Photomeson production in astrophysical sources

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Abstract. Photomeson production is the main energy loss for relativistic nucleons in dense radiation fields like the cosmic microwave background and the radiation fields in Gamma Ray Bursts (GRB) and jets of Active Galactic Nuclei (AGN). In this paper we study photomeson production in typical GRB and AGN jet radiation fields by using the recently developed Monte Carlo event generator SOPHIA (see these proceedings). We discuss processes that are relevant for the physics of cosmic ray acceleration and the production of neutrinos and gamma rays. We compare our results with widely used approximations, and find significant deviations, particularly for GRBs. The photoproduction of antibaryons as a so far not considered effect in astrophysics is briefly discussed.

1. Introduction

Ultrahigh-energy nucleons lose their energy mainly through photomeson production while traveling through dense radiation fields, such as the Cosmic Microwave Background Radiation (CMBR), Active Galactic Nucleus (AGN) jet and Gamma Ray Burst (GRB) photon fields. The secondary products of such interactions decay, and lead eventually to the emission of neutrino and gamma-ray fluxes from the source, which may be observable. This has triggered several authors (e.g. Stecker 1973 [1, 2], Berezinsky & Gazizov 1993 [3], Mannheim & Schlickeiser 1994 [4]) to study photopion production in more detail. Collider measurements indicate a complicated structure of the cross section, especially in the astrophysically important lower energy range. In order to overcome this problem, either simplified approximations for the cross section, e.g. the so-called Δ–approximation (Stecker 1973 [2], Gaisser et al. 1995 [5]), or Stecker's isobar model [1], have been used. Berezinsky & Gazizov [3] used interpolated cross section measurements and implemented them into numerical codes to derive neutrino production spectra. Recently, it has been shown that in realistic photon fields photon–proton collisions may happen at low *and* high center–of–mass (CM) energies (Mücke et al 1999a [6]), making a more realistic treatment of the pion production process necessary. For example, hadronic interactions of ultrarelativistic protons in flat ambient photon spectra, e.g. in Gamma Ray Burst radiation fields and the synchrotron radiation field in γ-ray loud AGN, are roughly equally likely to occur in the resonance and the multiparticle production regions. A powerful method to treat processes with complicated cross sections and particle production properties is the Monte-Carlo technique.

In this paper we discuss photopion production in typical GRB and AGN jet radiation fields. We discuss microphysical quantities relevant for the photohadronic production of gamma-rays, neutrinos, and neutrons (Section 2), by using our newly developed Monte Carlo event generator SOPHIA (presented also in these proceedings (Mücke et al 1999b [7])), and compare them with results from widely used approximations (Section 3). As a qualitatively new effect we also discuss the photoproduction of anti-baryons (Section 4). The relevance of our results is briefly discussed in the context of neutrino and cosmic ray production (Section 5).

2. Relevant microphysical quantities

One of the major motivations for discussing photohadronic interactions in astrophysical sources like AGN jets and GRB is the prediction of observable neutrino fluxes from these systems. The total flux of neutrinos for a specific source model can be related to the predicted fluxes of gamma rays and cosmic rays, which in turn can be compared with current observations. Neutrino fluxes from hadronic AGN jet models are not expected to be observable as point sources by current neutrino telescopes, and therefore contribute to the extragalactic neutrino background. Hence, estimates for diffuse neutrino fluxes originating from blazar jets can be derived from measurements of the diffuse extragalactic gamma ray background (EGRB) (see e.g. Mannheim 1995 [8]) if the entire EGRB is produced photohadronically, or upper limits if only part of the EGRB may be due to unresolved blazars (see Chiang & Mukherjee 1997 [9], Mücke & Pohl 1998 [10]).

Of particular relevance is here the production of gamma rays. In photohadronic sources, the opacity for the primary gamma rays emerging from the decay of neutral pions must be large, since otherwise the efficiency for the photohadronic interactions themselves would be too low to produce observable fluxes. The interaction of primary photons (and electrons) causes an unsaturated electromagnetic cascade which reprocesses the leptonic power to lower photon energies, and photons are eventually emitted in the range < 100 GeV (Mannheim 1993 [11]).

The exact relation between the gamma ray and neutrino fluxes is determined by the microphysics of photomeson production, i.e., by the photon-to-neutrino total energy ratio per interaction, $\mathcal{E}_\gamma/\mathcal{E}_\nu = \sum E_\gamma / \sum E_\nu$. The Δ–approximation, which has been often used, gives $\mathcal{E}_\gamma/\mathcal{E}_\nu = 3$. This ratio has been slightly modified by considering other photon producing processes, like Bethe-Heitler pair production off the energetic protons (Mannheim 1993 [11]).

Another way to constrain neutrino fluxes is a comparison with the cosmic ray spectrum. This is motivated by the fact that neutrino producing interactions also cause an isospin-flip of the proton into a neutron, which is not magnetically confined and can be ejected from the accelerator. In contrast, protons need to be confined in order to be accelerated, and their escape from sources involving relativistic flows, like AGN jets or GRB, is strongly suppressed by adiabatic losses. Neutron ejection can also be suppressed if the opacity for $n\gamma$ interactions exceeds unity. It is possible however to relate the $n\gamma$ opacity to the $\gamma\gamma$ opacity of very high energy photons, and one can show that sources transparent to very high energy (VHE) gamma rays are also transparent to neutrons at most energies [13]. Then, regardless of the proton confinement, the *minimum* cosmic ray ejection is given by the produced neutron flux, which allows an upper limit on the possible neutrino flux (Waxman & Bahcall 1999 [12]). It has been pointed out by Mannheim et al. [13], that the complicated propagation properties of cosmic rays make it difficult to apply a cosmic ray bound on the neutrino flux with the same generality as for gamma rays. The relation of the cosmic ray flux to neutrino flux is again determined by a microphysical parameter, namely the neutrino-to-neutron total energy relation $\mathcal{E}_\nu/\mathcal{E}_n = \sum E_\gamma / \sum E_\nu$, which is predicted as ≈ 0.19 in the Δ–approximation.

