Ultrahigh Energy Neutrinos from Gamma Ray Bursts

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Protons accelerated to high energies in the relativistic shocks that generate gamma ray bursts photoproduce pions, and then neutrinos *in situ*. I show that ultrahigh energy neutrinos ($>10^{19}$ eV) are produced during the burst and the afterglow. A larger flux, also from bursts, is generated via photoproduction off cosmic microwave background photons in flight but is not correlated with currently observable bursts, appearing as a bright background. Adiabatic and synchrotron losses from protons, pions, and muons are negligible. Temporal and directional coincidences with bursts detected by satellites can separate correlated neutrinos from the background. [S0031-9007(98)05884-0]

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The recent discovery of gamma ray bursts' (GRBs) afterglows [1], accurately predicted by theoretical models [2], and disappearance of flares in the radio flux [3] have bolstered our confidence in the correctness of the fireball model [4]. According to the model, bursts are generated when two or more hyperrelativistic shells, issued by an as of yet unspecified source, collide with each other. A relativistic shock forms, where nonthermal electrons are accelerated and then dissipate their internal energy through synchrotron (and possibly inverse Compton) radiation. After the internal collision, the resulting shell will collide with the interstellar medium (ISM), thereby forming a second, relativistic shock, which will continue to expand into the ISM even after the burst proper, thus generating the afterglow.

The relativistic environment surrounding the above-mentioned shock is ideal for the acceleration of protons to high energies [5]. The highest energy that can be attained is [6]

$$\epsilon_{\max} = (10^{20}\ \mathrm{eV})\theta^{-5/3}\eta_2^{1/3}E_{52}^{1/3}n_1^{1/6}. \qquad (1)$$

Here the explosion energy is $E = E_{52}10^{52}$ erg, the expansion Lorenz factor $\eta = \eta_2 10^2$, the beaming angle θ, and the ISM number density $n = n_1\ \mathrm{cm}^{-3}$. Currently popular values inferred from afterglows are $\theta \approx 1/3$, $E_{52} \approx 1$ [7] implying $\epsilon_{\max} \approx 6 \times 10^{20}$ eV.

When energetic protons interact with synchrotron photons emitted by electrons, they can produce pions; the decay of charged pions then produces electron and muon neutrinos. In this Letter, I consider only ultrahigh energy neutrinos (UHENs, $>10^{19}$ eV) and neglect lower energy ones [8,9].

Expected fluxes of ultrahigh energy neutrinos.—Let us consider a burst of duration T seconds; according to the fireball theory for external shocks [4], this occurs at a distance $r_e = \eta^2 cT$ from the unspecified burst source, and, in the shell frame, the shell thickness is $\delta r = \eta cT$. The total energy density in the shell frame is then $U_\gamma = L_\gamma/4\pi r_e^2 c\eta^2$; inserting this into Eq. (3) of Ref. [9] I find the inverse of the time scale for photopion losses, t_π^{-1}; multiplying by the time the proton spends in the shell, in the shell frame ($= \eta T$), I find that, for a proton of energy ϵ_p as seen by an outside observer, immersed in a radiation field with turnover frequency $\epsilon_\gamma \approx 1$ MeV, beyond which the spectrum significantly steepens, the total probability for photopion production is

$$f_\pi^{(0)} = 0.03\eta_2^{-4}\frac{L_\gamma}{10^{50}\ \mathrm{erg\,s^{-1}}}\frac{1\ \mathrm{MeV}}{\epsilon_\gamma}\frac{10\ \mathrm{s}}{T}, \qquad (2)$$

for proton energies exceeding [9] $\epsilon_b = (2 \times 10^{15}\ \mathrm{eV})\eta_2^2(1\ \mathrm{MeV}/\epsilon_\gamma)$. I have used here a typical luminosity for long-lasting bursts, such as those with the ISM are thought to be, and a typical long duration.

