

Neutrinos from Pulsar Wind Bubbles as Precursors to Gamma-Ray Bursts

Jonathan Granot[†] and Dafne Guetta[‡]

[†]*Institute for Advanced Study, Princeton, NJ 08540; E-mail: granot@ias.edu*

[‡]*Osservatorio astrofisico di Arcetri, Fermi 5, 50125 Firenze, Italy; E-mail: dafne@arcetri.astro.it*

(Dated: January 3, 2008)

The supranova model for γ -ray bursts (GRBs) has recently gained popularity. In this scenario the GRB occurs weeks to years after a supernova explosion, and is located inside a pulsar wind bubble (PWB). High energy protons from the PWB can interact with photons from the rich radiation field inside the PWB or collide with cold protons from the supernova remnant, producing pions which decay into $\sim 10 - 10^3$ TeV neutrinos. The predicted neutrino flux from the PWBs that host the GRBs should be easily detectable by planned 1 km² detectors.

PACS numbers: 96.40.Tv, 98.70.Rz, 98.70.Sa

The leading models for Gamma-Ray Bursts (GRBs) involve a relativistic outflow emanating from a compact source. The γ -rays are attributed to synchrotron (and possibly also inverse-Compton) emission from relativistic electrons accelerated in internal shocks within the ejecta. The ultimate energy source is rapid accretion onto a newly formed stellar mass black hole. Long duration ($\gtrsim 2$ s) GRBs, which include all GRBs with observed afterglow emission and $\sim 2/3$ of all GRBs, are widely assumed to originate from a massive star progenitor. This is supported by growing evidence for GRBs occurring in star forming regions within their host galaxies [1]. The leading model for long duration GRBs is the collapsar model [2], where a massive star promptly collapses into a black hole, and forms a relativistic jet that penetrates through the stellar envelope and produces the GRB. An interesting alternative, though somewhat more debated, model is the supranova model [3], where a supernova explosion leaves behind a supra-massive neutron star (SMNS), of mass $\sim 2.5 - 3 M_\odot$, which loses its rotational energy on a time scale, $t_{\text{sd}} \sim$ weeks to years, and collapses to a black hole, triggering the GRB. The most natural mechanism by which the SMNS can lose its rotational energy is through a strong pulsar type wind, which is expected to create a pulsar wind bubble (PWB) [4, 5].

In this Letter we consider the neutrino production in the PWB in the context of the supranova model for GRBs. These ν 's have ~ 10 TeV energies and are emitted over the time t_{sd} between the supernova and GRB events, for $t_{\text{sd}} \lesssim 1$ yr, while for $t_{\text{sd}} \gtrsim 20$ yr, that is required for GRBs with typical afterglows (for spherical PWBs) [5], they are emitted mainly over the first few years after the supernova. For $t_{\text{sd}} \lesssim 0.1$ yr or for GRBs not pointed towards us, the ν 's would not be accompanied by a detectable GRB. We find that the ~ 10 TeV neutrino fluence from a PWB at $z \sim 0.1 - 1$ implies $\sim 0.1 - 10$ upward moving muons in a km² detector. We expect ~ 10 nearby ($z \lesssim 0.1$) PWBs per year. The neutrino signal from an individual PWB for which the GRB jet is pointed towards us, and is therefore detectable in γ -rays, is above the atmospheric neutrino background.

Neutrino production in the PWB. — The main mechanisms for neutrino production are (1) photomeson interactions between relativistic protons and nonthermal photons inside the PWB ($p\gamma$), (2) p-p collisions between the PWB protons and cold SNR protons (pp), (3) p-p collisions between shock accelerated SNR protons and cold SNR protons (sh); p-p collisions between two relativistic protons inside the PWB are unimportant. The pulsar wind is expected to have a comparable energy in protons and in e^\pm pairs. The proton velocities are randomized at the wind termination shock, and are expected to be quasi-monoenergetic, with a random Lorentz factor $\gamma_p = 10^{4.5} \gamma_{p,4.5}$ (i.e. an energy $\epsilon_p = 30\gamma_{p,4.5}$ TeV) since this is the value needed to explain GRB afterglow observations with $t_{\text{sd}} \gtrsim 20$ yr (for a spherical PWB) [5]. However, γ_p can be larger for $t_{\text{sd}} = 0.1t_{\text{sd},-1}$ yr < 20 yr.