Other kinematical quantities of interest are the inelasticity of the proton, $\Delta E_p/E_p$, which determines the proton energy loss time scale due to photohadronic interactions, and the average fractional neutrino energy per interaction, $\langle E_\nu \rangle / E_p$, which determines the maximum neutrino energy if the maximum proton energy is determined by the acceleration process. In the same way, we may also consider the fractional neutron energy per interaction.

3. Cosmic ray, gamma ray and neutrino production

In the typical scenario of hadronic interactions in AGN jet and GRB radiation fields, relativistic nucleons with energy $E_p \gg \epsilon$ are assumed to interact in an isotropic radiation field in the comoving frame of the relativistic plasma flow. Because of the strong magnetic fields required to accelerate protons, photoproduced electrons and positrons can be assumed to have 100% radiation efficiency, and transform their energy completely into photons through synchrotron emission. The total and average energy of the produced neutrinos includes ν_e and ν_μ and their antiparticles. The $\nu_\mu/\bar{\nu}_\mu$ contribution, possibly detectable in current or planned underwater/-ice neutrino experiments, is roughly 2/3 of the total neutrino flux. We assume that protons are magnetically confined, and count only photohadronically produced neutrons as ejected cosmic rays.

3.1. Blazar/AGN jets

There exists a large variety of models to explain the observed γ-ray emission from blazars (= flat spectrum radio quasars and BL Lac objects). The leptonic models, which assume inverse Compton scattering of low energy photons up to gamma ray energies, currently dominate the thinking of the scientific community. Alternatively, photopion production has been proposed to be the origin for the observed γ-ray flux (Mannheim 1993 [11]). A clear distinction between both models is the production of neutrinos, which is negligible in the leptonic models, but may be equally important as the photon production in the hadronic models, and has been predicted to cause observable fluxes in large underwater/-ice neutrino detectors.

Gamma ray and neutrino production in hadronic blazar models occurs through photopion production (and subsequent cascading) of relativistic protons in either external (accretion disk or the IR radiation field from a molecular torus) radiation fields or the synchrotron radiation field produced by electrons which are shock accelerated together with the protons. Here, we confine our discussion to the latter model. For simplicity, we consider TeV-blazars only, which are distinguished by a low energy spectrum extending to X-ray energies. The synchrotron emission from blazar jets at low energies can be well explained by a superposition of several self-absorbed synchrotron components (e.g. Cotton et al 1980 [14], Shaffer & Marscher 1979 [15]) leading to a flat target spectrum. The *local* synchrotron radiation spectrum follows a power law with photon index $\alpha = 1.5$ ($n(\epsilon) \propto \epsilon^{-\alpha}$) up to a break energy (see e.g. Mannheim 1993 [11]). Above the break energy $\epsilon_b \approx 10^{-4}$eV (see e.g. Rachen, & Mészáros [16]) it is loss dominated to become $n(\epsilon) \propto \epsilon^{-2}$. The synchrotron emission in TeV-blazars like Mkn 421 and Mkn 501 is observed to continue up to 1-10 keV. Thus, for our application we approximate the typical target photon spectrum in the jet frame (assuming a Doppler factor of D=10) by

$$\begin{aligned} n(\epsilon) &\propto \epsilon^{-3/2} \qquad \text{for} \qquad 10^{-5}\text{eV} \leq \epsilon \leq 10^{-4}\text{eV} \\ n(\epsilon) &\propto \epsilon^{-2} \qquad \text{for} \qquad 10^{-4}\text{eV} \leq \epsilon \leq 10^{3}\text{eV} \end{aligned} \tag{1}$$

For the maximum proton energy we use $E_{p,\max} = \gamma_p m_p c^2 = 10^{10}$ GeV in the rest frame of the jet, corresponding roughly to the highest observed cosmic ray energies after Doppler boosting. This is also consistent in order of magnitude with the values derived by equating the acceleration time of the proton with its total loss time due to adiabatic, synchrotron and photohadronic cooling (see Rachen & Mészáros [16] for a more detailed discussion). Due to the threshold condition for photopion production of protons with Lorentz factor γ_p interacting with photons of energy ϵ

$$\gamma_p > \frac{m_\pi c^2}{2\epsilon}\left(1 + \frac{m_\pi}{2m_p}\right) \tag{2}$$

only photons from the steep part of the target radiation field interact photohadronically with protons of $\gamma_p \leq 10^{10}$.

Fig. 1 shows $\mathcal{E}_\gamma/\mathcal{E}_\nu$ from SOPHIA simulations for protons of energy E_p interacting in the synchrotron field of blazar jets. The prominent resonance/threshold region dominates the interaction, independently of input proton energy. Consequently, the total fractional photon energy $\mathcal{E}_\gamma/E_p \approx 0.1$, independent of E_p, and an overall photon-to-neutrino ratio of $\mathcal{E}_\gamma/\mathcal{E}_\nu \approx 1.2$. We note that this result differs by a factor ≈ 3 from the prediction of the Δ-approximation, although the steep spectrum emphasizes the threshold region with the dominant $\Delta(1232)$ resonance. This can be understood in view of the strong contribution of non-resonant direct π^+ production at threshold, and the contribution of other resonances with different isospin in the vicinity of the $\Delta(1232)$ resonance (see Mücke et al., these proceedings [7]).

