Searching for PeV neutrinos from photomeson interactions in magnetars

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Abstract – In this paper we estimate the flux of PeV neutrinos and gamma-rays from magnetar polar caps, assuming that ions/protons are injected, and accelerated in these regions and interact with the radiative background. The present study takes into account the effect of the photon splitting mechanisms that should modify the radiative background, and enhance the neutrino and gamma-ray fluxes at PeV energies, with a view to explain the PeV neutrino events detected in IceCube. The results indicate that in the near future, the possibility of any significant excess of neutrino events from a magnetar in the Milky Way is extremely low. Further, we suggest that the simultaneous observation of neutrinos and gamma-rays at Earth from expanded “Gen2” IceCube detector and/or High Altitude Water Cherenkov Observatory would provide opportunities to explore the possible origin of very high-energy neutrinos and gamma-rays.

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Introduction. – The detection of very-high-energy (VHE) cosmic neutrinos with the IceCube detector has recently opened up a whole new window on the energetic Universe. Although the significance of the IceCube excess over the atmospheric component is quite high, detection of point sources (and thus individual source classes) has of yet eluded the neutrino astrophysics community. In this context, the present paper in principle proposes and explores a viable physical model of the interactions taking place in source regions for the prediction of astrophysical neutrinos and accompanying gamma-rays.

Probable candidates of VHE neutrinos and gamma-rays include various extragalactic sources, viz. active galactic nuclei (AGNs), gamma-ray bursts (GRBs), or starburst galaxies. The VHE neutrinos from these sources can travel over extragalactic distances retaining their directional information unaffected and not experiencing strong absorptions. However, the extragalactic PeV gamma-ray component will be attenuated significantly due to pair-production processes in cosmic background radiations and no longer remain as important cosmic messengers in order to explore their origin. A continuous effort is being made by the 1 km\(^3\) IceCube neutrino observatory in order to detect such astrophysical neutrinos [1]. The IceCube detector has recently observed two VHE neutrinos above 1 PeV satisfying all selection criteria in two years data collection, might be of astrophysical origin [2].

The possible origins of these PeV neutrino events have been discussed by many in recent times [3,4], but still remains a topic of much speculation. A fundamental question is therefore being raised: what classes of astrophysical objects could accelerate hadrons to very high energies, and in which types of interactions are neutrinos then produced?

In this situation, acceleration of protons in the vicinity of the surface of relatively young local neutron stars with super-strong magnetic fields (\(B \sim 10^{14-16}\) G), widely known as magnetars, is in fact supposed to be a possibility. Although, it may be not a highly probable process and as of yet not observationally supported. The subsequent production of photomesons by interactions with radiative background proceeds, and that has already been studied by many authors. In this paper, we have proposed an additional contribution to the target photon fields for photomeson production from the photon splitting mechanism. The photon splitting process is expected to modify the radiative background, and enhance the neutrino and gamma-ray fluxes at PeV energies from the object. The two astrophysical PeV neutrino events detected in IceCube could have their origin within a young...
local magnetar environment. It is also found that our model-dependent calculation on the PeV neutrino flux limits the upper bound of the accompanying gamma-ray flux at these energies.

Recently identified magnetar candidates are traditionally known to be either anomalous X-ray pulsar (AXPs) or soft gamma-ray repeaters (SGRs), mainly considered as high-energy X-ray emitters [5,6]. Like pulsars [7–9], it has been learned that if magnetars polar caps with $\Omega \cdot B < 0$ can accelerate protons/ions, TeV neutrinos and gamma-rays could be produced via photomeson productions due to interactions of these accelerated protons with UV/X-rays that close to polar caps regardless of their relatively slow rotations [10].

The phase diagram of a magnetar describes the variation of the star’s magnetic field ($B$) with spin period ($P$). The diagram $P$-$B$ corresponds to a phase in which the star could pass a neutrino-loud regime for some suitable set of parameters characterizing its evolution [10]. The present work shows that if the spin-down power of a local magnetar for a favorable set of $P$ and $B$ at a particular evolutionary phase is consumed to accelerate protons, then the object might emit PeV muon neutrinos ($\nu_\mu$) and gamma-rays through photomeson interactions between these protons in polar caps and the star’s radiative background. The radiative background of the star is believed to be filled mainly with soft ultraviolet (UV)-A or B photons that are in turn produced from the effect of the photon splitting mechanism on the magnetar’s unmodified radiative background (i.e. UV-C/X radiations). It is worth noting that this type of magnetars have not been reported from observation yet; they are predicted theoretically only [10].

