Revealing the Supernova–Gamma-Ray Burst Connection with TeV Neutrinos

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Gamma-ray bursts (GRBs) are rare, powerful explosions displaying highly relativistic jets. It has been suggested that a significant fraction of the much more frequent core-collapse supernovae are accompanied by comparably energetic but mildly relativistic jets, which would indicate an underlying supernova-GRB connection. We calculate the neutrino spectra from the decays of pions and kaons produced in jets in supernovae, and show that the kaon contribution is dominant and provides a sharp break near 20 TeV, which is a sensitive probe of the conditions inside the jet. For a supernova at 10 Mpc, 30 events above 100 GeV are expected in a 10 s burst in the IceCube detector.

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Long duration gamma-ray bursts (GRBs) have been found to be tightly connected with core-collapse supernovae [1] (short duration GRBs may have another origin, such as compact star mergers [2]). Although many mysteries remain, this strongly indicates that the central remnants of the core-collapse event, most likely black holes, drive the observed relativistic (bulk Lorentz factor $\Gamma_b \gtrsim 100$) jets of GRBs. High-energy neutrinos from accelerated protons in GRB internal shocks are predicted to be detectable at future 1 km^3 Čerenkov detectors such as IceCube [3]. (If the protons escape and collide with external material, both the delayed gamma rays and neutrinos could be observable [4].) The jet signature, but more mildly relativistic, may be common to supernovae, which are much more frequent than GRBs, even correcting for the effects of jet opening angle on observability. If a significant fraction of core-collapse supernovae are accompanied by jets with $\Gamma_b \sim 3$, perhaps $\sim 1\%$ according to late-time radio observations [5], then neutrinos could be the only prompt signature of these hidden sources.

Besides being more frequent, mildly relativistic jets are expected to be much more baryon rich (a "dirty fireball"). Both properties work quite positively for neutrino detectability. Recently, Razzaque, Mészáros, and Waxman (RMW) developed a model of high-energy (TeV) neutrino emission from jets with $\Gamma_b \sim 3$ [6]. Because of the low Lorentz factor and high baryon density, collisions among accelerated protons (pp) occur efficiently, making pions that decay into neutrinos, and a nearby core-collapse supernova at 3 Mpc is predicted to be detectable at IceCube [6]. If those high-energy neutrinos are detected, and correlated with an optical supernova, then it would strongly and directly show the presence of a mildly relativistic jet with significant kinetic energy, as well as potentially being the first detection of extragalactic neutrinos. Data from many supernovae would give the distribution of the jet Lorentz factor, providing important insight into the supernova-GRB connection.

We extend the RMW model and significantly improve the detection prospects; most importantly, we consider the kaon contribution, since compared to pions, kaons have several advantages. Because of their larger mass and shorter lifetime, kaons undergo less energy loss before decaying into neutrinos. This, and the relatively larger energy transferred to the daughter neutrinos, means that the neutrino spectrum from kaons is harder and more detectable than that from pions. The neutrino spectrum from kaon decay has a sharp drop near 20 TeV, which is a sensitive diagnostic of the acceleration mechanism and the conditions inside the jet. Since many detected events are expected (e.g., ~ 30 at 10 Mpc in IceCube), our results greatly extend the range of detectability, which increases the frequency as $\sim d^3$, where d is the distance of the furthest detectable objects. While these models have many uncertainties, our results significantly improve their detectability, such that even the existing AMANDA detector can provide important constraints.

Jet dynamics.—We briefly summarize the RMW model, using their notation [6]. The jet kinetic energy is set to be $E_j = 3 \times 10^{51}$ erg, which is typical for GRBs. Since we discuss a baryon-rich jet, we use the mildly relativistic value for the bulk Lorentz factor $\Gamma_b = 3$, and an assumed opening angle of $\theta_j \sim \Gamma_b^{-1} = 0.3$. By analogy with observed GRBs, it is natural to set the variability time scale of the central object as $t_v = 0.1$ s. The internal shocks due to shell collisions then occur at a radius $r_j = 2\Gamma_b^2 c t_v = 5 \times 10^{10}$ cm, smaller than a typical stellar radius. The comoving number densities of electrons and protons inside the jet are $n'_e = n'_p = E_j/(2\pi\theta_j^2 r_j^2 \Gamma_b^2 m_p c^3 t_j) = 4 \times 10^{20}$ cm^{-3}, where $t_j = 10$ s is the typical GRB jet duration; the superscript $'$ represents quantities in the comoving frame of the jet. It is assumed that fractions $\epsilon_e = \epsilon_B = 0.1$ of the jet kinetic energy are converted into relativistic electrons and magnetic fields, also by analogy to GRBs. These electrons lose energy immediately by synchrotron radiation. The

