Proton energy loss in photohadronic interactions on the microwave background

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Abstract

Photomeson production is the main energy loss process for relativistic nucleons in dense radiation fields like the cosmic microwave background. In this paper we study the energy evolution of cosmic rays due to pion photoproduction losses in the 2.7K-background radiation field traveling over cosmological distances. We give the median energy of a proton at source as a function of its detected energy together with its energy fluctuations.

1 Introduction

Extragalactic cosmic rays (CR) propagating long distances through dense radiation fields like the cosmic microwave background (CMBR) will suffer energy losses due to primarily pion photo production and lepton pair production. As a fingerprint, a cut-off in the CR spectrum at $E \sim 50$EeV (1 EeV = 10^{18}eV) is expected (Greisen 1966, Zatsepin & Kuzmin 1966) due to the catastrophic CR energy losses in the former process if CRs originate in uniformly distributed extragalactic sources. However, a number of CR events has recently been observed with higher energies (Bird et al 1995, Hayashida 1996, Elbert & Sommers 1995, etc.). Below the sharp cut-off, a pile-up ("bump") in the CR spectrum is expected (e.g. Hill & Schramm 1985, Berezinsky & Grigor'eva 1988). The exact energy and shape of these features on the observed cosmic ray spectrum depend on the propagation time, the energy loss distribution and the model of the source distribution.

In this paper we study the evolution of CRs while propagating through the 2.7K universal background radiation field up to distances of 100 Mpc, a region dominated by the supergalactic plane. This allows us to neglect effects due to redshifting of the background radiation field.

We are especially interested in the highest observed CRs $\simeq 100$ EeV. Here, pion photoproduction is the dominant loss process. Thus we restrict radiative energy losses to this process only using the recently developed Monte-Carlo code SOPHIA (Mücke et al 1999). The photoproduction event generator reproduces well all available experimental data. It is based on detailed phenomenological descriptions of the physical processes fitted to data.

2 Energy losses and propagation

The energy evolution of cosmic ray protons is governed by the photoproduction energy loss, which in turn depends on the interaction cross section and proton inelasticity. Fig. 1 shows the mean free path λ, energy loss distance and proton inelasticity with proton input energy due to photomeson production on the microwave background radiation of temperature T=2.735K using the Monte-Carlo code SOPHIA.

The mean free path and energy loss distance are in essential agreement with previous calculations (except for Yoshida & Teshima (1993), who give significantly larger loss distances), although SOPHIA takes a better account for the cross section close to the photoproduction threshold (direct pion production), in the secondary resonance region and at high $\sqrt{s}$. In particular, our result is in good agreement with Rachen & Biermann (1993) for proton energies $\geq 10^3$ EeV. At energies ≤ 100 EeV SOPHIA gives somewhat larger loss distances, which is in excellent agreement with Protheroe & Johnson (1996) and Berezinsky & Grigor'eva (1988), and is the energy region of interest in this paper.

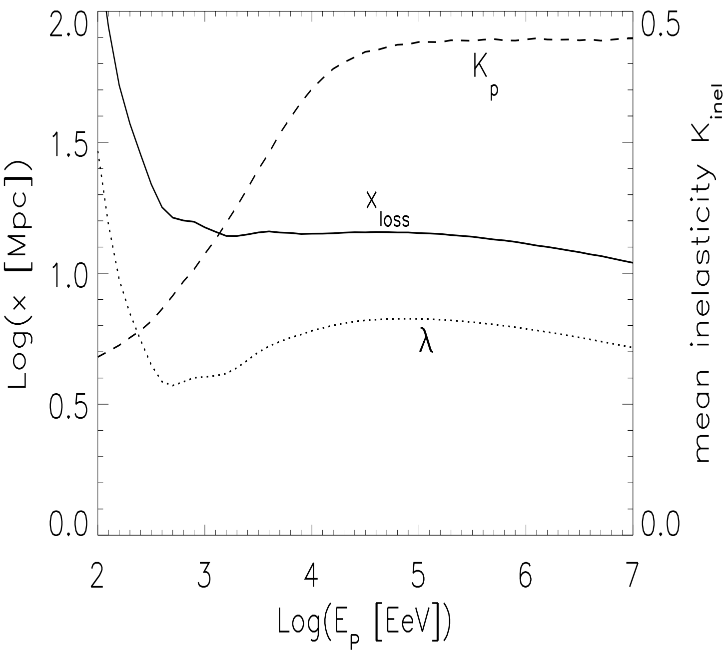

Figure 1: *Mean free path* λ *(dotted line), mean energy loss distance* x_{loss} *(solid line) and mean inelasticity* K_{inel} *(dashed line) of protons due to pion photoproduction in the CMBR of temperature T=2.735K.*