Experiments such as AIRWATCH [10,11] have appreciable detection efficiencies for neutrinos exceeding the threshold energy $\epsilon_{\nu,l} \approx 10^{19}$ eV. Since neutrinos emitted through photopion processes typically carry away a fraction $q \approx 0.05$ of the proton energy (losses will be discussed later), I have to compute the energy release in protons with energies exceeding $\epsilon_l = \epsilon_{\nu,l}/q \approx 2 \times 10^{20}$ eV. The spectrum in high energy protons accelerated at relativistic shocks is roughly $\propto \epsilon^{-2}$, and defining the total energy released in ultrahigh energy cosmic rays (UHECRs, $\epsilon > \epsilon_1 = 10^{19}$ eV) as E_U, I have that the whole energy in UHECRs which can emit detectable UHENs (i.e., $\epsilon > \epsilon_l = \epsilon_{\nu,l}/q$) is $E_U \ln\epsilon_{\max}/\epsilon_l/\ln\epsilon_{\max}/\epsilon_1$. Only a fraction $2qf_\pi^{(0)}$ of this ends up in UHENs. Thus the total energy emitted in UHENs is

$$E_\nu = 2qf_\pi^{(0)}E_U\frac{\ln\epsilon_{\max}/\epsilon_l}{\ln\epsilon_{\max}/\epsilon_1}. \qquad (3)$$

The total flux of UHENs can then be obtained by integrating the flux over all distances:

$$\dot n_\nu = \dot n_{\mathrm{GRB}}\frac{E_\nu}{\bar\epsilon_\nu}\frac{cK}{H_\circ} = 2qf_\pi^{(0)}\frac{\dot n_{\mathrm{GRB}}E_U}{\bar\epsilon_\nu\ln\epsilon_{\max}/\epsilon_1}\frac{cK}{H_\circ}, \qquad (4)$$

where $\bar\epsilon_\nu = \epsilon_{\nu,l}\ln\epsilon_{\max}/\epsilon_l$ is the average neutrino energy from this process, and the delicate factor K, to be discussed later on, takes account of such unknowns as the GRBs' redshift and luminosity distributions, and the details of the cosmological model.

The dependence of these neutrino rates upon physical factors of individual bursts, such as η, L_γ, and ϵ_γ, is all contained within $f_\pi^{(0)}$ [Eq. (2)], and will be omitted from now on for the sake of conciseness. The key factor in the above equation is $\dot{E} = \dot{n}_{\rm GRB} E_U$, the injection rate per unit volume of nonthermal proton energy, because the others either are known or enter logarithmically. It is known already that, under the hypothesis that GRBs emit about as much energy in the form of γ-band photons and UHECRs, the flux of UHECRs at Earth is reproduced to within a factor of ≈ 3 [6,12]. I show later that UHECRs are accelerated within afterglows, which dominate the energy balance by about a factor of 10. Then, if the same rough equipartition between radiation and UHECRs holds during the afterglow, the total energy release required to explain the UHECRs' flux seen at Earth is correctly accounted for.

That the equipartition argument yields a correct answer can be checked by considering that the observed burst rate (≈ 30 yr^{-1} Gpc^{-3}) times the observed energy release including afterglow ($\approx 10^{52}$ erg) yields an energy release rate, 3×10^{44} erg yr^{-1} Mpc^{-3}, very close to that deduced [13] without explicit reference to the nature of the sources of UHECRs: $\dot{E} = 4.5 \times 10^{44}$ erg yr^{-1} Mpc^{-3} for the restricted range of proton energies $10^{19} < \epsilon < 10^{21}$ eV.

Thus, under the equipartition assumption I can use the energy release necessary to explain Earth observations as the energy released in UHECRs by GRBs; taking $\epsilon_1 = 10^{19}$ eV, and defining $h \equiv H_\circ/50$ km s^{-1} Mpc^{-1}, I obtain

$$\dot{n}_\nu = 2.2 \times 10^{-11} \frac{f_\pi^{(0)}}{0.03} h^{-1} K \text{ yr}^{-1} \text{cm}^{-2}. \qquad (5)$$

The flux determined above is *not* the whole flux of UHENs from GRBs detectable at Earth. The reason is that *all* UHECRs eventually will emit UHENs by photoproduction with photons of the cosmic microwave background, the so-called Greisen-Zatsepin-Kuz'min effect [14]. This neutrino production will occur in flight, rather than *in situ,* with a typical mean free path of order ≈ 10 Mpc. As they cross this distance, UHECRs are slowed down in their progress toward Earth by the turbulent intergalactic magnetic field. While estimates of this delay are very uncertain because of our ignorance of both strength and correlation length of the field, they still all agree in putting it above 10^2–10^3 yr, i.e., in washing away any correlation with GRBs observed within our lifetimes. The total flux of background UHENs $\dot{n}_\nu^{(bg)}$, uncorrelated with observable GRBs, is thus

$$\dot{n}_\nu^{(bg)} = \frac{\dot{n}_\nu}{f_\pi^{(0)}} = 7.3 \times 10^{-10} K h^{-1} \text{ yr}^{-1} \text{cm}^{-2}. \qquad (6)$$

The computation of the factor K requires an explicit hypothesis on the distribution of redshifts and luminosities of GRBs. A detailed computation [15] for idealized redshift distributions of standard candles has been carried out. Comparison of Table I of Ref. [15] with the above equation shows that their computed values of K vary by a factor of 3 either side of the value I obtained.

