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Neutrino oscillations in a magnetic field: the three-flavor case

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We adopt the approach to the problem of neutrino oscillations in a magnetic field introduced in [1] and extended to the case of three neutrino generations in [2] to investigate the impact of ultrahigh-energy neutrino oscillations in the interstellar magnetic field. Based on the assumption that UHE neutrinos flavour distribution follows the pattern 1:2:0, we have estimated the fluxes detected by a terrestrial neutrino telescope. We find out that the interaction with a magnetic field does not significantly modify the flavour distribution of UHE neutrinos unless they possess transition magnetic moments.

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Ultrahigh-energy neutrino oscillations in a magnetic field

In [2] we showed that the probabilities of neutrino spin-flavour oscillations in a magnetic field can be expressed by the following decomposition

$$P(\nu_\alpha^h \to \nu_\beta^{h'};x) = \delta_{\alpha\beta}\delta_{hh'} - 4\sum_{\{i,j,s,\sigma\}} \mathrm{Re}([A_{\alpha\beta}^{hh'}]_{i,j,s,\sigma})\sin^2(\omega_{ij}^{ss'}x/2) + 2\sum_{\{i,j,s,\sigma\}} \mathrm{Im}([A_{\alpha\beta}^{hh'}]_{i,j,s,\sigma})\sin(\omega_{ij}^{ss'}x), \quad (1)$$

where the amplitude coefficients were introduced

$$[A_{\alpha\beta}^{hh'}]_{i,j,s,\sigma} = U_{\beta i}^* U_{\alpha i} U_{\beta j} U_{\alpha j}^* C_{is}^{h'h}\left(C_{j\sigma}^{h'h}\right)^*, \quad (2)$$

and

$$\sum_{\{i,j,s,\sigma\}} = \sum_{i>j;s,\sigma} + \sum_{s>\sigma;i=j}, \quad (3)$$

where α,β are neutrino flavours e,μ,τ and h,h' are neutrino helicities. In general, the probabilities of neutrino oscillations exhibit a complicated interplay of oscillations on both vacuum $\Delta m_{ij}^2/4p$ and magnetic $\mu_\nu B$ frequencies [1]. Antineutrino oscillations probabilities $\bar{P}(\nu_\alpha^h \to \nu_\beta^{h'};x)$ can be obtained by replacing $U \to U^*$ or, equivalently, $x \to -x$. Fig. 1 shows the probabilities of $\nu_e \to \nu_e$, $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_\tau$ oscillations as functions of distance in parsec for the case of neutrino energy equal to 10 ZeV. Below we connect the oscillations probabilities (1) with the observable neutrino fluxes.

Astrophysical objects as active galactic nuclei, gamma ray bursts and supernova remnants are considered to be the sources of ultrahigh-energy (UHE) neutrinos, i.e. neutrinos with energies higher that 1 PeV. It is expected that UHE neutrinos flavour distribution follows a simple pattern $\Phi_e^0 : \Phi_\mu^0 : \Phi_\tau^0 = 1:2:0$. In [3] the impact of neutrino interaction with the interstellar magnetic field on neutrino oscillations was analysed in the two-flavour approximation. In this paper we consider neutrino oscillations in the interstellar magnetic field in the three flavour case. Given the initial neutrino fluxes Φ_α^0, the fluxes at the distance x are computed as follows

$$\Phi_\alpha(x) = \sum_\beta \Phi_\beta^0 P_{\alpha\beta}(x), \quad (4)$$

where $P_{\alpha\beta}(x)$ are the active-active transitions probabilities $P(\nu_\alpha^L \to \nu_\beta^L)$. As neutrinos travel throughout cosmic scales, they undergo the wave packet separation resulting in the decoherence effect. Thus, to calculate the fluxes at a neutrino telescope we replace $P_{\alpha\beta}(x)$ in eq. (4) with the distance-averaged probabilities $\langle P_{\alpha\beta}\rangle$, which can be obtained from eq. (1):

$$\langle P_{\alpha\beta}\rangle = \delta_{\alpha\beta} - 2\sum_{\{i,j,s,\sigma\}} \mathrm{Re}([A_{\alpha\beta}^{LL}]_{i,j,s,\sigma}). \quad (5)$$

Note that $\langle \bar{P}_{\alpha\beta}\rangle = \langle P_{\alpha\beta}\rangle$ since the distance-odd parts of the probabilities disappear after averaging.

It is known that after vacuum oscillations and decoherence, neutrino distribution by flavours is almost uniform: $\Phi_e : \Phi_\mu : \Phi_\tau \approx 1:1:1$. Using (5), we find out that the pattern 1:1:1 holds even if we consider oscillations of Dirac neutrinos with non-zero diagonal magnetic moments in the interstellar magnetic field. Since $\langle \bar{P}_{\alpha\beta} \rangle = \langle P_{\alpha\beta} \rangle$, antineutrino flavour distribution follows the same relation $\bar{\Phi}_e : \bar{\Phi}_\mu : \bar{\Phi}_\tau \approx 1:1:1$.

However, this is the case only if neutrinos do not possess transition magnetic moments. Oscillations of neutrinos with non-diagonal magnetic moments (particularly Majorana neutrinos) require more thorough analysis.

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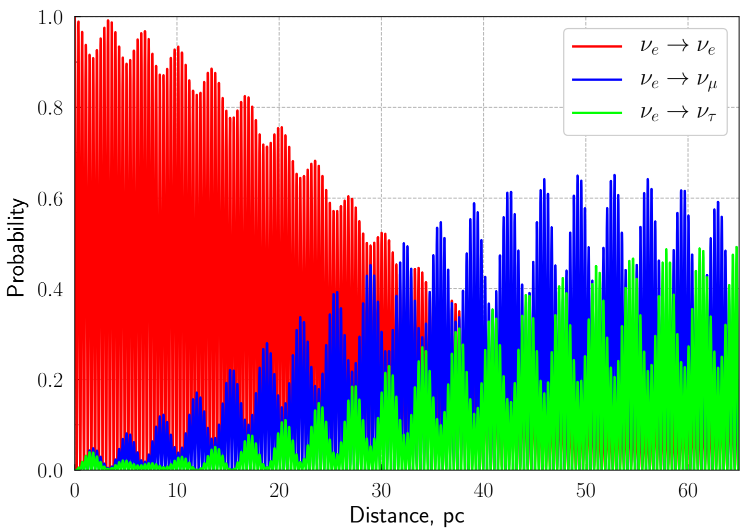

Figure 1: The probabilities of $\nu_e \to \nu_e$, $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_\tau$ oscillations as functions of distance in parsec for the case of neutrino energy 10 ZeV.