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New Class of High-Energy Transients from Crashes of Supernova Ejecta with Massive Circumstellar Material Shells

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A new class of core-collapse supernovae (SNe) has been discovered in recent years by optical/infrared surveys; these SNe suggest the presence of one or more extremely dense ($\sim 10^{5-11} \text{ cm}^{-3}$) shells of circumstellar material (CSM) on 10^{2-4} AU scales. We consider the collisions of the SN ejecta with these massive CSM shells as potential cosmic-ray (CR) accelerators. If $\sim 10\%$ of the SN energy goes into CRs, multi-TeV neutrinos and/or GeV-TeV gamma rays almost simultaneously with the optical/infrared light curves are detectable for SNe at $\lesssim 20-30$ Mpc. A new type of coordinated multi-messenger search for such transients of duration $\sim 1-10$ months is required; these may give important clues to the physical origin of such SNe and to CR acceleration mechanisms.

I. INTRODUCTION

The much-anticipated era of multi-messenger astronomy is coming. GeV-TeV gamma rays, which are powerful tracers of cosmic rays (CRs), are detected by *Fermi* and ground-based Cherenkov detectors. Neutrinos, which can uniquely identify the production of hadronic CRs and probe dense sources, are detectable by the nearly-completed IceCube and the planned KM3Net [1]. They are useful for studying sources especially when photons cannot escape directly.

Violent explosions of massive stars, such as supernovae (SNe) and gamma-ray bursts (GRBs) may be prodigious neutrino/gamma-ray sources [2]. High-energy observations should reveal their physical origin, nonthermal processes, and extreme environments. TeV-PeV neutrino detections from extragalactic sources may be possible for GRBs [3, 4] and certain other kinds of SNe, e.g., those with hidden relativistic jets [5], relativistic pulsar winds [6], or semi-relativistic external shocks [7]. But are SNe with more ordinary explosions also detectable?

In recent years, blind surveys for optical transients have discovered ultra-bright SNe such as SN 2008am [8], 2008iy [9], 2006gy [10], 2005ap [11] and 2003ma [12], which are much more luminous than ordinary SNe. Their physical origin is not settled, but a plausible interpretation is strong shock dissipation by collision with a massive ($M_{\text{sh}} \sim 1-30 M_{\odot}$) circumstellar material (CSM) shell at $R \sim 10^{2-3}$ AU [14, 15], which is more or less analogous to the mechanism of type IIIn SNe, though some may be pair-instability SNe [16]. The local rate of these ultra-bright SNe may be $\sim 10^{3-4}$ times larger than the local apparent rate of classical long GRBs [13]. But SNe with CSM do not have to be optically ultra-bright, and the existence of massive CSM shells may be even more common. The existence of dense CSM shells is indicated from other SNe, e.g., SN 2006jc, 2005ip and PTF 09UJ [17, 18]. Also, massive CSM eruptions were observed in luminous blue variables such as η Carinae [19], and are supported by the discovery of a self-obscured SN [20].

These observations motivate us to investigate the sys-

tem of SN ejecta crashing into massive CSM shells at various radii. We consider the possibility of CR acceleration at strong shocks formed by the crashes, and suggest a new class of high-energy transients that are neither bursts like GRBs nor persistent sources like SN remnants. Given their rate and timescales, new types of searches at intermediate time scales, with coordinated observations of these extragalactic SNe at $\lesssim 100$ Mpc, are required. We adopt the conventional notation $Q_x = Q/10^x$.

II. THE SCENARIO

As the SN ejecta crashes into an external medium with density n_{ext} , a pair of shocks (forward and reverse) are typically formed. As deceleration starts, significant fractions of the ejecta kinetic energy ($\mathcal{E}_{\text{ej}} \sim 10^{51}$ erg) are converted to the internal and kinetic energy of the shocked shells. The forward shock (FS) velocity in the deceleration phase is estimated to be $V_f \simeq 4000 \text{ km s}^{-1} \mathcal{E}_{\text{ej},51}^{1/2} n_{\text{ext},11}^{-1/2} R_{15.5}^{-3/2}$ in the non-radiative limit, and the reverse shock (RS) velocity can be estimated from $\rho_{\text{ej}} V_r^2 \approx \rho_{\text{ext}} V_f^2$, where ρ is the mass density and V_s is the shock velocity (where the index “s” indicates a forward or a reverse shock). In the case of ordinary SN shocks sweeping up the interstellar medium, deceleration becomes significant around the Sedov radius, $R_d \approx R_{\text{Sed}} = \left(\frac{3M_{\text{ej}}}{4\pi\rho_{\text{ext}}}\right)^{1/3} \simeq 4.4 \times 10^5 \text{ AU} (M_{\text{ej}}/M_{\odot})^{1/3} n_{\text{ext}}^{-1/3}$. If massive ($M_{\text{sh}} \gtrsim M_{\text{ej}}$) CSM shells are located at $R_{\text{sh}} \sim 10^{2-4}$ AU, with CSM shell densities of $n_{\text{sh}} \sim 10^{5-11} \text{ cm}^{-3}$, significant deceleration and shock dissipation are instead expected at $R_d \sim R_{\text{sh}}$, which is thought to be the case for the bright SNe we consider here [9, 14, 15]. Then, the shock velocities are evaluated via the Rankine-Hugoniot relations, and the FS will show a decelerating behavior self-similarly. Such violent eruption of massive CSM shells may be challenging for theories of the progenitor star, but one of the plausible mechanisms is the pulsational pair instability, which might occur at the deaths of main-sequence stars in the

mass range $\sim 95 - 130 M_\odot$ [15]. Ejection of smaller mass would be more common, and for smaller CSM mass, the SN shock dynamics is not as affected and the dissipated energy would be scaled down as $\propto M_{\text{sh}}/(M_{\text{ej}} + M_{\text{sh}})$.

