GAMMA-RAY BURSTS FROM BARYON DECAY IN NEUTRON STARS

Ue-Li Pen and Abraham Loeb
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

And

Neil Turok
DAMTP, Cambridge University, Cambridge, England, UK

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ABSTRACT

The standard unbroken electroweak theory is known to erase the baryon number. The baryon number symmetry can be restored in the core of a neutron star if its density diverges via gravitational instability due to a binary merger event. We argue that for certain double Higgs models with discrete symmetries this process may result in an expanding self-sustained burning front that would convert the entire neutron matter into radiation. This process would release \( \sim 10^{52} \) ergs in electromagnetic radiation over \( \sim 10^{-4} \) s with negligible baryonic contamination. The resulting fireball would have all of the properties necessary to produce a \( \gamma \)-ray burst as a result of its interaction with ambient interstellar gas. The subsequent Higgs decay would produce a millisecond burst of \( \sim 10^{52} \) ergs in \( \sim 100 \) GeV neutrinos, which might be observable. The above mechanism may also cause electroweak baryogenesis in the early universe, which gives rise to the observed matter-antimatter asymmetry today.

Subject headings: cosmology: theory — gamma rays: bursts — stars: neutron

1. INTRODUCTION

The energy source for \( \gamma \)-ray bursts (GRBs) has been enigmatic since their discovery (for a recent review, see Fishman & Meegan 1995). The recent detection of absorption lines at redshift \( z = 0.835 \) in the optical afterglow spectrum of the event GRB 970508 (Metzger et al. 1997) established a firm lower bound on its distance, and hence on its total radiation energy of \( \gtrsim 10^{52} \) ergs (Waxman 1997). A more indirect lower energy bound for GRB 971214 of \( \gtrsim 3 \times 10^{53} \) ergs (Kulkarni et al. 1998) from its host galaxy association poses even more challenges for GRB models. The long duration of some GRBs is difficult to reconcile with their millisecond time structure. If the variability is caused by an external shock due to the interaction of the fireball with an ambient medium (Mészáros & Rees 1993a, 1993b), then the conversion efficiency must be small (Sari & Piran 1997a) and the total energy released approaches the rest mass energy of a neutron star. A further challenge to GRB models is the baryon contamination problem. The high Lorentz factors implied by the short variability and nonthermal spectra of GRBs (see, e.g., Woods & Loeb 1995) require that the baryonic fraction be \( \lesssim 1\% \) of the total energy. This constraint is particularly difficult to satisfy in stellar environments such as neutron star mergers (Ruffert et al. 1997; Eichler et al. 1989, and references therein), where a considerable amount of baryonic debris is unavoidable.

The standard electroweak theory allows for baryon number violating processes (’t Hooft 1976). Through a combination of chirality and topology, the baryon and lepton number may be violated. A change in the winding number of the gauge fields results in fermions being pulled out or pushed into the Dirac sea. Normally in the broken symmetry vacuum such effects are very strongly suppressed since the gauge fields are massive and difficult to excite; however, in the unbroken phase it is well established that when the electroweak symmetry is restored, the baryon and lepton number violation processes are unsuppressed (for a review, see Rubakov & Shaposhnikov 1996). It is natural to ask whether these intriguing processes could be excited in the universe today. There are two fundamental barriers that make their appearance rare: (1) a large energy input is required to change the gauge/Higgs winding numbers; and (2) the energy must be input in a coherent fashion into the long-wavelength components of the bosonic fields (and this, for example, does not happen in high-energy collisions of single elementary particles).

In this paper we argue that baryon number symmetry might be restored in the core of a neutron star if its density is raised to extreme values. Such a process might be triggered during the catastrophic gravitational collapse caused by some cataclysmic event (such as binary coalescence or substantial accretion), which raises the neutron star mass above its stability limit. Once the symmetry is restored in a sufficiently large (macroscopic) volume, a self-sustained burning front would propagate throughout the star and convert the entire neutron mass into radiation and release \( \sim 1 \) GeV baryon \(^{-1}\) in the process. The burning front will be accompanied by an electroweak domain wall in which the barrier to baryon number violation is greatly reduced. The existence of dense nuclear matter allows long-wavelength modes of the gauge fields to be naturally excited. Overall, the burning front could release \( \sim 10^{54} \) ergs in electromagnetic radiation with negligible baryonic contamination. The resulting fireball would have all the properties necessary to produce a GRB because of its interaction with ambient interstellar gas.

