Possible High-Energy Neutrino and Photon Signals from Gravitational Wave Bursts due to Double Neutron Star Mergers

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As the technology of gravitational-wave and neutrino detectors becomes increasingly mature, a multi-messenger era of astronomy is ushered in. Advanced gravitational wave detectors are close to making a ground-breaking discovery of gravitational wave bursts (GWBs) associated with mergers of double neutron stars (NS-NS). It is essential to study the possible electromagnetic (EM) and neutrino emission counterparts of these GWBs. Recent observations and numerical simulations suggest that at least a fraction of NS-NS mergers may leave behind a massive millisecond magnetar as the merger product. Here we show that protons accelerated in the forward shock pushed by a magnetar wind launching the ejecta during the merger process would interact with photons generated in the dissipation of the magnetar wind and emit high energy neutrinos and photons. We estimate the typical energy and fluence of the neutrinos from such a scenario. We find that $\sim$PeV neutrinos could be emitted from the shock front as long as the ejecta could be accelerated to a relativistic speed. The diffuse neutrino flux from these events, even under the most optimistic scenarios, is too low to account for the two events announced by the IceCube Collaboration, but it is only slightly lower than the diffuse flux of GRBs, making it an important candidate for the diffuse background of $\sim$PeV neutrinos. The neutron-pion decay of these events make them a moderate contributor to the sub-TeV gamma-ray diffuse background.

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I. Introduction

The next-generation gravitational-wave (GW) detectors, such as the advanced LIGO, advanced VIRGO and KAGRA interferometers$^1$, are expected to detect GW signals from mergers of two compact objects. One of the top candidates of these gravitational wave bursts (GWBs) is the merger of two neutron stars (i.e. NS-NS mergers)$^2$. The study of the electromagnetic (EM) counterpart of such GWBs is of great interest$^2$. Numerical simulations show that mergers of binary neutron stars would leave two remnants, a post-merger compact object and a mildly anisotropic ejecta with a typical velocity of $\sim 0.1 - 0.3c$ (where $c$ is the speed of light) and typical mass of $\sim 10^{-4} - 10^{-2}M_\odot$$^3$. Even though a black hole is usually taken as the post-merger product, observational data and numerical simulations suggest that for a stiff equation of state of nuclear matter and a small enough total mass of the two neutron stars, the postmerger product could be a stable hypermassive, millisecond magnetar$^3-9$. Recently, Ref. $^7,8$ have systematically studied the EM signals for the NS-NS scenario with a stable millisecond magnetar post-merger product. Zhang$^7$ proposed that the proto-magnetar would eject a near-isotropic Poynting-flux-dominated outflow, the dissipation of which would power a bright early X-ray afterglow for essentially every GWB of NS-NS merger with a magnetar central engine. Gao et al.$^8$ proposed that after the dissipation, within the framework of an energy injection scenario$^{10}$, a significant fraction of the wind energy would be used to push the ejecta launched during the merger, which would accelerate the ejecta to mildly or even highly relativistic speed, making a strong external shock upon interaction with the ambient medium. Electrons are accelerated in the shocked region, giving rise to broad band afterglow through synchrotron emission$^8$.

Protons are also expected to be accelerated in these shocks, serving as efficient high-energy cosmic ray accelerators. On the other hand, as propagating to us, photons emitted via magnetic dissipation at a smaller radius from the engine$^7$ would first pass through the external shock front, and have a good chance to interact with the accelerated protons. Strong photo-pion interactions happen at the $\Delta$-resonance, making the proton energy $E_p$ and photon energy $E_\gamma$ satisfy the threshold condition

$$E_pE_\gamma \geq \frac{m_\Delta^2 - m_p^2}{2} \Gamma^2 = 0.147 \text{ GeV}^2 \Gamma^2,$$  

(1)

where $\Gamma$ is the bulk Lorentz factor, $m_\Delta = 1.232$ GeV and $m_p = 0.938$ GeV are the rest masses of $\Delta^+$ and proton, respectively. The $\Delta^+$ particle decays into two channels. The charged pion channel gives $\Delta^+ \rightarrow n\pi^+ \rightarrow ne^+\nu_e\bar{\nu}_\mu$, with a typical neutrino energy $E_\nu \simeq 0.05E_p$. The neutron pion channel gives the $\Delta^+ \rightarrow p\pi^0 \rightarrow p\gamma\gamma$ interaction. Note that the broad-band photons produced in the shocked region could also serve as the seed photons for $p\gamma$ interaction. However, since their peak flux in the X-ray band$^8$ is much lower than that of the internal dissipation photons$^7$, we do not consider their contribution.

