Probing the birth of fast rotating magnetars through high-energy neutrinos

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We investigate the high-energy neutrino emission expected from newly born magnetars surrounded by their stellar ejecta. Protons might be accelerated up to 0.1–100 EeV energies possibly by, e.g., the wave dissipation in the winds, leading to hadronic interactions in the stellar ejecta. The resulting PeV-EeV neutrinos can be detected by IceCube/KM3Net with a typical peak time scale of a few days after the birth of magnetars, making the characteristic soft-hard-soft behavior. Detections would be important as a clue to the formation mechanism of magnetars, although there are ambiguities coming from uncertainties of several parameters such as velocity of the ejecta. Nondetections would also lead to useful constraints on the scenario.

I. INTRODUCTION

Magnetars are neutron stars endowed with the strongest magnetic fields known in the universe, $B \sim 10^{14-15}$ G (for reviews see [1]). It is believed that $\sim 10\%$ of young galactic neutron stars possess such strong fields (for reviews see [1]). Although the precise origin of these strong fields is uncertain, It has been argued that their amplification occurs via the dynamo mechanism during the Kelvin-Helmholtz cooling time, $t_{KH} \sim 10$–100 s, in the protoneutron star (PNS) phase [2]. The dynamo efficiency is partly determined by the initial rotation rate of $\Omega_i = 2\pi/P_i$, and analytical estimates suggest that the formation of global strong magnetic fields might require $P_i \sim 1$ ms at birth. This will affect the dynamics of the PNS wind, by providing a significant reservoir of rotational energy comparable to that of the accompanying supernova (SN) explosion. The strong magnetic fields can facilitate the SN explosion, and may be responsible for the more powerful subclass of SNe known as hypernovae (HNe), related to long gamma-ray bursts (GRBs) (e.g. [3] for reviews), which together with the PNS wind acts as a piston on the compressed stellar ejecta, i.e. the young expanding SN remnant (SNR) [4].

Newly born magnetars with rapid rotation rates may be efficient ultra-high-energy cosmic-ray (UHECR) accelerators [5,6]. Particle acceleration in neutron stars has been considered at both the polar or outer gap inside the magnetosphere, and near the wind zone [1,7]. If ions are accelerated as well as electrons, up to sufficiently high energies, they can produce high-energy neutrinos via, e.g., the $p\gamma$ or pp reaction. Based on the polar gap models, Refs. [8] discussed neutrino production via the $p\gamma$ reaction between ions and surface x rays, or by curvature pion radiation of ions. In this work, we investigate the high-energy magnetar neutrino emission resulting from a different scenario suggested by Ref. [5], where cosmic-ray acceleration is attributed to the wake-field acceleration mechanism beyond the light cylinder. We consider the pp and $p\gamma$ interactions of cosmic-ray ions with cold SNR nucleons and thermal photons. In the case of fast rotating magnetars, we find that the resulting neutrino energy fluence peaks around $t \sim$ a few days due to hadronic cooling of mesons and muons. Such high-energy neutrinos can be detected by future km^3 telescopes such as IceCube/KM3Net [9] in a few years or if magnetars are born at $\lesssim 10$ Mpc.

II. THE MODEL

In the dynamo scenario, newly born magnetars have a large rotational energy [2]. During t_{KH} the PNS winds would be thermally neutrino-driven or magnetically dominated but subrelativistic, and the spin down rate may be enhanced by neutrino-driven mass loss [4]. After t_{KH}, the winds become magnetically dominated and relativistic, similarly to the case of pulsar winds. The rotational energy is extracted by the Poynting flux and gravitational waves [5]. Using the vacuum dipole formula, the rotational energy loss rate by the magnetic wind at $t(>T_{EM} \simeq 10^{2.5}$ s $I_{45}\,\mu_{33}^{-2}\,\Omega_{i,4}^{-2})$ in the stellar frame can be estimated as $L(t) \simeq 6.1 \times 10^{47}$ erg s$^{-1}\,I_{45}^2\,\mu_{33}^{-2}\,t_4^{-2}$, where $\mu \equiv \frac{1}{2}B_{NS}R_{NS}^3 \simeq 0.5 \times 10^{33}$ G cm$^3\,B_{NS,15}\,R_{NS,6}^3$ is the magnetic dipole moment and the moment of inertia I is set to 10^{45} g cm^2 throughout this work. The particles are expected to gain a fraction of the magnetar rotational energy during their acceleration, by tapping a fraction of the open field line voltage on their ways from the magnetar to the outside region. The maximum cosmic-ray energy accelerated at $t(>T_{EM})$ is

