Cosmological evolution of neutrino balls

A. D. Dolgov and O. Yu. Markin

Institute of Theoretical and Experimental Physics

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We examine the burning of neutrino balls, which are kept from collapsing by the gas pressure exerted by right-handed Majorana neutrinos. Outside a ball, the latter have large mass, but inside they are massless. Accretion onto a neutrino ball can significantly reduce its lifetime. We discuss the possibility that quasars are neutrino balls, slowly burning up their mass.

1. INTRODUCTION

One of the most remarkable results of field theory in the last decade and a half is the discovery of stable classical states of a field with nonvanishing energy. Such fields include well-known topological solitons–domain walls that come about when discrete symmetries are broken, vortex lines (strings) that result from the breaking of $U(1)$ symmetry, and monopoles that result from the breaking of $SU(2)$ or $O(3)$ (see, e.g., Refs. 1, 2). In addition to these field configurations, which are stabilized by their topological properties, nontopological solitons produced by scalar fields have previously appeared in the literature.[3] More recently, other similar objects have been discovered, and their relevance to cosmology has been assessed (for example, see Ref. 4, which contains further references).

In the present paper, we examine a special kind of nontopological soliton known as a neutrino ball (NB hereafter), first proposed by Holdom.[5] The basic assumption is that the vacuum is chirally degenerate, and that left-handed Majorana neutrinos above our vacuum (the L-vacuum) are light or massless, while right-handed neutrinos are heavy. On the other hand, above the chirally conjugate vacuum, the ν_L are heavy and the ν_R are light. The relevant energy scale[5] is perhaps of the order of TeV. Domain walls arise upon spontaneous breaking of left–right symmetry, separating the L- and R-vacuums. Usually, when the two are degenerate, a bubble of one type of vacuum inside the other will collapse due to surface tension. That collapse can be inhibited, however, by the pressure exerted by massless neutrinos, which cannot leave since their mass is large outside the bubble.

When a discrete symmetry is broken, there arises in cosmology the well-known domain wall problem,[6] which relates to the high energy density of the latter and the fact that the inhomogeneities associated with them are too large. The problem can be sidestepped in models that have broken left-right symmetry from the outset, so that the probability that an L-vacuum will be formed is higher than the probability of forming an R-vacuum. The volume of space occupied by the latter can then be made quite small. It would not be difficult to construct such a model, but that is not the main concern of the present note. We also note that the stabilization of closed bubbles bounded by a domain wall by means of right-handed neutrinos, although it looks attractive, is by no means the only possibility. There are indeed other models that lead to the same cosmological consequences as the one considered here.

The evolution of NB after it has been created is described in Ref. 5. The pressure due to surface tension,

$$p=2\sigma/R, \tag{1}$$

where σ is the surface energy density and R is the radius of curvature of the wall, should be balanced by the pressure of the neutrino gas. The mass of the ball comes from the mass of the wall and the mass of the neutrino gas inside:

$$M=4\pi R^2\sigma+{}^4/_3\pi R^3\left(3\frac{2\sigma}{R}\right)=12\pi R^2\sigma. \tag{2}$$

A neutrino ball that is formed at a temperature $T\gtrsim 0.2m_e$ will disappear by virtue of the annihilation process $\nu_R\bar\nu_R\to e^+e^-$. For $T\lesssim 0.2m_e$ the NB can only cool via that process, and the neutrino gas inside the ball becomes degenerate when the age of the universe is $t\approx 10^8$ sec. For that to happen, the mass of the NB must be greater than

$$M_0\approx 10^5\,M_\odot\,(\sigma/\mathrm{TeV}^3)^3/k_\nu^2,$$

where $k_\nu=3$ is the number of kinds of neutrinos, and $M_\odot$ $2\cdot 10^{33}$ g is the mass of the sun. A neutrino ball with a mass greater than

$$M_1\approx 10^8\,M_\odot\,(\mathrm{TeV}^3/\sigma),$$

turns into a black hole, and will live practically forever. The minimum radius at which a NB will collapse is $R_1=3\times 10^{13}$ cm(TeV^3/σ). A neutrino ball with $M<M_1$ (and accordingly $R<R_1$) is unstable, although it may well be long-lived on a cosmological time scale.

We note here that at the high temperatures encountered in the early universe, the process $\nu_R\bar\nu_R\to e^+e^-$ does not necessarily lead to the collapse of a fairly large neutrino ball, since it may be balanced by the inverse process if the pressure at a wall, $p=2\sigma/R$, is low compared with the thermal pressure, $p_T\sim T^4$. Large balls, larger by far than the horizon at the time of their appearance, could therefore be produced fairly early (for $T\approx\sigma^{1/3}$), and survive to the present epoch.