In many astrophysical shocks, sizable fractions of the kinetic energy seem to go into magnetic and CR energies. SN remnants are believed to be CR accelerators, and gamma rays from Galactic remnants are indeed detected by *Fermi* and air-Cherenkov detectors (e.g., [21]). It is expected that plasma and/or MHD instabilities can amplify not only the downstream field but also the upstream field up to $\varepsilon_B \equiv 2U_B/\rho V_s^2 \sim 10^{-3} - 10^{-2}$ (e.g., [22]), where U_B is the magnetic energy density. If Galactic CRs come from SN remnants, CRs should carry $\epsilon_{\text{cr}} \sim 0.1$ of the explosion energy, which seems consistent with observations, $2U_{\text{cr}}/\rho V_s^2 \sim 0.1 - 1$ [21, 23]. In addition, CR acceleration in more dense environments ($n \sim 10^{8-9} \text{ cm}^{-3}$) is suggested by detections of gamma rays from V407 Cyg [24] and possibly η Carinae [25], which may imply that $\sim 1 - 10\%$ of the kinetic energy still goes to CRs.

Analogously, we may expect such magnetic field amplification and particle acceleration for the SN-CSM system. Unless the Thomson depth is $\tau_T \gg 1 - 10$, one may expect collisionless shocks, as in SN shock breakout [26]. The ion temperature behind the shock would become

$$T_i^s \sim 9.8 \times 10^4 \text{ eV } V_{s,4}^2, \quad (1)$$

where the ion-ion collision frequency is $\nu_{ii} \sim 4 \times 10^{-4} \text{ s}^{-1} n_{10} T_{i,5}^{-3/2}$. Electrons would be heated by ions while cooled by the Compton process and bremsstrahlung emission. When only the Coulomb collision is considered, the equilibrium electron temperature is estimated to be

$$T_e \sim 10^4 \text{ eV } T_{i,5}^{2/5} T_{\gamma,0.5}^{-8/5} n_{10}^{2/5} \quad (2)$$

over the length of $\sim \nu_{ie}^{-1} V_s$, where $\nu_{ii} \gtrsim \nu_{ie} \sim 3 \times 10^{-4} \text{ s}^{-1} n_{10} T_{e,4}^{-3/2}$. Here, the photon temperature is $T_\gamma^s = (U_\gamma/a)^{1/4} \sim 4.2 \text{ eV } n_{10}^{1/4} V_{s,4}^{1/2}$ in the radiation-dominated case. On the other hand, one may expect that electromagnetic instabilities, e.g., $\nu_{\text{EM}} \sim 4 \times 10^4 \text{ s}^{-1} n_{10}^{1/2} V_{s,4}$, are faster than all relevant collision frequencies [26], such as ν_{ii} and ν_{ie} , so collisionless shocks would be formed.

However, the shocks can be radiation-mediated when R_{sh} is sufficiently small (n is sufficiently large) and $\tau_T \gg c/V_s$ [27]. For example, in the SN 2006gy-like case, we have

$$\tau_T^{\text{sh}} = n_{\text{sh}} \sigma_T \Delta R_{\text{sh}} \simeq 210 n_{\text{sh},11} \Delta R_{\text{sh},15.5}, \quad (3)$$

where the radiative deceleration length for the FS, $L_{\text{dec}}^f \sim \frac{c}{n_{\text{sh}} \sigma_T V_f} \simeq 1.4 \times 10^{15} \text{ cm } n_{\text{sh},11}^{-1} V_{f,3.5}^{-1}$, is smaller than the width, ΔR_{sh} . In this situation, the flow is decelerated by radiation in the upstream region rather than collisions or plasma instabilities, and CRs would not carry a significant energy fraction, though the details are uncertain.

Hence, we here consider CRs only when the shocks are not radiation-mediated.