$$E^M(t) = \eta Z e \Phi_{\text{mag}} \simeq 2.0 \times 10^{20} \text{ eV } Z\,\eta_{-1}\,I_{45}\,\mu_{33}^{-1}\,t_4^{-1},$$

(1)

where η parametrizes the uncertainties in the utilization of the potential drop. In polar gap models, the parallel electric fields would be significantly screened in very young pulsars, implying $\eta \ll 0.1$ [1,8]. Nevertheless, as in pulsars, a significant fraction of the Poynting energy could be converted to the kinetic energy well outside the light cylinder, via mechanisms such as surf-riding acceleration. Ref. [5] suggested UHECR acceleration by the wake-field acceleration in the equatorial wind, where it was argued that, for an oblique rotator, much of the Poynting flux might be tied up in waves and the crinkled frozen-in current sheets dissipate around $r_{\rm diss} \sim 10^{3-4}(c/\Omega)$. If wave emission is the relevant dissipation process, it might form large amplitude electromagnetic waves pushing ions by the ponderomotive force, $F_{\rm pond} \approx mc\Omega(Ze\delta B/mc\Omega)$ [10]. Hence, the work on a particle moving a distance l through the wave is $F_{\rm pond}l \approx \eta Ze\Phi_{\rm mag}$, as long as $\delta B \sim B$ and $\eta \equiv l/r \sim 0.1$. Following Ref. [5], we hereafter assume that such prompt cosmic-ray acceleration mechanism is in operation, and use Eq. (1). The exact nature of the dissipation and acceleration mechanisms in the wind is currently uncertain and a detailed study is beyond the scope of this paper. Approximately, since we may expect that the ion injection rate around the equatorial sector is the Goldreich-Julian rate [11], the cosmic-ray spectrum can be written as [5,12]

$$\frac{dN}{dE} = \frac{9}{8}\frac{c^2 I}{Ze\mu}\frac{1}{E(1 + E/E_G)}, \qquad (2)$$

where $E_G \equiv (5/72)(\eta Ze\mu^3/GI^2\epsilon^2)$ and, for simplicity, we have assumed that all the particles accelerated at t have $E^M(t)$. Note that since the acceleration is expected to occur promptly, energy losses can be neglected. Hence the adiabatic and radiation losses in the wind become irrelevant since accelerated ions will not be coupled to the fields and their curvature radius is large enough [5].

III. THE NEUTRINO SPECTRUM AND FLUX

A newly born magnetar will be surrounded by the young SNR, separated by a cavity evacuated by the wind or rapidly expanding SN shock. The particle acceleration in the wind occurs around $r_{\rm acc} \sim r_{\rm diss} \sim 10^{10.5}$ cm $\mu_{33}t_4^{1/2}$ (hereafter we consider the cosmic-ray ions to be protons [11]). The wind termination shock and the SN shock radii are both larger than $r_{\rm acc}$ for sufficiently late times as considered here. Thus, a significant fraction of cosmic rays will interact with the stellar ejecta, unless the latter is punctured or disrupted by the wind itself (see below for general cases). First, we consider the interaction between cosmic rays and SNR nucleons assuming that cosmic rays are emitted isotropically, to obtain conservative results.