The decay of a neutrino ball that has cooled via the reaction $\nu_R\bar\nu_R\to 3\gamma$ was considered in Ref. 5. The process $\nu_R\bar\nu_R\to 2\gamma$, which at first glance seems faster, turns out to be possible only to second order in the weak interaction,[7] and is negligible. According to Ref. 5, the typical lifetime of a neutrino ball is

$$\tau_{3\gamma}\approx 10^{14}\left(\frac{m_e}{\mu}\right)^{13}\mathrm{sec}, \tag{3}$$

where μ is the chemical potential of a degenerate neutrino gas.

The burnup of a neutrino ball via the reaction $\nu_R\bar\nu_R\to 3\gamma$ takes place explosively. In fact, expressing the energy density of a degenerate neutrino gas in terms of its chemical potential,

$$\rho=2k_\nu\mu^4/8\pi^2,$$

and making use of (1) and (2), we obtain

$$\mu\approx 0{,}15\ \mathrm{MeV}\left(\frac{M}{10^6 M_\odot}\right)^{-1/8}\left(\frac{\sigma}{1\,\mathrm{TeV}^3}\right)^{3/8}. \qquad (4)$$

Thus, as the mass of the NB decreases, μ increases, and the rate of the process increases as μ^{13}. For $\mu < m_e$, however, the time (3) can easily exceed the age of the universe.

In the present note, we examine a different possibility for NB burnup, involving the accretion of matter and annihilation of neutrinos in the reaction

$$\nu_R\bar{\nu}_R e^-\to e^-\gamma. \qquad (5)$$

As we shall see shortly, the lifetime of a neutrino ball as a result of this process goes as μ^{-4}, and can easily turn out to be less than $\tau_{3\gamma}$. Burning can then be fairly leisurely, rather than explosive, since the electron products in (6) acquire high energy, while the photons inhibit the accretion of new electrons. Furthermore, the deceleration of incident protons and electrons by previously accreted matter means that those particles will accumulate near the boundary of the NB, which should lead to surface burning, rather than volume burning. If this scenario is actually realized, then quasars might possibly be neutrino balls that are slowly being incinerated in the reaction (5).

In Sec. 2, we estimate the reaction rate of (5). We go on to examine the accretion of matter onto a neutrino ball, which becomes efficient following the recombination of hydrogen in the early universe, i.e., for $T < 3000$ K (Sec. 3). Finally, in the fourth section, we assess the cosmological consequences of the putative existence of neutrino balls.

2. REACTION RATE FOR $\nu_R\bar{\nu}_R e^-\to e^-\gamma$

The rate at which neutrinos are converted into photons via reaction (5) is given by

$$\dot{n}_\nu=-\frac{(2\pi)^4}{2E_\nu}\int \delta^4(\nu_1+\nu_2+p_1-p_2-k)\,\overline{|A|^2}n_\nu n_{\bar\nu}n_{e_i}\prod_j d\nu_j. \qquad (6)$$

The product here is taken over the phase-space volumes of all particles participating in the reaction, except the neutrinos:

$$j=\bar\nu,\ e_i,\ e_f,\ \gamma;$$

$$d\nu_j=\frac{d^3p_j}{(2\pi)^3 2E_j}$$

is the volume of an element of phase space, $\overline{|A|^2}$ is the squared magnitude of the matrix element, averaged over the helicity of the incoming electron e_i, and n_α is the phase-space density of particles of type α, such that the number of particles of type α per unit volume is

$$N_\alpha=\int n_\alpha\frac{d^3p_\alpha}{(2\pi)^3}.$$

For a neutrino ball,

$$n_\nu=n_{\bar\nu}=1\Big/\left[\exp\left(\frac{E_\nu-\mu}{T}\right)+1\right],$$

$$N_\nu=N_{\bar\nu}=\frac{k_\nu\mu^3}{6\pi^2}.$$

in the completely degenerate case. The inverse process, $e^-\gamma\to e^-\nu_R\bar\nu_R$, is negligible, since the state is far from equilibrium.

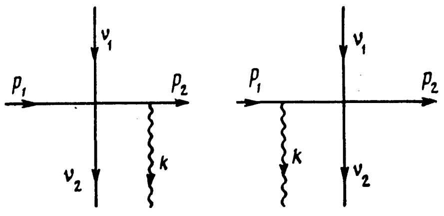

FIG. 1. Feynman diagrams for the reaction $\nu_R\bar\nu_R e^-\to e^-\gamma$.