The fraction, χ_p , of PWB protons that can reach the SNR and may interact with SNR protons, is uncertain. The ratio of the proton Larmor radius, R_L , and the SNR radius, R_b , is $\sim 4 \cdot 10^{-7} \gamma_{p,4.5} \xi_{B,-3}^{-1/2} t_{\text{sd},-1}^{1/2} \ll 1$, where $\xi_B = 10^{-3} \xi_{B,-3}$ is the fraction of PWB energy in magnetic fields, and the protons should largely follow the magnetic field lines. Polarization maps of the Crab nebula [6] suggest that the magnetic field in plerions is ordered on scales $\sim R_b$. This may suggest a reasonably high χ_p . Plasma instabilities can reduce χ_p , while a radial flow along the poles (jets) can increase χ_p . Therefore, the value of χ_p can range anywhere from $\sim 1/2$ to $\ll 1$.

The average optical depth for p-p collisions between a proton from the PWB, that propagates in the radial direction, and the protons of the SNR shell is

$$\tau_{pp}^{\text{rad}} = \frac{\sigma_{pp} M_{\text{SNR}}}{4\pi R_b^2 m_p} = 1.2 \left(\frac{M_{\text{SNR}}}{10 M_\odot} \right) \beta_{b,-1}^{-2} t_{\text{sd},-1}^{-2}, \quad (1)$$

where M_{SNR} and $\beta_b = 0.1\beta_{b,-1}$ are the mass and the velocity (in units of c) of the SNR shell, and $\sigma_{pp} \approx 50$ mb. The typical optical depth to photomeson interactions is $\tau_{p\gamma} \approx 0.14 \gamma_{p,4.5}^{1.3} \tau_{pp}^{\text{rad}}$, so that $\tau_{p\gamma} \gtrsim \tau_{pp}^{\text{rad}}$ for $\gamma_p \gtrsim 10^5$. The rotational energy lost by the SMNS prior to its collapse, $E_{\text{rot}} = 10^{53} E_{53}$ erg, is comparable to its total rotational energy [3]. Typically $M_{\text{SNR}} \sim 10 M_\odot$, implying $\beta_b \sim$

0.1 [3]. Even though initially β_b is probably $\ll 0.1$, the large pressure inside the PWB accelerates the SNR to a velocity such that its kinetic energy becomes $\sim E_{\text{rot}}$ [4, 5]. During the acceleration, Rayleigh-Taylor instabilities are expected to develop [5, 7] that may condense the SNR shell into clumps or filaments, as is seen in the Crab nebula. This increases the interface between the PWB and the now fragmented SNR, which helps increase χ_p .

The interaction with the pulsar wind drives a collisionless shock into the SNR shell [8], that crosses it on a time $\sim t_{\text{sd}}$, and can accelerate protons up to energies $\epsilon_{p,\text{max}} \sim 10^{16}$ eV, with a roughly flat $\epsilon_p^2(dN/d\epsilon_p)$ energy spectrum. These protons can collide with cold SNR protons, providing an additional channel for neutrino production. The neutrino energy spectrum will follow that of the protons, where $\epsilon_\nu \approx \epsilon_p/20$. The total energy in these protons is a fraction $f_p \sim 0.1 - 0.5$ of E_{rot} .

The pion luminosities in the different channels are

$$\frac{L_\pi^{p\gamma}}{\xi_p f_\pi^{p\gamma}} = \frac{L_\pi^{pp}}{\chi_p \xi_p f_\pi^{pp}} = \frac{L_\pi^{sh}}{f_p f_\pi^{pp}} = 3.2 \times 10^{46} \frac{E_{53}}{t_{\text{sd},-1}} \frac{\text{erg}}{\text{s}}, \quad (2)$$

where $\xi_p = (2/3)\xi_{p,2/3}$ is the fraction of wind energy in protons, and f_π^{pp} ($f_\pi^{p\gamma}$) is the fraction of the total proton energy lost to pion production through p-p collisions (p- γ interactions). A fraction $\eta_p \approx 0.2$ of the proton energy is lost to pion production in a single collision (interaction). The energy loss in multiple collisions can be approximated by a continuous process, where $\epsilon_p = \epsilon_{p,0} \exp(-\tau_i^\epsilon)$. On average, $n = -\ln(1 - \eta_p)^{-1} \approx 4.5$ collisions produce one e-folding, and $\tau_i^\epsilon = \tau_i/n \approx \tau_i/4.5$, where $i = pp, p\gamma$. This implies $f_\pi^i \approx 1 - \exp(-\tau_i^\epsilon) \approx 1 - \exp(-0.22\tau_i)$.