In contrast, kinematical quantities like inelasticity and fractional secondary particle energy are well reproduced by the Δ-approximation (see Fig. 2), since these quantities vary only slowly with energy. For example, the proton inelasticity is in general logarithmically rising with increasing nucleon input energy in the resonance region (Mücke et al 1999b [7]). Thus, when interactions occur near the $\Delta(1232)$-resonance like in this case, the Δ–approximation gives a good description. The same applies for the total neutrino-to-neutron energy ratio. Here, we find $\mathcal{E}_\nu/\mathcal{E}_n \approx 0.18$ (see Fig. 3).

3.2. Gamma Ray Bursts

The cosmological Gamma Ray Burst fireball model has been very successful in explaining the observed temporal evolution of the afterglow photon spectra (see Piran 1998 [17] and references therein). In this model a relativistically expanding pair fireball transforms most of the explosion energy into the kinetic energy of baryons in a relativistic blast wave with bulk Lorentz factor of 100 – 300. This energy is

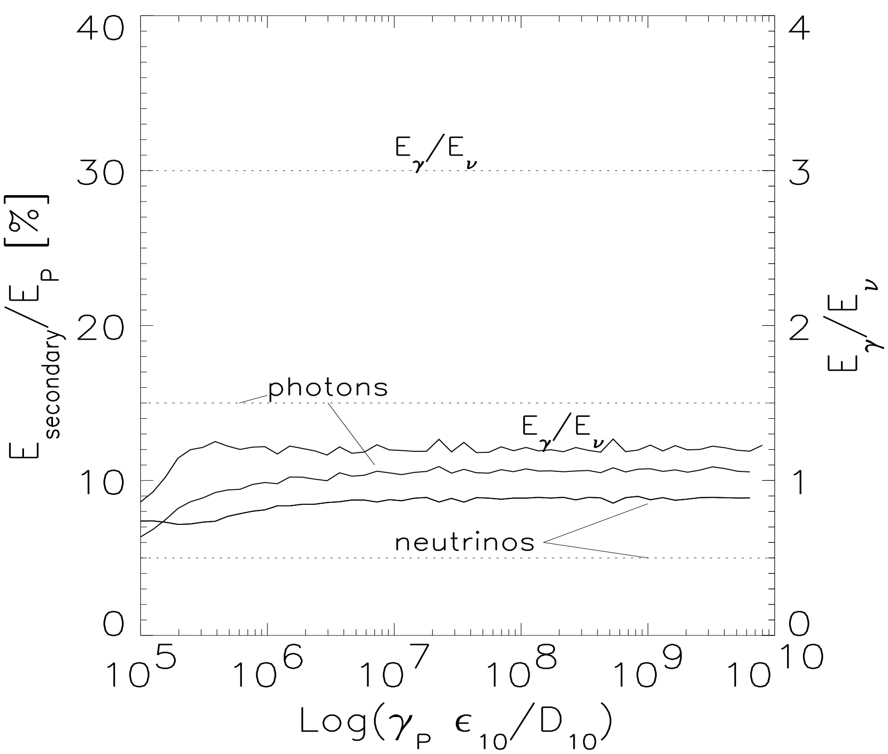

Figure 1. The total photon and ν-power (normalized to the proton input energy E_p), and their ratio emerging from a source due to photopion production of protons of energy E_p in a typical TeV-blazar ambient radiation field The $\mathcal{E}_\gamma/\mathcal{E}_\nu$–ratio is approximately unity, independent of proton input energy, which can be contrasted to the Δ-approximation (dotted lines). Solid lines denote the results from the SOPHIA simulations.

reconverted into radiation at shocks, produced either in collisions between different shells ejected from the central source (internal shock scenario), or through deceleration of the blast wave when it sweeps up the external medium (external shock scenario). The former process is thought to be responsible for the GRB itself, while the latter produces the afterglow. In this scenario, the observed photon radiation is explained as synchrotron radiation from the accelerated electrons. In the comoving shock frame this target radiation field for photopion production of the relativistic protons may be approximated by a broken power law:

$$
\begin{aligned}
n(\epsilon) &\propto \epsilon^{-2/3} \qquad \text{for} \qquad 10^{-3}\text{eV} \le \epsilon \le 10^{3}\text{eV} \\
n(\epsilon) &\propto \epsilon^{-2} \qquad \text{for} \qquad 10^{3}\text{eV} \le \epsilon \le 10^{5}\text{eV}
\end{aligned}
\tag{3}
$$

Waxman [18] and Vietri [19] suggested that if a significant fraction of the observed GRB power is transformed into ultrahigh energy cosmic rays (UHECRs), GRB may well be the source for all the observed UHECRs. In fact, it has been shown that comoving proton Lorentz factors of up to $\sim 10^9$ can be reached in GRB shells, which are boosted in the observers frame to $3 \cdot 10^{20}$ eV ([18],[16]). This scenario gives also rise to fluxes of very high energy neutrinos ($E_\nu > 100$ TeV) correlated with gamma ray bursts, which could be detected in a km^3 neutrino observatory because