With the multi-messenger era of astronomy ushered in, studying multi-messenger signals in astrophysical sources...
is of the great interest (e.g. [11]). The high-energy neutrino detectors such as IceCube have reached the sensitivity to detect high energy neutrinos from astrophysical objects for the first time. Gamma-ray bursts (GRBs) have been proposed to be one of the top candidates of PeV neutrinos [12]. However, a dedicated search of high energy neutrinos coincident with GRBs has so far led to null results [13,14], which already places a meaningful constraint on GRB models [14,15]. Very recently, the IceCube collaboration announced their detections of two neutrino events with an energy approximately 1-2 PeV [17,18], which could potentially represent the first detections of high-energy neutrinos from astrophysical sources. Among the proposed sources of such cosmic rays, GRBs stand out as particularly capable of generating PeV neutrinos at this level [13,18]. However, the absence of associated GRBs for these two events calls for alternative cosmological PeV neutrino sources. Here we investigate the possible neutrino signals associated with NS-NS mergers with a millisecond magnetar central engine using the photomeson interaction mechanism delineated above.

II. General picture. First of all, we adopt the ansatz that NS-NS merger events leave behind a massive millisecond magnetar and an essentially isotropic ejecta shell. In this case, a good fraction (η) of the total energy and the spindown luminosity of the new-born neutron star is able to cool down quickly so that NS-NS merger events leave behind a massive millisecond magnetar. Throughout the paper, the convention L = Lsd,t with Lsd dominates outflow and the spindown time scale critically depend on the dipole magnetic field strength Bp, i.e., Lsd = Lsd,0/(1 + t/Tsd)3, where Lsd,0 ∼ 1049 erg s−1 Bp,15 P0,−3 m−1 cm for the ejecta. Here we take the spindown luminosity Lsd,0 as the total luminosity of the Poynting-flux-dominated outflow and the spindown time scale Tsd as its duration. For simplicity, we neglect the possible gravitational wave spin down of the new-born magnetar [22]. Note that both dipole magnetic field strength and spindown timescale could have a relatively large parameter space, which would add uncertainties to the following results.

Initially, the heavy ejecta launched during the merger is not far away from the magnetar, so that in a large solid angle range, the magnetar wind would hit the ejecta before self-dissipation of the magnetar wind happens. In this case, a good fraction (η) of the magnetic energy may be rapidly discharged upon interaction between the wind and the ejecta. The Thompson optical depth for a photon to pass through the ejecta shell is τth ∼ σT Mej/(4πR2σp). By setting the optical depth equals to unity, we define a photosphere radius Rp = 2.5 × 1014M ej−3 cm for the ejecta. When R < Rp, the spectrum of the dissipated wind is likely quasi-thermal due to the large optical depth of photon scattering. The typical photon energy can be estimated as Eπ,th ∼ k(Tsd,0/104πR2σSB)3/4/τth ∼ 27 eV Lsd,0,47η−1/3 R−1/3, where σSB is the Stefan-Boltzmann constant. Alternatively, when R > Rp, the typical synchrotron energy could be estimated as Eγ,t ∼ 1.8 × 104 keV Lsd,0,47η−1/3 R−1/3, where σ is the magnetization parameter of the Poynting flux when the magnetar wind catches the ejecta [23]. In order to estimate the value of σ, we assume that the proto-magnetar has σ0 ∼ 107 at the central engine and the magnetized flow is quickly accelerated to Γ ∼ σ0 ∼ 10 at R0 ∼ 107 cm, where σ ∼ σ0/3 [21]. After this phase, the flow may still accelerate as Γ ∝ R−1/3. Consequently, we have Eγ,t ∼ 1.8 keV Lsd,0,47η−1/3 R−1/3 σ2/3 R15−5/3.