The process, $\gamma \rightarrow e^+ + e^-$ has so far been applied in polar caps with strong magnetic environment to account for the energy loss by a high-energy $\gamma$-ray photon. Another process, $\gamma \rightarrow \gamma + \gamma$, called photon splitting is expected to take place in the super-strong magnetic-field regions of polar caps [11,12]. The effect of the photon splitting mechanism on the star’s own radiation field prior to photomeson interactions is a principal step that could be applied to available astrophysical settings in magnetars.

**Photon splitting process in the magnetosphere.**

The photon splitting is a QED process that splits a high-energy $\gamma$-ray photon into pair of low-energy photons in the presence of a pure magnetic field and/or magnetized plasma. The effect leaves some important signatures in astrophysical environments e.g. magnetars, gamma-ray bursts etc. where magnetic fields approach or even exceed the quantum critical value, $B_{cr} = 4.41 \times 10^{13}$ G. Indication of spectral cutoffs in the observed gamma-ray spectra of SGRs, and the radio quiescence of SGRs and AXPs could be explained by the exotic processes (photon splitting cascades, merging etc.) under consideration [13,14].

Generally, in a strongly magnetized plasma or vacuum, two more competing processes, photon merging and Compton scattering, may arise along with the photon splitting [11,12]. No detailed calculation on the probabilities of these processes in the current scenario ($B > B_{cr}$ with plasma) is available except a numerical calculation used in [12]. The photon splitting rate could be affected considerably by the magnetized plasma. The environment affects the rate by changing the photodispersion properties of the region. The ambient radiation field in the vicinity of a magnetar can be approximated to an environment equivalent to a magnetized rarefied plasma (inclusion of $\gamma$-$\gamma$ pairs in combination with $e^+e^-$ pairs in super-strong field). On the other hand, a region of the magnetar’s magnetosphere where high-energy gamma-rays and neutrinos are generated, is considered to be a strong magnetized vacuum i.e. environment without plasma.

Photon splitting may occur via various possible channels which are determined by the electric field vector ($X$), momentum vector ($q$) associated with a photon, and the magnetic-field vector ($B$). The state “1” refers to a configuration where $X$ is perpendicular to the plane containing $q$ and $B$ while “2” corresponds the $X$ being parallel to their plane. For low-energy background target UV-C photons ($T_{kin} \approx 0.1–0.2$ keV $\ll m_e c^2$) the only physical mode $\gamma_1 \rightarrow \gamma_2 + \gamma_2$ is responsible for splitting and, thereby softening background photon spectra in the magnetized plasma [12]. In addition, the photon merging channel, $\gamma_2 + \gamma_2 \rightarrow \gamma_1$, also plays an important role in the attenuation and softening of target photons. But in the absence of plasma, the physical mode, $\gamma_1 \rightarrow \gamma_1 + \gamma_2$ is the significant one for photon splitting over the channel, $\gamma_1 \rightarrow \gamma_2 + \gamma_2$. It should be however mentioned that the influence of the Compton scattering has negligible effect on the softening of background target photons against photon splitting in the magnetar model.

In the magnetar model, conversion of $\pi^0$ into $\gamma$-rays generally occurs near the magnetic vacuum region of the magnetosphere where the magnetic-field intensity drops to $B_{cr}$ or lower. Consequently, the effect of the main exotic process $\gamma_1 \rightarrow \gamma_1 + \gamma_2$ on the modification of the emergent PeV gamma-ray spectra in such a pure magnetic field essentially becomes unimportant.