The CSM parameters (n_{sh} , R_{sh} and ΔR_{sh}) are likely to have a variety of values, including cases with $\tau_T \lesssim 1 - 10$, so that one may expect the situation where CRs are accelerated at shocks formed by the collision between the SN ejecta and the CSM shell. For demonstrative purposes, we suppose CSM shells of $M_{\text{sh}} \sim 1 - 30 M_\odot$ at $R_{\text{sh}} \sim 10^{15-17} \text{ cm}$, which are motivated by the SN-CSM collision model for explaining ultra-bright SNe [14, 15], and use two representative cases: Model A ($n_{\text{sh}} = 10^{11} \text{ cm}^{-3}$, $R_{\text{sh}} = \Delta R_{\text{sh}} = 10^{15.5} \text{ cm}$) and Model B ($n_{\text{sh}} = 10^{7.5} \text{ cm}^{-3}$, $R_{\text{sh}} = \Delta R_{\text{sh}} = 10^{16.5} \text{ cm}$). As for the SN ejecta, for simplicity, we assume fast moving, uniform ejecta with $\mathcal{E}_{\text{ej}} = 10^{51} \text{ erg}$ and $V_{\text{ej}} \sim 10^4 \text{ km s}^{-1}$ (where one may expect that the ejecta is several solar masses, which is lower than the CSM mass [15]). The corresponding shock velocities (in the deceleration phase) are $V_f \simeq 10^{3.5} \text{ km s}^{-1}$ and $V_r \simeq 10^4 \text{ km s}^{-1}$ in Model A, and $V_f \simeq 10^{3.7} \text{ km s}^{-1}$ and $V_r \simeq 10^{3.9} \text{ km s}^{-1}$ in Model B. These FS velocities are also consistent with observed ones (e.g., [10]). Model A is close to the case considered for explaining SN 2006gy [14, 15], whose radiation energy and peak luminosity was $\mathcal{E}_{\text{ph}} \sim 10^{51} \text{ erg}$ and $L_{\text{ph}} \sim 10^{44} \text{ erg s}^{-1}$ respectively. In our setup, we may assume shock acceleration of CRs, except for the FS, since $L_{\text{dec}}^f < \Delta R_{\text{sh}}$ there. In Model B, a larger collision radius is assumed, which may be more similar to the case of dimmer but longer-lasting ultra-bright SNe such as SN 2008iy [9], which had $\mathcal{E}_{\text{ph}} \sim 10^{50} \text{ erg}$ and $L_{\text{ph}} \sim 10^{42.5} \text{ erg s}^{-1}$, and we may consider CR acceleration at both the shocks. Note that, although we consider the uniform CSM shell with $\Delta R_{\text{sh}} = R_{\text{sh}}$, our results are not much changed if the CSM shell (with $\Delta R_{\text{sh}} = R_{\text{sh}}$) has a wind-like density distribution.

III. PRODUCTION OF NEUTRINOS AND GAMMA RAYS

CR acceleration.— When collisionless shocks are indeed formed, they would accelerate charged particles to high energies via the Fermi acceleration mechanism, producing a power-law distribution, $dN_p/dE_p \propto E_p^{-q}$ where $q \sim 2$ [28]. The acceleration time scale is written as $t_{\text{acc}}^s = \eta \frac{E_p}{e B_c}$, where $\eta \sim \frac{20}{3} \frac{c^2}{V_s^2}$ in the Bohm limit. We assume that the magnetic field grows to a fraction of the equipartition value, $B_f \simeq 26 \text{ G } \varepsilon_{Bf,-2.5}^{1/2} n_{\text{sh},11}^{1/2} V_{f,3.5}$ ($B_r \simeq 24 \text{ G } \varepsilon_{Br,-2.5}^{1/2} (M_{\text{ej}}/M_\odot)^{1/2} R_{15.5}^{-3/2} V_{r,4}$), from analogy with SN remnants. Then we have

$$\begin{aligned} t_{\text{acc}}^f &\sim 2.6 \times 10^4 \text{ s } E_{p,100} \text{ TeV } \varepsilon_{Bf,-2.5}^{-1/2} n_{\text{sh},11}^{-1/2} V_{f,3.5}^{-3} \\ t_{\text{acc}}^r &\sim 2.7 \times 10^3 \text{ s } E_{p,100} \text{ TeV } \varepsilon_{Br,-2.5}^{-1/2} (M_{\text{ej}}/M_\odot)^{-1/2} R_{15.5}^{3/2} V_{r,4}^{-3}, \end{aligned} \quad (4)$$

which are larger than collision time scales at the thermal energy.

The maximum CR energy, $E_{p,s}^{\text{max}}$, is determined by

comparison between the acceleration time and the cooling and dynamical time scales as well as the confinement condition. High-energy CRs lose their energies via adiabatic losses, and pp and $p\gamma$ inelastic scatterings. The CSM density is so large that the pp reaction is efficient. When the pp cooling time, $t_{pp} = \frac{1}{n\kappa_{pp}\sigma_{pp}c}$, limits $E_{p,s}^{\max}$, we have

$$\begin{aligned} E_{p,f}^{\max} &\simeq 81 \text{ TeV } \varepsilon_{Bf,-2.5}^{1/2} n_{\text{sh},11}^{-1/2} V_{f,3.5}^3 \\ E_{p,r}^{\max} &\simeq 8.6 \times 10^3 \text{ TeV } \varepsilon_{Br,-2.5}^{1/2} (M_{\odot}/M_{\text{ej}})^{1/2} R_{15.5}^{3/2} V_{r,4}^3. \end{aligned} \quad (5)$$