The shock going into the SNR shell can produce a tangled magnetic field with a strength similar to that inside the PWB. Thus, once a PWB proton enters the SNR shell, it is likely to stay there over a time $\gtrsim t_{\text{sd}}$. This can increase the effective value of τ_{pp} by up to a factor of $\sim [\beta_b(\Delta R/R_b)]^{-1} \sim 100$, compared to τ_{pp}^{rad} (Eq. 1). Therefore, $\tau_{pp} \gtrsim 1$ and $f_\pi^{pp} \sim 1$ for $t_{\text{sd}} \lesssim 1$ yr, $\tau_{p\gamma} \gtrsim 1$ and $f_\pi^{p\gamma} \sim 1$ for $t_{\text{sd}} \lesssim 0.04\gamma_{4.5}^{0.65}$ yr, and $\tau_{pp} \propto t_{\text{sd}}^{-2}$, $\tau_{p\gamma} \propto t_{\text{sd}}^{-2.1}$. We have $\tau_{p\gamma} \sim \tau_{pp}$ for $\gamma_p \sim 10^6 - 10^7$.

When $\tau_{p\gamma} > 1$, the PWB protons lose all their energy via photomeson interactions before they can reach R_b and collide with the SNR protons. When $\tau_{p\gamma} \sim 1$, $L_\pi^{pp} \sim L_\pi^{p\gamma}$, since the protons lose only $\sim 20\%$ of their energy in a single $p\gamma$ interaction, and in half of the cases are converted to neutrons, that can reach the SNR (since they are not effected by magnetic fields, and as long as $\gamma_p > R_b/c\tau_n \sim \beta_b t_{\text{sd}}/\tau_n$, where $\tau_n \approx 900$ s is the neutron mean lifetime) carrying $\sim 1/2$ of the PWB proton energy, and collide with the protons there (typically $\tau_{pp} \gtrsim \tau_{p\gamma}$).

So far, all the parameters were estimated at the time of the GRB, $t = t_{\text{sd}}$. However, since $\tau_i \propto t^{-a}$ where $a_{pp} = 3.5$ ($\tau_{pp} \propto t/R^3$) and $a_{p\gamma} = 2.2$ [5], even if $\tau_i(t_{\text{sd}}) < 1$, at early times, $t \lesssim t_i = t_{\text{sd}}\tau_i(t_{\text{sd}})^{1/a}$, $\tau_i > 1$ and $f_\pi^i \sim 1$. The mean value of f_π^i over $0 < t \lesssim t_{\text{sd}}$ is $\sim \tau_i(t_{\text{sd}})^{1/a}a/(a-1)$, and most of the neutrinos are emitted at $0 < t \lesssim t_i$.

The pions decay on a very short time scale, before they can suffer significant energy losses. The pion energy is divided roughly $1 : 1 : 1$ ($1 : 2 : 1$) between $\nu_\mu \bar{\nu}_\mu$, γ -rays and other products, for p-p (p- γ) reactions. The initial flavor ratio $\Phi_{\nu_e} : \Phi_{\nu_\mu} : \Phi_{\nu_\tau}$ is $1 : 2 : 0$, however, due to neutrino oscillations we expect a ratio of $1 : 1 : 1$ at the Earth. The $\nu_\mu \bar{\nu}_\mu$ fluence over the lifetime of the PWB is

$$\frac{8f_{\nu_\mu}^{p\gamma}}{\xi_p f_\pi^{p\gamma}} = \frac{6f_{\nu_\mu}^{pp}}{\chi_p \xi_p f_\pi^{pp}} = \frac{6f_{\nu_\mu}^{sh}}{f_p f_\pi^{pp}} = \frac{8.0 \times 10^{-5} E_{53}}{d_{L28}^2/(1+z)} \frac{\text{erg}}{\text{cm}^2}, \quad (3)$$

where z and $d_L = 10^{28} d_{L28}$ cm are the cosmological redshift and luminosity distance of the PWB, respectively. The average flux is just the fluence divided by t_{sd} , and the fluence in γ -rays is $f_\gamma^{p\gamma} = 4f_{\nu_\mu}^{p\gamma}$, $f_\gamma^{pp} = 2f_{\nu_\mu}^{pp}$, $f_\gamma^{sh} = 2f_{\nu_\mu}^{sh}$.