The amplitude of the reaction (5) is small because of the Fermi vertex (Fig. 1), but the rate will be fairly high if the number density N_e of incoming electrons is large. The reciprocal of the characteristic time for the reaction is

$$\tau_\gamma^{-1}=\frac{\dot N_\nu}{N_\nu}=(2\pi)^4\int\delta^4(\nu_1+\nu_2+p_1-p_2-k)\,\overline{|A|^2}n_\nu n_{\bar\nu}n_{e_i}\prod_q d\nu_q/N_\nu,$$

where the product is taken over all particles participating in the reaction:

$$q=\nu,\ \bar\nu,\ e_i,\ e_f,\ \gamma.$$

We restrict our attention to the evaluation of $\overline{|A|^2}$, which results solely from the interaction of the right-handed neutrino and electron currents:

$$\overline{|A|_R^2}=2^7g_R^2G_F^2e^2\Big\{\frac{1}{(p_1k)^2}(p_2\nu_2)[m_e^2(k\nu_1-p_2\nu_2)+(kp_1)(k\nu_2)]$$
$$+\frac{1}{(p_2k)^2}(p_1\nu_1)[(p_2k)(\nu_2k)-m_e^2(p_2\nu_2+k\nu_2)]$$
$$+\frac{1}{(p_1k)(p_2k)}\{2(p_1p_2)(\nu_1p_1)(\nu_2p_2)+(\nu_1p_1)[(p_1p_2)(k\nu_2)$$
$$-(p_1\nu_2)(p_2k)$$
$$+(p_1k)(p_2\nu_2)]$$
$$-(p_2\nu_2)[(p_1p_2)(\nu_1k)+(p_1\nu_1)(p_2k)-(p_1k)(p_2\nu_1)]\}\Big\}.$$

Here $g_R\approx 1$ is the coefficient of the product of the right-handed currents in the interaction Lagrangian. The initial electrons are nonrelativistic. Bearing in mind that the neutrino energies are less than the electron mass, we may also assume the same to be true of the final electrons, greatly simplifying the integration.

In that approximation, then

$$\overline{|A|_R^2}=\frac{g_R^2 2^7G_F^2e^2}{E_\gamma}[(\nu_1k)E_\nu+(\nu_2k)E_{\bar\nu}]. \qquad (7)$$

Integration and substitution of $e^2=4\pi\alpha$ yields

$$\tau_\gamma^{-1}=\frac{8}{\pi^2}g_R^2\alpha G_F^2N_e\frac{\mu^4}{m_e^2}. \qquad (8)$$

Plugging in some numbers, we obtain

$$\tau_\gamma\approx 4\cdot 10^{21}\mathrm{c}\left(\frac{m_e}{\mu}\right)^4\left(\frac{N_e}{1\ \mathrm{eV}^3}\right)^{-1}. \qquad (9)$$

3. ACCRETION ONTO A NEUTRINO BALL

Neutrino burning in a neutrino ball throught the reaction (5) becomes important at a time

$$t\approx\tau_\gamma. \qquad (10)$$

The value of τ_γ falls off with time due to the growth of N_e, which results from plasma accretion prior to, and neutral matter accretion following, recombination; the plasma comes from the immediate environment of the neutrino ball.

Let us examine the growth of N_e in the vicinity of an NB. Prior to recombination, the latter is immersed in an expanding photon-gas background, with density $N_\gamma(t) = 0.24T^3(t)$ and temperature

$$\frac{T}{1\text{ MeV}}=\left(\frac{t}{1\text{sec}}\right)^{-1/2},$$

containing a mixture of protons and electrons with a frozen-in density of

$$N_{ef}(t)=N_{pf}(t)\approx 3\cdot 10^{-10}N_\gamma(t).$$

The infall of massive particles onto the NB opposes its light pressure. The net result is that particle diffusion through the photon gas in the direction of the NB sets in at velocity v_d and N_e continues to grow, until Eq. (10) is satisfied.

In a reference frame tied to the NB, a parcel of gas at a distance r emerges with the Hubble velocity $v_H = r/2t$. In that coordinate system, then, particles approach the NB with $v_d \gtrsim v_H$. As will be shown below, that inequality is satisfied only by particles located within some capture radius r_c, and the number of such particles, $[4\pi r_c^3(t)/3]N_{pf}(t)$, will grown with time. Following capture, they will collect in the vicinity of the NB, One can then assume that N_e is proportional to the increasing volume of the capture sphere of raidus r_c:

$$N_e(t)=N_{pf}(t)\frac{r_c^3(t)}{R^3}. \tag{11}$$

Here we have neglected the time that it takes to get from r_c to the neutrino ball.