Here $\sigma_{pp} \simeq 10^{-25.5} \text{ cm}^2$ is the pp cross section and $\kappa_{pp} \simeq 0.5$ is the pp inelasticity. At large R , the adiabatic cooling time t_{ad} , comparable to the dynamical time $t_s \approx R/V_s$, may become more important. When they limit $E_{p,s}^{\max}$, one obtains

$$\begin{aligned} E_{p,f}^{\max} &\simeq 3.9 \times 10^4 \text{ TeV } \varepsilon_{Bf,-2.5}^{1/2} n_{\text{sh},11}^{1/2} V_{f,3.5}^3 t_{f,7} \\ E_{p,r}^{\max} &\simeq 1.2 \times 10^5 \text{ TeV } \varepsilon_{Br,-2.5}^{1/2} (M_{\text{ej}}/M_{\odot})^{1/2} R_{15.5}^{-3/2} V_{r,4}^3 t_{r,6.5}. \end{aligned} \quad (6)$$

At sufficiently high energies, $p\gamma$ processes occur, as often expected in extragalactic sources such as GRBs [3–5]. Both the photomeson cooling time ($t_{p\gamma}$) and Bethe-Heitler cooling time (t_{BH}) depend on the radiation field. The emission from SNe is the reprocessed emission of ultraviolet, x-ray, and gamma-ray photons. In type II SNe, the reprocessing is expected to occur in the dense CSM. Calculating the spectrum requires detailed numerical modeling including the radiative transfer [14, 29], and we do not treat the details of its production here. Just for simplicity, we adopt a black-body spectrum that is valid in the thermal equilibrium limit (though the thermalization would be incomplete especially in Model B). In the case of SN 2006gy, the CSM shell is opaque even for Compton scattering, where stronger thermalization is expected and radiation should diffuse out of the shell [14], and the interior temperature is set by assuming that radiation with \mathcal{E}_{ph} fills a sphere with radius $R_{\text{sh}} + \Delta R_{\text{sh}}$. In Model B, where $\tau_T \sim 1 < c/V_s$, radiation can escape the shell in the shock crossing time. We instead estimate the radiation energy density to be $\approx \frac{L_{\text{ph}}}{4\pi(R_{\text{sh}} + \Delta R_{\text{sh}})^2 c}$, where $L_{\text{ph}} \approx \mathcal{E}_{\text{ph}} V_s / R_{\text{sh}}$. The typical energy of protons interacting with T_{γ} photons is $E_p^{p\gamma} \simeq 1.6 \times 10^5 \text{ TeV } T_{\gamma,0}^{-1}$ and $E_p^{\text{BH}} \simeq 4.8 \times 10^3 \text{ TeV } T_{\gamma,0}^{-1}$, respectively [6].

We numerically evaluated t_{pp} , $t_{p\gamma}$ and t_{BH} , and determined $E_{p,s}^{\max}$ by comparing t_{acc} to cooling time scales and t_s [4], where we assumed $\mathcal{E}_{\text{ph}} = 10^{51} \text{ erg}$ in Model A and $\mathcal{E}_{\text{ph}} = 10^{50} \text{ erg}$ in Model B. We obtained $E_{p,r}^{\max} \simeq 3.2 \times 10^3 \text{ TeV}$ in Model A, and $E_{p,f}^{\max} \simeq 5.0 \times 10^3 \text{ TeV}$ and $E_{p,r}^{\max} \simeq 2.0 \times 10^4 \text{ TeV}$ in Model B. We found that both $t_{p\gamma}$ and t_{BH} are not very relevant in our cases.

Accelerated CRs are mostly confined and produce mesons via inelastic pp scattering, which leads to the production of neutrinos and gamma rays. At R_{sh} , the efficiencies of the pp reaction during t_s are estimated to

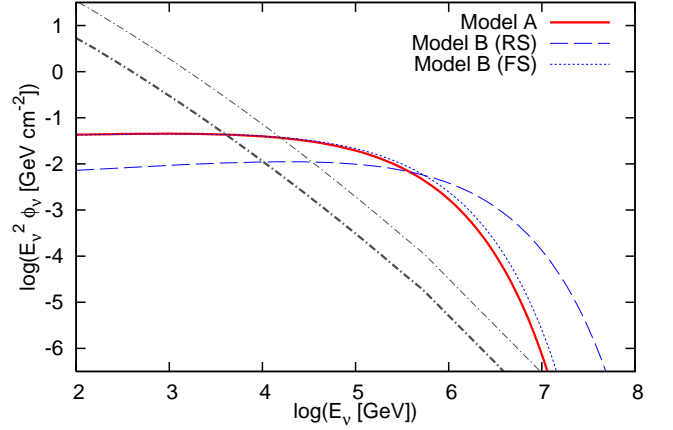


FIG. 1. Energy fluences of muon neutrinos from a SN crashing into dense CSM, where $\varepsilon_B = 10^{-2.5}$, $\epsilon_{\text{cr}} = 0.1$ and $d = 10 \text{ Mpc}$ are assumed. Thick and thin curves represent Model A and Model B, respectively (see text). The dotted-dashed curves show the zenith-angle-averaged ANB within a circle of radius 1° [31]; we use $\Delta t = 10^7 \text{ s}$ for Model A (thick line) and $\Delta t = 10^{7.8} \text{ s}$ for Model B (thin line).