One of the essential differences between our simulations and any previous work is the energy dependence of the proton inelasticity distribution. Fig. 2 shows the inelasticity distribution for interactions with the microwave background at proton energies of 100 EeV to 10^5 EeV. While the distribution peaks close to 0.2 at the lowest proton energy, a number often used in back of the envelope calculations, it becomes significantly wider with energy, asymptotically approaching a value close to 0.5. A significant feature of the distribution is the diffractive peak at very low K_{inel}, which at high energy represents about 15% of the total interaction cross section. This elastic process generates neutral vector mesons, mostly ρ^0, that carry away only a small fraction of the proton energy. This channel was not considered in any previous work on cosmic ray propagation.

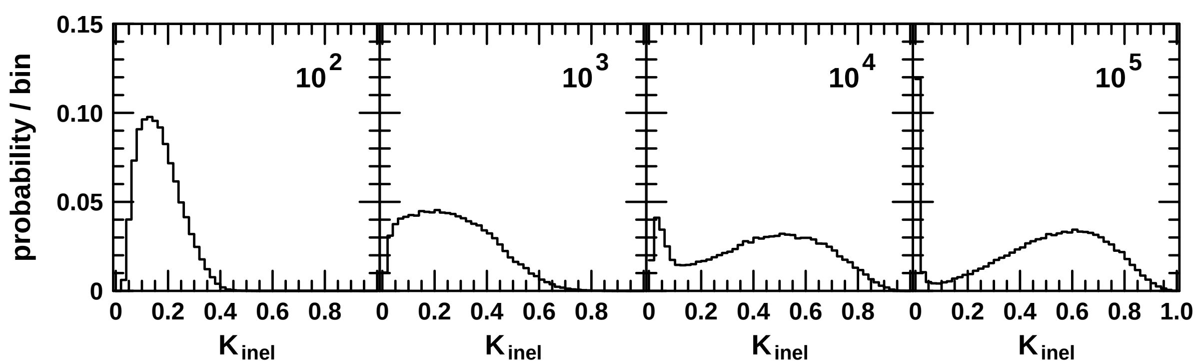

Figure 2: *Inelasticity* (K_{inel}) *distributions for proton energies* $10^{2...5}$ *EeV. The significant peak at small* K_{inel} *for* $E_p > 10^4$ *EeV is due to the diffractive channel in pion production interactions.*

The cosmic ray propagation presented in this paper is done backwards, i.e. we start with a nucleon of a given energy (100 EeV, 200 EeV, or 300 EeV) at detection and evaluate its energy at a certain distance. We injected an equal number of protons and neutrons, which are experimentally not distinguishable. Steps of 100 kpc were used in the backpropagation.

At each energy step we sample the nucleon interaction length and decide whether an interaction has occured. If the interaction has occured, the parent nucleon energy is chosen from the pre–calculated inelasticity distributions, some of which are shown on Fig. 2. This approach simplifies significantly the propagation calculation, although it introduces small errors in the energy evolution of individual particles, related to the inexact treatment of the cross section and inelasticity energy dependence. The hope is that multiple backpropagation will average over the differences in the K_{inel} distributions and will not seriously affect the final result. While traveling, protons are deflected in the intergalactic magnetic field. For our propagation calculations we adopt deflection of protons on the 100 kpc stepsize. The probability of isospin flip of the propagating nucleons is calculated from SOPHIA simulations. We also include neutron decay in the propagation code.

The nucleon energy distributions are created in steps of 2 Mpc. After a nucleon has reached the maximum propagation distance of 100 Mpc, the energy distributions as a function of distance are inspected. These have generally a very wide, non–Gaussian shape, as already noted by Lampard et al 1997. If treated as Gaussian ones, the σ values would significantly exceed the average for propagation over $\sim$ 50 Mpc. To estimate the most likely energy value and its fluctuations, we use the integral energy distributions. The energy that was reached by 15.85%, 50% and 84.15% of all propagated nucleons correspond to the median energy and the $\pm 1\sigma$ deviations.