Afterglows.—I show now that acceleration of protons to the highest energies does continue unabated through most of the afterglow. After the burst, the relativistic shell keeps plowing through the interstellar medium, sweeping up more matter and decelerating. The shell Lorenz factor scales as $\eta = 6.4 n_1^{-1/8} E_{52}^{1/8} t_d^{-s}$, where t_d is the postburst time in days neglecting redshift. For adiabatic expansion $s = 3/8$ [7] while $s = 3/7$ for radiative expansion [16]. The maximum energy of nonthermal protons [Eq. (1)] decreases very slowly with time, as $t^{-1/8}$ or $t^{-1/7}$ for adiabatic or radiative expansion, respectively. In particular, for the best values $E_{52} = 1$ and $\theta = 1/3$, production of UHENs ceases (i.e., $\epsilon_{\max} < \epsilon_{\nu,l}/q$) for $\eta < 3.3$, corresponding to ≈ 6 d after the burst, nearly independent of whether expansion is adiabatic or radiative.

I also have to check that the probability of photopion production through the afterglow does not change by much from the value computed [Eq. (2)] for the burst proper. This requires some discussion. From observations [17] we know that the instantaneous luminosity scales as $t^{-\alpha}$, with $\alpha \approx 1.1$. Also, we know from fireball theory that $T \propto r/\eta^2$, and that $r \propto \eta^{-v}$, where $v = 2/3$ for adiabatic or $v = 1/3$ for radiative expansion. So the factor $L_\gamma \eta^{-4} T^{-1} \propto t^{s(2-v)-\alpha}$. However, it is more difficult to establish the variation of the spectral break ϵ_γ with time, which is not currently observed. It seems however that, given the general softening of radiation within the afterglow, it is unlikely to remain constant; a more likely hypothesis is that it decreases slowly with time. Phenomenologically, one may take $\epsilon_\gamma \propto \eta^q$. The limits within which q is expected to vary are easy to ascertain. On the one hand, $q = 0$ would imply that the cutoff does not evolve, despite the shell slowdown. This is both unphysical, and contrary to some weak evidence that it may decrease within the burst proper. On the other hand, the synchrotron turn-on frequency (i.e., that beyond which synchrotron emits most of the energy) scales as $\propto \gamma^4$; in the afterglow model, all emission is due to synchrotron processes. However, the very long lasting optical emission from GRB 970228 seems to imply a very extended synchrotron spectrum, so that $q = 4$ may be considered an upper limit. Thus $0 < q < 4$. I then obtain $\epsilon_\gamma \propto \eta^q \propto t^{-qs}$. From Eq. (2) I then find $f_\pi^{(0)} \propto t^z$, with $z = s(q + 2 - v) - \alpha$. Only taking a small value, $q = 1$, and then only for adiabatic expansion, do I find $z < 0$. Thus we see that overall, the probability $f_\pi^{(0)}$ is unlikely to decrease: if anything, $f_\pi^{(0)}$ is likely to *increase* through the afterglow, so that our estimates are, most likely, lower limits. Thus, by taking in the previous section $f_\pi^{(0)} \approx$ const, I did not overestimate the neutrino fluxes. An interesting consequence of this is that the luminosity in UHENs scales approximately as $L_\nu = f_\pi^{(0)} L_\gamma \propto t^{-1}$, which means that equal logarithmic post-burst-time intervals are equally likely to contain an observable neutrino.

Losses.—Proton losses (synchrotron and photohadronic) were shown to be negligible in Ref. [6]: the proton energy is limited by the size of the shell. I have to consider however adiabatic and synchrotron losses by pions and muons, which could considerably limit the highest energies achieved by neutrinos.

