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High energy neutrinos from astrophysical sources: a self-consistent approach

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Abstract: We calculate the yield of high energy neutrinos produced in astrophysical sources for arbitrary interaction depths τ_0 and magnetic field strengths B. We take into account energy loss processes like synchrotron radiation and diffusion of charged particles in turbulent magnetic fields as well as the scattering of secondaries on background photons and the direct production of charm neutrinos. Diffusion leads to an increased path-length before protons leave the source of size R_s and therefore magnetized sources lose their transparceny below the energy $E = 10^{18}\text{eV}\ (R_s/\text{pc})\ (B/\text{mG})\tau_0^{-\alpha}$, where $\alpha = 1/3$ and 1 for Kolmogorov and Bohm diffusion, respectively. Below this energy, the neutrino spectra from meson and muon decays are strongly modified with respect to the injection spectrum of protons even for sources with $\tau_0 \lesssim 1$.

Introduction

Experimental high energy neutrino physics has become one of the most active areas of astroparticle physics, offering among others the prospect of identifying the sources of ultra-high energy cosmic rays [1, 2]. Since high energy neutrinos from astrophysical sources are the decay products of secondary mesons produced by scattered high energy protons on background protons or photons, the resulting neutrino flux is closely connected to the cosmic ray and photon fluxes.

Two different kind of bounds on high energy neutrino fluxes exist: The cascade or EGRET limit uses bounds on the diffuse MeV-GeV photon background to limit the energy transferred to electromagnetically interacting particles that are produced unavoidably together with neutrinos [3]. The cosmic ray upper bounds of, e.g., Refs. [4, 5] use the observed ultra-high energy cosmic ray flux to limit possible neutrino fluxes. The latter limit assumes that all neutrino sources are transparent to hadronic interactions and thus at least neutrons can escape from the source region without interactions. Dropping the assumption of transparent sources and hidding the acceleration region by sufficient material absorbing ultra-high energy cosmic rays allows one to avoid the cosmic ray limits. One might therefore speculate that large neutrino fluxes at high and ultra-high energies might be produced in opaque sources.

An essential aspect that has to be taken carefully into account is the self-consistent treatment of multiple scattering of the hadrons with the particles in the medium. This, however, turns out to be crucial not only in thick sources, but also in transparent sources with turbulent magnetic fields. In this work, we discuss how the increase of the number of collisions of the diffusing particles leads to a non-trivial distortion of the neutrino flux in the "low-energy" range. Since moreover energy losses lead to a steepening of the "high-energy" range of proton and thus neutrino fluxes, the resulting energy spectrum may deviate in a broad range from the canonical $1/E^2$ spectrum.

Simulation

We idealize a neutrino source as an acceleration region surrounded by a sphere of radius R_s containing photons and turbulent magnetic fields. The probability $\mathcal{N}$ that a particle diffuses outwards the distance Δr without scattering or decay is given by

$$\mathcal{N} = \exp\left(-\int_r^{r+\Delta r} \frac{\mathrm{d}l}{(l_{1/2}+l_{\rm int})}\right) , \quad (1)$$

where $l_{1/2}$ and $l_{\rm int}$ are its decay and interaction length, respectively. The path length Δl of the trajectory and the distance Δr diffused outwards are connected by

$$\nu(E) = \frac{\Delta l}{\Delta r} = \frac{R_s}{6D} . \quad (2)$$

Following Ref. [6], we use as phenomenological diffusion coefficient

$$D(E) = D_0 \left[\left(\frac{R_L}{l_c}\right)^\alpha + \left(\frac{R_L}{l_c}\right)^2\right] , \quad (3)$$

where $\alpha = 1/3$ and 1 correspond to the case of Kolmogorov and Bohm diffusion, respectively, and R_L is the Larmor radius,

$$R_L = 1.08 \times 10^{-3}\mathrm{pc}\, \frac{E}{10^{18}\mathrm{eV}}\, \frac{\mathrm{G}}{B} . \quad (4)$$

The normalization factor is defined as

$$D_0 = \frac{cl_c}{3}\left(\frac{l_c}{2R_s}\right)\frac{1}{1+(l_c/R_s)^{2-\alpha}} , \quad (5)$$

so that the typical effective size of the source for a diffusing particle without energy losses, $R_{\rm eff} = cR_s^2/(6D)$, becomes equal to R_s at the energy $E_L = 10^{18}\mathrm{eV}\ (R_s/\mathrm{pc})\ (B/\mathrm{mG})$ where the Larmor radius equals to the source, $R_L(E_L) = R_s$. In the following we shall assume Bohm diffusion, $\alpha = 1$, and in order to reduce the number of parameters we set the coherence length l_c equal to R_s.