The magnitude of $r_c(t)$ is determined by the condition

$$v_d=v_H. \tag{12}$$

In a reference frame comoving with a small parcel of gas, the conditions are ultimately such that the gravitational force is counterbalanced by light pressure:

$$v_d=\frac{MGm}{r^2}b.$$

Here b is the mobility of particles of mass m in a photon gas,

$$b\approx\frac{1}{TN_\gamma\sigma_{\gamma m}},$$

where $\sigma_{\gamma m}$ is the photon interaction cross section of those particles, which itself is responsible for generating light pressure as well.

Prior to the recombination epoch,

$$v_d=\frac{GMm_p}{r^2}\frac{1}{TN_\gamma\sigma_{\gamma e}}\approx\frac{GMm_pm_e^2}{0{,}24T^4\alpha r^2}. \tag{13}$$

Here we have taken into account the fact that protons experience a gravitational attraction m_p/m_e times as strong as electrons, and that Compton scattering slows electrons down more than protons, since the ratio of their mobilities is

$$\frac{b_e}{b_p}=\frac{\sigma_{\gamma p}}{\sigma_{\gamma e}}=\left(\frac{m_e}{m_p}\right)^2.$$

Electrons diffuse together with protons, however, preserving the electrical neutrality of the plasma.

We can now express r_c^3 as a function of the temperature of the universe:

$$\left(\frac{r_c}{1\text{sec}}\right)^3\approx 3\cdot 10^{20}\left(\frac{T}{1\text{ eV}}\right)^{-6}\frac{M}{10^6M_\odot}. \tag{14}$$

From (2), (4), (9), (11), and (14), we obtain for the epoch prior to recombination ($T\gg 0.3$ eV)

$$\tau_\gamma\approx 2{,}5\cdot 10^{19}\text{ sec}\frac{M}{10^6M_\odot}\left(\frac{\sigma}{1\text{TeV}^3}\right)^{-3}\left(\frac{T}{1\text{ eV}}\right)^3. \tag{15}$$

When the temperature of the universe drops below the recombination temperature $T_r\approx 0.3$ eV, deceleration is abruptly curtailed, since we have $\sigma_{\gamma H}\sim T^4$ for scattering from hydrogen and the mobility goes at T^{-8}. The region defined by Eq. (12) grows rapidly with decreasing T, and the growth of N_e in the vicinity of the NB is no longer suppressed. One can obtain a simple estimate for N_e in the post-recombination era by neglecting the interaction of accreting particles with the medium, based on the following considerations.

Gravitational capture of a particle requires that the Hubble expansion velocity $v_H = Hr$ be less than the escape velocity $(Gm/r)^{1/2}$. Hence, after recombination, in the matter-dominated phase, we obtain for the capture radius

$$r_{cMD}^3\approx {}^9/_2GMt^2.$$

Here we have used the fact the $H = 2/3t$ holds in the matter-dominated universe. Assuming a hydrogen density

$$N_H=N_{pf}=10^{-10}T^3,$$

we obtain for the electron density in the neighborhood of a neutrino ball

$$N_e={}^9/_2GMN_Ht^2R^{-3}.$$

In the matter-dominated phase, N_Ht^2 is constant, and can thus be expressed in terms of the present-day values of N and t.

Adopting this value of N_e and the chemical potential (4), we obtain τ_γ for the post-recombination era:

$$\tau_\gamma\approx 0.5\cdot 10^{15}\text{ sec}\frac{M}{10^6M_\odot}\left(\frac{\sigma}{1\text{ TeV}^3}\right)^{-3}.$$

As will shortly be made clear, this is a lower limit on the estimated lifetime of a neutrino ball.

In Fig. 2, we have plotted $\tau_\gamma(T)$ and the cosmological time $t(T)$ for $M = 10^6M_\odot$ and $\sigma = 1$ TeV^3.

Consideration of a number of other factors is a prerequisite to a more detailed description of the growth of N_e.

1. *Time required for accretion from large distances.* This is neglected prior to recombination; instead, we fall back on the following estimate. The time t_{dr} to move from $r_c(t)$ to the neutrino ball is a combination of the diffusion time t_d at a velocity

$$v_{dc}=\frac{r_c}{2t}\approx 10^{-5}$$

and the time required to be accelerated to that speed by a force GM/r_c^2. The time t_a before recombination is much less than t_d:

$$t_a\approx v_{dc}r_c^2/MG\ll t_d.$$

In that event,

$$t_{dr}\approx t_d=r_c/v_{dc}=2t.$$

This means that all of the electrons and protons collect fairly quickly in the neighborhood of the NB, and the accretion time does not restrict the growth in N_e. After recombina-