The cosmic rays will interact with the SNR via pp reactions, producing mesons. When the (magnetar-powered) SN shock has a high velocity of $\beta_{\rm SN}c$, the effective optical depth for the pp reaction is $f_{pp} \approx$

$\kappa_{pp}\sigma_{pp}n_p\Delta_{\rm SN} \simeq 5.7 \times 10^4 M_{\rm SN,1}\beta_{\rm SN,-1}^{-2}t_4^{-2}$, where $\kappa_{pp} \sim 0.5$–0.6, $\sigma_{pp} \sim 10^{-25}$ cm^{-2} (in the 100 PeV range) [13], and $\Delta_{\rm SN} \sim r_{\rm SN} \approx \beta_{\rm SN}ct \simeq 10^{13.5}$ cm $\beta_{\rm SN,-1}t_4$. The meson production efficiency is estimated as $f_{\rm mes} \sim \min(1, f_{pp})$. Since the effects of magnetic fields in the SNR can typically be neglected, the interaction time is $t_{\rm int} \approx \Delta_{\rm SN}/c$.

The resulting charged mesons decay into neutrinos via $\pi^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \nu_\mu + \bar{\nu}_\mu$. The neutrino spectrum roughly follows the cosmic-ray spectrum, but the high-energy spectrum is modified when mesons and muons cool down before they decay. In our cases, the inelastic $\pi p/\mu p$ collision can be relevant. When $f_{\pi p} \approx t_{\rm int}/t_{\pi p} \gtrsim 1$, the pion neutrino flux is suppressed as $f_{\rm sup} \sim \min(1, (t_{\pi p}/\gamma_\pi\tau_\pi))$, where the break energy is $E_\nu^{\rm had} \approx 0.25(t_{\pi p}/\tau_\pi)m_\pi c^2 \simeq 32$ TeV $M_{\rm SN,1}^{-1}\beta_{\rm SN,-1}^3 t_4^3$. $\tau_{\pi/\mu}$ is the proper life time of charged pions/muons and $t_{\pi p/\mu p} \approx (\kappa_{\pi p/\mu p}\sigma_{\pi p/\mu p}n_p c)^{-1}$ is their hadronic cooling time. Since the neutrino spectrum is proportional to $f_{\rm mes}f_{\rm sup}$, its rough expression for $dN/dE \propto E^{-p}$ is

$$E_\nu^2\phi_\nu \propto \begin{cases} (E_\nu/E_\nu^{\rm had})^{2-p} & (\text{for } E_\nu \le E_\nu^{\rm had}) \\ (E_\nu/E_\nu^{\rm had})^{1-p} & (\text{for } E_\nu^{\rm had} < E_\nu \lesssim \frac{1}{4}E^{\rm max}) \end{cases} \quad (3)$$

The resulting neutrinos can propagate in the SNR matter without significant attenuation because $\tau_{\nu p} \approx \sigma_{\nu p}n_p\Delta_{\rm SN} \simeq 0.017\,E_{\nu,{\rm EeV}}^{0.363}M_{\rm SN,1}\beta_{\rm SN,-1}^{-2}t_4^{-2} \ll 1$.

We have performed detailed numerical calculations to evaluate neutrino spectra and fluxes through the method of Refs. [14]. The calculations are performed during a time $t_{\rm int}$, taking into account the high meson multiplicity of the high-energy pp reaction, based on the SIBYLL code [13], and hadronic cooling of pions and muons with the approximated cross sections of $\sigma_{\pi p} \simeq 5 \times 10^{-26}$ cm^2 and $\sigma_{\mu p} \simeq 2 \times 10^{-28}$ cm^2 [15]. We neglect contributions from meson production via $\pi p/\mu p$ processes which can affect the spectra by factors $\mathcal{O}(1)$, since their influence is modest and only at relatively early times, $t \lesssim$ day. As shown later, the detailed spectra will be somewhat different from Eq. (3) especially at high energies, due to the high meson multiplicity of the pp reaction and the accumulation of cooled mesons and muons. The only necessary input quantities are the cosmic-ray flux and target nucleon density. The former is given by Eqs. (1) and (2) and the latter by $M_{\rm SN}$ and $\beta_{\rm SN}$.