In § 2 we present the hydrodynamic solution for the associated electroweak burning front. We then discuss the trigger mechanism for the explosive process described above in § 3. Section 4 considers the energetics of electroweak baryon number violation on moving walls. Finally, we examine the implications of our model for cosmological baryogenesis and electroweak theory in § 5, and we summarize its testable predictions for GRBs in § 6.
2. SELF-SIMILAR EXPLOSION

In our model, we consider three regions of the dynamical explosion. In the outer region, the cold neutron star material is at rest. The shock front propagates through this material at some speed \( \lambda c \), where \( c \) is the speed of light. This burning front is the second region under consideration, which has a characteristic thickness of an electroweak length \( \sim 10^{-16} \text{ cm} \). The burning front is sustained by the presence of an electroweak domain wall. While the microphysics in this region is complicated, we can describe its hydrodynamic implications as if it were infinitely thin. We will return to this discussion in § 4. The global conservation of energy and momentum thus dictate the global dynamics of this burning region. The last region under consideration includes the postshock (burnt) radiation phase. This heated region will initially expand owing to the increase in pressure. This pressure is directly exerted against the domain wall, which then propagates further outward. The goal of this section is to quantify the self-sustained dynamics of these regions assuming that the process has already been triggered. The possible trigger mechanism will be considered in the next section.

The equations of motion of a relativistic fluid are given by the energy-momentum conservation equations \( T^\mu_\nu = 0 \), where \( T^\mu_\nu = (\rho + p)u^\mu u^\nu + pg^\mu_\nu \). We use a metric signature convention of \((- + + + \cdots)\). In the rest frame of the star, we have

\[
\frac{\partial}{\partial t} \left( \rho + p \beta^2 \right) + \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 (\rho + p) \beta^2 \right) = 0 ,
\]

\[
\frac{\partial (\rho + p) \beta}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 (\rho + p) \beta^2 \right) + \frac{\partial \rho}{\partial r} = 0 ,
\]

where \( r \) is the radial coordinate and the speed of light is set to unity. We ignore gravity for now, assuming that the star is initially in static equilibrium and that the final phase is gravitationally fully unbound.

We assume that the preshocked neutron star material is described by an equation of state \( p_0 = \alpha \rho_0 \). The preshock density of a neutron star, \( \rho_0 \sim 2 \times 10^{14} \text{ g cm}^{-3} \), is slightly above nuclear density. The pressure is typically small, \( \alpha \sim 0.1 \), but it can reach relativistic values near the center of the star where \( \alpha \sim 1/3 \). The burnt phase consists of radiation and electroweak false vacuum energies, \( \rho_{\text{burnt}} = \rho_\gamma + \rho_{\psi^+} \rho_{\text{burnt}} = \rho_\psi(3 - \rho_{\psi}) \). Typically \( \rho_{\psi} \sim \rho_0/100 \), as is discussed further in § 5. The burning front has a width of order of the electroweak scale \( \sim 10^{-16} \text{ cm} \), which is much smaller than the macroscopic scale of the neutron star and can therefore be approximated as a sharp discontinuity. Since the neutron star density is nearly constant (Shapiro & Teukolsky 1983), the explosion should be well approximated by a self-similar solution (see examples in Blandford & McKee 1976; Pen 1994). The amount of energy released per baryon equals its rest mass, and therefore the Lorentz factor of the burning front cannot be much greater than unity. This implies that any self-similar, self-sustained burning front (which does not decay as it expands) must propagate at a constant speed through the neutron matter.

