factors below $\sim 5 \times 10^9$, for which most CMB photons are below the peak of the giant resonance for photodisintegration. Due to the fragmentation of the nuclei by photodisintegration and the pair creation energy losses, the final energies of the fragments are typically below 2×10^{20} eV for travel distances ~ 10 Mpc, and below 10^{20} eV for distances ~ 100 Mpc. The new value of the IR density is then of little help in the attempts to understand the highest energy events observed ($E \sim 2$–3×10^{20} eV), which could not have originated as heavy nuclei at distances beyond ~ 10 Mpc. The lack of obvious candidate sources at closer distances [7] leave the nature and origin of these events still a mistery.

Acknowledgments

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