As it is pushed forward by the magnetar wind, at a late time the ejecta is far away enough from the central engine, so that before hitting the ejecta, the magnetar wind already starts to undergo strong self-dissipation, rather than the blastwave radius [7,23], i.e. Eγ,t ∼ 8 keV Lsd,0,47η−1/3 R−1/3 σ2/3 R15−5/3. Notice that for a substantial range of Mej, we have Rp < R. Overall, the seed photon energy for pγ interaction can be summarized as

\[
E_{\gamma,t} = \begin{cases} 
27 \text{ eV} & L_{sd,0,47}^{1/3} \eta^{-1/3} R_0^{-1/3} M_{ej}^{-3/2} \text{, } R < R_{ph}; \\
1.8 \text{ keV} & L_{sd,0,47}^{3/4} \eta^{-1/3} R_0^{2/3} M_{ej}^{-3/2} R_{ph}^{2/3} R_{15}^{-5/3} \text{, } R_{ph} < R < R_{ph}; \end{cases}
\]

\[
1.8 \text{ keV} L_{sd,0,47}^{3/4} \eta^{-1/3} R_0^{2/3} M_{ej}^{-3/2} R_{ph}^{2/3} R_{15}^{-5/3} \text{, } R > R_{ph};
\]

In the mean time, the magnetar-wind-powered ejecta would interact with the ambient medium, forming a blastwave similar to GRB afterglow. Depending on the unknown parameters such as Mej, Bp, and hence Lsd,0 [5], the blastwave could be accelerated to a mildly or even highly relativistic speed, due to the continuous energy injection from the magnetar wind. Protons are accelerated from the forward shock front along with electrons via the first-order Fermi acceleration process. Consequently, when the seed photons due to magnetar wind dissipation (Eq2) pass through the shocked region, significant neutrino production due to pγ interaction through Δ-resonance would happen, as long as the condition R ≫ \frac{\Gamma_{max} m_{p} c^{2}}{E_{p,t}} > 1 is satisfied. Here, E_{p,t} = 0.147 \text{ GeV}^{2}T^{2}/E_{\gamma,t} is the corresponding proton
energy for the typical seed photon at Δ-resonance, and
\(\gamma_M\) is the maximum proton Lorentz factor. It can be esti-
mated by balancing the acceleration time scale and the
dynamical time scale, which gives \(\gamma_M \sim \frac{\Gamma \omega B}{c m_p c}\), where \(\zeta\)
is a parameter of order unity that describes the details of
acceleration and \(B^2\) is the comoving magnetic field
strength. Once \(\gamma\) interaction happens, significant neu-
tronos with energy \(E_\nu \sim 0.05 \text{E}_{p, t}\) would be released, the
neutrino emission fluence may be estimated as
\[
\nu_f = \frac{E_{\text{tot}} \times f_{\gamma p} \times f_\nu}{4 \pi d^2},
\]
where \(E_{\text{tot}} \sim 4 \pi R^3 m_G (\Gamma - 1) m_p c^2 / 3\) is the total energy
of all the protons, \(f_{\gamma p} \equiv \frac{E_{\gamma p}}{E_{\text{tot}}}\) is the energy fraction
of the relevant protons, and \(f_\nu\) is the fraction of the pro-
ton energy that goes to pion production. Assuming a
power-law distribution of the shock accelerated protons:
\(N(E_\nu) dE_\nu \propto E_\nu^{-p} dE_\nu\) (hereafter assuming \(p > 2\)),
one can obtain
\[
f_{\gamma p} = \left( \frac{2 \pi}{\gamma_\nu} \right)^{2-p} \frac{\gamma_\nu}{(\Gamma - 1) \frac{m_p c^2}{E_\nu} + 1}
\]
is the minimum proton Lorentz factor. The fraction of
the proton energy that goes to pion production could be
estimated as \(f_\nu \approx \frac{\Gamma}{(1 - (1 - \sqrt{\chi_{\gamma p}}))^{2-p}}\), where \(\chi_{\gamma p}\) is
the \(\gamma\) optical depth and \(\chi_{\gamma p} \gg 0.2\) is the average
fraction of energy transferred to pion. Notice that
\(f_\nu\) roughly proportional to \(\gamma_\nu\), when \(\gamma_\nu < 3 \times 10^4\).