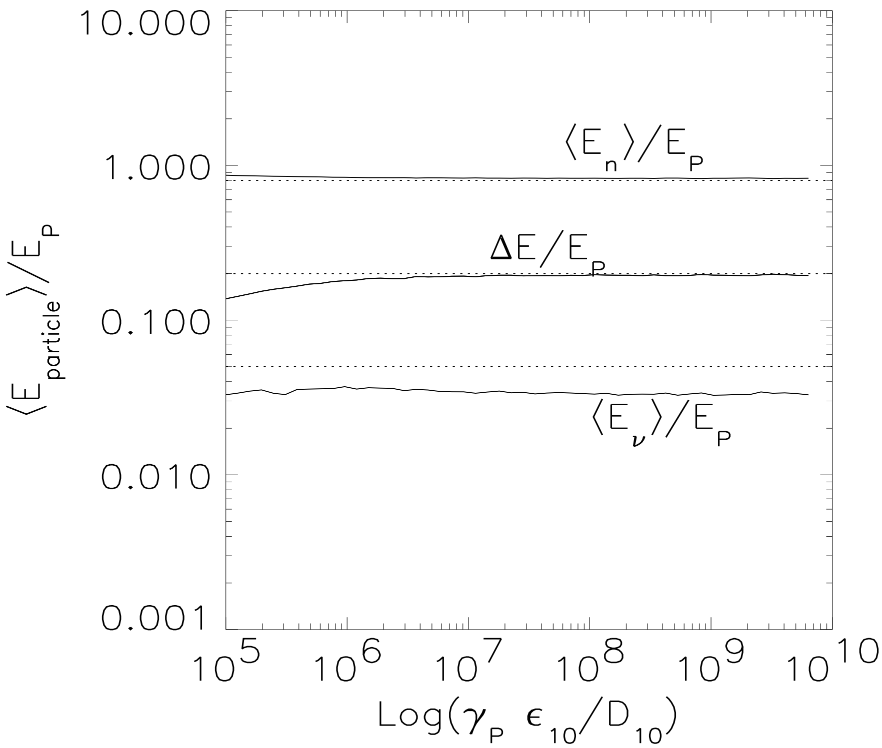

Figure 2. Average neutron (upper curves) and neutrino energy (lower curves) with respect to the proton input energy E_p, and the mean proton inelasticity due to photon–proton pion production of protons with energy E_p in a typical TeV-blazar ambient radiation field. The dotted lines represent the respective values from the Δ-approximation while solid lines denote the results from the SOPHIA simulations.

the exact temporal and directional information reduces the background to virtually zero (Waxman & Bahcall 1997 [20]). The neutrino emission, however, is suppressed at the highest energies because of the adiabatic and synchrotron losses of pions and muons prior to their decay (Waxman & Bahcall 1997 [20], Rachen & Mészáros 1998 [16], Waxman & Bahcall 1999 [12]).

In the highly energetic GRB photon field mostly photons from the flat part of the ambient radiation field interact photohadronically. For incident protons with $\gamma_p > 10^7$ interactions predominantly occur in the multiparticle region of the cross section, while for $\gamma_p \leq 10^7$ the resonance/threshold region determines the secondary particle production. This leads to an increase of photon and neutrino production by roughly a factor of 2 with $\mathcal{E}_\gamma \approx \mathcal{E}_\nu$ for protons with $\gamma_p > 10^7$ in comparison with protons with $\gamma_p \approx 10^5$ (see Fig. 4). The photon-to-neutrino total energy ratio seems to be fairly robust $\mathcal{E}_\gamma \approx \mathcal{E}_\nu \approx 1$ at all proton energies, except for a slight deviation at $\gamma_p \approx 3 \cdot 10^5$ where photons from the flat part of the target photon spectrum interact mainly via the $\Delta(1232)$-resonance. Also here, this result is about a factor of 3 different from the Δ–approximation.

The average number of neutrinos produced per interaction can increase with CM energy by up to an order of magnitude for the proton energy range relevant in GRB (see Mücke et al 1999b [7]). Because of the high multiplicity of the secondaries, the mean

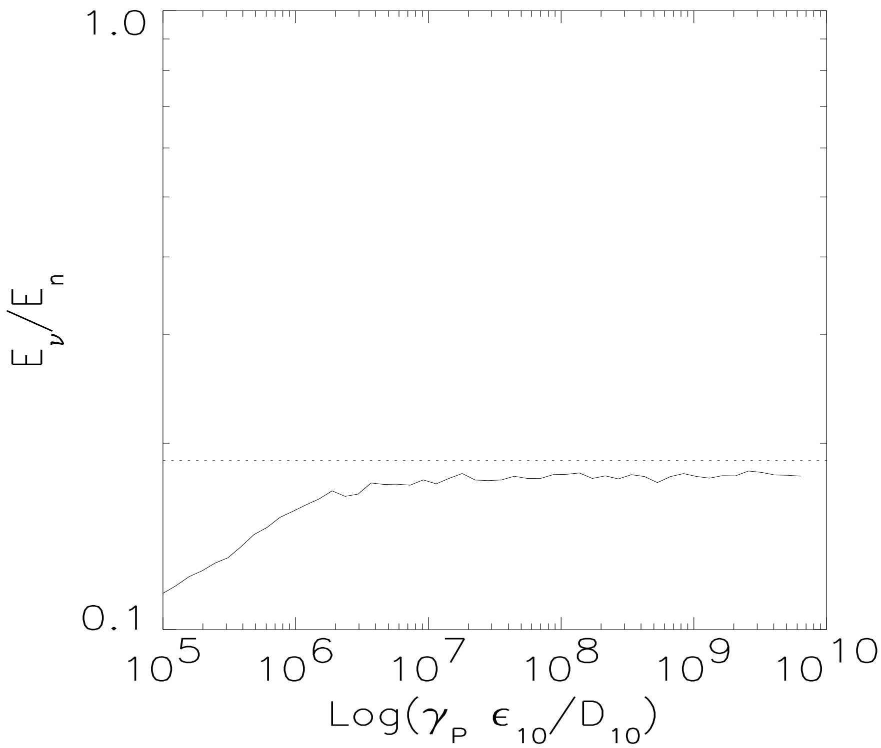

Figure 3. The ratio of total ν-energy to neutron energy emerging from a TeV-blazar jet due to photopion production of a protons with energy E_p. The Δ–approximation (dotted line) gives an adequate description of the ν-to-neutron ratio.