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synchrotron photons, however, thermalize because of the high optical depth, $n'_e\sigma_T\Gamma_b c t_v = 2\times10^6$, where σ_T is the Thomson cross section, which makes the jets invisible with prompt gamma rays, unlike GRBs. As a result, the magnetic field strength, photon temperature, and number density are given by $B' = [4\epsilon_B E_j/(\theta_j^2 r_j^2\Gamma_b^2 c t_j)]^{1/2} = 10^9$ G, $E'_\gamma = [15(\hbar c)^3\epsilon_e E_j/(2\pi^3\theta_j^2 r_j^2\Gamma_b^2 c t_j)]^{1/4} = 4$ keV, and $n'_\gamma = E_j\epsilon_e/(2\pi\theta_j^2 r_j^2\Gamma_b^2 c t_j E'_\gamma) = 8\times10^{24}$ cm^{-3}. It is assumed that the internal shocks accelerate protons with a spectrum $\sim E_p^{-2}$, normalized to the jet total energy. The maximum proton energy is set by comparing the acceleration time scale $t'_{\rm acc} \simeq E'_p/eB' = 10^{-12}$ s$(E'_p/1$ GeV) [7] with the energy-loss time scales. RMW assume that radiative cooling by the synchrotron and Bethe-Heitler ($p\gamma\to pe^+e^-$) processes dominates, and that the maximum proton energy is 2×10^6 GeV.

Proton and meson cooling.—We describe our extension of the RMW model, including the maximum acceleration and meson cooling arguments. At energies below the photopion production (hereafter $p\gamma$) threshold $E'_{p\gamma,\rm th} = 0.3/E'_\gamma$ GeV$^2 = 7\times10^4$ GeV, the proton acceleration time scale is much shorter than any energy-loss time scale. Above the $p\gamma$ threshold, we find that the most competitive cooling mechanism is the $p\gamma$ process itself, due to the very high photon density. Assuming 15% energy lost from an incident proton in each $p\gamma$ interaction, $\Delta E'_p = 0.15E'_p$, and using $\sigma_{p\gamma} = 5\times10^{-28}$ cm^2 [8], we obtain a cooling time scale $t'_{p\gamma} = E'_p/(c\sigma_{p\gamma}n'_\gamma\Delta E'_p) = 6\times10^{-8}$ s. Equating $t'_{\rm acc} = t'_{p\gamma}$, we obtain $E'_p = 5\times10^4$ GeV, slightly less than the threshold energy of the $p\gamma$ interaction. Thus when the $p\gamma$ interaction becomes accessible, it prevents further acceleration, so we take $E'_{p,\rm max} = 7\times10^4$ GeV, in contrast to RMW. As discussed below, we focus on the break in the kaon-decay neutrino spectrum as a direct observable of the maximum proton energy.

Accelerated protons produce mesons efficiently via pp interactions, since the optical depth is $\tau'_{pp} = n'_p\sigma_{pp}\Gamma_b c t_v = 2\times10^5$, where $\sigma_{pp} = 5\times10^{-26}$ cm^2 [8]. The meson multiplicity in each pp interaction is taken to be 1 for pions and 0.1 for kaons; this is the right ratio [9], but we have been conservative in the normalization to focus on the most energetic mesons. We assume that the mesons are produced with 20% of the parent proton energy, so that they follow the original spectrum of accelerated protons. They cool, however, by radiative (synchrotron radiation and inverse Compton scattering off thermal photons) and hadronic (πp and Kp) processes. The cooling time scales are $t'_{rc} = 3m^4c^3/[4\sigma_T m_e^2 E'(U'_\gamma + U'_B)]$ and $t'_{hc} = E'/(c\sigma_h n'_p\Delta E')$ for radiative and hadronic cooling, where m and E' are the meson (π or K) mass and energy, $U'_\gamma = E'_\gamma n'_\gamma$ and $U'_B = B'^2/8\pi$ are the energy densities of photon and magnetic fields, σ_h is the cross section for meson-proton collisions, and $\Delta E'$ is the energy lost by the meson per collision. Adopting $\Delta E' = 0.8E'$ [10] and $\sigma_h = 5\times10^{-26}$ cm^2 for pions and kaons [8], t'_{hc} is energy independent, while $t'_{rc}\propto E'^{-1}$. The total cooling time scale is $t_c'^{-1} = t_{hc}'^{-1} + t_{rc}'^{-1}$; it is dominated by hadronic cooling at lower energies, and radiative cooling at higher energies.