be [4, 5]

$$\begin{aligned} f_{pp}^{\text{sh}} &\approx t_f/t_{pp}^{\text{sh}} \simeq 470 R_{\text{sh},15.5} n_{\text{sh},11} V_{f,3.5}^{-1} \\ f_{pp}^{\text{ej}} &\approx t_r/t_{pp}^{\text{ej}} \simeq 13 R_{\text{sh},15.5}^{-2} (M_{\text{ej}}/M_{\odot}) V_{r,4}^{-1}. \end{aligned} \quad (7)$$

Hence, the pp reaction should be efficient for typical parameters, $R_{\text{sh}} \lesssim 10^{16.5} \text{ cm}$ and $M_{\text{sh}} \sim 1 - 30 M_{\odot}$, which are consistent with the parameters suggested for explaining ultra-bright SNe in the SN-CSM collision model [9, 14, 15]. (In ordinary SN remnants, $f_{pp} \sim 10^{-5} (M_{\text{ej}}/M_{\odot})^{1/3} n_{\text{ext}}^{2/3} V_{f,3.5}^{-1}$ at the Sedov time.) Although CRs may make further pions through diffusion even after the shock crossing, CRs would also have adiabatic cooling due to an expansion with $\sim M_{\text{ej}} V_{\text{ej}} / (M_{\text{ej}} + M_{\text{sh}})$ (which is the fluid velocity of the merged ejecta). Our estimates on the pp efficiencies are relatively conservative and adequate.

Neutrinos.— To calculate neutrino and gamma-ray spectra from the pp reaction, we performed numerical calculations [30], where the CR spectrum was assumed to be $dN_p/dE_p \propto E_p^{-2} e^{-(E_p/E_{p,s}^{\max})}$, normalized by the total CR energy, $\mathcal{E}_{\text{cr}} \equiv \epsilon_{\text{cr}} \mathcal{E}_{\text{ej}}$. The effects of radiative and/or hadronic cooling of mesons on spectra, which are relevant in GRBs [4, 5] and magnetars [6], can be neglected.

After flavor mixing, $\sim 1/6$ of the pion energy is carried by each neutrino flavor, so the muon neutrino fluence is

$$E_{\nu}^2 \phi_{\nu} \sim 6 \times 10^{-2} \text{ GeV cm}^{-2} \min[1, f_{pp}] \epsilon_{\text{cr},-1} \mathcal{E}_{\text{ej},51} d_1^{-2}, \quad (8)$$

which agrees with our numerical results shown in Fig. 1. Here $d = 10 \text{ Mpc}$ d_1 is the distance. The signals compete with the atmospheric neutrino background (ANB), so one has to know both the source direction and timing for detections. The SN direction can be determined well

by optical/infrared observations. Importantly, the high-energy transients from the new SN class discussed here have *much longer* duration (months-years) than GRBs (seconds-minutes) [3, 4] and SNe with relativistic components (minutes-days) [5, 6], and thus form a new type of neutrino sources. In the shock model for ultra-bright SNe such as SN 2006gy [14], thermal photons leave the source when the photon diffusion time is comparable to the shell expansion time, where

$$t_{\gamma-D} \approx \frac{(\Delta R_{\text{sh}})^2}{2c} n_{\text{sh}} \sigma_T \sim 10^7 \text{ s } n_{\text{sh},11}^{-1} V_{f,3.5}^{-2} \quad (9)$$

(which is consistent with the observation, $\mathcal{E}_{\text{ph}} \sim 10^{51}$ erg and $L_{\text{ph}} \sim 10^{44}$ ergs $^{-1}$). For the neutrino search by IceCube-like detectors, we have to set a time window Δt , which is relevant to estimate the ANB. In Model A, it would be appropriate to use $\Delta t = 10^7$ s since the duration of the SN thermal emission is $t_{\gamma-D} \sim t_f \sim 10^7$ s, where the muon yield from SN-CSM neutrinos for IceCube is $N_{\mu,>4 \text{ TeV}} \sim 2$. In an optically thin case like Model B, the SN emission time is order of

$$t_s \simeq 5.0 \times 10^7 \text{ s } R_{\text{sh},16.5} V_{s,3.8}^{-1} \quad (10)$$

(which is consistent with $\mathcal{E}_{\text{ph}} \sim 10^{50}$ erg and $L_{\text{ph}} \sim 10^{42.5}$ ergs $^{-1}$), and we obtain $N_{\mu,>20 \text{ TeV}} \sim 1$ for the FS ($N_{\mu,>50 \text{ TeV}} \sim 0.2$ for the RS) for this time window. For up-going neutrino sources, attenuation in Earth should be considered, but will be modest at a wide range of zenith angles for the most important energies [32].

The rate of SNe with dense and massive CSM is uncertain, but a few % of all SNe may be such systems [13, 18, 20], so that their rate within 20 Mpc is order of $\sim 0.1 \text{ yr}^{-1}$. Note that the cumulative background muon neutrino flux, $E_\nu^2 \Phi_\nu \sim 2.7 \times 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, though comparable to that from GRBs [3, 4], is less than the ANB up to $E_\nu \sim 300 \text{ TeV}$, so that we focus on detections of individual nearby explosions.