**Emission of PeV neutrinos and gamma-rays.**

*Photomeson production.* There has been a consensus among researchers in particle astrophysics over the last few decades that the VHE protons and/or heavier ions are injected, and accelerated in surrounding regions of cosmic accelerators e.g. pulsars, nebulae, supernovae remnants, young magnetars. These accelerated ions then interact with the radiative background and/or the ambient matter. Subsequently VHE neutrinos and gamma-rays are generated through several reaction channels following dominant photomeson interactions in the radiative background as

$$p + \gamma \rightarrow \Delta^+ \rightarrow \left\{p + \pi^0 \rightarrow p + 2\gamma, \atop n\pi^+ \rightarrow n + e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu \right\}.$$  

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The final products of all neutrino flavours with gamma-ray keep the ratio approximately as $\nu_e : \nu_\mu : \nu_\tau : \gamma = 1 : 2 : 0 : 2$ at the sources but the process of neutrino oscillation turns this into a ratio of $\nu_e : \nu_\mu : \nu_\tau : \gamma = 1 : 1 : 1 : 2$ while observing at Earth.

In magnetar’s early life, the spin-down power is consumed to accelerate protons/ions, and the magnetic-field-driven power supplies ambient photon targets. The kinematic threshold for the photomeson interaction process in eq. (1) is determined by the accessible photon energies in the radiative field. Most of the radiative target photons are of UV type, as characteristic of many stars (pulsars, nebulae, accreting objects), the kinetic energy of protons has to range from a few tens to hundreds of PeV.

For common magnetars like SGRs and AXPs, the surface magnetic field might be of the order of $10^{15}$ G. The photon splitting process is assumed to take place much above the polar caps (away from the $\gamma$-ray generation point) where the star’s magnetic field does not sharply reduce to $\sim 10^{12}$ G. Below the $B_{\text{cr}}$, the magnetic field inhibits the photon splitting mechanism. Emission of VHE neutrinos and gamma-rays from these slowly rotating objects is described by the outer gap model [15]. In this gap closure scenario, this class of magnetars experiences dominant gamma-ray energy degradation via the $\gamma$-B and the $\gamma\gamma$ cascade formation, and the photon splitting process. Degraded gamma-ray energies fall below the cutoffs for direct observationsviz. EGRET and Fermi-LAT [16,17].

It is clear that the principal effect of the exotic photon splitting process is responsible to lower photon energies estimated at points away from a source with extreme physical conditions [12]. But in the present work, it has been suggested and believed that the exotic process in a magnetar may also degrade energies of background target photons in the star’s radiative field along with conventional pair-production loss i.e., $\gamma \rightarrow e^+ + e^-$. Though in [12] the photon splitting process was studied around $\epsilon_0 \sim 0.51$ MeV, its effect in pure magnetic field might be significant even at lower energies ($\epsilon_0 \ll m_e c^2$). If so, a main fraction of the UV photons (0.2–0.4 keV) of the radiative background might convert into softer radiation consisting chiefly of UV-A and UV-B types with average photon energy $\approx 0.01$ keV. The accelerated protons in polar caps will interact with these modified UV photon targets via photomeson processes in open field line regions of the magnetosphere. As a consequence, the PeV neutrinos and gamma-rays are generated and be detected on Earth.

**Physical model and photomeson threshold.** For young pulsars/magnetars with large spin-down power, acceleration of protons/ions has been considered by the widely used polar cap [18–20] and outer gap models [15] inside the magnetosphere. More clearly, charged particles undergo acceleration in the open field line zone near the magnetar’s pole in the polar cap model. In the latter model, the acceleration of particles takes place in the empty gaps within the bounded region by the neutral and last open lines in the magnetosphere.

The neutron star (NS) remnant or merger that appears from the massive binary NSs ($M \sim 2M_\odot$) coalescence, may form a millisecond magnetar with thin ejecta walls across polar caps in its very early phase. As the star receives a huge angular momentum from the binary it possesses a rapid rotation at the moment of its birth. These magnetars also have super-strong magnetic fields [21,22]. However, the formation of a prompt black hole from the merging cannot provide such a spin-down driven energy injection. On the other hand, the detection of quiescent emission and flares from some magnetars (normally as slow rotators with $P \sim 5–12$ s) can only be interpreted in terms of magnetic-field-driven power [14,22]. Here, we suggest that in the evolutionary phase of a magnetar after NSs merger, the star may transit through a state when the spin-down power is comparable with its magnetic power, and the spin period falls in the range 200–500 ms [10]. At this phase, the magnetar may induce photomeson processes in the polar cap that in turn produce PeV neutrinos and gamma-rays.