If mesons decay faster than they cool, then the daughter neutrinos maintain the spectrum shape; otherwise, the spectrum becomes steeper. Below the cooling break energy $E_{cb}'^{(1)}$, obtained by equating $\gamma'\tau = t'_c(\sim t'_{hc})$, where γ' and τ are the meson Lorentz factor and proper lifetime, there is no suppression because mesons immediately decay after production. Above $E_{cb}'^{(1)}$, the cooling suppression factor is the ratio of two time scales, i.e., $t'_c/\gamma'\tau$. When the energy-loss process is dominated by hadronic cooling, the suppression factor is $\propto E'^{-1}$. When it is dominated by radiative cooling, above an energy $E_{cb}'^{(2)}$, it is $\propto E'^{-2}$; we obtain $E_{cb}'^{(2)}$ by solving $t'_{hc} = t'_{rc}$. RMW neglected hadronic cooling of mesons; it is not a large effect for pions, but it is important for kaons.

Neutrino spectrum.—Charged pions and kaons, which are assumed to carry 20% of the original proton energy, decay into neutrinos through $\pi^\pm, K^\pm \to \mu^\pm + \nu_\mu(\bar\nu_\mu)$ with branching ratios 100% and 63%. The neutrino energy in the observer frame is related to the parent meson energy in the jet rest frame as follows: $E_\nu = \Gamma_b E'_\pi/4$ and $E_\nu = \Gamma_b E'_K/2$. The Lorentz factor represents the Doppler boosting effect, and 4 and 2 in the denominators reflect the fraction of the parent energy conveyed by the daughter neutrino in the case of pion and kaon decays. Secondary neutrinos from muon decays are irrelevant since muons immediately undergo radiative cooling [6]. The energies and densities here are similar to the case of neutrino production in Earth's atmosphere, which makes the calculation more robust.

Figure 1 is a diagram for the neutrino spectrum from meson decays, characterized by two spectral breaks and a maximum neutrino energy. For neutrinos from pion decay, we obtain the cooling break energies:

$$E_{\nu,cb}^{\pi(1)} = 30\ \text{GeV}, \qquad E_{\nu,cb}^{\pi(2)} = 100\ \text{GeV}, \qquad (1)$$

corresponding to $E_{\pi,cb}'^{(1)}$ and $E_{\pi,cb}'^{(2)}$. The dependence on the jet parameters is given by $E_j^{-1}\Gamma_b^7\theta_j^2 t_j t_v^2$ and $(\epsilon_e+\epsilon_B)^{-1}\Gamma_b$ for $E_{\nu,cb}^{\pi(1)}$ and $E_{\nu,cb}^{\pi(2)}$, respectively. We note that the first break energy is strongly sensitive to the value of Γ_b (it is less severe if one assumes $\Gamma_b\sim\theta_j^{-1}$, following RMW). This means that the model is quite uncertain, but at the same time, that the detection of neutrinos could precisely constrain the Lorentz factor of the jet.

The neutrino spectrum from kaon decays is much more favorable for three reasons. First, radiative cooling is much less efficient than for pions, since kaons are heavier and the radiative cooling time scale is $t'_{rc}\propto m^4$. Second, the kaon lifetime is a factor $\sim$2 shorter. Third, a larger mass also shortens the particle lifetime because of a smaller Lorentz

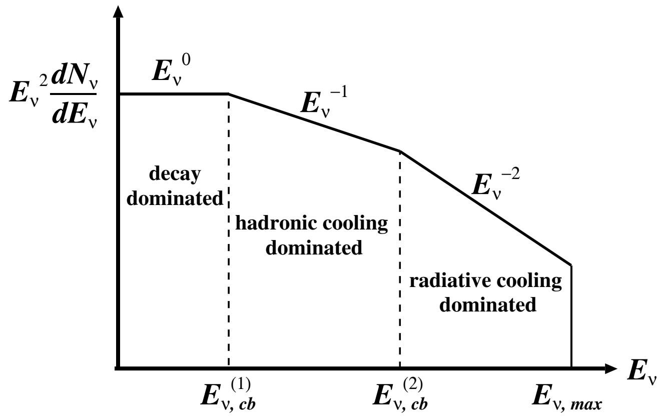

FIG. 1. Schematic spectrum for neutrinos from meson decays. The break energies are Eq. (1) for pions and Eq. (2) for kaons. The spectral features are smeared in detection (see Fig. 2).