Gamma rays. — Neutral pions lead to gamma rays that are interesting targets for *Fermi* and future Cherenkov telescopes such as Cherenkov Telescope Array (CTA), where one has to consider their interactions inside and outside the source. At relevant energies, there will be attenuation on matter (Bethe-Heitler pair-creation) and radiation ($\gamma\gamma$ pair-creation) in the source. They are also attenuated by the extragalactic background light (EBL).

In Fig. 2, the attenuated pionic gamma-ray fluxes are shown, taking into account gamma-ray attenuation numerically. For demonstrative purposes, the non-attenuated flux in Model A is also shown. Here, for simplicity, we employ $\sim \exp(-\tau_{\gamma\gamma} - \tau_{\text{BH}})$ for the screen region and $\sim 1/(1 + \tau_{\gamma\gamma} + \tau_{\text{BH}})$ for the emission region. For example, the Bethe-Heitler and $\gamma\gamma$ pair-creation depths in the CSM shell are estimated to be $\tau_{\text{BH}}^{\text{sh}} \simeq 3.2 n_{\text{sh},11} \Delta R_{\text{sh},15.5}$ at $\sim \text{GeV}$ and $\tau_{\gamma\gamma}^{\text{sh}} \simeq 3000 T_{\gamma,0}^3 \Delta R_{\text{sh},15.5}^{-1}$ at $\sim 260 \text{ GeV } T_{\gamma,0}^{-1}$, respectively. (Note that the photomeson and photodisintegration processes can also happen at sufficiently high energies.

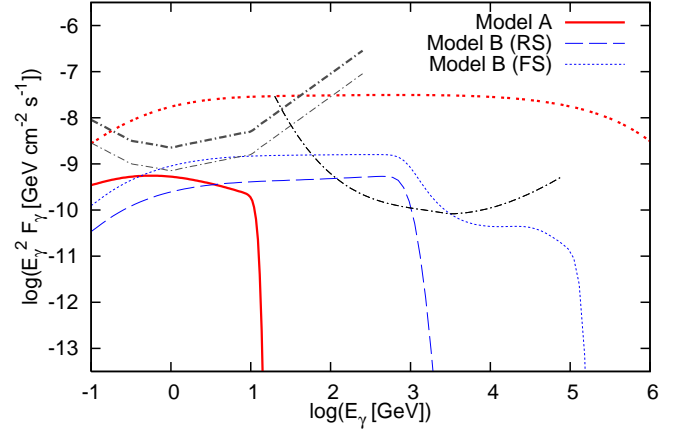


FIG. 2. Energy fluxes of pionic gamma rays, corresponding to Fig. 1. Gamma-ray attenuation inside and outside the source is included; the double-dotted curve shows the intrinsic spectrum without attenuation in Model A. Left dot-dashed curves show *Fermi*/LAT differential sensitivities at $t = 10^{6.5} \text{ s}$ ($\sim t_r$ in Model A) and $t = 10^{7.5} \text{ s}$ ($\sim t_r$ in Model B). The 100 hr differential sensitivity of CTA is also overlaid (right).

When τ_T is sufficiently small, low-frequency synchrotron far-infrared emission may also increase the attenuation far above a TeV). Outside the source, the EBL attenuation is significant only at $\gtrsim 100 \text{ TeV}$ for $d \sim 10 \text{ Mpc}$.

In Model A, the Bethe-Heitler and $\gamma\gamma$ attenuation would make it difficult to detect $\sim \text{GeV}$ and $\sim \text{TeV}$ gamma rays, respectively, although the attenuated flux just represents the relatively conservative case (see below). Also, though we show the differential sensitivities of *Fermi* and CTA, the integrated sensitivities over several energy bins are much better, which would help detection of the signal. In Model B, $\tau_{\text{BH}}^{\text{sh}} \ll 1$ and the $\gamma\gamma$ attenuation is negligible at $\lesssim \text{TeV}$, so that gamma rays seem detectable by *Fermi* for $d \lesssim 20 - 30 \text{ Mpc}$, which motivates searches for $\sim 0.1 - 1 \text{ yr}$ transients via multi-year *Fermi* observations. With coordinated follow-up searches, $\sim 0.1 - 1 \text{ TeV}$ gamma rays may also be detected by Cherenkov telescopes such as CTA. The High Altitude Water Cherenkov Experiment (HAWC), with a larger field of view and lower sensitivity, may also be helpful for nearby SNe.

The neutrino signature is quite direct and more important as a smoking gun of the CR acceleration, while the gamma-ray signature would be more complicated. While we are here mainly concerned with pionic gamma-ray emission that is the more direct hadronic signal, gamma rays are also produced by electrons, which come from muon-decay, primary acceleration, and pair-creation processes. When they lose energy via inverse-Compton (and synchrotron) processes, electromagnetic cascades can be induced, so that gamma-ray signals may be enhanced. Let us estimate the cascade effects on the gamma-ray emission briefly. As noted above, gamma rays of $\sim 260 \text{ GeV } T_{\gamma,0}^{-1}$ lead to generating energetic pairs. The syn-

chrotron and inverse-Compton cooling times are $t_{e-\text{syn}} \simeq 7.7 \times 10^3 \text{ s } \gamma_{e,3}^{-1} B_1^{-2}$ and $t_{e-\text{IC}} \simeq 2.2 \times 10^2 \text{ s } \gamma_{e,3}^{-1} T_{\gamma,0}^{-4}$, respectively (while the bremsstrahlung cooling time is $t_{e-\text{brem}} \simeq 1.0 \times 10^4 \text{ s } n_{\text{sh},11}^{-1} (\ln \gamma_{e,3})^{-1}$). If interactions with matter could be neglected, the situation would be much simpler. When we consider only a one-zone black-body radiation field (though it may not be a good approximation), unless the synchrotron cooling becomes more important, we obtain an inverse-Compton cascade, which leads to a broken power-law energy spectrum with a high-energy cutoff E_γ^{cut} (e.g., [33]).