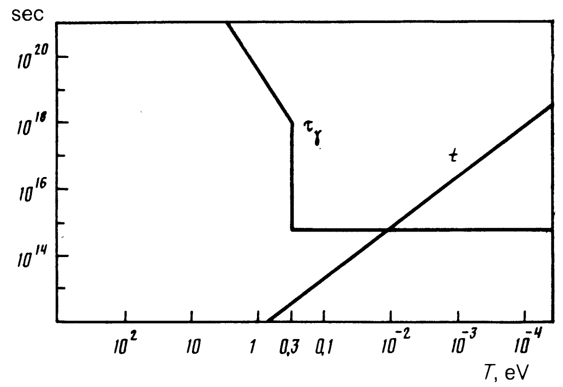

FIG. 2. Characteristic time τ_γ for the reaction $\nu_R \bar{\nu}_R e^- \to e^- \gamma$ in the neighborhood of a neutrino ball as a function of the temperature of the universe, for a neutrino ball of mass 10^6 $M_\odot$ and domain-wall surface tension of 1 TeV^3. The point at which the two lines cross corresponds to the time at which the burning of a neutrino ball through this reaction becomes significant.

tion, however, when the region accessible to accretion abruptly grows to $4\pi r_{c\,\mathrm{MD}}^3/3$, the growth of $N_e(T)$ in the vicinity of the NB starts to feel the effects of the rate at which particles are garnered from large distances.

2. *Internal pressure of the neutrino ball.* At the point at which (10) is first satisfied, a neutrino ball is an analog of a massive star of mass M, and with a plasma temperature equal to.[8]

$$\left(\frac{T}{1\ \mathrm{K}}\right)=10^7\left(\frac{M^3}{M_a M_\odot^2}\right)^{1/12} m_p N_e.$$

Here

$$M_a = m_p N_e^4 / {}_3\pi R^3$$

is the mass of the accreted plasma. For $M = 10^6$ $M_\odot$, the temperature is 10^8 K, and the pressure inside the star is determined essentially by the blackbody radiation of the plasma. In that approximation, the equilibrium size of a blob of plasma is indifferent to its density,[8] i.e., the pressure inside the neutrino ball does not prevent further increases in N_e.

3. *Slowing of accretion by radiation pressure from the star.* The photons that are emitted induce substantial radiative drag during accretion. Furthermore, after protons and electrons are initially accumulated within a neutrino ball, their mean free path, as determined by scattering from one another, becomes small compared with R. Scattering from neutrinos is also negligible, although the number density of the latter is extremely high, because of their small cross section. Further accretion only leads to a pileup of particles at the boundary of the accretion zone, and only there is the reaction $\nu_R \bar{\nu}_R e^- \to e^- \gamma$ efficient (surface burning). It is still possible for the inverse process to take place, with the neutrino ball emitting high-energy electrons and protons.

4. *Slowing of accretion due to mass burnup in the neutrino ball.* A detailed account of the evolution of a neutrino ball would require that one incorporate all of the above factors. The necessary calculations are quite lengthy, and are therefore outside the scope of the present paper.

4. COSMOLOGICAL CONSEQUENCES

The cosmological manifestations of neutrino balls depend strongly on their mass and lifetime. It would seem that the most interesting possibility is that a neutrino ball with a mass of order 10^6–10^8 $M_\odot$ and a lifetime of order 10^{10} y might serve as the energy source in an active galactic nucleus or a quasar. It seems likely that such objects ought to undergo surface burning, which should therefore be fairly slow in order to explain the observed radiation from quasars. Photons emitted as a result of the reaction (5) and interacting with the surrounding medium might give rise to the observed spectrum.

If the chemical potential of a neutrino gas is of order $m_e/2$, the emergent photons may have usfficient energy to produce e^+e^- pairs.

High-mass neutrino balls might also serve as the condensation centers for nascent galaxies. Here the unanswered question relates to the magnitude of angular fluctuations in the cosmic background radiation, which is a stumbling-block in all models of the formation of the large-scale structure of the universe.

Another interesting possible "use" for neutrino balls is that if there are enough of them and they live for 10^{14}–10^{15} sec, they could reionize the cosmic plasma and thereby smooth out fluctuations in the background radiation.

Naturally, all of these problems require more detailed study.

In closing, we should like to reiterate that it is not necessary to relate this theory to a specific mechanism for realizing the nontopological solitons discussed above. Other models, which might lead to the same consequences, are not ruled out; they might give rise, in particular, to the existence of long-lived, macroscopic objects with colossal yields due to the total conversion of their mass to energy.

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