Diffusion increases interactions and energy losses by the factor $\nu(E) \propto E^{-\alpha}$ for $E \leq E_L$. The energy of the particle along the path l is obtained by integrating the energy losses $\beta(E)$ due to synchrotron radiation, inverse Compton scattering, etc. In our Monte Carlo simulation, we track explicitly all secondaries ($N, \pi^\pm,\ K^\pm,\ K^0_{L,S}$) for which the interaction rate is non-negligible compared to their decay rate; for details see [7].

Results

For the discussion of the results it is useful to introduce the "interaction depth" defined as the ratio $\tau_0 = R_s/l_{\rm int}$ of the size R_s of the source to the interaction length $l_{\rm int}$. This ratio determines, if most of the protons leave the source without interactions ($\tau_0 \ll 1$ or "transparent source"), or if multiple-scattering of nucleons is important and mesons are efficiently produced ($\tau_0 \gg 1$ or "opaque source"). For the illustration of our numerical results, we determine in the following τ_0 via $l_{\rm int} = 1/(n_\gamma\sigma)$ with $\sigma = 0.2$ mb as reference cross section.

However, since the time spent in the source region by a charged particle or equivalently the effective size of the source $R_{\rm eff}$ increases for a magnetized source, it is convenient to introduce aditionally an effective optical depth $\tau_{\rm eff} = R_{\rm eff}/l_{\rm int}$ for charged particles as

$$\tau_{\rm eff} = \begin{cases} \tau_0 & \text{for } E \geq E_L \\ \tau_0\left(\frac{E_L}{E}\right)^\alpha & \text{for } E < E_L . \end{cases} \quad (6)$$

Therefore a source that is transparent at high energies, when particles move in the ballistic regime, becomes thick in the diffusion regime below the energy $E_L\tau_0^{-\alpha}$ in the case of charged particles. In Fig. 1 we illustrate the effective size of a source with thermal photons at $T = 10^5$ K and $B = 10^4$ G, and $R_s = 2.5 \times 10^{10}$ cm ($\tau \approx 0.1$) together with the interaction length for protons and for a source. By comparing both lines it is possible to estimate the increase of $\tau_{\rm eff}$ at low energies. Given a τ_0 the effect of $\tau_{\rm eff}$ depends on two factors: the diffusion regime, which determines the slope of $R_{\rm eff}$, and the width of the energy window delimited by $E_{\rm th}$ and E_L.

In the same figure it is also shown the typical length scale of synchrotron losses $l_{\rm syn}$ for proton, pions, and kaons. At high energies $l_{\rm syn}$ is smaller than R_s. Therefore charged particles will strongly lose energy until they reach an energy $E^i_{\rm syn}$ such that $l_{\rm syn}(E^i_{\rm syn}) = R_s$. Thus, the scale

$$E^i_{\rm syn} = \frac{3}{2}\frac{4\pi}{e^2}\left(\frac{B^i_{\rm cr}}{B}\right)^2 \frac{1}{R_s} , \quad (7)$$

defines the energy above which the flux will be suppressed. This limit is proportional to the particle mass via $(B^i_{\rm cr})^2 = (m_i^2/e)^2$, as can be seen in the Fig. 1.

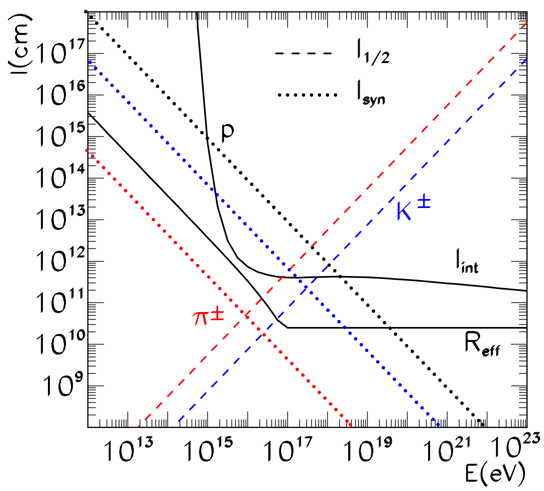

Figure 1: Typical length scale of synchrotron losses (dotted) for proton (black), charged pions (red) and kaons (blue), together with the decay length (dashed) of the pions and kaons for a source at a temperature $T = 10^5$ K and $B = 10^4$ G. The interaction length and the effective size of a source with $R_s = 2.5 \times 10^{10}$ cm for protons is also shown.