The average Thomson optical depth of the SNR shell is $\langle \tau_T \rangle = (\sigma_T/\sigma_{pp})\tau_{pp}^{\text{rad}} \approx 13\tau_{pp}^{\text{rad}} \approx (t_{\text{sd}}/0.4 \text{ yr})^{-2}$. Thereby $f_\pi^{pp} \sim 1$ requires $\tau_{pp} \sim 100\tau_{pp}^{\text{rad}} \gtrsim 1$ and $\langle \tau_T \rangle \gtrsim 0.1$, while $f_\pi^{p\gamma} \sim 1$ requires $\langle \tau_T \rangle \gtrsim 100\gamma_{4.5}^{-1.3}$. If $\tau_T > 1$, low energy photons cannot escape. High energy photons, above the Klein-Nishina limit ($\epsilon_\gamma > m_e c^2$) have a reduced cross section and can escape if $\epsilon_\gamma \gtrsim \tau_T m_e c^2 \approx 5t_{\text{sd},-1}^{-2}$ MeV. Since ϵ_γ is typically $\lesssim m_e c^2$ in the prompt GRB, it would not be detectable for a uniform SNR with $t_{\text{sd}} \lesssim 0.4$ yr. The synchrotron self-Compton GRB emission could still escape. However, the optical depth of high energy GRB photons to pair production with the low energy PWB photons is $\tau_{\gamma\gamma} \gtrsim 1$ for $\epsilon_\gamma \gtrsim 30t_{\text{sd},-1}^2$ MeV [5]. This leaves a narrow range of photon energies that can escape the PWB, $\epsilon_\gamma \sim 5 - 30$ MeV, for the parameter range where neutrino production is most efficient ($t_{\text{sd},-1} \lesssim 1$). If the SNR shell is clumpy, then $\tau_T \ll \langle \tau_T \rangle$ at the under-dense regions, relaxing the constraints related to τ_T . Moreover, $f_\pi^{pp} \sim 1$ for $t_{\text{sd}} \lesssim 1$ yr, so that efficient neutrino production via p-p collisions can occur while all photons with $\epsilon_\gamma \lesssim 3(t_{\text{sd}}/1 \text{ yr})^2$ GeV can escape for $1 \lesssim t_{\text{sd},-1} \lesssim 10$ (or $4 \lesssim t_{\text{sd},-1} \lesssim 10$ for a uniform shell).

Detecting the GRB emission helps distinguish between ν 's from the PWB and ν 's from the atmospheric background, since the PWB ν 's arrive from the same direction and are correlated in time with the GRB photons.

The π^0 's that are produced decay into $\epsilon_{\gamma,0} \sim \epsilon_p/10 \sim 3\gamma_{p,4.5}$ TeV photons. These high energy photons will produce pairs with the low energy PWB photons. The high energy e^\pm pairs will, in turn, upscatter low energy photons to high energies, etc., thus creating a pair cascade. This enables some photons to escape the system, even if initially $\tau_{\gamma\gamma}(\epsilon_{\gamma,0}) > 1$, after having undergone $\sim \log_2[\tau_{\gamma\gamma}(\epsilon_{\gamma,0})]$ scatterings, and shifted down to an energy $\epsilon_\gamma \sim \epsilon_{\gamma,0}/\tau_{\gamma\gamma}(\epsilon_{\gamma,0})$, such that $\tau_{\gamma\gamma}(R_b) \lesssim 1$ and $\tau_T \min(1, m_e c^2/\epsilon_\gamma) \lesssim 2$. Since $\tau_{\gamma\gamma}(R_b) \lesssim 1$ for $\epsilon_\gamma \gtrsim 90t_{\text{sd},-1}^2$ MeV, then for $2 \lesssim \tau_T \lesssim 180t_{\text{sd},-1}^2$ the escape of the photons is limited by $\tau_{\gamma\gamma}(R_b)$, and the photons that escape have a typical energy $\epsilon_\gamma \sim 90t_{\text{sd},-1}^2$ MeV. These photons should accompany the high energy neutrinos.