Generally, the spin-down power induces strong electric fields in polar caps where charged particles are injected, and experience acceleration, and are directed towards the open field lines near the star’s pole. The ultimate limit of potential drop of a magnetar with angular velocity $\Omega = 2\pi/P$ corresponding to the induced electric field across the magnetic-field lines from the magnetic pole to the last line, that extends to infinity, is $\Delta \phi = B_S R^2 \Omega^2/2c^2$ [23]. In this expression, $R$ denotes the radius of the magnetar, $B_S$ is the strength of magnetic field at the star’s surface, and $c$ is the speed of light. In the present work, the evolutionary phase of a magnetar is considered to be nearly analogous to a young pulsar except for its magnetic-field intensity ($B_S \equiv B_{15} \times 10^{15}$ G) and the existence of $\gamma\gamma$ pair cascades in addition to $e^+e^−$ pairs. The magnitude of the potential drop would be huge with a value of $7 \times 10^{21} B_{15} P_{ms}^{-2}$ volts. In magnetar’s polar caps, the presence of $e^+e^−$ pair cascades in the strong magnetic field may topple the electric field slightly along the field lines due to the screening effect in comparison with pulsars. The presence of such $e^+e^−$ pair cascades was validated by the results obtained from the observation of the Crab and other pulsar wind nebulae (PWN). But the current understanding related to various aspects of the cascade formation is still incomplete and hence it needs more research.

An extension of previous calculations for young pulsars [7] and [8] to magnetars reveals that protons or heavier ions undergo acceleration in the magnetar’s polar caps attaining energies close to $10^{16}–10^{17}$ eV, provided the magnetar’s magnetic moment vector $\boldsymbol{\mu}$ and $\Omega$ parameter satisfy the strong condition; $\boldsymbol{\mu} \cdot \Omega < 0$. These VHE protons will interact with soft UV-A and UV-B photons close to the magnetar’s polar caps, the $\Delta$ resonance state may form satisfying the kinematic threshold condition for the process in eq. (1). The photomeson production threshold
for a proton to reach the $\Delta^+$ state is something where the kinetic energies of the proton ($\epsilon_p$) and UV-A/B photon ($\epsilon_{\gamma}$) would satisfy

$$\epsilon_p\epsilon_{\gamma}(1 - \cos\theta_{p\gamma}) \geq 0.3 \text{ GeV}^2,$$

where $\theta_{p\gamma}$ is the incident angle between the proton and photon as measured in the laboratory frame. In a young magnetar, the typical photon energies near the polar caps are much smaller than a young pulsar because of the intense magnetic field. The energy of the modified target photons is $2.8kT_\infty(1 + z_\infty) \sim 0.01 \text{ keV}$, where $z_\infty \sim 0.4$ is the gravitational red-shift. Thus the proton threshold energy $\epsilon_{p,\text{Th}}$ for the $\Delta^+$ resonance state ranges as $\geq 3 \times 10^{16} \text{ eV}$.

The ion/proton flux interaction in radiative fields. Since one may expect that the approximate ion injection rate around the equatorial sector is the Goldreich-Julian rate [24], hence for a quasi-static magnetospheric environment the charge density near the magnetar surface can be approximated to $n_q \simeq e2n_0$ when the Goldreich-Julian density of ions at a radial distance $r$ is equal to $n_0(r) \equiv B_sR^3\Omega/(4\pi Ze c^2)$ [25]. There must be charged-depleted gaps above the stellar surface to induce acceleration where the density of ions may be parametrized as $f_d(1 - f_d)n_0$, where $f_d < 1$ for a moderate depletion) is the depletion factor depending on the adopted models, and is an unreliable one. The VHE proton flux emitted from the polar cap region would therefore be

$$\Phi_{\text{PC}} \simeq c f_d(1 - f_d)n_0A_{\text{PC}},$$

where $A_{\text{PC}}$ denotes polar cap area, and it equals $\eta_A(4\pi R^2)$ with $\eta_A$ the ratio of polar cap area to the magnetar surface area. Earlier calculations in [7,8] for estimating proton/ion flux in pulsar’s polar caps took the parameter $\eta_A$ as unity. The characteristic polar cap radius can be estimated by $r_{\text{PC}} = R(\Omega R/c)^{1/2}$, and hence $\eta_A$ takes the form $\Omega R/(4c)$ [25].