energy of the neutrinos produced in the multipion region (i.e. for $\gamma_p > 10^7$) is $\approx 1\%$ of the proton input energy (see Fig. 5). At lower energies it reaches $\langle E_\nu \rangle / E_p \approx 0.04$, approximately in agreement with the Δ–approximation. Therefore, the ejection of ultra-high energy neutrinos ($E_\nu > 10^{19}$ eV), as recently proposed by Vietri [21] (but note also [12]) requires observer frame proton energies of 10^{21} eV, which is further increased if GRBs are mainly at large redshifts, as suggested by afterglow observations. Such high proton energies are generally not expected from shock acceleration scenarios in GRB shells. In the general case, however, the synchrotron losses of charged pions and muons in the highly magnetic ($B \sim 10^3 - 10^6$G) GRB environment and their adiabatic deceleration determine the high energy end of the observable neutrino flux from GRB (see Rachen & Mészáros 1998 [16]).

The proton-neutron conversion probability determines the production of neutrons (and possibly of cosmic rays) in photohadronic sources. At high energies it decreases from ≈ 0.5 to 0.3 (see Mücke et al, these proceedings [7]), and the average fractional energy of the neutron decreases to < 0.5 of the proton energy. Together with the increasing power going into secondary particles, this leads to a neutrino-to-neutron ratio $\mathcal{E}_\nu / \mathcal{E}_n \approx 1$, about a factor of 5 above the the Δ–approximation. This increase of the neutrino power relative to the cosmic ray power of GRB (if protons are confined) is, however, masked by the secondary particle losses (see Rachen & Mészáros 1998 [16], Waxman & Bahcall 1999 [12]). At lower energies, where the neutrino spectrum

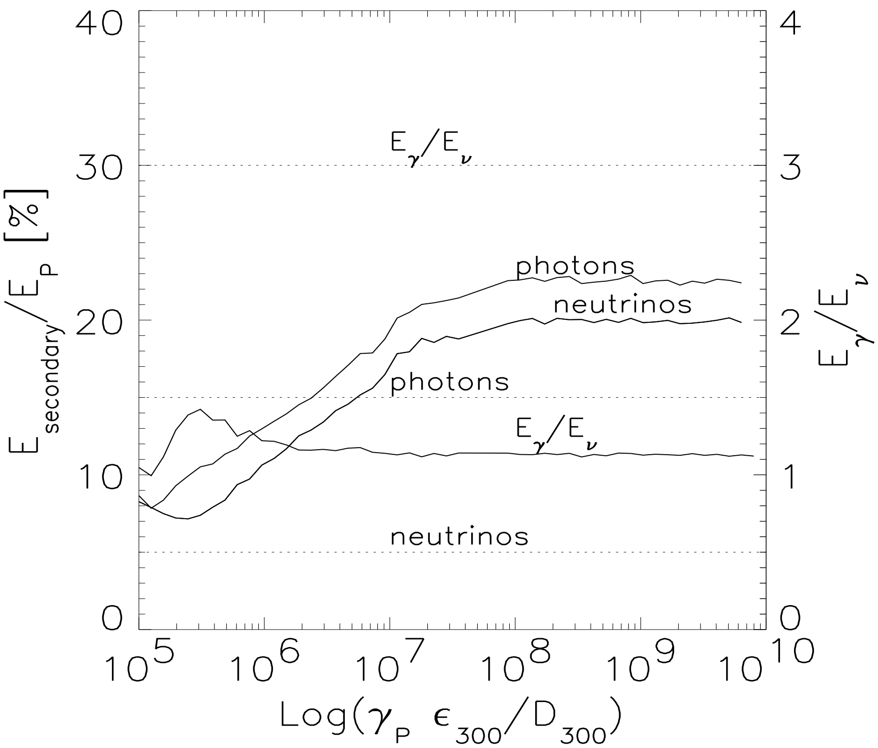

Figure 4. The total photon and ν-power (normalized to the proton input energy E_p), and their ratio due to photomeson production in a typical GRB ambient radiation field. The $\mathcal{E}_\gamma/\mathcal{E}_\nu$–ratio is nearly always unity, independent of proton input energy, which can be contrasted to the Δ-approximation (dotted lines). Solid lines denote the results from the SOPHIA simulations.

is unattenuated, the neutrino-to-neutron ratio approaches the value expected in the Δ-approximation (see Fig. 6).

4. High energy anti-baryon production

A qualitatively new effect which can be investigated with SOPHIA is the production of secondary baryon/anti-baryon pairs in high energy photohadronic interactions. This requires a detailed simulation of QCD string hadronization, which is implemented in SOPHIA. The theoretical threshold of this process is $\sqrt{s} = 3m_pc^2$, corresponding to a photon energy in the proton rest frame $\epsilon' = 4m_pc^2$. For $\epsilon' > 2$ TeV, about 40% of all events contain antinucleons. This raises the interesting question about the contribution of antiprotons to the cosmic ray flux from extragalactic photopion production sources.

Due to the threshold condition, this process can only affect the antimatter to matter ratio at extremely high energy. In AGN jets and GRB protons may also be magnetically confined. Assuming the minimal cosmic ray ejection hypothesis, (only neutral baryons can leave the source and become cosmic rays) the relevant quantities are the anti-neutron to neutron ratio $\mathcal{E}_{\bar{n}}/\mathcal{E}_n$ and the corresponding multiplicity ratio $N_{\bar{n}}/N_n$.