III. Neutrino energy and fluence. The dynamics of the
blastwave is defined by energy conservation [8]
\[
L_0 = (\gamma - 1) M_{\text{ej}} c^2 + (\gamma^2 - 1) M_{\text{sw}} c^2,
\]
where \(L_0 = \xi L_{\text{sd}, 0}\) is the magnetar injection luminosity
into the blastwave, and \(M_{\text{sw}} = (4 \pi / 3) R^3 m_p\) is the swept-up mass from the
interstellar medium. Initially, one has \((\gamma - 1) M_{\text{ej}} c^2 \gg (\gamma^2 - 1) M_{\text{sw}} c^2\),
so the kinetic energy of the ejecta would increase linearly with
time until \(R = \min(R_{\text{sd}}, R_{\text{dec}})\), where the deceleration
radius \(R_{\text{dec}}\) is defined by the condition \((\gamma - 1) M_{\text{ej}} c^2 = (\gamma^2 - 1) M_{\text{sw}} c^2\).
By setting \(R_{\text{dec}} \sim R_{\text{sd}}\), we can derive a critical ejecta mass
\[
M_{\text{ej}, c, i} \sim 10^{-3} M_{\odot} \eta_{i}^{1/2} \frac{\Gamma^4}{45} B_p^{1/4} P_{10}^{-3/4} \frac{R_6}{0.13} \xi^{7/8},
\]
which separate regimes with different blastwave dynam-
ics [8]:
Case I: \(M_{\text{ej}} < M_{\text{ej}, c, i} \) or \(R_{\text{sd}} > R_{\text{dec}}\). In such case,
the ejecta can be accelerated linearly until the decelera-
tion radius \(R_{\text{dec}} \sim 3.9 \times 10^{17} M_{\odot}^{2/3} \xi^{-1/3} \eta_{i}^{1/3} R_6^{1/3}\),
where bulk Lorentz factor of the blastwave is \(\Gamma_{\text{dec}} \sim 12.2 L_{\text{sd}, 0}^{3/10} M_{\text{ej}, -4}^{1/3} \eta_{i}^{1/10}\).
After that, the blastwave de-
celerates, but still with continuous energy injection un-
til \(R_{\text{sd}} \sim 1 \times 10^{18} \xi^{1/3} \eta_{i}^{1/3} R_6^{1/4}\), where \(\Gamma_{\text{sd}} \sim 7.5 \xi^{-1/3} L_{\text{sd}, 0}^{3/5} \eta_{i}^{1/5}\).
During the acceleration phase, the blastwave passes the non-relativistic to relativis-
tic transition line \(\Gamma = 1\) at radius \(R_N \sim 2.2 \times 10^{14} M_{\text{ej}, -4} L_{\text{sd}, 0}^{-1}\).
For the different radius range of the typical photon
energy shown in Eq. [2] we can investigate whether
\(\gamma\) interaction at Δ-resonance can occur, and if so,
the typical energy and fluence of neutrino emission.
We first assume that the blastwave is always non-
relativistic when \(R < R_{\text{ph}}\), since \(R_{\text{ph}}\) is comparable
with \(R_{\text{ph}}\) with a high probability. In this range, we have
\(\Re = 0.1 \eta_{i}^{1/4} L_{\text{sd}, 0.47}^{3/5} M_{\text{ej}, -4}^{1/3} R_{11/6}^{1/2} < 1\), implying
that \(\gamma\) interaction at Δ-resonance could hardly
happen. Second, at \(R_{\text{ph}} < R < R_{\text{dec}}\) we have \(\Re =
26.0 \eta_{i}^{3/2} L_{\text{sd}, 0.47}^{-1/6} M_{\text{ej}, -3}^{1/2} \sigma_{0.7} R_{7/3}^{1/3} R_{15}^{4/3} > 1\), so that
\(\gamma\) interaction would happen at Δ-resonance. The
typical neutrino energy and fluence could be estimated as
\(E_{\nu} = 1.1 \times 10^{-2} \text{ PeV } \eta_{i}^{1/4} L_{\text{sd}, 0.47}^{-3/5} M_{\text{ej}, -4}^{1/3} R_{7/3}^{-3/5} \Gamma_{\text{ph}}^{-1/2}\), and
\(f_{\nu} = 1.6 \times 10^{-12} \eta_{i}^{1/4} L_{\text{sd}, 0.47}^{3/5} R_{0.7}^{-1/2} R_{15}^{1/2}\). Next,
similar to the previous stage, at \(R < R < R_{\text{dec}}\), we have
\(\Re = 120.7 \eta_{i}^{3/2} L_{\text{sd}, 0.47}^{-1/6} M_{\text{ej}, -3}^{1/2} \sigma_{0.7} R_{7/3}^{1/3} R_{15}^{4/3} > 1\), and
the typical neutrino energy and fluence are \(E_{\nu} =
0.21 \text{ PeV } \eta_{i}^{1/4} L_{\text{sd}, 0.47}^{-3/5} M_{\text{ej}, -4}^{1/3} R_{7/3}^{-3/5} R_{15}^{4/3} > 1\),
and the typical neutrino energy and fluence are \(E_{\nu} =
0.24 \text{ PeV } \eta_{i}^{1/4} L_{\text{sd}, 0.47}^{-3/5} M_{\text{ej}, -4}^{1/3} R_{7/3}^{-3/5} R_{15}^{4/3} > 1\), and
\(f_{\nu} = 1.6 \times 10^{-12} \eta_{i}^{1/4} L_{\text{sd}, 0.47}^{3/5} R_{0.7}^{-1/2} R_{15}^{1/2}\times\)
respectively. Finally, when approaching the spin-
down radius, i.e., \(R_{\text{dec}} < R < R_{\text{sd}}\), one has
\(\Re = 12.0 \eta_{i}^{1/4} L_{\text{sd}, 0.47}^{3/5} M_{\text{ej}, -4}^{1/3} R_{7/3}^{-3/5} R_{15}^{4/3} > 1\), and
the typical neutrino energy and fluence are \(E_{\nu} =
0.24 \text{ PeV } \eta_{i}^{1/4} L_{\text{sd}, 0.47}^{-3/5} M_{\text{ej}, -4}^{1/3} R_{7/3}^{-3/5} R_{15}^{4/3} > 1\),
and the typical neutrino energy and fluence are \(E_{\nu} =
0.24 \text{ PeV } \eta_{i}^{1/4} L_{\text{sd}, 0.47}^{-3/5} M_{\text{ej}, -4}^{1/3} R_{7/3}^{-3/5} R_{15}^{4/3} > 1\), and
\(f_{\nu} = 1.6 \times 10^{-12} \eta_{i}^{1/4} L_{\text{sd}, 0.47}^{3/5} R_{0.7}^{-1/2} R_{15}^{1/2}\times\)
respectively. For better illustration, we take \(L_{\text{sd}, 0} = 10^{47}\)
and \(M_{\text{ej}} = 10^{-4} M_{\odot}\) as an example and plot the evolution of \(E_{\nu}\)
and \(f_{\nu}\) for this dynamical case in Figure 1.
fluence $\epsilon$ and fluence $f_\nu$, for different dynamics: Case I (dash-dot), Case II (solid) and Case III (dashed). Blue lines represent green lines show $f_\nu$ for each case, see text. For the magnetar parameters $R_{sd} = 300$ Mpc, the optimistically typical neutrino fluence could be as large as $10^{-6} - 10^{-5}$ GeV cm$^{-2}$ (corresponding to $\sigma_0 = 10^7$, $10^6$ respectively), one or two orders of magnitude lower than the typical fluence of GRBs\cite{15}. Given the typical neutrino energy $\sim$PeV and the IceCube effective area $\sim$ several 10$^4$ cm$^2$ \cite{20, 27}, optimistically only several $10^{-6} - 10^{-5}$ neutrinos are expected to be detected by IceCube for a single event.