factor at fixed energy. Thus the cooling breaks of kaons occur at much higher energies:

$$E^{K(1)}_{\nu,cb} = 200 \text{ GeV}, \qquad E^{K(2)}_{\nu,cb} = 20\,000 \text{ GeV}, \qquad (2)$$

where the scaling is the same as $E^{\pi(1)}_{\nu,cb}$ and $E^{\pi(2)}_{\nu,cb}$. The maximum energy $E_{\nu,\max} = \Gamma_b E'_{K,\max}/2$ is only slightly above the second break for a canonical parameter set, although this could be changed for other parameter choices. Measurement of the sharp edge of the neutrino spectrum would be a sensitive test of the maximum proton energy, and hence the physical conditions in the jet.

*Neutrino burst detection.—*We first estimate the normalization of the neutrino spectrum, evaluating the fluence at the first break energy, $F_{\nu,0} \equiv F_\nu(E^{(1)}_{\nu,cb})$. Assuming efficient energy conversion from protons to mesons, and that half of the mesons are charged, we obtain

$$F_{\nu,0} = \frac{\langle n \rangle B_\nu}{8} \frac{E_j}{2\pi\theta_j^2 d^2 \ln(E'_{p,\max}/E'_{p,\min})} \frac{1}{E^{(1)2}_{\nu,cb}}, \qquad (3)$$

where d is the source distance, $\langle n \rangle$ is the meson multiplicity (1 for pions and 0.1 for kaons), B_ν is the branching ratio of the decay into neutrino mode (1 for pions and 0.6 for kaons), and the factor $\ln(E'_{p,\max}/E'_{p,\min})$ normalizes the proton spectrum to the jet energy. For canonical parameter choices and for a nearby source at $d = 10$ Mpc, $F_{\nu,0}$ becomes 5×10^{-2} and 5×10^{-5} $\text{GeV}^{-1}\,\text{cm}^{-2}$, for neutrinos from pion and kaon decays, respectively. The parameter dependence is $E_j^3 \Gamma_b^{-14} \theta_j^{-6} t_j^{-2} t_v^{-4} d^{-2}$.

We calculated the signal from one supernova neutrino burst, using the code ANIS (All Neutrino Interaction Generator) [11]. We neglect the effects of neutrino oscillations, as they are below the uncertainties of the model. Figure 2(a) shows the event spectrum from the muon neutrinos and antineutrinos from a supernova at 10 Mpc, and in Fig. 2(b), we show the yields above a given energy. We used a detector effective area of 1 km^2, which is

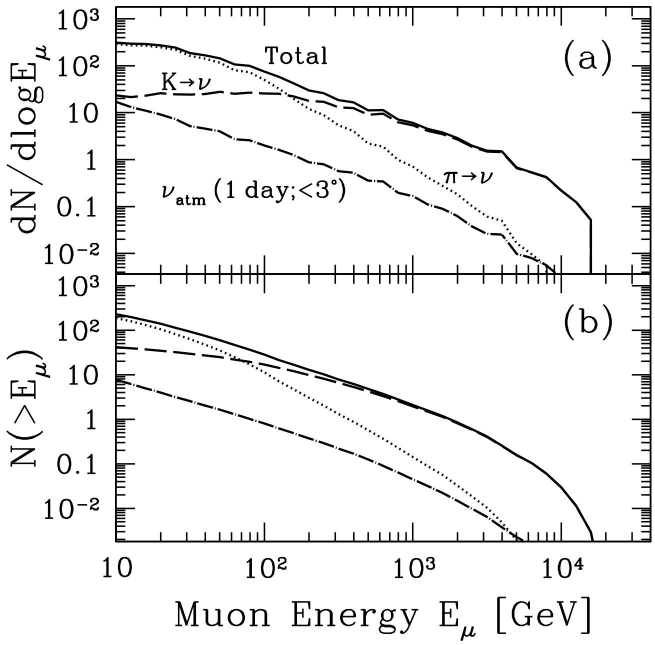

FIG. 2. (a) Spectrum of neutrino-produced muons from a supernova at 10 Mpc in a 1 km^3 detector (solid line), showing the contributions from $\pi^\pm$ (dotted line) and $K^\pm$ (dashed line) decays. The atmospheric neutrino background within 1 day and 3° is also shown. (b) Cumulative versions of the same.

reasonable for IceCube using upgoing muons [12]. We took into account the muon range, which effectively enlarges the detector volume, and evaluated the muon energy when it enters the detector if it is produced outside, or at the production point otherwise. Since the spectrum of neutrinos from pions falls steeply, their event spectrum is also steep, and therefore, if we lower the threshold, many more events would be expected, as shown in Fig. 2(b). The spectrum of neutrinos from kaons, on the other hand, is much flatter, making them the dominant component at high energies.