We therefore seek solutions to equations (1) and (2) that depend on \( r, t \) only through the combination \( \lambda = r/t \). We define the dimensionless pressures \( \tilde{\rho} = \rho/\rho_0 \) and \( \tilde{\rho}_\psi = V(\psi^-)/\rho_0 \), where \( V \) is defined in § 5 below. After some algebra, we find that the equation for \( \beta(\lambda) \) separates from the equation for \( \tilde{\rho} \):

\[
\lambda \beta' = \frac{2(1 - \beta^2)(1 - \beta \lambda)}{\beta^2(3 - \lambda^2) - 4 \beta \lambda + 3 \lambda^2 - 1} ,
\]

and that the density is given as a simple integral over the fluid velocity,

\[
\tilde{\rho} = \tilde{\rho}_s \exp \left[ \int_{\lambda_s}^\lambda \frac{8 \beta \lambda' - \beta |d\lambda'|}{\beta^2(3 - \lambda'^2) - 4 \beta \lambda' + 3 \lambda'^2 - 1} \right] .
\]

This self-similar scaling imposes a constant shock speed with velocity \( \lambda_s \). The subscript \( s \) on a fluid variable denotes its value immediately behind the shock front, e.g., \( \tilde{\rho}_s = \lim_{\lambda \to \lambda_s} \tilde{\rho}(\lambda) \).

In order to solve the system of equations (3) and (4), we need to specify the postshock boundary conditions. Equations (1) and (2) provide the postshock velocity in the star rest frame and the postshock density in the fluid frame:

\[
\beta_s = 2[\lambda_s^2(1 - \tilde{\rho}_\psi) - \alpha - \tilde{\rho}_\psi] - \sqrt{-3(1 + \alpha)^2 \lambda_s^2 + 4[\alpha - \lambda_s^2(1 - \tilde{\rho}_\psi) + \tilde{\rho}_\psi]^2 \lambda_s(3 - \alpha - 4 \tilde{\rho}_\psi)} ,
\]

\[
\tilde{\rho}_s = \frac{3(1 + \alpha)(1 - \beta^2)\lambda_s}{4(\lambda_s - \beta)(1 - \beta^2)} .
\]

Requiring the postshock velocity to be real in the shock frame yields the inequality

\[
3 + \alpha(3\alpha - 2) + 8\tilde{\rho}_\psi(\tilde{\rho}_s + \alpha - 1) + \sqrt{3(1 + \alpha)(4\tilde{\rho}_\psi + \alpha - 3)(4\tilde{\rho}_\psi + 3\alpha - 1)} < \lambda_s^2 < 1 ,
\]

which simplifies to \( \frac{3}{8} < \lambda_s^2 < 1 \) if \( \alpha = \tilde{\rho}_\psi = 0 \) in the idealized case of a low-pressure neutron star and a negligible burning potential. Since the sound speed of a relativistic fluid is \( C_s = C/\sqrt{3} \), we conclude that the burning front must propagate supersonically in the star frame. In the shock frame, the post-shock velocity of the fluid is smaller than its preshock value; therefore, this solution corresponds to a detonation front.

By examining equation (3) we find that all solutions must pass through the point \( \beta = 0, \lambda = (1/3)^{1/2} \). The only physical solution in the range \( 0 \leq \lambda \leq (1/3)^{1/2} \) is \( \beta = 0 \), so any solution is matched continuously at the boundary with discontinuous derivatives. Normally one specifies a boundary condition away from the shock front, but in our case this boundary condition is automatically satisfied. The shock speed \( \lambda_s \) is therefore a free parameter that can lie anywhere in the allowed range. The actual value of \( \lambda_s \) is either set by the trigger mechanism (i.e., the initial conditions) or by the viscous forces acting on the
domain wall boundary. In the generic case where viscous forces slow down the shock to its minimum velocity, the unique solution is

$$\frac{\lambda_4}{\lambda_0} = \frac{3}{4} \frac{x}{2} \frac{\rho_v}{2}, \quad (8)$$

to leading order in $x$ and $\rho_v$. The postshock density is $n_s \approx 3 - 4x - 7\rho_v$, and the exact postshock velocity is

$$\beta_s^2 = 1 - \frac{2(1 + x)}{3 - x - 4\rho_v}, \quad (9)$$

which gives the constraint $3x + 4\rho_v < 1$. Even though the velocity derivative $\beta'$ formally diverges, the solution is well defined.