In Model A, because of the large $\gamma\gamma$ pair-creation depth, a flat energy spectrum is expected from $\sim 0.1 \text{ GeV } (E_\gamma^{\text{cut}}/10 \text{ GeV})^2 T_{\gamma,0}$ to $E_\gamma^{\text{cut}} \sim 10 \text{ GeV}$ (and the photon index becomes ~ 1.5 at lower energies). The cascaded flux is $\sim 2 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1}$ (which is comparable to the intrinsic flux without attenuation), enhancing the $\sim 1 - 10 \text{ GeV}$ flux only by a modest factor; this estimate was also checked via the numerical cascade calculation [34]. However, interactions with matter cannot be neglected, so that even $\sim \text{GeV}$ gamma rays are attenuated mainly because of the Bethe-Heitler attenuation in the CSM shell and the eventual gamma-ray emission is expected at even lower energies, $\sim 10 \text{ keV} - 100 \text{ MeV}$, below the range of our interest (and note that the radiation temperature around the photosphere would be lower). Then, further downgrades are unavoidable, since the Compton opacity becomes larger than unity for photons, and electrons mainly lose their energies via the Coulomb interaction ($t_{e-\text{Coul}} \simeq 1.2 \times 10^3 \text{ s } \gamma_{e,2} n_{e,11}^{-1}$), and the bremsstrahlung process can overtake the inverse-Compton process. Then, the GeV-TeV emission would be significantly suppressed as expected above, and low-energy emission is largely thermalized. However, the CSM might be clumpy as suggested in SN 2005ip [18], where the Bethe-Heitler process might not be so significant depending on the unknown volume filling factor. If that is true, *Fermi* may find the signal if $\sim 3\%$ of gamma rays (including both the attenuated/cascaded components) can escape from the source, where the flat energy spectrum in the $\sim 0.1 - 10 \text{ GeV}$ range is expected because of the inverse-Compton cascade. But, since strong thermalization is required in the SN 2006gy-like case, this is recognized as optimistic for detectability.

On the other hand, in Model B, the $\gamma\gamma$ pair creation is relevant only at $\gtrsim \text{TeV}$ and the Bethe-Heitler process is negligible, so that the attenuated flux shown in Fig. 2 (which is essentially the intrinsic flux without attenuation) gives the dominant contribution for the detectability of *Fermi* and CTA. Here, the inverse-Compton cascade is suppressed by the synchrotron cooling ($t_{e-\text{syn}} < t_{e-\text{IC}}$) but the secondary synchrotron flux in the $\sim 10 \text{ keV} - 100 \text{ MeV}$ range (see also the next section) would be enhanced by a factor. Note that the $\gamma\gamma$ pair-creation opacity by synchrotron x rays coming from the generated secondary pairs is small enough. Let us suppose all of the pair luminosity goes into x rays of $E_X \sim \text{keV}$, though it is not true. The maximum

number of x ray photons is $\approx \frac{L_e}{4\pi(R_{\text{sh}} + \Delta R_{\text{sh}})^2 c E_X}$ and a keV photon travels $\sim 3.8 \times 10^{15} \text{ cm } n_{\text{H},7.5}^{-1}$ in a homogeneous medium, so that the $\gamma\gamma$ pair-creation opacity is $\sim 6.2 \times 10^{-5} L_{e,41.5} R_{16.5}^{-2} E_{X,\text{keV}}^{-1} n_{\text{H},7.5}^{-1}$.

Generally speaking, calculating the detailed gamma-ray spectrum is not easy without knowing the multi-zone spectral energy distribution of target photons, which depends on details of the model via the frequency dependence of the opacity and the density gradient in the CSM [29]. The radiation deviated from a black-body spectrum, including x-ray emission from thermal bremsstrahlung expected in the downstream region, may affect results. Though we defer such studies, we have discussed both the relatively conservative (with attenuation) and optimistic (with cascade) cases, which are enough for our purpose of demonstrating detection potential of the gamma-ray signal. Also, one should keep in mind that the cascade outside the source is also initiated, but the resulting gamma-ray emission cannot be detected unless the intergalactic magnetic field is weak enough [34].

IV. IMPLICATIONS AND DISCUSSIONS

We have shown that SNe crashing into dense CSM are interesting targets for current and near-future high-energy detectors. Importantly, new types of coordinated multi-messenger searches are required to detect such $0.1 - 1 \text{ yr}$ transients.