The neutrino and gamma-ray fluxes on Earth. It is seen from the process in eq. (1) that the charge-changing reaction goes on just after the reaction time, about three high-energy neutrinos (or a pair of $\nu_\mu$, $\bar{\nu}_\mu$) will accompany with four high-energy gamma-rays on the average when a significant number of such reactions proceed successfully. The muon neutrinos and gamma-rays that are produced from charged and neutral pions via $\Delta$ resonance will be moving almost in the original direction of protons. These neutrinos will arrive at Earth without suffering any change in their flux and energy. But, the high-energy gamma-ray flux might suffer a change due to QED effects in the presence of strong magnetic field in magnetar’s magnetosphere. Suppose, the factor $f_s$ accounts for such a modification in the gamma-ray flux.

The accelerated ions in polar caps will suffer interaction in the UV-A/B dominated radiative background of a magnetar. For a young magnetar with surface temperature $T_\infty$, the UV-C photon density in the vicinity of the star surface area is $n_\gamma(R) = (a_{\text{SB}}/2.8k)[(1 + z_\infty)T_\infty]^3$, $a_{\text{SB}}$ being the Stefan-Boltzmann constant. A numerical value of $n_\gamma(R)$ could be approximated as $9 \times 10^{19}T_{0.1\text{ keV}}$ (close to $R$, $T_{0.1\text{ keV}} \sim 0.5$). The photon density increases due to splitting and at the same time will decrease with the increase of radial distance from the stellar surface. We assume that these two variations will keep the overall photon density nearly constant not much distance away from the star’s surface. The UV-C type photon spectra will reduce to soft UV-A/B spectra only. Now, the conversion probability for $p \rightarrow \Delta^+$ via UV-A/B interaction along the distance from $R$ to $r$ is given by $P_s(r) = 1 - P_s(r)$ [7], where $dP_s/P(r) = -n_\gamma(r)\sigma_{p\gamma}dr \simeq -n_\gamma(R)\sigma_{p\gamma}dr$ with $\epsilon_{\gamma} \sim 0.01 \text{ keV}$, and conversion is to continue in the range from $R$ to $1.2R$. The threshold level $\epsilon_{p,\text{Th}}$ for $\Delta^+$ production in p-UV(A/B) interaction according to eq. (2) increases rapidly with $r$ because of the angle factor $(1 - \cos\theta_{p\gamma})^{-1}$. The conversion probability can be parametrized as $P_s = T_0^{3/4} \text{ keV}$ using the modified radiative field temperature [8]. Therefore, very near to the upper bound of the $p \rightarrow \Delta^+$ transformation region, the total flux of neutrinos/gamma-rays that is originated from the disintegration of the $\Delta^+$ resonance state will be

$$\Phi_{\nu,\gamma}(r \approx 1.2R) = 2c f_s A_{\nu,\gamma} f_d(1 - f_d)n_0P_{\nu,\gamma},$$

where $f_s = 4/3$ and $2/3$ for $\gamma$-rays and $\nu_\mu$'s, respectively. If now the duty cycle factor $f_{\text{dc}}$ of the gamma-ray/nuon neutrino is taken into account, the phase-averaged gamma-ray/\nu_\mu flux on the Earth from a magnetar at a distance $D$ is given by

$$\Phi_{\nu,\gamma}(r \approx 1.2R) = 2c f_s f_{\text{dc}} A_{\nu,\gamma} f_d(1 - f_d)n_0 \left( \frac{R}{D} \right)^2 P_{\nu,\gamma}.$$

In eq. (5), the flavor ratio of neutrino at their production point to a very large distance, say, at a detection level on Earth, is different due to the well-known neutrino oscillations. The effect of neutrino oscillations is represented by the parameter $f_s(1/2$ and 1 for muon neutrinos and gamma-rays). The factor $f_s$ is set equal to 1 for $\nu_\mu$ but it is not yet known correctly for gamma-rays. The factor 2 comes in eq. (4) or (5) due to $\bar{\nu}_\mu$ production via the processes in eq. (1).

