Neutrino Balls and Gamma-Ray Bursts

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ABSTRACT

We propose a mechanism by which the neutrino emission from a supernova-type explosion can be converted into a gamma-ray burst of total energy $\sim 10^{50}$ ergs. This occurs naturally if the explosion is situated inside a ball of trapped neutrinos, which in turn may lie at a galactic core. There are possible unique signatures of this scenario.

1. INTRODUCTION

The BATSE experiment on board Compton-Gamma Ray Observatory has unequivocally demonstrated that gamma-ray bursts (GRBs) cannot originate from a local disk distribution (Meegan et al. 1992). Although a distribution compatible with an extended galactic halo cannot at this time be ruled out, this recent data has spurred renewed speculation that GRBs have a cosmological origin. The detectability threshold of BATSE is $\sim 10^{-7}$ ergs cm$^{-2}$, and GRBs are observed with fluences extending from this threshold up to $\sim 10^{-3}$ ergs cm$^{-2}$. A detected fluence of $10^{-5}$ ergs cm$^{-2}$ at a distance of 1 Gpc corresponds to an isotropic energy output of $\sim 10^{50}$ ergs. Cosmological models which purport to account for the observed GRB characteristics require the
rapid release of this amount of energy, typically within a source region of dimensions \(\lesssim 100\) km in order to be consistent with variability timescales.

Neutrino balls (Holdom 1987) are large spherical regions of trapped degenerate neutrino gas. Just like other cosmological defects such as cosmic strings and monopoles, neutrino balls are remnants of symmetry breaking processes occurring in the very early universe. They have a lower mass bound in the supermassive range and would thus be ideal seeds for structure formation. Neutrino balls in an accretion mode have been associated with the large luminosities of quasars (Dolgov and Markin 1990,1991).

Right-handed neutrinos may be trapped in a region of space within which the local vacuum structure conveys upon them a light Majorana mass. Outside the trapped region the right-handed neutrinos possess a large Majorana mass. The converse is true for left-handed neutrinos. Such a circumstance can arise in left-right symmetric electroweak theories. Subsequent to a phase transition in the early universe, the spontaneous breaking of parity leads to the occurrence of domain walls separating the left and right vacua. The neutrino mass difference on either side of the wall forbids neutrino transport from one side of the wall to the other. All other fermions have the same mass on both sides. The infinite domain walls must disappear and the closed walls quickly damp to their equilibrium (spherical) form; these are the neutrino balls. The maximum number of neutrino balls in the universe is constrained by the mass density of the universe, but a neutrino ball per galaxy or more is easily accommodated. We will say nothing further here about the production and particle physics aspects of neutrino balls (see Holdom 1987).

Neutrino balls stabilize due to the equilibration of the internal neutrino pressure, \(\rho\), with the pressure induced by the surface tension of the wall,

\[
\rho = \frac{6\sigma}{R_b},
\]

\(1\)
where $\sigma$ is the surface energy density of the wall, and $R_b$ is the ball radius. The total mass of the ball is then given by

$$M_b = 4\pi R_b^2 \sigma + \frac{4}{3} \pi R_b^3 \rho = 12\pi R_b^2 \sigma .$$  \hspace{1cm} (2)$$

If a neutrino ball is too big it becomes a black hole, and if it is too small it rapidly disappears via the reaction $\nu \bar{\nu} \rightarrow e^+ e^-$. $M_b$ must lie within the range $M_c < M_b < M_h$, where

$$M_c \approx 10^4 [\sigma (\text{TeV}^3)]^3 \ M_\odot \hspace{1cm} (3a)$$

$$M_h \approx 10^8 / [\sigma (\text{TeV}^3)] \ M_\odot . \hspace{1cm} (3b)$$

This constrains $\sigma^{1/3}$ to be less than a few TeV. Neutrino balls within the above mass range rapidly cool through the reaction $\nu \bar{\nu} \rightarrow e^+ e^-$, which then shuts off once neutrino degeneracy is reached. The number density and energy density of the degenerate neutrinos are given by (assuming 3 neutrino families and equal numbers of neutrinos and antineutrinos)