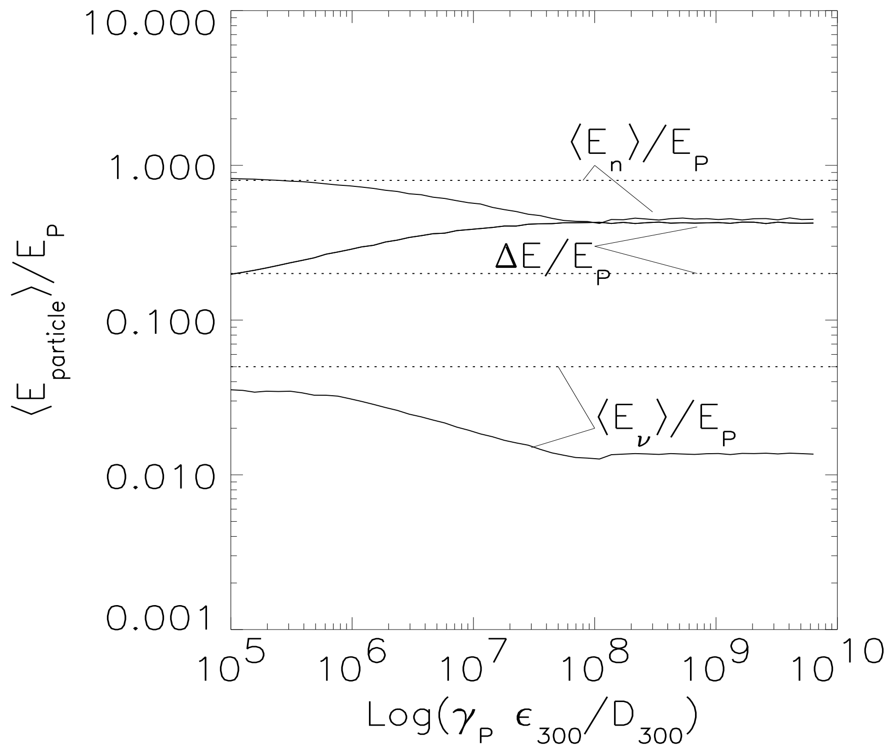

Figure 5. Average neutron and neutrino energy with respect to the proton input energy E_p, and the mean proton inelasticity due to photon–proton pion production in a typical GRB radiation field. The dotted lines represent the respective values from the Δ-approximation which are only met for interactions near threshold, e.g. at low input energies $\gamma_p < 10^6$. Solid lines denote the results from the SOPHIA simulations.

As noted above, cosmic rays with energy $\gamma_p > 10^7$ accelerated in GRBs tend to interact with photons from the flat part of the ambient radiation fields, in the multiparticle production regime. While the total energy dissipated into photons, neutrinos and neutrons is roughly the same ($\mathcal{E}_\gamma \approx \mathcal{E}_\nu \approx \mathcal{E}_n \approx 0.2E_p$) in this high energy part of the cross section, the antineutron production is only 1/40 of the neutron production. The neutrons carry on average 50% of the input energy (see Fig. 5) with a neutron multiplicity of roughly 0.4. Antineutrons have mean energies of $\simeq 0.1E_p$ with a multiplicity of approximately 0.05. Antineutrons and neutrons of the same energy are produced by protons of different energy. For example, we need an input proton energy of 10^{10}GeV for the production of a antineutron of energy 10^9GeV while for a neutron of the same energy the proton input energy must be $\approx 2 \cdot 10^9$GeV. One has to weight the ratio of the resulting neutron and antineutron multiplicities, and this is determined by the input proton spectrum. For this purpose we use a E^{-2} differential spectrum as a typical equilibrium particle spectrum for GRB. For photon–proton interactions at high CMF energies, as is the case for GRBs, we therefore expect antineutron-to-neutron multiplicities of the order 0.01.

Since photon–proton interactions in TeV-blazar ambient photon fields take part predominantly at threshold, these objects are not expected to be strong sources