The efficiency of the dynamo process in young magnetars is partly defined by the initial angular speed $\Omega = 2\pi/P_i$. The associated analytical calculations suggest that the creation of such enormous magnetic field needs a rotational period with $P_i \sim 1 \text{ ms}$ at birth time [22]. Under such a circumstance, stars possess a huge rotational energy for a small period before transforming into another class of stars through rapid evolutions. But, in this work we have taken $P_i$ as $\sim 350 \text{ ms}$ which indicates that the magnetar has just passed the neutrino-loud regime during its evolutionary phase [10].

We now calculate numerical values for $\nu_\mu$ and $\gamma$-ray fluxes using the formula in eq. (5) for a typical galactic magnetar with $D \sim 2 \text{ kpc}$, $P_i \sim 350 \text{ ms}$, $B_{15} \sim 1.5$, and $\epsilon_{p,\text{Th}}$ for the $\Delta^+$ resonance state ranges as $\geq 3 \times 10^{16} \text{ eV}$.
$T_{0.1\,\text{keV}} \sim 0.0255$, and $f_{de} \leq 0.10$ in both the cases when $\eta_a$ is equal to i) 1 and ii) $\Omega R/(4c)$. The factor $f_{de}$ in the (5) is set equal to $\sim 1$ in accordance with the explanation pointed out above. We have taken the star radius equal to $R = 10\,\text{km}$ for the present calculation. For the purpose, we choose $Z = 1$ and $f_a = 1/2$ here.

The corresponding $\nu_{\mu}$ and $\gamma$-ray integral fluxes ($E^2d\Phi_{\nu\gamma}/d\Omega$) calculated out from eq. (5) are $6.03 \times 10^{-10}$ and $48.34 \times 10^{-10}$ in GeVcm$^{-2}\text{s}^{-1}$ for $\eta_a = 1$. These values are $0.0009 \times 10^{-10}$ and $0.007 \times 10^{-10}$ according to the case ii) in GeVcm$^{-2}\text{s}^{-1}$. If we compare with IceCube estimated integral PeV neutrino flux, that is $\sim 2.4 \times 10^{-9}$ GeVcm$^{-2}\text{s}^{-1}$, these predicted values look quite low, particularly in ii).

The neutrino and gamma-ray energies. The average percentage of proton energy converted to the pion in the photomeson process is $\sim 20\%$, or in terms of temperature the pion energy would be $\sim 200 \times T_{0.1\,\text{keV}}\,\text{TeV}$ [7]. Since the pion resides only a very short time in the dense UV radiation zone and hence suffers negligible energy loss through inverse Compton scattering. Subsequently pion decay occurs and $\frac{1}{3}$ of its energy will be transferred into the muon neutrino, the rest will be equally shared by the other three leptons. The average energy of the $\nu_\mu$ for a young magnetar with $T_{0.1\,\text{keV}} \sim 0.0255$ is therefore

$$\epsilon_{\nu_\mu} \sim 50 \times T_{0.1\,\text{keV}}^{-1}\,\text{TeV} \sim 1.97\,\text{PeV}. \quad (6)$$

On the other hand, the average energy of $\gamma$-rays is expected to be

$$\epsilon_{\gamma} \sim 100 \times T_{0.1\,\text{keV}}^{-1}\,\text{TeV} \sim 3.93\,\text{PeV}. \quad (7)$$

But, the resulting $\gamma$-ray energy is expected to be smaller than the model prediction due to QED phenomenon in the region around $1.2R$ stellar distance where the magnetic-field intensity reduces to $B_\perp \approx 4.4 \times 10^{13}\,\text{G}$ in magnetars. This energy degradation aspect of gamma-rays is already discussed. It should be however mentioned that in the present calculation the loss due to the pion curvature process is considered inefficient [26].