$$n_\nu \approx \frac{\mu(t)^3}{\pi^2} \hspace{1cm} (4a)$$

$$\rho_\nu \approx \frac{3\mu(t)^4}{4\pi^2} . \hspace{1cm} (4b)$$

$\mu(t) < m_e$ is the chemical potential of the neutrino gas and $m_e$ is the electron mass. The neutrino ball then very slowly shrinks and releases energy through the reaction $\nu \bar{\nu} \rightarrow 3\gamma$, and $\mu(t)$ gradually increases. The ball lifetime in terms of the initial $\mu_0$ is

$$\tau_b \approx 10^{14} \left[ \frac{m_e}{\mu_0} \right]^{13} \ \text{secs} . \hspace{1cm} (5)$$

The mass and radius of the ball may be written as functions of $\mu(t)$,

$$M_b(t) \approx 50 \left[ \frac{m_e}{\mu(t)} \right]^8 [\sigma (\text{TeV}^3)]^3 \ M_\odot \hspace{1cm} (6)$$
\[ R_b(t) \approx 2 \times 10^{10} \left[ \frac{m_e}{\mu(t)} \right]^4 \sigma(\text{TeV}^3) \text{ cm} . \quad (7) \]

2. PRIMARY SIGNAL

If neutrino balls exist they will have a range of masses. Of most interest for us will be balls at the high end of their mass range; that is, \( M_b \sim 10^{8-9} M_\odot \) for \( \sigma \sim 1 \text{ TeV}^3 \).

This implies \( \mu \sim 50 \text{ keV} \) and \( R_b \sim 10^{14} \text{ cm} \). Since the chemical potential evolves so slowly we may treat these quantities as constants. Gravity will influence the properties of the largest balls (Mańka, Bednarek, and Karczewska 1993), but we will ignore these effects.

Let us assume that the ball is located in the vicinity of other stars, perhaps in a galactic core. The neutrino ball wall is transparent to all matter except neutrinos and thus stars pass freely into the ball interior. Stars will be captured by the gravitational field of the ball, and some will remain in the ball interior. We will consider the sequence of events if a supernova-type explosion were to take place within the ball. The actual type of explosion is not important, all that we require is that a large neutrino flux is emitted from the surface of some compact object. Since the compact source is in a region with a parity flipped version of our vacuum, the weak interactions are parity flipped, and therefore the neutrinos emitted from the compact source are all right handed. We wish to determine the gamma-ray signal caused by the interactions of these emitted neutrinos, \( \nu \), with the ambient right-handed neutrinos, \( \nu' \), in the ball.\[^{1}\]

The cross section for \( \nu \bar{\nu}' \rightarrow e^+ e^- \) is given by
\[
\sigma_{\nu} = \frac{G_F^2}{3\pi} \epsilon \epsilon' (1 - \cos \theta)(1 \pm 4 \sin^2 \theta_W + 8 \sin^4 \theta_W) , \quad (8)
\]

\[^{1}\] By “neutrinos” we often mean both right-handed neutrinos and left-handed antineutrinos.
where $G_F$ is Fermi’s constant, $\epsilon$ and $\epsilon'$ are the emitted and ambient neutrino energies, $\theta$ is the angle between their momenta, and $\sin^2\theta_W = 0.23$. For the ambient neutrinos $\epsilon' \approx \frac{3}{4} \mu$. The positive (negative) sign in eq. (8) is to be used for $\nu_e\bar{\nu}_e$ ($\nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau$) interactions, since $\nu_e\bar{\nu}_e$ interactions involve both charged and neutral currents. From eqs. (4a) and (8) the mean free path of the electron neutrinos is

$$\lambda \approx \frac{8 \times 10^{14}}{\epsilon(\text{MeV})} \left( \frac{m_e}{\mu} \right)^4 \text{ cm} . \tag{9}$$

For muon and tau neutrinos the mean free path is $\sim 5$ times larger. We use $\epsilon \sim 15$ MeV (30 MeV) as the average energy for electron (muon and tau) neutrinos. Combined with eq. (7) this determines the number, $N_e$, of electrons and positrons produced by the emitted electron neutrinos during their propagation to the neutrino-ball wall. If this distance is of order the radius of the ball then

$$\frac{N_e}{N_\nu} \approx 8 \times 10^{-4} \sigma(\text{TeV}^3) , \tag{10}$$

where $N_\nu$ is the total number of emitted electron neutrinos. The corresponding ratio for muon and tau neutrinos is about $2/5$ as large.