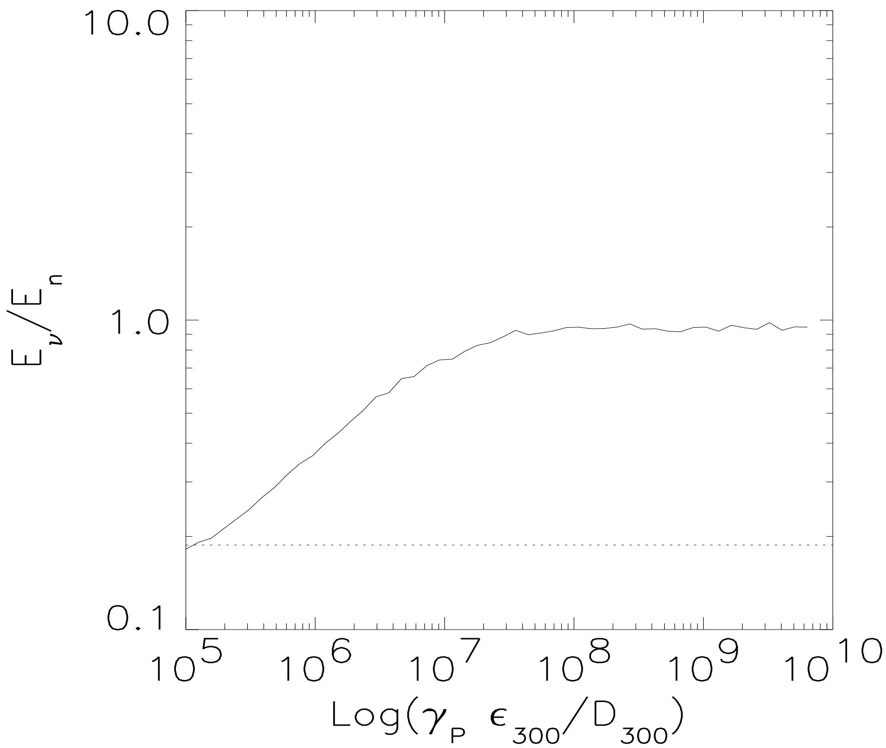

Figure 6. The total ν-energy to neutron energy emerging from a source due to photopion production in a typical GRB photon field. With increasing input proton energy the total neutrino power per produced cosmic ray is underestimated by a factor < 5 in comparison to the Δ–approximation (dotted line).

of antinucleons. SOPHIA simulations show that the total energy for antineutron production does not exceed 10^{-4} of the proton input energy with the average antineutron carrying roughly 1/10 of E_p. Neutrons, on the other hand, take up about 20% of the input energy with a mean particle energy of $0.8E_p$, as expected from the Δ–approximation. Weighting again with the typical equilibrium differential particle spectrum expected in blazar jet environments, which follows a E^{-1} power law, we find that the $\bar{n}/n$–ratio does not exceed 10^{-3}.

The $\bar{n}/n$–ratios resulting from SOPHIA in GRB and TeV-blazar radiation fields as a function of proton energy are shown in Fig. 7. After β-decay, the ejected $\bar{n}/n$ contribute to the overall $\bar{p}/p$ flux. The $\bar{n}/n$ ratio derived here has to be regarded as an upper limit to the observable $\bar{p}/p$ ratio, since direct proton injection may contribute to the cosmic ray flux without increasing the anti-proton population.

5. Discussion and outlook

Our simulation results obtained with the new photomeson production event generator SOPHIA [7] demonstrate that the widely used Δ-approximation for photohadronic interactions has only a limited applicability to the most interesting astrophysical applications, namely the secondary gamma ray, neutrino and neutron production in

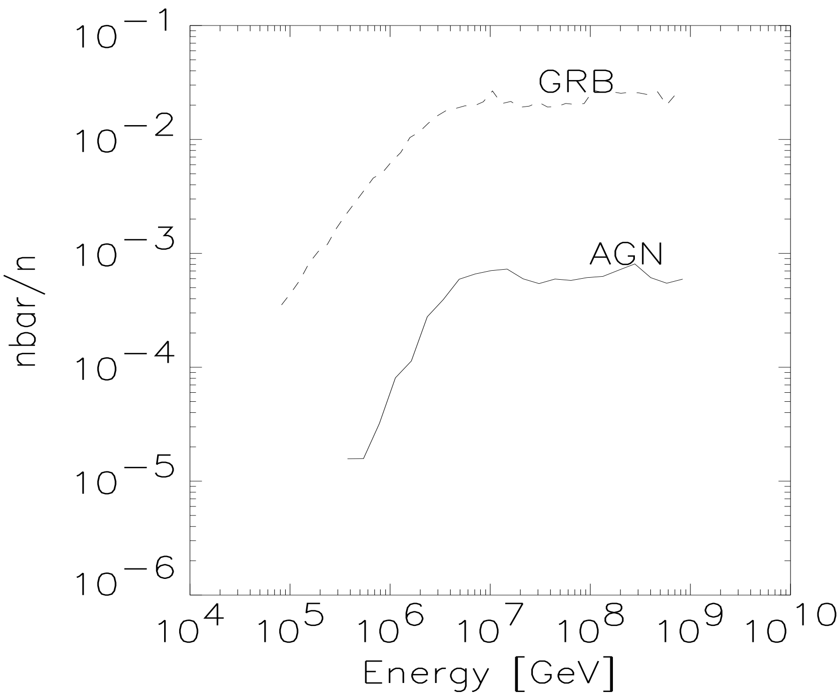

Figure 7. Predicted antineutron-to-neutron ratio at production in the shock frame of Gamma Ray Burst (GRB) and in TeV-blazar jets. GRBs predict a antibaryon-to-baryon production ratio, which approaches 0.01 above 10^{16}eV, while TeV-blazars may produce antibaryons on a level of about one order of magnitude lower.

radiation fields of AGN jets and GRB. For AGN jets, where interactions at low center–of–mass energy dominate, the major kinematical quantities, like proton inelasticity, average fractional neutrino energy per interaction, and the neutrino-to-neutron energy ratio are found to be well predicted by the Δ-approximation. For interactions of ultra-high energy cosmic rays in GRB shells, however, we find a deviation up to about one order of magnitude in some of these quantities.