In any case, these events would contribute to the $\sim$PeV neutrino background. The NS-NS merger event rate is rather uncertain, i.e., $(10 - 5 \times 10^4)$ Gpc$^{-3}$ yr$^{-1}$ \cite{28}. Considering that only a fraction of NS-NS merger event would leave behind a massive neutron star rather than a black hole, and that only a sub-fraction of these mergers have the right $M_{ej}$ and $L_{sd,0}$ to make relativistic blast-waves, the event rate of NS-NS mergers that generate PeV neutrinos may be at least one order of magnitude lower, i.e., $\sim (1 - 5 \times 10^3)$ Gpc$^{-3}$ yr$^{-1}$. Even with the most optimistic estimate, the $\sim$PeV diffuse background is $\sim 10^{-10}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. It takes tens of years to get two events. So these systems are not likely the origin of the two reported PeV events announced by the Icecube collaboration \cite{17}. Nevertheless, compared with the GRB event rate 1 Gpc$^{-3}$ yr$^{-1}$ \cite{31}, this scenario may gain the event rate by 1-2 orders of magnitude than GRBs. Noticing that a typical GRB has a fluence 1-2 orders of magnitude higher than a magnetar-wind-powered NS-NS merger remnant, our scenario could contribute to the $\sim$PeV neutrino diffuse background, which is comparable or slightly lower than that of GRBs.