When the SMNS collapses to a black hole and triggers the GRB, the pulsar wind stops abruptly. However, the relativistic protons in the PWB or SNR can still produce pions, and the neutrino emission via p-p collisions would not stop abruptly after the GRB, but would rather decay over the expansion time, $\sim t_{\text{sd}}$, over which the hot protons lose most of their energy via adiabatic cooling, and τ_{pp} decreases. Neutrino emission via photomeson interactions typically decays on a shorter time scale since the PWB radiation field is produced by fast cooling electrons.

The neutrino spectrum (for each of the 3 ν flavors) for a mono-energetic proton distribution is given by [9]

$$\Phi_\nu \equiv \frac{dN_\nu}{d\epsilon_\nu dA dt} = K \frac{1}{4\epsilon_\nu} g_\pi \left(\frac{4\epsilon_\nu}{\epsilon_p} \right), \quad (4)$$

$$\begin{aligned} K &= \left\{ \frac{(1/2)L_\pi^{p\gamma}}{(2/3)L_\pi^{pp}} \right\} \times \frac{(1+z)^2}{\pi\epsilon_p d_L^2} \left(\int_0^1 g_\pi(x) dx \right)^{-1} \\ &= \left\{ \frac{2.7 f_\pi^{p\gamma}}{3.6 \chi_p f_\pi^{pp}} \right\} \times \frac{\xi_{p,2/3} E_{53} (1+z)^2}{\gamma_{p,4.5} t_{\text{sd},-1} d_{L28}^2} \frac{10^{-12}}{\text{s cm}^2}, \end{aligned} \quad (5)$$

where $g_\pi(x) = (1-x)^{3.5} + \exp(-18x)/1.34$, and ϵ_p ranges between $m_\pi c^2/4 \approx 25 \text{ MeV}$ (or $\sim \gamma_{\text{cm}} m_\pi c^2/4 \sim 3\gamma_{p,4.5}^{1/2} \text{ GeV}$ for p-p collisions) and $\epsilon_p/4 \approx 7.4\gamma_{p,4.5} \text{ TeV}$. The normalizations for $p\gamma$ and for pp are given separately. The original spectrum of the γ -rays produced in the π^0 decay should be roughly similar to that of the neutrinos.

The probability of detecting a muon neutrino in a terrestrial ice detector is $P_{\nu\mu} \approx 1.3 \times 10^{-6} (\epsilon_\nu/\text{TeV})^\beta$, with $\beta = 2$ for $\epsilon_\nu < 1 \text{ TeV}$ and $\beta = 1$ for $\epsilon_\nu > 1 \text{ TeV}$ [10]. For $\epsilon_\nu > 10^{15} \text{ eV}$, $P_{\nu\mu} \propto \epsilon_\nu^{1/2}$. The expected number of neutrino events during the life time of the PWB is

$$N_\mu = A \min[(1+z)t_{\text{sd}}, T] \int \Phi_{\nu\mu}(\epsilon_\nu) P_{\nu\mu}(\epsilon_\nu) d\epsilon_\nu, \quad (6)$$

$$N_\mu^{p\gamma} = 0.05 f_\pi^{p\gamma} \xi_{p,2/3} E_{53} (1+z) d_{L28}^{-2} (A/\text{km}^2), \quad (7)$$

$$N_\mu^{pp} = 0.07 f_\pi^{pp} \chi_p \xi_{p,2/3} E_{53} (1+z) d_{L28}^{-2} (A/\text{km}^2), \quad (8)$$

$$N_\mu^{sh} = 0.05 f_\pi^{pp} f_p E_{53} (1+z) d_{L28}^{-2} (A/\text{km}^2), \quad (9)$$

where A and $T \sim 1 \text{ yr}$ are the area and integration time of the detector, and we have assumed $T > (1+z)t_{\text{sd}}$. These expected numbers of events are valid when absorption in the Earth is not important, and apply to GRBs that point at the detector horizontally, and to $\epsilon_\nu < 100 \text{ TeV}$ neutrinos from GRBs at the hemisphere opposite of the detector. Absorption may reduce the number of $\epsilon_\nu > 100 \text{ TeV}$ events, which are expected only for $\gamma_p \gtrsim 10^6$.