In Figs. 1 and 2, the resulting spectra and light curves are shown for $M_{\rm SN} = M_{\rm SN,1} \equiv 10M_\odot$ and $\beta_{\rm SN} = 0.1$. We can see that the neutrino energy fluence becomes maximal around $t \sim 2$ days, because of hadronic cooling of pions and muons at earlier times and a decrease of $E^2\frac{dN}{dE}(t) \propto E^M/\mu \propto t^{-1}$ at later times. As a result, we expect a hardening spectrum at $t \lesssim 2$ days, and a softening spectrum at $t \gtrsim 2$ days in the 100 TeV–10 PeV range (Fig. 2). The peak time $T_{\rm had}$ is determined by equating $E_\nu^{\rm had}$ with the typical neutrino energy $E_\nu^{\rm typ} \sim 0.03E^M$ [13]. We have $T_{\rm had} \sim 2 \times 10^5$ s $\eta_{-1}^{1/4}\mu_{33}^{-1/4}\beta_{\rm SN,-1}^{-3/4}M_{\rm SN,1}^{1/4}$
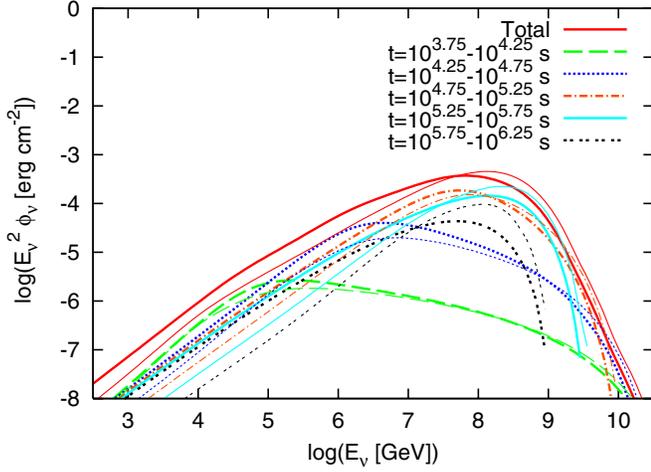
FIG. 1 (color online). The $(\nu_\mu + \bar{\nu}_\mu)$ fluence from a newly born magnetar at 5 Mpc, at different time intervals. The fluence peaks around $t \sim 2$ days because hadronic cooling of mesons and muons is important at earlier times, while the amount of cosmic rays decreases with time. Thick/thin lines are for the cases without/with the radiation field. Vacuum neutrino oscillations are considered.

and the corresponding peak energy $E_{\nu,pk}^{had} \sim$ 300 PeV $\eta_{-1}^{3/4} \mu_{33}^{-3/4} \beta_{SN,-1}^{3/4} M_{SN,1}^{-1/4}$ which agree with Figs. 1 and 2. Note that cases of $T_{had} \gg T_{EM}$ are considered. The main contribution comes from the cosmic rays produced at $t \sim T_{had}$. Since $E_\nu^2 \phi_\nu(t) \propto E^2 \frac{dN}{dE}(t) \propto E^M/\mu$, the neutrino fluence per flavor around the peak time is roughly estimated as $\sim 10^{-4}$ erg cm^{-2} $D_{5\,Mpc}^{-2} f_{mes} f_{sup} \times$ $\eta_{-1}^{3/4} \mu_{33}^{-7/4} \beta_{SN,-1}^{3/4} M_{SN,1}^{-1/4}$. The total expected muon event
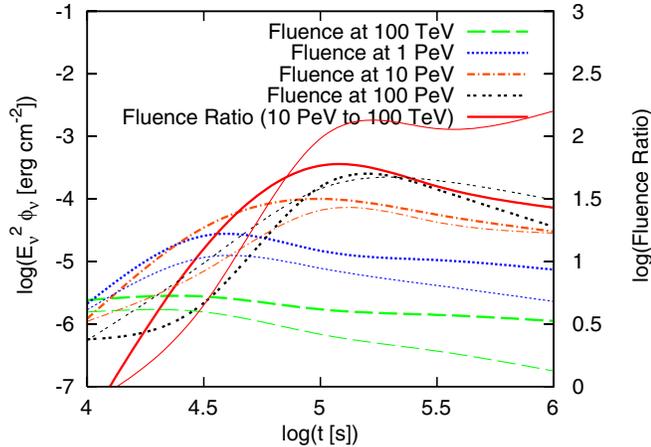