CR acceleration in dense surroundings is also motivated by recent gamma-ray observations [24, 25]. Both detections and non-detections of SN-CSM emission will be useful, since physical mechanisms in such extreme environments are uncertain, especially when $\tau_T \gtrsim 1$. In particular, neutrinos have the benefit of probing hadronic CR accelerators, and they can escape earlier than thermal photons, which may be delayed by diffusion. In addition, the detections of signals would support the SN-CSM scenario [14, 15] rather than the pair-instability scenario [16], useful for revealing the origin of bright SNe.

One may expect synchrotron emission in the infrared-to-gamma-ray bands, as electrons of energy E_e emit photons with $\sim 44 \text{ keV } E_{e,\text{TeV}}^2 B$. But the emission should be reprocessed to energies $\lesssim 10 \text{ keV}$ and/or strongly thermalized when $\tau_T \gg 1$, so we basically expect thermal emission observed from such SNe. But the synchrotron emission can be seen in the sufficiently hard x-ray range, if the collision happens at $\tau_T < 1$, as in Model B. The unabsorbed energy flux is estimated to be $\sim 7 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} f_{\text{syn}} \min[1, f_{pp}] \epsilon_{\text{cr},-1} \mathcal{E}_{\text{ej},51} d_1^{-2} t_{s,7.8}^{-1}$, where $f_{\text{syn}} \leq 1$ is the efficiency of synchrotron cooling. In Model B, the synchrotron cooling is more important than the synchrotron self-Compton and external Compton cooling at sufficiently high energies, so that pionic gamma rays are dominant in the GeV-TeV range while the synchrotron component, whose high-energy photon index is $(q+2)/2 \sim 2$, is relevant below $\sim 100 \text{ MeV}$. (But

other cooling processes such as the Coulomb interaction becomes more important especially at $E_e \lesssim 0.1 - 1$ GeV.) Hence, this signal will be an interesting target for the near-future x-ray monitor *NuStar* (softer x rays can be masked by strong thermal bremsstrahlung emission that seems to be observed [9]). The radio emission is suppressed by the Razin effect, free-free absorption, and synchrotron self-absorption when the collision radius is small enough, though it may be expected at very large radii.

For more quantitative theoretical studies, hydrodynamical simulations with radiation transfer and CR back-reaction are desirable. But our results are enough for the purpose of this work, which, in part, is to motivate new searches starting now. The relevant quantities, \mathcal{E}_{cr} , $E_{p,s}^{\text{max}}$ and q , have uncertainties, but we could see a source up to $d \sim 30 - 60$ Mpc if ϵ_{cr} is larger than 0.1. The spectral index also affects the results. Although we adopt $q = 2$, steeper indices lead to lower muon yields from SN-CSM neutrinos. But harder indices may also be expected since the gas may be radiation-dominated and/or the shock may be CR-mediated [28]. Since $E_{p,s}^{\text{max}}$ depends on shock velocities, the non-uniformity of the ejecta affects the RS velocity and ratio of the RS dissipation to the FS dissipation [35], but its pre-collision velocity distribution is uncertain since the ejecta may sweep the CSM before the collision. Also, the shock evolution may be radiative rather than adiabatic [36].

Plasma effects can modify the results, via e.g., wave damping by neutral particles or radiation. Especially, $E_{p,s}^{\text{max}}$ may be limited by the size of the ionization region, since damping occurs in a time $\sim \frac{1}{n_n < \sigma_{i-n} v_{\text{th}} >} \sim$

$10^{0.5} \text{ s } n_{n,7.5}^{-1} T_0^{-0.4}$ in the neutral region [37]. Although the CSM gas would be initially neutral, ionization in the downstream and upstream region (not far from the shock) seems expected observationally [18] and theoretically [38] since the post-shock temperature is high.

We have considered extragalactic SNe with dense and massive CSM shells. Such collisions may happen even for GRBs, where the jet breakout emission can be expected. The high-energy neutrino and gamma-ray emission is also possible, which would be more or less analogous to the (sub-)photospheric emission [4, 5]. In the Galaxy, η Carinae is a promising candidate that showed violent mass eruptions [19]. The radius of its massive nebula is larger than our typical values that are required for bright SNe. But the neutrino detection seems possible if the star explodes, since $N_{\mu, > \text{TeV}} \sim 2 \times 10^5 \mathcal{E}_{\text{cr},50} (M_{\text{sh}}/10M_{\odot}) R_{\text{sh},17}^{-2} V_{s,3.5}^{-1}$ (where $f_{pp} < 1$). For smaller CSM mass, though the radiation might push the CSM shell, SN dynamics are not largely affected as in ordinary SNe [39], where \mathcal{E}_{cr} , $E_{p,s}^{\text{max}}$ and f_{pp}^{sh} are much smaller. Detections would be challenging, but it may be interesting for a Galactic event.

After this work was submitted and put onto the arXiv (arXiv:1012.2834), we became aware of Ref. [40], which is closely related to ours, and which supports our claims that these unusual SNe are interesting and that their high-energy emission is an important probe. We thank K. Ioka, C. Kochanek, C. Rott and R. Yamazaki for discussions. This work is supported by JSPS and CCAPP (KM), E. C. Howald Presidential Fellowship (BCL), Sloan Fellowship and NSF Grant AST-0908816 (TAT), and NSF CAREER Grant PHY-0547102 (JFB).

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