3 Results and discussion

The results are shown in Fig. 3 for nucleons of observed energy 100 EeV, 200 EeV and 300 EeV. The striking feature is the very large fluctuations for all three energies, possibly resulting from CRs interacting in the diffractive pion production channel. Fig. 3 shows that there is a 15% probability for a 100 EeV proton to reach us from a source at 40 Mpc without significant energy loss. The backpropagation of higher energy nucleons is somewhat more restrictive, yet still allows cosmic rays to reach us with minimal energy loss from relatively large distances. Taking into account that CRs can not be injected at source with energies exceeding $3 \cdot 10^4$EeV due to observational contraints (Protheroe & Johnson 1996), we find that for CRs with observed energy 300 EeV a 15% probability for their origin at 75 Mpc.

The shape of the median CR energy is defined by the resonant character of the photoproduction cross section at its energy threshold. The mean free path used in this calculation is 29.3 Mpc at 100 EeV. It rapidly decreases with proton energy to reach a minimum of 3.7 Mpc at $\sim$ 500 EeV. Combined with the K_{inel}–energy dependence it results in a relatively low energy loss in the initial several tens of Mpc and increased evolution afterwards.

Significant energy fluctuations in the range 10-100 Mpc has been already noted by Aharonian & Cronin (1994). However, for energies at source of $< 10^4$EeV their maximum energy spread does not exceed a factor 1.5 of the mean energy, while our calculations indicate significantly larger fluctuations. This may influence the more detailed features of the CR spectrum below the cutoff by CRs possibly leaking beyond the bump and GZK-cutoff. Considering the median fractional energy loss during propagation, our calculations are in reasonable agreement with previous works (e.g. Aharonian & Cronin (1994), Lampard et al 1997).

One phenomenon that cannot be properly treated with the backpropagation technique is the nucleon scattering angle, in particular nucleon deflection. Deflection occurs mostly at the lowest nucleon energy, after the last interaction before detection. In this work, we injected an equal number of protons and neutrons at Earth, which however would underestimate the number of protons because of neutron decays. Thus, in backpropagation one often ends with neutrons at source, which is not a valid assumption for arbitrary acceleration scenarios.

Better handling of the cosmic ray propagation, including the production of gamma ray and neutrino signals, can only be achieved by forward propagation. We are in the process to build such a program and hope to be able to present the first results at the Conference in Salt Lake City.

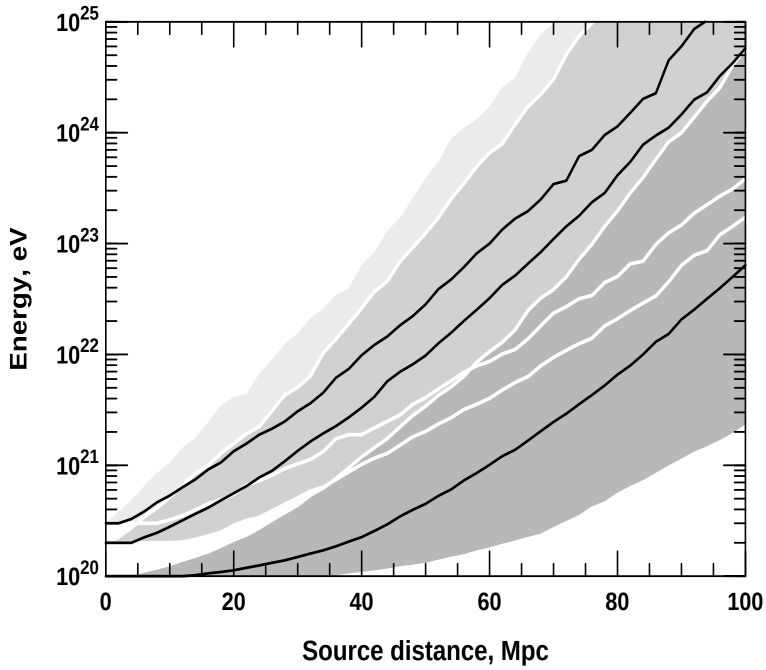

Figure 3: *Energy evolution with source distance of protons of energy 100 EeV, 200 EeV, 300 EeV (lower to upper black curve) as measured at Earth. The solid lines give the median proton energy, while the shaded areas represent fluctuations corresponding to* $\pm 1\sigma$ *for a Gaussian distribution.*

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