Each electron and positron in a produced pair will have energies close to half of the neutrino energy and with momenta close to the outward radial direction, since the center of mass energy of most of the pairs is not much greater than $2m_e$. Most will stay contained within the moving shell of thickness $\Delta\tau c$ where $\Delta\tau$ is the duration of the burst. For a typical supernova $\Delta\tau \sim 10$ secs. Only when the radius of the shell approaches $10^{14}$ cm $\sim R_b$ will the electron shell start to significantly spread in the radial direction, due to velocities which are not exactly $c$.

We now consider the self-interactions of the $e^+e^-$ pairs. We will have to require that they do not interact so much that they thermalize and significantly reduce their
average energy. Thermalization can only happen if the total number of electrons, positrons, and photons in the shell increases. The cross sections for number changing interactions, such as bremsstrahlung, contain an extra factor of $\alpha$ and will be approximated by $\alpha \sigma_T$ where $\sigma_T$ is the Thomson cross section. With this we estimate the total increase in the number of particles including photons in the shell compared to the total number of electrons and positrons produced from neutrino scattering:

$$\frac{\Delta N}{N_e} = \int_0^{R_b/c} n_e(t) \alpha \sigma_T \Delta v \frac{N_e(t)}{N_e} dt.$$  \hfill (11)

$\Delta v$ is a typical relative velocity of electrons and positrons. We may write $N_e \approx 2 \frac{R_b}{\lambda} \frac{E_i}{m_e}$, $N_e(t) = \frac{d}{dt} N_e$, and $n_e(t) = N_e(t)/V(t)$, where $E_i$ is the total initial energy in neutrinos and $V(t)$ is the volume of the shell. The result is

$$\frac{\Delta N}{N_e} \approx 10^6 \frac{E_i (10^{53} \text{ergs})}{\Delta \tau_{\nu}(\text{secs})} \frac{\Delta v}{c} \left( \frac{\mu}{m_e} \right)^4.$$  \hfill (12)

With $\Delta v \sim c/10$, $E_i \sim 10^{53}$ ergs, and $\mu = 50$ KeV we find $\frac{\Delta N}{N_e} \approx 1$.

We have thus found that $\mu$ cannot be much greater than 50 KeV in order for the spectrum of gamma-rays to remain largely in the 1-10 MeV energy range. When $\mu$ is of this order then we are also guaranteed that the total energy is equi-partitioned among the electrons, positrons and photons, due to the lowest order electromagnetic interactions. For a typical supernova event in which $2 \times 10^{53}$ (4 x $10^{53}$) ergs is carried away by emitted electron (muon and tau) neutrinos, eq. (10) implies $\sim 10^{50}$ ergs end up in the gamma-ray burst, the duration of which is $\Delta \tau_{\nu}$. This then is the expected signature of the initial propagation of neutrinos emitted by a supernova within a neutrino ball of sufficient size. For neutrino balls much smaller than $R_b \approx 10^{14}$ cm, for which $\mu$ is significantly larger, the signal is likely damped.
We now comment on how the ambient neutrino gas can affect stellar evolution, as a consequence of scattering with the stellar matter. We first note that the chemical potential of the degenerate neutrino gas is larger than typical stellar temperatures. But precisely because of the degeneracy, the collisions which could serve to heat the stellar matter do not take place due to phase-space blocking. Instead, an ambient neutrino must absorb sufficient energy to emerge above the Fermi surface. We find that this can constitute a stellar cooling mechanism several orders of magnitude larger than ordinary neutrino losses. An exact description of how this alters the stellar evolution would require detailed stellar modeling. However, a rapid increase in the evolutionary timescales could be expected, and this would enhance the probability of supernova explosions occurring within the neutrino ball.