V. High energy photon emission. Besides high-energy neutrino emission, the decay of $\pi^0$ produced in $\gamma\gamma$ interactions would lead to the production of high energy gamma-ray photons. Assuming that half of the $\Delta^+$ decays go to the $\pi^+$ channel (neutrino production), while the other half go to the $\pi^0$ channel ($\gamma$-ray production), the typical gamma-ray photon energy and fluence values would be comparable to the neutrinos we studied in section III. However, such high-energy photons may interact with the synchrotron emission photons in the shock to produce electron/positron pairs, $\gamma\gamma \to e^+e^-$, and initiate an electromagnetic cascade: the pairs would emit photons via synchrotron and inverse Compton, which would be converted back to pairs, and the pairs would emit photons again, etc. Photons can escape only when the optical depth becomes lower than unity \cite{29}. Following the calculation shown in Ref.\cite{30}, we find that the optical depth exceeds unity for photon energy above $\epsilon_{\gamma\gamma} \sim 100$ GeV. For simplicity, we assume that the total energy of the $\pi^0$-decay photons would finally show up around 100 GeV through an EM cascade. These photons are within the energy windows of the Fermi/LAT. In the most optimistic situation, the photon flux for an event at 300 Mpc could be as high as $10^{-11}$ erg cm$^{-2}$ s$^{-1}$, which is essentially $10^{-10}$ photons cm$^{-2}$ s$^{-1}$. The effective area of LAT for 100 GeV photons is around 9000 cm$^2$ \cite{31}, suggesting that even for $T_{sd} \sim 10^5$, one single NS-NS merger event could not trigger LAT. Nevertheless, the total diffuse flux from these events could reach several $10^{-7}$ MeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ optimistically, giving a moder-
ate contribution to the sub-TeV $\gamma$-ray background, i.e., $4 \times 10^{-4}$ MeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$, according to Fermi/LAT observation\cite{32}.

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[1] B. P. Abbott et al., Rep. Prog. Phys. 72, 076901 (2009); F. Acernese et al., Class. Quant. Grav. 25, 114045 (2008); Kuroda, K., & LCGT Collaboration, Class. Quant. Grav. 27, 084004 (2010).