By virtue of equation (2), all shock solutions automatically satisfy total energy conservation:

$$\frac{4/3\pi}{\rho_0 t^2} \int_0^1 T_{00} r^2 dr = \frac{4}{3} \pi \lambda_4^3 = \frac{4}{3} \pi \rho \left( \frac{1}{\sqrt{3}} \right)^{3 - 3/2} + \frac{4}{3} \pi \lambda_4^3 \rho_v + 4\pi \int_{\lambda_4}^{\lambda_0} \frac{1 + \beta^2/3}{1 - \beta^2} \beta^2 d\lambda, \quad (10)$$

which provides a consistency check for the final numerical solution. Figure 1 shows the numerical solutions for the velocity and density profiles behind the shock for three different choices of $\lambda_4$, assuming $x = 0$ and $\rho_v = 0$.

3. TRIGGER MECHANISM

We have found that if triggered, a self-sustained burning front would propagate at a constant speed and spontaneously convert baryons at nuclear density into radiation; however, we still need to demonstrate how this process might be spontaneously triggered, and under which conditions the burning front would release sufficient energy to sustain itself.

The rate of neutron star mergers in the Hubble volume is similar to the observed rate of GRBs (Narayan, Piran, & Shemi 1991; Phinney 1991). It is therefore natural to examine the question of whether an electroweak burning front would be triggered by such mergers. Typically the combined mass of the two neutron stars would exceed the maximum mass for a
stable star at nuclear densities, and the merger product would be gravitationally unstable and would tend to collapse toward a black hole. An electroweak burning front might be produced if there is an inner region where the density is sufficiently high to restore electroweak symmetry before being engulfed by a black hole horizon. In this region, the baryon number will be strongly violated, and most baryons will decay into antileptons. Similar conditions might occur in binary systems where a neutron star exceeds the maximum stable mass due to accretion from its companion; however, the formation of black holes by much more massive systems, such as the direct collapse of massive stars, are characterized by much lower densities (at the Schwarzschild radius, $\rho \propto 1/r^2$) and are not expected to trigger the electroweak transition before their horizon forms.

The details of the trigger process depend on the equation of state of neutron star matter above nuclear density, which is not yet fully understood. Some nuclear equations of state predict that $p > \rho/3$ for densities about 10 times nuclear (Prakash et al. 1997). The sound speed $c_s^2 = \partial p/\partial \rho$ then obtains a maximum value above that of a pure radiation fluid. At yet higher densities, the sound speed eventually declines back to the $\frac{1}{3}$ value of a locally interacting radiation field due to asymptotic freedom of QCD.

At this point there are two possibilities that could lead to our trigger, both of which are speculative at this stage. We first consider a hydrodynamic scenario and then a gravitational possibility. The regions of slower sound speed could trap sound waves driven by the merger event. It has been pointed out that this change in sound speed could lead to sonoluminescence in neutron stars (Simmons et al. 1996). They proposed that the spontaneous trapping may be sufficient to nucleate a region above the electroweak phase transition in a small region of the neutron star.

For the gravitational scenario we consider a neutron star that collapses slowly through phases of hydrostatic equilibrium; the central equation of state will then stiffen until it reaches its maximum sound speed, and then soften again. The region that enters the softened phase will collapse faster than its surroundings, potentially leading to a runaway density. The compression of this region is caused by the weight of the column of matter above it. The electroweak symmetry would be restored in this region at a density of $\sim 10^{27}$ g cm$^{-3}$, some 12 orders of magnitude above the initial density. This region will not be surrounded by a black hole horizon if its radius is $\lesssim 1$ cm, or if its mass is $\lesssim 4 \times 10^{-8} M_\odot$. A lower bound on the radius of the trigger region arises from the requirement that a self-sustained burning front needs to release more energy interior to it than the total energy stored in the domain wall. At nuclear density the energy released is $\sim (200 \text{ MeV})^3 R^3$, which implies a radius of $\gtrsim 10^{-3}$ cm. Higher background densities will only weaken this constraint. In the limit that the fluid pressure is dynamically negligible compared to the surrounding driving forces, Christodolou (1984) has proven that one generically forms naked density singularities. For realistic fluids, the problem is still open (Christodolou 1995). Neutron star equations of state are notoriously complex, and the above-mentioned softening of the equation of state may also serve to accelerate the formation of high-density patches. The physical processes are still debated at this point (Mitra 1998); we leave this speculative subject for future research.