The ambient neutrino gas also produces a dynamical friction for stellar motion. The timescale for the star to settle at the center of the ball through dynamical friction will be

\[ \tau_f \sim \frac{M_b}{m_s} \frac{1}{\sqrt{G\rho}}, \]

where \( G \) is Newton’s constant. For our adopted ball parameters and assuming \( m_s = 10M_\odot \), we find \( \tau_f \sim 10^4 \) years. The star may therefore settle at the ball’s center in a relatively short timescale. This in turn raises the possibility of stellar mergers at the ball’s center leading to the formation of massive stars, or to enhanced collisions of white dwarfs and neutron stars. These effects further increase the likelihood of supernova explosions within the ball.†

† A detailed discussion of mergers in dense stellar environments can be found in Quinlan and Shapiro (1990).
3. SECONDARY SIGNALS FROM REFLECTED NEUTRINOS

Additional distinctive signatures of our picture could occur due to the peculiar reflective property of a neutrino-ball wall. On leaving the supernova the neutrinos expand with only a small fraction converted to the primary $\gamma e^+ e^-$ shell. However, on reaching the wall the neutrinos are energetically forbidden from entering the other vacuum, and are therefore reflected back into the interior of the ball. As the neutrino shell propagates back in from the wall it generates another $e^+ e^- \gamma$ shell traveling with it. The fate of this secondary $e^+ e^- \gamma$ shell can be influenced by any $e^+ e^-$ gas left behind the primary $e^+ e^- \gamma$ shell. The source of particles lagging behind the primary $e^+ e^-$ shell could be due to the bremsstrahlung type interactions considered above, or due to the initial shell interacting with any ambient particles already in the ball. The scattering of secondary-shell particles with the remnant $e^+ e^-$ gas no longer involves the factors of $\alpha$ or $\Delta v/c$ explicitly shown in eq. (11). Such scatterings can degrade the energy of the particles. If a significant fraction of the electrons and positrons produced in the primary burst are left behind in the ball ($\sim$ a few percent) then substantial damping of the secondary gamma-ray signal could occur.

We will proceed in this section by assuming that this damping of the secondary signal does not happen, at least in some cases. Even then the secondary shells of $e^+ e^-$ pairs will still collide with other $e^+ e^-$ shells traveling in other directions. One could easily envisage a large variety of signals depending on the position of the explosion within the ball. For explosions sites not on center one could expect that after several reflections the neutrinos propagate no longer in thin shells, but instead propagate more randomly throughout the ball. $e^+ e^-$ pairs and photons are then produced uniformly over the ball. The expected signal for this process would possibly include some secondary gamma-ray bursts from the first few reflections. But the signal would
gradually turn into a continuous gamma-ray flux $\Delta t/R_b \sim 10^{-3}$ times smaller than the original burst, lasting for a total time $\lambda/c \sim 1$ month.

In the special case where the explosion event occurs near the ball’s center an interesting phenomena can take place – after reflection the emitted neutrinos will be re-focused at the center of the ball. That the explosion event may take place at the ball’s center does not seem too unreasonable considering our discussion of eq. (13). Assuming an on-center explosion, we wish to determine what fraction of the neutrino energy will be lost to $\nu\bar{\nu} \rightarrow e^+e^-$ pair production when the neutrinos re-focus at the center. If we consider a re-focus region of the same size $r_\nu$ as the original neutrinosphere of the supernova then we find that the ratio of energy lost to pair production to the initial energy of explosion is approximated by

$$\frac{E_p}{E_i} \sim 10^{-3} \frac{E_i(10^{53}\text{ergs})\epsilon(\text{MeV})}{r_\nu(10^6\text{cm})\Delta \tau_\nu(\text{secs})}.$$ (14)

For a typical explosion event then, roughly $10^{-3}E_i$ is removed from the neutrino energy during the re-focusing.