If we take 100 GeV as the threshold muon energy for IceCube (for a transient point source), we expect about 30 events from a core-collapse supernova at 10 Mpc, mostly from kaons. (If the proton spectral index is not -2.0, but is instead -1.5 or -2.5, the number of events is 40 or 3, respectively.) These events cluster in a 10 s time bin and a $\sim$3° angular bin, which allows very strong rejection of atmospheric neutrino backgrounds. If the source is farther and the expected number only a few events, then we may use a more conservative time bin, e.g., a 1 day bin correlated with optical observations, considering the time uncertainty between the neutrino burst and an optical supernova. The atmospheric neutrino background within 1 day and 3° is also shown in Fig. 2. The spectral break corresponding to the maximum proton energy might be detectable around $E_\mu \sim 20$ TeV, if the source is very close or the jet energy E_j larger than assumed. Recalling that the proton acceleration is limited by the $p\gamma$ interaction, this probes the photon density in the jet, an essential quantity. If the neutrinos come from below the detector, it may be possible to reduce the detector threshold, so that the large yield due to pion decays could be detectable, too.

Discussions.—The RMW model, while speculative, is a specific and intriguing proposal for a common thread connecting GRBs and core-collapse supernovae, namely, the presence of jets with energies around 3×10^{51} erg. For GRBs, which are rare events, the jets would be highly relativistic and revealed; for supernovae, which are frequent, the jets would be mildly relativistic and hidden, except from neutrino telescopes. The basic features of the RMW model are a proton spectrum falling as E_p^{-2}, carrying most of the jet energy, and a suitable target density for neutrino production. In analogy to the observed properties of GRBs, and evidence for a supernova-GRB connection, these requirements do not seem unreasonable. It is significant that these considerations can be directly and easily constrained with neutrino detectors, lessening the dependence on theory.

The key remaining issue is the fraction of supernovae which have these jets. Some type Ic supernovae do suggest the presence of mildly relativistic jets, based on their late-time radio emission; the fraction of all core-collapse supernovae with jets is perhaps $\sim$1% [5], significantly larger than the fraction of supernovae with highly relativistic jets, i.e., GRBs. It is possible that mildly relativistic jets are even more common, but are completely choked in the hydrogen envelopes of type II supernovae (RMW assumed that nearly all supernovae have jets). If such mildly relativistic jets accompanied SN 1987A and were directed toward Earth, the Kamiokande-II and IMB detectors would have seen many events, the small detector sizes being more than compensated by the closer distance. This suggests that such jets did not exist in SN 1987A; additionally, it was dark in the radio [13].

In any case, the nearby core-collapse supernova rate is high enough to allow testing these models soon, especially if type II supernovae have jets which can only be revealed by neutrinos. Within 10 Mpc, the rate of core-collapse supernovae is more than 1 yr^{-1}, with a large contribution from galaxies around 3–4 Mpc [14]. At 3 Mpc, we expect about 300 events in a 10 s burst in IceCube, which would be very dramatic. The electron neutrino shower channel, where the detected energy more faithfully reveals the neutrino energy, may be especially helpful [15]. Even in the already-operational AMANDA, though the effective area is smaller than that of IceCube, we expect $\sim$10 events. Since these events would arrive within 10 s, from a specific point source, the background rejection should be excellent, and AMANDA could already constrain these models.

At larger distances, the galaxy distribution is smooth enough to allow simple scaling: the number of sources increases as d^3, while the neutrino signal per supernova decreases as d^{-2}. For example, at 20 Mpc, the expected number of neutrino events in IceCube is still several, and the total supernova rate is $\gtrsim 10\ \mathrm{yr}^{-1}$. That distance contains the Virgo cluster (which increases the supernova rate somewhat beyond the simple scaling) in the northern hemisphere, an attractive target for South Pole neutrino telescopes. The effect of beaming is to reduce the source frequency at a given distance, but to increase the source fluence in a compensating way. Given the large assumed opening angle, the probability of having the jets directed towards Earth is relatively large, around $\sim$10%. Even taking into account that perhaps not all supernovae have jets, this model predicts rich detection prospects for IceCube. The detection of a prompt burst of high-energy neutrinos would reveal the time and direction of the core-collapse event, which would be useful for forecasting the optical supernova, and for searching for a gravitational wave signal in coincidence.

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