We still have two apparently contradictory requirements. The fluid must collapse to electroweak densities and then expand again in order to drive the explosion. In the dense phase, the relative pressure gain from the burning of each nucleon is small. One would expect that the gravitational collapse and the subsequent phase transitions will raise the entropy of the fluid in the central region and cause entropy inversion, therefore resulting in convective flows. A fluid element taken through the electroweak phase transition that would subsequently rise because of buoyancy forces could trigger the explosion as it cools adiabatically and is trapped in the false vacuum.

4. KINEMATICS OF BARYON NUMBER VIOLATION ON PROPAGATING WALLS

In this section we discuss the energetics and timescales of the baryon number violating processes on bubble walls moving through cold neutron matter. We consider the possibility that neutrons are converted into antineutrinos as the bubble wall passes. Our analysis will be extremely schematic and at best a pointer to the key issues involved. At the end of this section we shall comment on the additional work that is needed in order to settle the microphysics of electroweak bubble walls in neutron matter.

We shall consider particle physics models that include more than one Higgs doublet field. These models are among the most plausible extensions of the standard model and occur as submodels of low-energy supersymmetry, and they attempt to incorporate generational symmetries in the standard model (Gunion et al. 1990). We are particularly interested in these models because they possess stable domain wall solutions within which the Higgs fields may be very small. The domain wall solutions arise as an inevitable consequence of discrete symmetries imposed to prevent phenomenologically unacceptable flavor-changing neutral currents. For example, if the field $\phi_U$ gives mass to the up quark and $\phi_D$ gives mass to the down quark, one imposes a symmetry: $\phi_U \rightarrow -\phi_U, U_R \rightarrow -U_R$, with $U_R$ being the right-handed up quark. This prevents tree-level processes in which neutral Higgs intermediate states allow up-type quarks to change into down-type quarks (Glashow & Weinberg 1977). Of course, these symmetries mean that at least at the classical level the theories possess degenerate vacua and the domain walls are stable classical field configurations interpolating between them.

The domain walls are interesting to us because in their interior the gauge field masses may be very small, and therefore the barrier to baryon number violating processes are small. Furthermore, as pointed out by Preskill et al. (1991), in these particular theories the domain walls pose no problems for cosmology, since the vacuum degeneracy is actually broken by very small instanton induced effects, the vacuum energy being different by $\sim 1/3f^2 m_n^2 \sim (80 \text{ MeV})^4$. They may in fact be useful for producing a cosmological baryon asymmetry, as we discuss below.

The electroweak baryon number violating processes violate the baryon and lepton number but conserve their difference. A unit change in the gauge/Higgs winding number destroys three baryons and three leptons. Since quarks, but not leptons, are allowed to change flavors through Cabibbo-Kobayashi-Maskawa (CKM) mixing, one can have the processes $3n \rightarrow \bar{\nu}_e + \nu_e + \nu_e$ or $2n \rightarrow \bar{\nu}_e + \nu_e + \nu_e$. A key prediction of our mechanism is that the high-energy neutrinos measured from these processes would exhibit an equal excess of antineutrinos from each generation.
The basic equation governing the rate of baryon number violation in the standard model reads
\[ \frac{dn_b}{dt} = \frac{\mathcal{N}}{8\pi} \left( g_2^2 E \cdot B - g_2^2 e \cdot b \right), \] (11)
where \( n_b \) is the baryon number density, \( \mathcal{N} = 3 \) is the number of generations, \( g_2 \) and \( g_1 \) are the SU(2) and U(1) gauge coupling constants, and \( E, B, e, \) and \( b \) are the corresponding electric and magnetic fields. The linear combination occurring on the right-hand side of equation (11) vanishes for electromagnetic fields: baryon number violation requires the \( W \) and \( Z \) fields. If the wall moves at velocity \( v_w \), then the number of neutrons hitting the wall per unit time per unit area is \( \gamma_w n_n v_w \), where \( n_n \) is the ambient neutron density. Requiring that a sizeable fraction of these neutrons are converted then leads to an estimate of the required electric and magnetic fields.