FIG. 2 (color online). Neutrino light curves corresponding to Fig. 1 at 100 TeV (dashed line), 1 PeV (dotted line), 10 PeV (dotted-dashed line), 100 PeV (double dotted line), and the ratio of 10 PeV fluence to 100 TeV fluence (thick line). Cooling of mesons and muons is important at $t \lesssim 2$ days, while the amount of accelerated protons decreases with time. Thick/thin lines are for the cases without/with the radiation field.

rates (above $10^{0.5}$ TeV) by IceCube is $N_\mu \sim 2D_{5\,Mpc}^{-2}$ events in two days, which will be more than the atmospheric neutrino-induced event rates within 1°, $N_\mu^{atm} \sim 10^{-2.5}$ events/day. Magnetars arising at distances closer than 5 Mpc would yield higher fluxes observed as neutrino multiplets, which allow us to recognize them as signals without coincident detections with photons and even to see the characteristic soft-hard-soft behavior. Since the magnetar birth rate is $\sim 10^{-3}$ yr^{-1} galaxy^{-1}, the probability to encounter a birth is non-negligible. From the number of local galaxies, we expect ~ 0.02–0.05 yr^{-1} for the birth of magnetars within 5 Mpc [16].

One may expect an additional radiation field, leading to $p\gamma$ neutrinos in addition to pp neutrinos. For example, if the magnetar wind drives the SN explosion in its birth [4], a significant fraction of the outflow energy may be dissipated as radiation via the shocks. (The radiation field can also be expected in case of GRB jets in the star [17].) Therefore, we also show the case where the radiation field is included. In Figs. 1 and 2, the case for $kT_\gamma \simeq$ 0.4 keV$\epsilon_\gamma^{1/4} E_{exp,51}^{1/4} \beta_{SN,-1}^{-3/4} t_3^{-3/4}$ is also shown. Here E_{exp} is the outflow energy and ϵ_γ is the radiation efficiency. When the radiation field exists in the SN ejecta, the previous expression of f_{mes} should be replaced with $f_{mes} \sim$ min(1, max($f_{pp}, f_{p\gamma}$)), where the effective optical depth for the photomeson production, $f_{p\gamma}$, is roughly estimated as $f_{p\gamma} \approx \kappa_{p\gamma} \sigma_{p\gamma} n_\gamma \Delta_{SN} \simeq 380 \epsilon_\gamma^{3/4} E_{exp,51}^{3/4} \beta_{SN,-1}^{-5/4} t_4^{-5/4}$ around the Δ-resonance energy of $E_\Delta \simeq$ 2.4 PeV $\epsilon_\gamma^{-1/4} E_{exp,51}^{-1/4} \beta_{SN,-1}^{3/4} t_4^{3/4}$. Here, $\kappa_{p\gamma} \sim 0.2$, $\sigma_{p\gamma} \sim 5 \times 10^{-28}$ cm^{-2} at the Δ-resonance. Correspondingly, the expression of f_{sup} includes the cooling of mesons and muons due to interactions with photons as well as their hadronic cooling. Following Ref. [14], neutrino spectra are numerically calculated, taking into account the radiation field. Although the radiation field can change spectra as a result of the difference in the meson multiplicity, we may expect that the total energy fluence around the peak energy and the qualitative feature are similar.