Implications. The atmospheric neutrino background flux is $\Phi_\nu^{\text{bkg}} \sim 10^{-7} (\epsilon_\nu/\text{TeV})^{-2.5} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. The angular resolution, θ , of the planned neutrino telescopes ICECUBE and NEMO will be 0.7° [11] and 0.3° [12], respectively. The number of background events above a neutrino energy ϵ_ν , in the range $\sim 1 - 10^3 \text{ TeV}$, is $N_{\text{bkg}}(> \epsilon_\nu) \sim 10^{-2} (\theta/0.3^\circ)^2 (\epsilon_\nu/10 \text{ TeV})^{-1.5} (t/0.1 \text{ yr})$ per angular resolution element, over a time t . There is

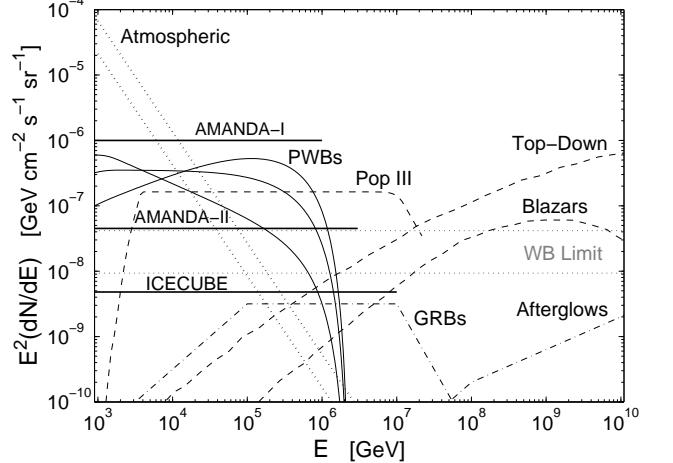


FIG. 1: The diffuse neutrino flux from different sources is compared to the sensitivities of present and future telescopes. The expected flux from PWBs that host GRBs, due to the $p\gamma$ and pp mechanisms (see text for details), is shown for 3 different distributions of γ_p among the different PWBs (thin solid lines): $dPr/d\log(\gamma_p) \propto \gamma_p^\alpha$, $10^4 \leq \gamma_p \leq 10^7$, $\alpha = -0.5, 0, 0.5$. The dotted lines show the Waxman-Bahcall cosmic-ray limit.

better signal to noise ratio for larger $\epsilon_p = \gamma_p m_p c^2$, which are possible for the parameter range where neutrino emission is most efficient ($t_{\text{sd}} \lesssim 1 \text{ yr}$). Thus, the neutrino signal from a single PWB with $t_{\text{sd}} \sim 0.1 \text{ yr}$, at $z \sim 1$, could be detected with high significance above the background.

GRBs that occur inside spherical PWBs with $t_{\text{sd}} \sim 0.1 - 1 \text{ yr}$ would have a peculiar and short lived afterglow emission [5] (such events may be related to X-ray flashes, for which no afterglow emission was detected so far). Since they occur for a wide range of t_{sd} values, we expect their rate to be similar to that of typical GRBs (i.e. $\sim 10^3 \text{ yr}^{-1}$ that are beamed towards us and $\sim 10^5 \text{ yr}^{-1}$ that are beamed away from us). Therefore, a km^2 neutrino detector should detect $\sim 100 \text{ yr}^{-1}$ neutrinos correlated with GRBs. Furthermore, $\sim 10 \text{ yr}^{-1}$ close by ($z \lesssim 0.1$) PWBs are expected, where each PWB will produce at least several events, and would thereby be above the atmospheric background, even if the GRB cannot be detected in γ -rays, as it is beamed away from us or since $\tau_T > 1$ for $t_{\text{sd}} \lesssim 0.1 \text{ yr}$. In the limit of very small t_{sd} (\lesssim a few hours), this reduces to the chocked GRBs in the collapsar model [13].