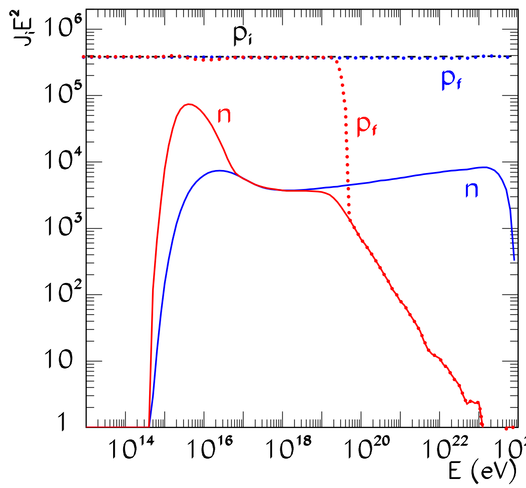

Figure 2: Unnormalized fluxes of initial (dashed) and final (dotted) protons, as well as neutrons (solid) for a source with (red) and without (blue) magnetic field, see text for details.

We illustrate the main features of the previous discussion by calculating the proton and neutrino fluxes for the source parameters used for Fig. 1. For illustration, we will also compare the results with those for a source without magnetic field.

A) Proton Flux

In the case with negligible magnetic fields the initial and final proton fluxes basically coincide for transparent sources, see Fig. 2. However, the presence of synchrotron radiation induced by the magnetic fields in the source strongly suppresses the final proton flux for energies larger than $E^i_{\rm syn}$ ($\approx X$ in our case).

For completeness we also show the flux of neutrons leaving the source before decaying. These are created by scattering of the initial protons with the photons present in the medium. In the case of transparent sources its flux is not only suppressed by the smallness of τ but additionally by other factors like the energy transfer or the probability to produce a neutron in each collision. The small energy dependence of σ leads to a plateau structure at energies above $E_{\rm th}$.

They are neutral particles and consequently they are not directly affected by the synchrotron radiation. Nevertheless the original protons, from which they are produced, do feel the energy losses. That translates, in the case of strong B, into an effective suppression of the neutron flux at $E \gtrsim E^i_{\rm syn}$.. At intermediate energies the neutron flux presents a plateau which stems from the weak dependence of $l_{\rm int}$ on the energy. At lower energies, more precisely between $E_{\rm th}$ and E_L a bump shows up in the neutron flux in the case with magnetic field. This is a direct consequence of an increase in the interaction depth of protons due to the diffusion regime at energies below E_L, see Fig. 2. The enhancement of the collisions will eventually reduce the final proton flux at those energies.

B) Neutrino Flux

In Fig. 3 we show the different contributions to the neutrino flux. In a transparent source without B most neutrinos are produced in π decays. In pres-

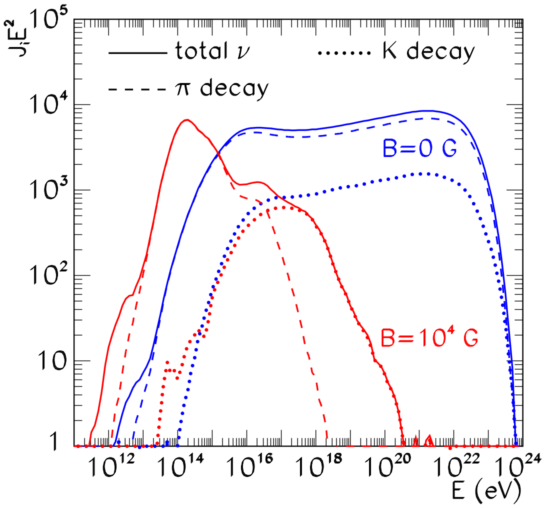

Figure 3: Unnormalized fluxes of neutrinos as well as the different contributions for the same sources as in Fig. 3.

ence of magnetic fields there is a suppression of the ν flux at high energies due to the synchrotron radiation of charged pions and kaons. Since $E^K_{\rm syn} > E^\pi_{\rm syn}$ the contribution to the high energy tail comes basically from the kaon decay. Finally, at low energies there is a bump in pion neutrinos, analogous to the one observed for neutrons in Fig. 2. This is a direct consequence of the multi scatterings steaming from the higher interaction depth as protons start to diffuse.

Conclusions

We have discussed the flux of high energy neutrinos produced in astrophysical sources in terms of interaction depths τ_0 and magnetic field strengths B. We have stressed the importance of considering not only energy loss processes like synchrotron radiation but also diffusion of charged particles in turbulent magnetic fields as well as the scattering of secondaries on background photons. We have shown how diffusion leads to an increased path-length before protons leave the source of size R_s and as consequence magnetized sources lose their transparency below the energy $E = 10^{18}{\rm eV}\ (R_s/{\rm pc})\ (B/{\rm mG})\tau_0^{-\alpha}$, where $\alpha = 1/3$ and 1 for Kolmogorov and Bohm diffusion, respectively. Below this energy, the neutrino spectra from meson and muon decays are strongly modified with respect to the injection spectrum of protons even for sources with $\tau_0 \lesssim 1$.

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