Next, let us consider the sum of neutrinos from individual magnetars, i.e., the *cumulative* neutrino background. The typical magnetar rate would be $\sim 10\%$ of core-collapse (CC) SN rate, $R_{SN}(0) \sim 1.2 \times 10^5$ Gpc^{-3} yr^{-1} [1,18]. Possibly, the birth rate of fast rotating magnetars may be comparable to that of HNe that may be powered by magnetars, implying $R_{HN}(0) \sim 2 \times 10^3$ Gpc^{-3} yr^{-1} [18]. By using our numerical results, the cumulated fluxes can be estimated as [14,19]

$$E_\nu^2 \Phi_\nu \sim 3 \times 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ str}^{-1} f_{mes} f_{sup} \eta_{-1}^{3/4} \mu_{33}^{-7/4}$$

$$\times \beta_{SN,-1}^{3/4} M_{SN,1}^{-1/4} \frac{f_{geo}}{0.5} \frac{f_z}{3} \frac{R_{mag}(0)}{1.2 \times 10^3 \text{ Gpc}^{-3} \text{ yr}^{-1}},$$

(4)

where f_{geo} is the fraction of the magnetars with the preferred geometry for ion acceleration [5] and f_z expresses the contribution from the high redshift sources [14,19].

The numerical results are shown in Fig. 3, where the birth rate evolution is included with the SFR2 model for magnetars [14]. The muon event rates are $N_\mu \sim$ 18 events/yr for $R_{mag} = 0.1 R_{SN}$ and $N_\mu \sim 4$ events/yr for $R_{mag} = R_{HN}$, respectively. Note that cross-correlation studies between neutrinos and CC SNe/HNe can be important, but we may expect one time- and space-coincident event among $\sim 10^{4-5}$ magnetar births. However, from Fig. 3, we still expect future constraints on the "diffuse" neutrinos are important to test the magnetar scenario since expected neutrinos have rather high energies.

We consider the possible beaming effects of the cosmic rays, SNR puncture and disruption by the winds, since these can affect the escape and detectability of the cosmic rays. Cosmic rays themselves may be beamed, enhancing the neutrino signals from individual sources by the beaming factor while the background is unchanged. In addition, if the PNS winds are significantly collimated, they may puncture the stellar envelope, leading to long GRB jets [4]. Only cosmic rays that are emitted along the penetrating jets can escape without depletion. However, even if cosmic rays are beamed along the jet, we still expect neutrino
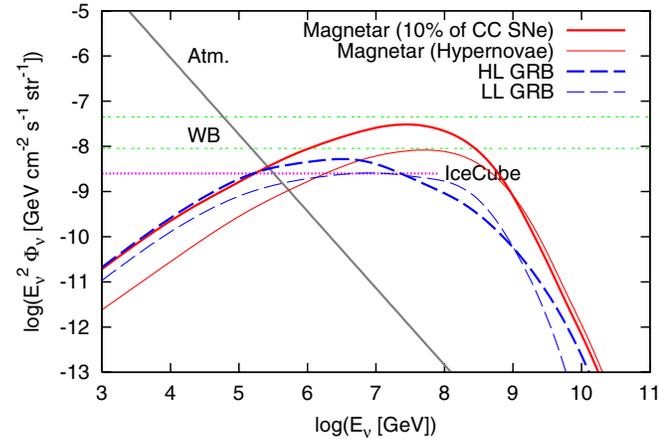