Adiabatic losses are significant whenever the particle lifetime $\gamma_\star \tau_\star$ in the shell frame exceeds the characteristic time scale on which the magnetic field decreases because of the shell expansion; here $\star$ indicates either pion or muon, and $\tau_\pi = 2.6 \times 10^{-8}$ s and $\tau_\mu = 2.2 \times 10^{-6}$ s are their respective lifetimes in their rest frames. The limiting Lorenz factors are found when the two time scales match, i.e., when $\gamma_\star \tau_\star = 2B/\dot{B}$. Following Ref. [18] I take $B \propto R^{-2}$, where R is the transverse dimension of the causally connected region, which, following Refs. [18,19] is given by r/η, even through the afterglow, and obviously $\dot{R} \approx c$. Then I obtain the limiting Lorenz factor in the observer frame $\gamma_l = r/c\tau_\star$, independent of whether the afterglow is adiabatic or radiative. Scaling $r \equiv x r_i$ by its lowest value, that at the moment of the burst proper, $r_i = 2\eta^2 cT = (6 \times 10^{15}\ \mathrm{cm})\eta_2^2 (T/10\ \mathrm{s})$, I find $\gamma_\pi = 10^{13} x$, and $\gamma_\mu = 10^{11} x$ for $x \geq 1$, both exceeding the proton's Lorenz factor in Eq. (1). For protons with Lorenz factor γ_p in the shell frame, the synchrotron cooling time is $t_s = 1\ \mathrm{yr}\ (10^{11}/\gamma_p)(1G/B)^2$. For synchrotron losses to be negligible, the Lorenz factor of pions and muons must not exceed the limiting $\gamma_\star$ given by [18] $\gamma_p t_s (m_\star/m_p)^3 = \gamma_\star^2 \tau_\star$, where $m_\star/m_p \approx 0.1$ for both pions and muons. From Ref. [19], $B \approx 1G\eta_2^{1/2}$ for the external shock scenario and the afterglow. Transforming back to the observer frame I find $\gamma_\pi = 3 \times 10^{13} \eta_2^{1/2}$, and $\gamma_\mu = 3 \times 10^{12} \eta_2^{1/2}$. Both exceed the Lorenz factors of the proton [Eq. (1)]. Thus adiabatic and synchrotron losses of pions and muons do not affect the arguments of this paper.

Detectability.—Currently planned experiments such as AIRWATCH [11] will monitor from satellites fluorescent light profiles of cosmic ray cascades over areas of order $A = A_6 \times 10^6\ \mathrm{km}^2$, with $A_6 \approx 1$. The interaction probability for UHENs is proportional to the monitored column density ($10^3\ \mathrm{g\,cm^{-2}}$); it also depends on the extrapolation of the cross section to currently unobserved energies, but typical values are $\sigma \approx 3 \times 10^{-32}\ \mathrm{cm}^2\ (\epsilon_\nu/10^{19}\ \mathrm{eV})^{1/2}$ [11,20]. Once the neutrino has interacted, a detection efficiency close to 1 for UHENs is reported by feasibility studies, at energies $\epsilon_\nu \approx 10^{19}$ eV, yielding interaction probabilities of $P_\nu \approx 3 \times 10^{-5}$. This translates into an expected number of detectable UHENs of

$$\dot{N}_\nu = (7KA_6\ \mathrm{yr})^{-1} \frac{f_\pi^{(0)}}{0.03}\, h^{-1}. \tag{7}$$

At the same time, we expect a background flux from Eq. (6) given by

$$\dot{N}_\nu^{(bg)} = (200KA_6\ \mathrm{yr}^{-1}) h^{-1}. \tag{8}$$

It is safe to state that Eqs. (7) and (8) have large errors, due to our ignorance both of the neutrino-nucleon cross section at these large, and untested neutrino energies, and to the sources' redshift distribution (the parameter K).

The requirement that the expected number of neutrinos correlated with bursts be large enough to ensure detection within a year of operation can be turned, using Eq. (2), into a requirement on the area covered by the experiment:

$$A_6 \gg 0.2K^{-1}\eta_2^4 \frac{10^{50}\ \mathrm{erg\,s^{-1}}}{L_\gamma} \frac{\epsilon_\gamma}{1\ \mathrm{MeV}} \frac{T}{10\ \mathrm{s}}. \tag{9}$$

Detection of correlated neutrinos seems possible provided bursts due to external shocks are well represented by the average values employed above.

The flux of Eq. (8) of an event per day, completely uncorrelated with currently observable bursts, obliges us to face the issue whether we can distinguish from casual associations a much smaller ($f_\pi^{(0)} \approx 0.03$) flux which is indeed correlated (to within the afterglow duration, $\approx$6 d) with simultaneously observed bursts. The answer would be an easy yes if UHENs arrived simultaneously with the burst proper, because we could then use very tight directional and temporal coincidences to distinguish the signal from background noise. But, since I argued above that most neutrinos are produced during the afterglow which is observed to last for a few days after the burst, it has to be ascertained whether this can still be done. The answer is a qualified yes.