The diffuse muon neutrino flux from PWBs that host GRBs is shown in Fig. 1, for the $p\gamma + pp$ mechanisms, using the flux normalization from Eq. (5) with $f_\pi^{p\gamma} = f_\pi^{pp} = 2\chi_p = 1$, and a rate of 10^5 yr^{-1} at $z \sim 1$. It is slightly below the existing upper bound on the diffuse flux established by AMANDA [14], and may be detected by AMANDA II. It is above the Waxman-Bahcall (WB) cosmic ray limit [15]. This is not a problem as these are obscured sources. Since the diffuse flux is the sum of the contributions from all PWBs, its energy spectrum

reflects the distribution of γ_p among the different PWBs (see Fig. 1), and could teach us about this distribution. The spectrum is typically quite different from that of other sources, which would make it easier to identify if it is detected. The diffuse flux from the *sh* mechanism is $\epsilon_\nu^2 \Phi_\nu \approx 10^{-7} f_p \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, and extends over $\epsilon_\nu \sim 10^8 - 10^{15}$ eV. The exact value of the diffuse flux for our 3 neutrino production mechanisms (*p* γ , *pp* and *sh*), is somewhat uncertain; the largest uncertainty is for *pp*.

Our modeling of the neutrino emission from PWBs that host GRBs also applies to normal PWBs, like the Crab or Vela, when they are very young and have not spun down considerably, $t \lesssim t_{\text{sd}}$. The main differences are that $E_{\text{rot}} \sim 10^{51}$ erg, $\beta_b \sim 0.01$, $t_{\text{sd}} \sim 100$ yr and $R_b \propto t$. Since there are ~ 100 times more regular PWBs, the total energy budget is comparable. Photomeson interactions become unimportant, but $a_{\text{pp}} = 2$ and $f_\pi^{\text{pp}} \sim 1$ at $t \lesssim t_{\text{pp}} \sim 20$ yr so that f_π^{pp} time averaged over $0 < t \lesssim t_{\text{sd}}$ is $\langle f_\pi^{\text{pp}} \rangle \sim 2(t_{\text{pp}}/t_{\text{sd}}) \sim 0.4$, and neutrino production via p-p collisions is rather efficient. The diffuse flux from normal PWBs is therefore expected to be comparable, to that from PWBs that host GRBs. The neutrino emission from normal PWBs was recently calculated [17] assuming larger proton energies, resulting in a diffuse neutrino spectrum extending to higher energies but with similar $\epsilon_\nu^2 (dN/d\epsilon_\nu)$ peak flux levels. Since normal PWBs are much more common, galactic PWBs like the Crab and Vela might be detected by planned km² detectors even though $t > t_{\text{sd}}$ for these sources [18].

In order for GRBs to have typical afterglow emission, we need $t_{\text{sd}} \gtrsim 20$ yr, $\gamma_p \lesssim 10^5$ (for spherical PWBs) [5], implying $f_\pi^{\text{p}\gamma} < f_\pi^{\text{pp}}$, $\langle f_\pi^{\text{pp}} \rangle \lesssim 0.25$ and $N_\mu \sim 0.01 \text{ km}^{-2}$ events per PWB. The expected detection rate of $\nu_\mu \bar{\nu}_\mu$ from all PWBs hosting GRBs with typical afterglows, that are detectable in γ -rays (i.e. pointed towards us), is $\sim 10 \text{ km}^{-2} \text{ yr}^{-1}$. However, most of these ν 's will arrive $\sim 20(1+z)$ yr before the GRB, at $0 < t \lesssim 4(1+z)$ yr. Around the time of the GRB $f_\pi^{\text{pp}} \sim 10^{-3}$ and the rate of events is $N_\mu \sim 10^{-4} \text{ km}^{-2} \text{ yr}^{-1}$. Since the ν 's from the PWB are emitted isotropically, the diffuse neutrino flux from these sources, $\epsilon_\nu^2 \Phi_\nu \sim 2 \times 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, is dominated by GRBs that point away from us. This diffuse flux is somewhat lower than that expected for PWBs with $t_{\text{sd}} \lesssim 1$ yr and normal PWBs, and is below the atmospheric neutrino background (since $\gamma_p \lesssim 10^5$).