[2] Taylor J. H. Weisberg J. M., Astrophys. J. 253, 908 (1982); Kramer M. et al., Science 314, 97 (2006).

[3] Li L.-X. Paczyński B., Astrophys. J. 507, L59 (1998); B. Metzger et al., Mon. Not. R. Astron. Soc. 406, 2650 (2010); Nakar E. Piran T., Nature 478, 82 (2011); Nissanke, S. et al., Astrophys. J. 767, 124 (2013).

[4] T. Piran et al., arXiv e-prints [arXiv:1204.6342]; K. Hotakezaka et al., Phys. Rev. D 87, 024001 (2013); L. Rezzolla et al. Astrophys. J., 732, L6 (2011).

[5] Z.-G. Dai et al., Science 311, 1127 (2006); W. H. Gao, and Y. Z. Fan, ChJAA, 6, 513 (2006)

[6] J. M. Lattimer, Annu. Rev. Nucl. Part. Sci. 62, 485, 2012.

[7] B. Zhang, Astrophys. J. Lett. 763, L22 (2013).

[8] H. Gao et al., Astrophys. J. 771, 86 (2013)

[9] B. Giacomazzo & R. Perna, Astrophys. J. Lett 771, L26 (2013)

[10] Z. G. Dai & T. Lu, Phys. Rev. Lett. 81, 4301 (1998).

[11] I. Bartos et al., Phys. Rev. Lett. 107, 251101 (2011)

[12] E. Waxman, J. Bahcall, Phys. Rev. Lett. 78, 2292 (1997);

[13] R. Abbasi et al., Astrophys. J. 710, 346 (2010); R. Abbasi et al., Phys. Rev. Lett. 106, 141101 (2011); M. Ahlers, M. C. Gonzalez-Garcia, F. Halzen., Astroparticle Phys. 35, 87 (2011)

[14] R. Abbasi et al., Nature 484, 351 (2012)

[15] H.-N. He et al., Astrophys. J. 752, 29 (2012)

[16] B. Zhang, P. Kumar, Phys. Rev. Lett. 110, 121101 (2013)

[17] IceCube Collaboration et al. 2013, arXiv eprint [arXiv:1304.3356]

[18] I. Cholis, D. Hooper, arXiv eprint [arXiv:1211.1974]

[19] R. Y. Liu, X. Y. Wang, Astrophys. J. 766, 73 (2013)

[20] B. D. Metzger et al., Mon. Not. R. Astron. Soc. 413, 2031 (2011).

[21] V. V. Usov, Nature 357, 472 (1992)

[22] B. Zhang, P. Mészáros, Astrophys. J. 552, L35 (2001); A. Corsi, P. Mészáros, Astrophys. J. 702, 1171 (2009); Y.-Z. Fan, X.-F. Wu, D.-M. Wei, [arXiv:1302.3328]

[23] B. Zhang, H. Yan., Astrophys. J. 726, 90 (2011)

[24] S. S. Komissarov et al., Mon. Not. R. Astron. Soc. 394, 1182 (2009).

[25] Drenkhahn G. Spruit H. C., Astron. Astrophys. 391, 1141 (2002).

[26] E. W. Liang et al., Astrophys. J. 662, 1111 (2007); D. Wanderman, T. Piran, Mon. Not. R. Astron. Soc. 406, 1944 (2010).

[27] Z. Li arXiv eprint [arXiv:1210.6504]

[28] S. S. Komissarov et al., Mon. Not. R. Astron. Soc. 394, 1182 (2009).

[29] K. Murase J. F. Beacom, J. Cosmol. Astropart. Phys. 43 (2012); K. Murase J. F. Beacom H. Takami, J. Cosmol. Astropart. Phys. 8, 30 (2012)

[30] E. W. Liang et al., Astrophys. J. 662, 1111 (2007); D. Wanderman, T. Piran, Mon. Not. R. Astron. Soc. 406, 1944 (2010).

[31] W. B. Atwood et al., Astrophys. J. 697, 1071 (2009)

[32] A. A. Abdo, Phys. Rev. Lett. 104, 101101 (2010)