By assuming equipartition between electric and magnetic fields, and a semirelativistic wall velocity, we find that the needed fields are
\[ B_{\text{required}} \sim E_{\text{required}} \sim \sqrt{\gamma_w n_n v_w m_H/\alpha_2} \sim (1.5 \text{ GeV})^2, \] (12)
with \( \alpha_2 = g_2^2/4\pi \sim 1/30 \) as the weak fine structure constant. Here we have integrated the anomaly across the wall width, taken to be the inverse Higgs mass \( m_H \sim 100 \text{ GeV} \), and have ignored \( g_1 \) since it is much smaller than \( g_2 \). The resulting fields are indeed large, but they are very much smaller than the electroweak scale. We have ignored the CKM mixing angle suppression. Could the required fields be accreted on the wall? It is clear that the physics of the domain walls is quite complex and that there are many possible contributing effects. Fermions are attracted to the wall, since their masses are lower on it, and form bound states that may support currents flowing without resistance on the wall. Since the neutrons carry weak isospin, their presence automatically causes weak isospin electric fields of order \( gn_n^2/\alpha_2 \) on the wall if the gauge fields are massless there. But the most likely mechanism for generating the required \( \sim 1 \text{ GeV}^2 \) fields is the Meissner effect—\( W \) and \( Z \) gauge fields would be swept along by the back edge just because they are light on the wall and massive off of it. It is also possible that a dynamo mechanism would operate on the wall, which would build up the magnetic fields to the saturation value \( B_{\text{crit}} \sim (100 \text{ GeV})^2 \).

How much energy do the fields in equation (12) cost? And how does this compare with the rate of energy input in the form of neutrinos onto the wall? By equating the energies per unit area \( B_{\text{required}}^2/m_H \sim n_n L_N m_n \), where \( L_N \) is the path swept up in the cold neutrons, we find that the required field energy could be accreted in a distance as short as \( \sim 3 \) neutron spacings at nuclear density, or \( L_N \sim (\alpha_2 m_n)^{-1/3} \). So there is certainly no shortage of energy input to maintain the fields.

We require aligned electric and magnetic fields in order to violate the baryon number; we may think of the process occurring in two stages. First, magnetic fields are established on the wall via some kind of dynamo mechanism coupled to the Meissner effect. In a constant SU(2) magnetic field, the lowest energy levels for the quark consist of left-handed particles with positive isospin (up quarks) moving against the field, and left-handed particles with negative isospin (down quarks) moving along the field. Right-handed particles do not couple to the field. A beam of neutrons streaming into such a field would undergo isospin separation, leading to an electric field aligned with the magnetic field. The resulting change in the gauge field winding causes neutrons to disappear.

Some elementary steps toward establishing the viability of this mechanism would be: (1) finding the energy barrier required for baryon number violation in the presence of a domain wall; (2) studying the fate of currents on the wall and whether they can support magnetic fields of the required magnitude; and finally (3) studying the possibility of a dynamo mechanism that would establish such fields out of a seed magnetic field that is likely to be present in the neutron star. We shall return to these questions in future work.

Assuming the electroweak baryon number violation processes are sustained in the bubble wall, the latter will be pushed forward through the neutrons by the excess pressure of the hot medium behind it. Presumably it will reach a terminal speed determined by collisions with the neutron matter. The self-sustained detonation front described in § 2 could convert all the nuclear matter mass \( M_\text{tot} \) into neutrinos and photons, releasing \( \sim 5 \times 10^{54} \text{ ergs} \times (M_\text{tot} / 3 M_\odot) \) over a time \( \leq (30 \text{ km/c}) \sim 10^{-4} \text{ s} \).

When the electroweak domain wall emerges from the surface of the neutron star, the domain wall will still expand out to \( R_\text{max} \sim R_\text{eq}^{-1/3} \) because of the thermal pressure behind it, where \( R_\text{eq} \) is the radius of the neutron star. The lack of additional fuel will prevent it from expanding further; beyond this radius, the radiation fireball will diffuse out and separate from the domain wall. This energy release will be the primary source of energy for the GRB. As discussed in the next section, typically \( \rho_v \sim 1/100 \), and the limiting radius would be \( R_\text{max} \sim 10^7 \text{ cm} \). If \( \rho_v = 0 \) the wall will not expand forever, but rather at \( R \sim 10^{10} \text{ cm} \) it will contract again because of wall tension. Eventually, the wall would lose the radiation pressure support behind it and collapse again. The Higgs energy of the wall and the false vacuum behind it will be radiated as high-energy (\( \sim 100 \text{ GeV} \)) neutrinos, photons, and particle-antiparticle pairs. In contrast to supernovae, where neutrinos carry 99% of the energy (since photons are trapped by the opaque stellar envelope), there should be comparable energies in neutrinos and photons in the resulting fireball here. In addition to the \( \sim 10^{54} \text{ ergs} \) radiated in neutrinos of energy \( \sim 100 \text{ MeV} \), a second submillisecond burst carrying \( \sim 10^{52} \text{ ergs} \) of \( \sim 100 \text{ GeV} \) neutrinos is a generic prediction of our model.