PeV neutrino and gamma-ray events in VHE ground-based experiments.

Detection of PeV neutrino events in IceCube. Detection of two neutrino events with energies in the range 1–10 PeV has been reported by the IceCube experiment [2]. These high-energy muon neutrinos are usually detected indirectly through the observation of the Cherenkov light produced in ice by charged secondary particles created from neutral-current or charged-current interactions. The visible track length left behind the path of a produced high-energy $\mu$ is estimated from the reconstruction of the Cherenkov light detected by optical sensors buried in the Antarctic ice in configuration with the digital optical modules. Events with angular resolution $\leq 1^\circ$, 50% confidence level correspond to visible muon tracks out of all events [27]. Event selection for astrophysical neutrinos from backgrounds mostly arising from VHE cosmic ray air shower induced muons is implemented through Monte Carlo simulations [28,29]. The sensitivity of the IceCube to PeV neutrinos is found above a threshold of $\epsilon_{\nu_\mu} \sim 0.1\,\text{TeV}$. IceCube with that level of sensitivity has measured the neutrino flux as $E^2d\Phi_{\nu_\mu} \sim 3 \times 10^{-9}$ GeVcm$^{-2}\text{s}^{-1}$ sr$^{-1}$ corresponding to the neutrino energy range 0.2–2 PeV. For the typical magnetar considered in this work, the probability of conversion of $\nu_\mu \rightarrow \mu$ in ice is expected to be $p_{\nu_\mu \rightarrow \mu} \sim 1.3 \times 10^{-6}$ (GeV cm$^{-2}$ s$^{-1}$) [30], and the corresponding event rates in the IceCube detector would be

$$\frac{dN}{dA\,dt} = d\Phi_{\nu_\mu}p_{\nu_\mu \rightarrow \mu} \leq 2.5 \times 10^{-4}\,\text{km}^{-2}\text{yr}^{-1}. \quad (8)$$

It is clear that the model-dependent calculation for the PeV $\nu_\mu$ flux and the event rates obtained in previous sections are much lower for $\eta_a \neq 1$ compared to IceCube limits with its current sensitivity. It is expected that a next-generation (i.e. “Gen2” with instrumented volume $10\,\text{km}^3$ and $75\,\text{km}^2$ surface array) IceCube detector will be able to cover these lower limits of $\nu_\mu$ flux and hence will pinpoint the site of the VHE events in the Universe.

Detection of PeV gamma-rays in IceCube and HAWC. Cosmic rays (CRs) beyond 1 PeV and perhaps as close as 10$^3$ PeV, are believed to be of galactic origin. Therefore, detection of PeV gamma-rays provides an opportunity to know the possible origin and acceleration mechanisms of high-energy CRs. For observing TeV gamma-rays, the Imaging Air Cherenkov Telescopes (IACTs) and air fluorescence detectors have been used in many experiments [31]. High-energy gamma-rays might also be detected by ground-based air-shower arrays equipped with muon detectors [32]. The PeV energy scale is inaccessible to even present-generation IACTs viz. H.E.S.S. [33], MAGIC [34] and VERITAS [35]. Under the present perspective of the work, the simultaneous observation of muon neutrinos and gamma-rays at PeV energies has to be ensured in the IceCube experiment [36]. A new approach combining muon-poor air shower data from IceCube’s surface component i.e., IceTop with the in-ice array data of IceCube may identify the PeV gamma-ray events [37]. IceCube’s 5-year sensitivity to point sources indicates that if the spectral index remains unchanged across the energy range from 10 TeV to $\sim 1$ PeV, the gamma-ray flux would have been measured up to a lower limit of the order of $\sim 10^{-10}$ GeVcm$^{-2}\text{s}^{-1}$ at 1 PeV from regions at 5–8 l.kpc distance scale. This clearly suggests that the present sensitivity of IceCube to PeV gamma-rays from magnetars with $\eta_a \neq 1$ is still not within reach by the system. Due to the very low flux obtained from the model calculation, IceCube does not hint about any hypothetical detectable magnetar candidate even as an unidentified source in the near future in the existing gamma-ray data sets.