Since energy losses are small this means that after the neutrinos pass through the re-focusing region most of them repeat their cycle. That is, they propagate isotropically to the ball wall from which they are once again are reflected back toward the center. The types of signal we have just calculated in the previous section can therefore be repeated with a cycle time of $2R_b/c$. The duration of this signal – determined by damping effects as discussed above – can be no larger than $\lambda/c$. Nonetheless, we wish to emphasize the possibility of a unique periodic signal with decreasing amplitude.

In addition to signals produced through interaction with the ambient neutrinos, there remains the possibility of other gamma-ray signals – as a consequence of $\nu\bar{\nu}$-induced fireballs. The physics of fireballs has been developed in a series of previous
papers (eg. Cavallo and Rees 1978; Goodman 1986; Paczyński 1986, 1990; Shemi and Piran 1990; Piran and Shemi 1993). Assuming thermal equilibrium, the initial temperature $T_i$ of a fireball is determined only by the rate of energy input, $\dot{E}$, and the radius $R_i$ within which the initial energy is confined. For $\dot{E} \sim 10^{50}$ ergs s$^{-1}$ and $R_i \sim 10^6$ cm, we find $T_i \sim 1$ MeV. In the outer regions of the fireball a relativistic outflow is formed, and the apparent temperature of the escaping photons is approximately equal to $T_i$.

Using eq. (14) we have found that $\sim 10^{50}$ ergs can be input into the fireball. Refocusing of the $e^+e^-$ pairs produced by the incoming neutrinos gives a similar energy input. However, for on-center explosions it is unlikely that any gamma-ray signal will be observed. The main reason for this is the remnant supernova debris around the explosion site which is opaque to photons. There is also the effect of baryons on the fireball itself, since the thermal energy of the fireball tends to be diverted to kinetic energy of the baryons. Fireball effects, however, are not completely ruled out. For example, suppose that the source is some distance $r$ off-center with $r << R_b$. Then the emitted neutrinos are re-focused in a region diametrically opposite to the explosion site. For some range of $r$ it is possible that some re-focusing occurs in regions where the remnant debris has yet to reach, and observable fireballs are produced. There also remains the possibility of break-out and beaming effects – similar to that discussed by Mézáros and Rees (1993) for colliding neutron stars – arising from anisotropic debris distributions.

4. DISCUSSION

We have seen that supernova-type explosions within the confines of neutrino balls can produce the gross characteristics required for the production of a cosmological gamma-ray burst (GRB). The interaction of emitted neutrinos with ambient neutrinos
can readily lead to a $10^{50}$ erg GRB with a characteristic timescale of 10 secs. The latter timescale is set by the supernova itself. In the case that the ball remains transparent to photons after the initial pulse, then unique observational signatures can possibly arise from the neutrinos reflected back into the ball. For off-center events we could have one or more weaker secondary pulses before the signal fades into a continuous “afterglow” of duration $\sim \lambda/c$. An on-center event could produce a strictly periodic GRB with decreasing amplitude, and period $2R_b/c$.

We have mentioned various ways in which supernova-type events may be induced inside neutrino balls, including the cooling and rapid evolution of stars, the merging of stars into more massive stars, and collisions involving white dwarfs or neutron stars. All these possibilities – coupled with our lack of knowledge on the number and size of neutrino balls in the universe – make it difficult to predict the frequency of the events we have described here.

Neutrino balls may be associated with other exotic phenomena; colliding neutrino balls and the death of neutrino balls are but two examples. In the latter case the slow evolution of the neutrino ball comes to an abrupt end when the chemical potential $\mu$ becomes of order the electron mass. At this point the reaction $\nu\bar{\nu} \rightarrow e^+e^-$ for ambient neutrinos, which previously was energetically forbidden, now proceeds rapidly. We find that the time scale for the conversion of the neutrinos into $e^+e^-$ pairs is a few hours.

It may well be that the strange and perplexing phenomena of GRBs are indicating the presence in the universe of some new exotic configuration. If so, neutrino balls may be an ideal candidate. The most obvious test for the existence of a cosmological neutrino ball – optical observation of an extragalactic Type II supernova with no apparent neutrino burst – is not technically feasible. Continued scrutiny of GRB
signals for the various secondary signals we have discussed would seem to be the best alternative.

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