As a robust result for both kinds of sources we find that the average total energy channeled into neutrinos, $\mathcal{E}_\nu$, and gamma-rays, $\mathcal{E}_\gamma$ are approximately equal. By comparison, the Δ–approximation predicts $\mathcal{E}_\gamma/\mathcal{E}_\nu \approx 3$. This relation has been widely used to normalize expected neutrino fluxes from AGN jets to their photon flux. As a consequence of this deviation from the Δ–approximation found in our SOPHIA results, the expected neutrino fluxes from such AGN models would increase by a factor of 3 assuming that the observed gamma ray emission is entirely of photohadronic origin. The lower gamma-ray-to-neutrino ratio seen in our SOPHIA results, together with the neutrino-to-neutron ratio in agreement with the Δ–approximation, implies also that AGN neutrino models, which were initially designed to comply with the limitation set by the cosmic ray data in a straight line propagation scenario (Mannheim, 1995 [8], Model A), can no longer produce a large fraction of the 100 MeV gamma ray background as initially assumed. This may comply with the recent finding of Chiang &

Mukherjee (1997 [9]) that only part of the measured EGRB may be due to unresolved blazars. However, it has been pointed out by Mannheim et al. [13] that an increased and so far unexpected contribution from sources with maximum cosmic ray energies below 10^{19} eV can evade the problem without being in conflict with the cosmic ray data. Moreover, it is likely that the average opacity of blazars for ultra-high energy neutrons is larger than unity, which allows a higher diffuse neutrino and gamma ray flux for a given cosmic ray flux.

For the derivation of the upper bound of the neutrino emission, the neutrino-to-neutron energy ratio reflects the microphysics of the photohadronic interactions. The value $\mathcal{E}_\nu/\mathcal{E}_n \approx 0.19$, expected from the Δ-approximation and used in Waxman and Bahcall [12], was confirmed for AGN jets in our simulations. For GRB, however, we find a ratio of about 1. This implies that the cosmic ray upper bound for GRB neutrinos has to be increased by a factor of 5 at high energies. In practice this theoretical bound is unlikely to be reached by GRB neutrinos, since their emission is suppressed at such high energies by secondary particle (pion and muon) cooling in the hadronic cascade [20, 16]. Models which try to evade such losses by shifting the acceleration region into the outer shock and the afterglow of the GRB, as suggested by Vietri ([21]; note also [12]), can be shown to be generally inefficient to reach such fluxes for reasonable energetics [16].

The average neutrino energy due to photopion production in GRB spectra at very high proton energies is up to an order of magnitude below the value expected from the Δ-approximation. This has severe consequences for the prospects of GRB–correlated neutrino events above 10^{19} eV. The fact that the mean proton energy loss rises with increasing proton energy up to $\Delta E/E \simeq 0.5$ (compared to the Δ–approximation value $\Delta E/E = 0.2$) may add to the problem, since it leads to lower maximum proton energies in photohadronically limited acceleration scenarios.

A qualitatively new feature which can be explored with SOPHIA is the photoproduction of antibaryons [7]. Our prediction of the maximal antiproton contribution from GRB of about 2%, reached for energies above $5 \cdot 10^{17}$ eV, is several orders of magnitude above the background expected at this energy from cosmic ray-nucleon collisions in the galactic disk. The latter is measured at energies ~ 10 GeV as approximately 10^{-3}, and expected to decrease with $E_p^{-[0.3-0.6]}$ following the leaky box model. Since the expectation of a significant increase of the $\bar{p}$ contribution at high energies is unique for GRB, this could provide an independent test whether GRB are indeed the dominant sources of cosmic rays. Unfortunately, there is presently no imaginable way to distinguish between nucleons and anti-nucleons at such high energies, where cosmic rays can only be measured in air shower experiments. Our result may therefore be regarded as of rather academic interest, or may be kept in mind for presently not anticipated, future detection techniques.

In conclusion, we have demonstrated that the application of SOPHIA to astrophysical problems involving the interaction of energetic cosmic rays in photon backgrounds can (a) improve the accuracy of the predictions from such models, and (b) open the possibility to explore particle physics effects so far neglected in astrophysics.

Acknowledgments

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References

[1] Stecker, F.W., 1968, Phys. Rev. Lett., 21, 1016.
[2] Stecker, F.W., 1973, Astrophys. & Sp. Science, 20, 47.
[3] Berezinsky, V., & Gazizov, A., 1993, Phys Rev. D, 47, 4206 and 4217.
[4] Mannheim, K. & Schlickeiser, R., Astron. Astrophys., 1994, 286, 983.
[5] Gaisser, T.K., Halzen, F., Stanev, T., 1995, Phys. Rep., 258, no.3.
[6] Mücke, A., Rachen, J.P., Engel, R., Protheroe, R.J., Stanev, T., Publ. Astr. Soc. Australia (in press).
[7] Mücke, A., Engel, R., Rachen, J.P., Protheroe, R.J., Stanev, T., Comp. Phys. Comm. (submitted); also these proceedings.
[8] Mannheim, K., 1995, Astropart. Phys., 3, 295.
[9] Chiang, J. & Mukherjee, R., 1997, ApJ, 496, 752.
[10] Mücke, A. & Pohl, M., 1998, Proc. of the conference 'BL Lac Phenomenon', Turku, Finland, 1998.
[11] Mannheim, K., 1993, Astron. Astrophys., 269, 67.
[12] Waxman, E. & Bahcall, J., 1999, Phys. Rev., D 59, 023002; also these proceedings.
[13] Mannheim, K., Protheroe, R.J. & Rachen, J.P., astro-ph/9812398; also these proceedings.
[14] Cotton, W.D., Wittels, J.J., Shapiro, I.I. et al., 1980, ApJ Lett., 238, L123.
[15] Shaffer D.B.& Marscher, A.P., 1979, ApJ Lett., 233, L105.
[16] Rachen, J.P. & Mészáros, P., 1998, Phys. Rev., D 58, 123005.
[17] Piran, T. 1998, astro-ph/9810256.
[18] Waxman, E. 1995, Phys. Rev. Lett 75, 386.
[19] Vietri, M., 1995, ApJ, 485, L5.
[20] Waxman, E. & Bahcall, J., 1997, Phys. Rev. Lett., 78, 2292.
[21] Vietri, M. 1998, ApJ, 507, 40.