The upcoming planned Cherenkov Telescope Array (CTA) [38] with a factor of 5–10 times higher in sensitivity compared to current generation IACT instruments is expected to span from a few tens of GeV to around
100 TeV. Hence, observation of gamma-rays in the PeV energy scale by the CTA does not look bright.

In recent times, the High-Altitude Water Cherenkov (HAWC) gamma-ray observatory has already shown its potentiality to detect high-energy gamma-rays up to 100 TeV [39]. If the HAWC keeps its sensitivity to VHE gamma-rays unchanged in the region 10 TeV–1 PeV following a constant spectral index, the possible lower bound of gamma-ray flux results in $\sim 4 \times 10^{-11}$ GeV cm$^{-2}$ s$^{-1}$ for sources within 10 kpc. In comparison with the PeV gamma-ray flux obtained from a magnetar at $\sim 2$ kpc distance with $\eta_A \neq 1 \sim (0.007 \times 10^{-10}$ GeV cm$^{-2}$ s$^{-1}$), the HAWC results under some principle conditions casting some sign of improvement in the VHE gamma-ray astronomy.

The daughter particles from $p\gamma$ interactions are neutrinos, gamma-rays, degraded protons and neutrons. Among them protons may remain trapped in the star’s magnetic field and neutrons will decay and result in CRs. Hence these components cannot reach the Earth uninterrupted due to various interactions and deflections in the interstellar medium, and thereby obscuring directional information completely. In each such $p\gamma$ interaction, VHE protons lose about 20% of their initial energy from which $\nu_p$ and $\gamma$-ray gain $\sim 5\%$ of the proton energy each. This suggests a possibility of simultaneous detections of PeV neutrinos and gamma-rays from magnetars on Earth if the gamma-rays escape the emission region without making pairs (more likely since mean free path for $e^+e^-$ pair production is $\geq 10$ kpc [40]). The highly sensitive IceCube system and HAWC experiments in future may be useful to detect these PeV gamma-rays [37,41]. These PeV gamma-rays are unlikely to reach the detection site from extragalactic sources because of their pair-production losses with cosmic background radiations. Hence, results from HAWC on the VHE gamma-ray component and the simultaneous investigation for PeV neutrinos and gamma-rays by the upcoming IceCube’s Gen2 with higher sensitivity will resolve the enigma on the origin of PeV gamma-rays in coming years.

The simultaneous generation of PeV neutrinos and gamma-rays in the magnetar model follows some important astrophysical processes which are given in eq. (1). These processes altogether refer to an important viewpoint that PeV neutrinos and gamma-rays from magnetars are hadronic in fundamental origin. There is a recent prolific observational evidence on VHE gamma-ray emission from the Crab pulsar reaching up to 1.5 TeV energy. Such TeV gamma-ray observations strongly favor inverse Compton (IC) scattering off low-energy photons in the wind acceleration region very close to the light cylinder [42]. This clearly refers to another important viewpoint in which these gamma-rays may well be considered to be leptonic in fundamental origin. However, these TeV gamma-rays do not accompany any neutrinos at their birth from the production site. The absence of neutrinos and the upper limit of energy (up to 1.5 TeV only) bring important constraints on the functioning of their model at larger distances (where the fields will presumably be weaker) in the present scenario.

Conclusions. – If protons reach the 10–100 PeV energy scale in a magnetar then their interactions with modified UV-A/B photon targets may generate PeV neutrino events with energies between 1 and 10 PeV as observed by the IceCube experiment. The predicted event rates of PeV neutrinos by the model suggest no possible indication of any statistically significant excess from the direction of any local magnetar to be observed by IceCube in the future and is thus as per IceCube expectations [43]. Since the photon splitting mechanism in the PeV region is not completely studied yet in QED, and if the PeV gamma-rays might have generated in the magnetosphere where $B > B_{cr}$, then the modification of the PeV gamma-ray spectra detected at Earth from magnetars cannot be ruled out.

If gamma-rays are detected simultaneously with neutrinos at PeV energies then the origin of PeV astrophysical neutrinos would probably be resolved.

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