FIG. 3 (color online). The cumulative $(\nu_e + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau)$ background from newly born magnetars. Thick solid line: Magnetar (10% of CC SNe) shows the case where 10% of CC SNe bear fast rotating magnetars, with $M_{SN} = 10 M_\odot$. Thin solid line: Magnetar (Hypernovae) is a case where the fast rotating magnetar rate is comparable to the HN rate, with $M_{SN} = M_\odot$. For comparison, various GRB neutrino backgrounds for the GRB-UHECR hypothesis are also shown. Thick dashed line: HL GRB, prompt neutrinos from HL GRBs [14,19]. Thin dashed line: LL GRB, prompt neutrinos from LL GRBs [14]. WB: The Waxman-Bahcall bounds are shown as benchmarks [19]. Atm: the conventional atmospheric neutrino background. A ΛCDM cosmology $(\Omega_m = 0.3, \Omega_\Lambda = 0.7; H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1})$ and $z_{max} = 11$ is used.

production when jets are choked rather than successful [17].

The disruption resulting in the formation of supershells expanding into the interstellar medium was discussed in Ref. [5]. Such phenomena have never been observed in CC SNe/HNe, but we discuss them for the sake of generality. The effect of the disruption by energy shedding may be characterized by a clumpiness factor, $C \equiv \delta\rho/\rho$. The no shedding case corresponds to $C = 1$. In clumpy SNRs, neutrinos are produced when clumps lie along the line of sight. While values of C are uncertain, as an example $C \sim 3^3$ implies that the probability to see neutrinos is $\sim C^{-2/3} \sim 1/9$, and the background is similarly reduced.

IV. IMPLICATIONS AND DISCUSSIONS

The birth of fast rotating magnetars is a common scenario discussed in connection with HNe and GRBs [2], although the origin of their strong magnetic fields is controversial (e.g., dynamo vs fossil fields). Here we have shown that high-energy neutrino signals can serve as the smoking gun signal announcing the birth of fast rotating magnetars. A suppression of the highest-energy neutrinos at $t \lesssim T_{had} \sim$ a few days implies that cosmic-ray acceleration occurs inside the SNR, and a characteristic soft-hard-soft behavior is expected. Although our predicted fluxes are below the current observational limits, they can be tested by IceCube, KM3Net, ARIANNA and Auger in the near future. Even nondetections would provide useful constraints on this magnetar scenario.

There are also other possible ways to produce neutrinos. First, at earlier times ($\lesssim$ days), there may be radiation fields with the temperatures of 0.1–1 keV (at $r_{SN} \sim 10^{13.5}$ cm), in the shocked stellar ejecta ahead of the wind [15,17] or in the cavity [20]. The former case is also demonstrated in this work. Collimated winds launched at very early times ($\lesssim 10^3$ s) may become successful jets such as GRB jets. Then, a fraction of the cosmic rays interact with late internally dissipated or external-shock photons, making other very high-energy neutrino signals, similarly to the case of GRBs [14].

Cosmic rays and neutrinos could be expected possibly also in *normal* pulsars where $T_{had} \ll T_{EM}$ is anticipated. When they have weaker magnetic fields but rapid rotation speeds, the peak time of the energy fluence can be later than days, and then neutrino emission lasts longer. Since it was not the focus of this work, see Refs. [7] for comprehensive discussions.

Magnetar neutrinos may be useful for revealing the possible connection between magnetars and UHECRs. Since our purpose here is not an explanation of UHECRs, we make only two brief comments on this possibility: (a) only a fraction of magnetars can be UHECR sources, and (b) the Auger spectrum seems to conflict with Eq. (2) [21]. Concerning point (a), one may think of many possible reasons such as initial rotation rate,

geometry, puncture or disruption of the SNR. Interestingly, the rate required in the magnetar scenario is comparable to the HN rate [6,21]. Point (b) requires more careful consideration, but we may expect a realistic spectrum to differ from Eq. (2), depending on the detailed mechanism. For example, if test particles are stochastically accelerated by waves, $dN/dE \propto E^{-2}$ can be expected [10]. Although this requires further investigations beyond the scope of this work, the use of Eq. (2) is sufficient for demonstrations. Other cases can easily be predicted, once the cosmic-ray spectrum is given.

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