PeV neutrinos from centrifugally accelerated electrons in extragalactic new born pulsars

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Introduction

Cosmic rays (CR) observed at an energy $\geq$ 0.05 EeV and beyond are mostly of extragalactic origin. There has been a consensus that the known galactic objects usually do not possess the required energetics to produce CRs including electrons around $\sim$ 0.05 EeV and beyond. The detection of PeV energy scale neutrinos in the IceCube experiment may unfold a new possibility to correlate them with some astrophysical sources. This work hints that the extragalactic young millisecond pulsars (MSPs) might be able to supply enough energy to accelerate electrons to ultra-high-energies (UHE) and thereby producing PeV energy scale neutrinos via a lepton-lepton interaction; $e^- + e^+ \rightarrow \nu_l + \tilde{\nu}_l$; $l = e, \mu, \tau$. If the reaction $e^- e^+_{\rm cold}$ is the source of PeV neutrino events, there should be a supply of UHE electrons with energies all the way over 0.01 EeV. Such electrons could indeed be driven successfully by the new-born fast spinning MSPs through the Langmuir-Landau-Centrifugal-Drive (LLCD) mechanism [1].

Acceleration of electrons via LLCD

The LLCD completes via two successive steps. First, the Langmuir waves are generated by the bulk $e^- - e^+$ plasma with the relatively lower Lorentz factor (γ) region in the pulsar's magnetosphere. These excited Langmuir waves damp on a local electron beam in the high γ end of the plasma distribution, accelerating them to much higher level [1]. This constitutes the last step, and is known as Landau damping, which is a consequence of rapid Langmuir collapse. This above combination could supply relativistic e^-/e^+ with energies up to EeV range in MSPs [1].

The UHE electrons interact with cold positrons beyond the light cylinder zone, the unstable Z boson state may form, which then decays into five individual channels with different branching fractions. At Z boson peak, the branching ratio (BR) of the Z boson decay into $\nu_l \tilde{\nu}_l (l = e, \mu, \tau)$ together is roughly $\frac{1}{5}$. The remaining BR of amount $\frac{4}{5}$ accounts for the production of charged lepton pairs ($l = e^{\pm}, \mu^{\pm}, \tau^{\pm}$). The average percentage of UHE electrons energy carried out by the neutrinos via the unstable Z boson state is $\sim$ 20%. Hence, each of the neutrino, irrespective of their flavors could receive $\sim$ 3% of the projectile's energy via the $e^- e^+ \rightarrow \nu_l \tilde{\nu}_l$ reaction channel as

$$E_\nu \approx 0.03 E_e \approx 1.5 (PeV)\ \epsilon_{e,17} [2/(1+z)]. \quad (1)$$

Here, $\epsilon_{\rm e} = \epsilon_{e,17}(10^{17} eV)$, being the electron energy in the cosmic rest frame and z is the gravitational redshift of the source.

The acceleration time-scale is much smaller than the cooling time-scale for a broad range of γ values; the instability is indeed very efficient (instability time-scale is $\sim$ 0.1 ms, smaller than the Compton cooling time) . Moreover, the cooling time-scale of the inverse Compton scattering process is a continuously increasing function of $\epsilon_{\rm e}$. The most potential synchrotron loss mechanism does not affect the continuous energy acquiring mode of electrons.

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Diffuse neutrino flux

The UHE electron flux coming out of an extragalactic new-born MSP in terms of cosmic scale factors R in the Robertson-Walker (RW) metric (in the Friedmann or FRW cosmology) is given by

$$\Phi_e = \frac{L_{k,e}R^2(t_1)}{4\pi R^4(t_0){r_1}^2} \equiv \frac{\chi_f \xi_s \eta_k L_b R^2(t_1)}{4\pi R^4(t_0){r_1}^2}, \qquad (2)$$

where t_0 measures the time when the UHE electrons reached at observer location. Also, the parameter t_1 is the time when these electrons left the star, and r_1 is the corresponding radial distance of the source at that moment. Here, $R(t_0)$ and $R(t_1)$ are called the present and past cosmic scale factors of the universe.

The redshift parameter is conventionally expressed in terms of the ratio between the scale factors as,

$$z = \frac{R(t_0)}{R(t_1)} - 1. \qquad (3)$$

Inserting eqn.(3) in (2) and finally rearranging parameters in it, we have

$$\Phi_e(L_b) = \frac{\chi_f \xi_s \eta_k L_b}{4\pi R^2(t_0){r_1}^2(1+z)^2} \qquad (4)$$

A function $\mathrm{f(t_1/z, L_b)}$ is now introduced that gives the number density of MSPs in a luminosity range. Then, $\mathrm{f(z, L_b)dL_b}$ accounts the number of sources/volume with luminosities between $\mathrm{L_b}$ and $\mathrm{L_b + dL_b}$ at a z. The function $\mathrm{f(t_1/z, L_b)}$ is derived from a best-fit luminosity function to galaxy survey X-ray data including the cosmological evolution. The amount of UHE flux of electrons contributed by the MSPs from distances in the range, $\mathrm{r_1 : r_1 + dr_1}$ with luminosities between $\mathrm{L_b : L_b + dL_b}$ leads to

$$d\Phi_{e,d} = 4\pi\Phi_e(L_b)R^2(t_1){r_1}^2 f(t_1/z, L_b)|dt_1|\frac{dL_b}{L_*}, \qquad (5)$$

where L_* is called the break luminosity.

The luminosity-dependent density evolution (LDDE) model introduces a well represented XLF at a given z by combining a double power-law luminosity function (LF) with a luminosity-dependent evolution term in the following form

$$f(z, L_b) = \frac{A_*}{[(\frac{L_b}{L_*})^{\gamma_1} + (\frac{L_b}{L_*})^{\gamma_2}]} e(z, L_b), \qquad (6)$$

where γ_1 and γ_2 are slopes below and above the break luminosity L_*.

Following calculations from [1], we have finally obtained the diffuse neutrino (per flavor) flux contributed by the MSPs at $z = 0.002$–5 as

$$\Phi_{(\nu_l,\bar{\nu}_l)} \approx 2.51 \times 10^{90} \times \frac{cA_*\chi_f\xi_s\eta_k\chi_o}{4\pi H_0 L_*}. \qquad (7)$$

in GeV $\mathrm{cm^{-2}s^{-1}sr^{-1}}$.

Using values of all the relevant parameters [1], the PeV neutrino flux per flavor results from the theory, is $\approx 8.44 \times 10^{-7}\eta_k$ in GeV $\mathrm{cm^{-2}s^{-1}sr^{-1}}$.

The total observed diffuse energy flux of neutrinos per flavor at Earth in the energy range, ≈ 1–10 PeV can be written following [1],

$$\Phi_{(\nu,\bar{\nu}),d} = \int_1^{10} {E_\nu}^{-1} J_{(\nu,\bar{\nu})}(E_\nu) dE_\nu \approx 2.59\times10^{-9} \qquad (8)$$

in GeV $\mathrm{cm^{-2}s^{-1}sr^{-1}}$.

The expected muon neutrino energy flux leads to give a quantitative measure on the amount of conversion of the bolometric luminosity to power the Icecube's measured PeV neutrino flux. It is found that the flux arising out of the model calculation can fulfill the IceCube limit well if $\eta_k \approx 0.31\%$.

Conclusions

A certain percentage ($\sim 0.31\%$) of the bolometric luminosity of MSPs is necessary to power the IceCube's detected PeV neutrino flux.

References

[1] R. K. Dey *et al.* *Braz J Phys* **51**, 1406 (2021).