Suppose I can measure the directions of arrival of neutrinos and GRBs with a combined directional error of β. Calling $\dot{N}_{\mathrm{GRB}}$ the rate of detection of GRBs in the γ ray, the probability of casual association P_c is

$$P_c = \dot{N}_{\mathrm{GRB}} \delta t \frac{\beta^2}{4} = 4 \times 10^{-4} \frac{\delta t}{6d} \left(\frac{\beta}{1^\circ}\right)^2, \tag{10}$$

where I used $\dot{N}_{\mathrm{GRB}} = 300\ \mathrm{yr}^{-1}$, typical of burst and transient source experiment (BATSE) [21]. The rate of appearance of casual associations is $\dot{N}_\nu^{(bg)} P_c \approx 0.08\ \mathrm{yr}^{-1}$, reassuringly smaller than the rate of physical associations [Eq. (7)]. This condition, $P_c \dot{N}_\nu^{(bg)} \ll \dot{N}_\nu$, can also be written as

$$f_\pi^{(0)} \gg \dot{N}_{\mathrm{GRB}} \delta t \frac{\beta^2}{4} \approx 4 \times 10^{-4} \frac{\delta t}{6\ \mathrm{d}} \left(\frac{\beta}{1^\circ}\right)^2. \tag{11}$$

Comparison with Eq. (2) shows that the experiment can be done, provided angular errors of order

$$\beta \ll 7^\circ \left(\frac{L_\gamma}{10^{50}\ \mathrm{erg}\ \eta_2^4} \frac{\epsilon_\gamma}{1\ \mathrm{MeV}} \frac{T}{10\ \mathrm{s}} \frac{\delta t}{6\ \mathrm{d}} \right)^{1/2} \tag{12}$$

can be achieved.

Lastly, since the rate of Eq. (8) is comparable to that of GRBs detected by BATSE [21,22], measurement of dipole and quadrupole moments of the neutrino distribution may just be doable. The spectrum of UHENs (both background and correlated ones) will follow accurately that of UHECRs in GRBs, since the probability of photopion losses [Eq. (2)] is independent of proton energy. It should thus be possible to see the cutoff in the UHECR spectrum, Eq. (1), as mirrored in neutrinos.

Discussion.—The acceleration of UHECRs in GRBs is so effective that it has been proposed [6,12] that the whole flux of UHECRs at Earth comes from these events. However, since UHECRs can take $\approx 10^3$ yr more than photons to reach us from the closest GRBs, it will be impossible, within our finite lifespans, to establish a direct association between GRBs and UHECRs. A sure hint should be that no active galactic nuclei (AGNs), or peculiar object, ought to be seen close to the direction of arrivals of UHECRs, but this expectation is not unique to this model, and is common, for instance, to strings. On the other hand, a UHEN of $\approx 10^{19}$ eV would accumulate with respect to photons emitted simultaneously a delay of only $\approx 10^{-19}$ s$(m_\nu/10\text{ eV})$ in coming from even a distance of $c/H_\circ$, the radius of the Universe, with m_ν the neutrino mass. Thus it would be essentially simultaneous to photons (including afterglow's photons). Furthermore, the UHENs can be produced only by the highest energy protons, those, in other words, well beyond the Greisen-Zat'sepin-Kuzmin limit. Thus the UHENs produced *in situ* represent the surest smoking gun that UHECRs are accelerated in GRBs. Different, electromagnetic signatures of the association of UHECRs and GRBs have been discussed in Refs. [23,24].

In short, what detection of UHENs will allow us to do is to circumvent the shortsightedness imposed upon us by the Greisen-Zatsepin-Kuz'min limit, and to investigate the generation of the highest energy cosmic rays throughout the whole Universe. The only alternative sources of UHENs proposed so far are cosmic strings [25] and AGNs [26] which are also the only alternative sources proposed so far for UHECRs. I have discussed here that a fraction of all UHENs [Eq. (2)] should show an association with simultaneously observed GRBs, if they indeed originate in GRBs. Thus a potentially clear-cut way to distinguish between the three competing theories is available and it might, perhaps, already be accessible to AIRWATCH-class experiments.

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