The expected number of events per PWB with $t_{\text{sd}} \lesssim 1$ yr at $z \sim 1$ is $\sim 0.1 \text{ km}^{-2}$, with neutrino energies $\epsilon_\nu \sim 1 - 10^3$ TeV. These ν 's are emitted over a time $t_{\text{sd}} \sim 0.01 - 1$ yr before the GRB, and the emission decays over a similar time after the GRB. This emission is therefore easily distinguishable from ν 's emitted either simultaneously with the GRB [19] or $\lesssim 100$ s before the GRB [13], as predicted for the collapsar model of GRBs. The number of neutrino events from the PWB is at least

an order of magnitude larger than from the prompt GRB, and is much larger than from the afterglow [20]. Therefore, this GRB precursor neutrino signal is one of the best candidates for an early detection with the planned km² neutrino telescopes [21]. The detection of a neutrino signal from a PWB can serve to distinguish between the different progenitor models for GRBs.

Acknowledgments. We thank P. Goldreich, A. Königl, E. Waxman, A. Loeb, P. Mészáros and C. Peña-Garay for useful discussions. JG is supported by the Institute for Advanced Study, funds for natural sciences. DG thanks the IAS in Princeton, for the hospitality and the nice working atmosphere during the course of this work.

-
- [1] J. Bloom, R. Kulkarni, and G. Djorgovski, Astron. J. **123**, 1111 (2002).
 - [2] S. Woosley, Astrophys. J. **405**, 273 (1993); B. Paczyński, Astrophys. J. **494**, L45 (1998).
 - [3] M. Vietri, and L. Stella, Astrophys. J. **507**, L45 (1998).
 - [4] A. Königl and J. Granot, Astrophys. J. **574**, 134 (2002); J. Granot and D. Guetta, astro-ph/0211136, (2002).
 - [5] D. Guetta and J. Granot, Mon. Not. R. Astron. Soc. **340**, 115 (2003).
 - [6] I.S. McLean, C. Aspin, and H. Reitsema, Nature **304**, 243 (1983); P. Hickson and S. van den Bergh, Astrophys. J. **365**, 224 (1990).
 - [7] S. Inoue, D. Guetta, and F. Pacini, Astrophys. J. **583**, 379 (2003).
 - [8] S. Razzaque, P. Mészáros and E. Waxman, astro-ph/0212536, (2003).
 - [9] P. Blasi, Astropart. Phys. **15**, 223 (2001).
 - [10] T. Gaisser, F. Halzen, and T. Stanev, Phys. Rep. **258**, 173 (1995).
 - [11] A. Karle *et al.*, astro-ph/0209556 (2002).
 - [12] G. Riccobene *et al.*, in “Hamburg 2001, Methodical aspects of underwater/ice neutrino telescopes”, p.61.
 - [13] P. Mészáros and E. Waxman, Phys. Rev. Lett., **87**, 1002 (2001).
 - [14] E. Andres *et al.*, Nature (London) **410**, 441 (2001).
 - [15] E. Waxman and J.N. Bahcall, Phys. Rev. D **66** 023002 (1999).
 - [16] R. Schneider, D. Guetta, and A. Ferrara, Mon. Not. R. Astron. Soc. **334**, 173 (2002).
 - [17] W. Bednarek, Astron. Astrophys. **378**, L49 (2001); J.H. Beall and W. Bednarek, Astrophys. J. **569**, 343 (2002).
 - [18] D. Guetta and E. Amato, astro-ph/0209537 (2002); E. Amato, D. Guetta, and P. Blasi, A&A submitted (2002).
 - [19] E. Waxman and J.N. Bahcall, Phys. Rev. Lett., **78**, 2292 (1997); D. Guetta, M. Spada, and E. Waxman, Astrophys. J. **559**, 101 (2001).
 - [20] E. Waxman and J.N. Bahcall, Astrophys. J. **541**, 707 (2000).
 - [21] F. Halzen, *Proceedings of the International Symposium on High Energy Gamma-Ray Astronomy, Heidelberg, 2000*, AIP Conf. Proc. No. 558 (AIP, New-York, 2001).