5. IMPLICATIONS FOR ELECTROWEAK THEORY AND COSMOLOGICAL BARYOGENESIS

Electroweak domain walls can be cosmologically disastrous. When formed in a first-order phase transition, they will come to dominate the matter density of the universe (Zeldovich, Kobzarev, & Okun 1975). If we assume about one domain wall per horizon volume, electroweak domain walls would dominate the matter density of the universe if they persist until its
temperature is \( \sim 1 \text{ keV} \). Thus, there is a cosmological lower bound on the potential difference \( \Delta V \equiv V^- - V^+ \gg (1 \text{ keV})^4 \). Preskill et al. (1991) argued that discrete symmetries could be broken anomalously through QCD effects, which would yield an energy difference of \( \Delta V \sim (80 \text{ MeV})^4 \). The vacuum energy admits an equation of state \( p = -\rho \). The energy density of a neutron star is \( \sim (200 \text{ MeV})^4 \). Requiring the postshock pressure to be positive, we obtain an upper bound to this energy asymmetry of \( \Delta V \lesssim (150 \text{ MeV})^4 \) in order for the burning front to be self-sustained. This bound is well above the value predicted by Preskill et al. (1991). We also see that such electroweak explosions can only occur in matter that has densities close to nuclear, i.e., only in neutron stars.

A related enigma in cosmology is baryogenesis. The baryon number is strongly violated above the electroweak phase transition, and in some theories (where the baryon number minus lepton number is conserved) baryon asymmetries generated before this transition would be erased. The baryon number is conserved after the electroweak symmetry breaking, so the natural time to create the baryon number would be during this phase transition. The Sakharov criteria requires that baryon number \( B \), charge conjugation symmetry \( C \), and conjugation parity \( CP \) be violated and that the system be out of equilibrium. In the minimal standard model of particle physics, two of these criteria are problematic. The current measurement of the top mass \( m_{\text{top}} \sim 180 \text{ GeV} \) appears to preclude a first-order phase transition, which would be the natural way to bring the universe out of equilibrium. Also, the magnitude of \( CP \) violation in the minimal standard model cannot produce the observed baryon-to-photon ratio \( \eta \sim 10^{-10} \). Moving topological defects such as domain walls restores the out-of-equilibrium requirement (Prokopec et al. 1996), and the extra freedom in selecting the second Higgs field also allows a match for the required \( CP \) violation rates. The long persistence of the anomalous domain walls will also amplify the net baryon production to become more consistent with the small observed \( CP \) violation rates.

Another consequence of the long persistence of these walls is a coherence length of the baryon production regions that is intermediate to the horizon size at electroweak and the horizon size when the domain walls disappear. This length scale of \( \sim 10^{15} - 10^{19} \text{ cm} \) is significantly longer than the diffusion length at nucleosynthesis (Jedamzik & Fuller 1995). The baryon-to-photon ratio would generically fluctuate in different regions, which would result in inhomogeneous nucleosynthesis and affect the standard predictions for the abundance of light elements (Rehm & Jedamzik 1998).

6. CONCLUSIONS

We have argued that the gravitationally unstable core of a neutron star merger might trigger an electroweak burning front that would propagate outward and convert all the nuclear material into radiation. The necessary conditions for this mechanism are a transient triggering region of high density that is not engulfed by a black hole horizon and a catalytically sustained electroweak burning front. We have given examples of models that were previously proposed for entirely different reasons, which could satisfy both constraints. Our phenomenological conclusions do not strongly depend on these details.

The associated detonation front would be self-sustained and propagate at a constant semirelativistic speed of \( \sim 3/4c \). The baryon-number-violating reaction is induced by a domain wall, which is naturally predicted in double Higgs models of electroweak interactions. We have shown that the electroweak burning front can only be self-sustained if it propagates into material with nuclear densities. Although our mechanism provides an efficient way for alleviating the baryonic contamination problem, some surrounding stellar debris might remain unburnt and limit the Lorentz factor of the expanding fireball. This minimal contamination is required to make the emission spectrum from the fireball nonthermal (Goodman 1986; Paczyński 1986).

The electroweak explosion process releases \( \gtrsim 10^{54} \text{ ergs} \) over \( \lesssim \text{ms} \) and produces a fireball that subsequently impacts the ambient (interstellar) medium. This impact generates an external shock that could produce the observed spectrum of GRBs via synchrotron emission and inverse-Compton scattering of Fermi-accelerated electrons (Mészáros, Laguna, & Rees 1993a, 1993b; Mészáros, Laguna, & Rees 1993). In this model, the observed variability of GRBs might either be due to inhomogeneities in the ambient gas density or to instabilities at the shock front (see, e.g., Waxman & Piran 1994). The release of \( \gtrsim 10^{54} \text{ ergs} \) remedies the energy problem that was previously identified for external shock models (Sari & Piran 1997a, 1997b), and is in fact required if GRBs follow the star formation history of the universe with the dimmest bursts originating at redshifts as high as \( z \sim 6 \) (Wijers et al. 1998). In this case the excess in the merger rate of neutron star binaries relative to the GRB rate might in part be due to the environment; only a fraction of all GRB sources might reside in a sufficiently dense ambient medium so as to produce bright emission from their external shocks. There is also the possibility that only a small fraction of all merger events reach the conditions necessary for the electroweak phase transition within a region that is not engulfed by a black hole horizon. We note that the problem at hand is more complicated than that of a supernova explosion, and that the fraction of all stellar collapses that produce supernova explosions is not a settled issue as of yet. The integrated light from afterglow observations can set a lower bound on the total energy released and in principle challenge models that provide too little energy. The release of \( \sim 10^{54} \text{ ergs} \) in more conventional astrophysical settings (see, e.g., the hypernovae model of Paczynski 1997) is likely to be contaminated by baryons at a level that depends on many random parameters, such as the orientation of line of sight through the source. Under such circumstances, one would expect a continuous distribution of events with varying levels of baryonic contamination, from the level of \( \lesssim 10^{-2} M_\odot \) required for GRBs and up to the level of \( \sim 10 M_\odot \) found in supernovae. Such models would therefore predict the existence of softer events, such as X-ray bursts, which are not accompanied by a GRB. Our model naturally accounts for the gap between the baryonic contamination levels found in GRBs and supernovae.

The collapse of the bubble wall could also release a fraction \( \dot{\rho}_V \) of the neutron star rest mass, i.e., \( \sim 10^{52} \text{ ergs} \), when some of the Higgs potential energy is converted into nonthermal neutrinos with very high energies of \( \sim 100 \text{ GeV} \). The number of \( \sim 100 \text{ GeV} \) neutrinos per unit area from a source at a distance of \( \sim 3 \text{ Gpc} \) would be \( \sim 10^6 \text{ cm}^{-2} \). Full timing and directional coincidence with GRB events might allow statistical detections by large-area Cherenkov arrays, such as AMANDA. With a typical conversion efficiency of \( 10^{-8} \) into upward-moving muons (Gaisser et al. 1995), a year-long cross-correlation with
~300 bursts could yield ~3 events with a km$^2$ array. This neutrino burst supplements the predicted neutrino flux from standard fireball models (Waxman & Bahcall 1997; Paczynski & Xu 1994). A larger amount of energy, $\sim 10^{54}$, is released in $\sim 200$ MeV neutrinos, a remnant of the burnt phase behind the detonation front; however, these lower energy neutrinos would be more difficult to detect.

Finally, we note that the extended Higgs models are among the simplest extensions of the standard model, and the discrete symmetries needed to produce the domain walls are required by particle physics phenomenology. These models may well provide a new solution to the problem of electroweak baryogenesis with associated inhomogeneous cosmological nucleosynthesis. The quantitative constraints that are placed on the double Higgs theory by our GRB model could be tested with future accelerator experiments. Conversely, if our proposed link between electroweak theory and GRBs is established, GRBs might be used to place constraints on parameters of the Higgs sector that go beyond the capabilities of laboratory accelerators.

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