BOILING OF NUCLEAR LIQUID IN CORE-COLLAPSE SUPERNOVA EXPLOSIONS

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We investigate the possibility for the boiling instability to appear in a nuclear liquid in the inner core of a proto-neutron star (PNS) formed in the core collapse of a type II supernova. We derive a simple criterion for boiling to occur. Using this criterion for one of the best described equations of state of the supernova matter, we find that boiling is quite possible under the conditions realized inside the proto-neutron star. We discuss the consequences of this process such as an increase of the heat transfer rate and the pressure in the boiling region. We expect that taking this effect into account in the conventional neutrino-driven delayed-shock mechanism of type II supernova explosions can increase the explosion energy and reduce the mass of the neutron-star remnant.

1. Introduction

The detection of electron antineutrinos from SN 1987A (see [1–3]) confirmed the previous theoretical ideas of neutrinos playing a crucial role in the core collapse of type II supernovae. According to the well-established estimates, only about one percent of the gravitational binding energy (or $(1.4 \pm 0.4) \times 10^{51}$ erg for SN 1987A; see [4]) is released in the form of the thermal and kinetic energies of an expanding ejecta; the remaining part is accumulated and then carried away by different types of neutrinos [5] which are known to be trapped effectively within nuclear matter during the last stages of the core collapse (see [6] and references therein). Initially, it did not seem hard to explain the observed values of kinetic energy of the expanding ejecta using the neutrino-nucleon interaction as an effective channel of energy transfer from the emitted neutrinos to the nuclear matter [7, 8]. However, a specific realization of this mechanism of supernova explosions encountered with great difficulties. Thus, it was realized that the prompt shock wave generated during the core collapse fades away on the time scale of several milliseconds, by losing its energy for the nuclear dissociation [9, 10] and the radiation of $\nu\overline{\nu}$-pairs [11]. As a result, in simulations, the shock wave pushed down by the infalling matter starts to move inward, by leading to the formation of a black hole rather than to the explosion.

Considerable efforts were made to remedy this situation. Bethe and Wilson [12] showed that the shock wave could be revived in about 100 msec after the core bounce if the neutrino luminosity were sufficiently enhanced. The way to such an enhancement of the neutrino luminosity was opened after the neutrino diffusion inside the center of a PNS was discovered [13] and found to be convectively unstable (see [14, 15] and references therein). Nevertheless, numerical simulations of the neutrino-driven shock revival still yield contradictory results. While explosions with a kinetic energy up to 1.72×10^{51} erg are obtained in [16] (0.5×10^{51} erg in [15], 10^{50} erg in [17], 0.94×10^{51} erg in [18]), there is also a number of simulations where explosions are not observed at all [19, 20].

This inconsistency between the observational data and the results of core-collapse numerical simulations motivated some researches to look for alternative mechanisms. The magnetorotational mechanism proposed in [21] can produce explosions with energies up to 0.61×10^{51} erg on a time scale of $\sim$ 0.5 s after the core bounce [22, 23]. The acoustic mechanism developed in [24] also produces the explosion; although its energy is rather uncertain in the numerical simulations, it develops for a time range of several hundreds of milliseconds. Thus, even with new mechanisms and effects taken into account, the resulting energy release is marginally short of the observed values.

One can conclude that all mechanisms of core collapse require some additional engine to provide the observable explosions. Such a new engine is the subject of the present paper. By analogy with work [13], we consider an additional type of the transport of the nuclear matter in a core which is different from diffusion and convection. It occurs in the form of *boiling*, i.e., the first-order transition between different phases of nuclear matter.

We start with the observation that the supernova matter in the inner core can exist in several phases and their mixtures [25–30]. Among them are the following (in the order of increasing density):

- the phase of spherical nuclei,
- the phase consisting of elongated nuclei (often called *pasta*)
- the *slab-like* nuclei
- the phase with *cylindrical holes*
- the phase with charged *microscopic* bubbles or the *cheesed* phase (we will use this last term below not to confuse it with *macroscopic* bubbles, of which we will speak later on)
- the *homogeneous* supernova matter

It is natural to expect that several phase transitions can occur during the evolution of nuclear matter after the core collapse. Numerical simulations of the nuclear-matter phase transitions in supernovae were usually aimed at determining the thermodynamic properties at the pre-bounce stage of the collapse and were needed to understand the development of a prompt shock wave. Such transitions taking place in a rapidly changing environment during the collapse can be called "short-term" phase transitions. In our paper, we discuss what we call "long-term" phase transitions which occur in nuclear matter after the bounce under the condition of relative mechanical and *local thermodynamic equilibrium*. The main goal of this paper is to examine the potential importance of such "long-term" phase transitions for the supernova explosion dynamics.

In the "normal" case of the mechanical and local thermodynamic equilibrium, different phases occupy the corresponding radial shells of a PNS, and this spatial phase picture evolves continuously and relatively slowly in time. However, if the heating of nuclear matter (which is mainly due to the diffusion of neutrinos) is sufficiently strong and inhomogeneous, it can lead to a condition similar to that in an ordinary teakettle. Specifically, the bulk of a particular phase can overheat and become unstable with respect to the phase transition, and small bubbles of the lighter phase can spontaneously appear in its volume. The bubbles will grow and, due to the Archimedean force, rise upwards. Henceforth, such a process is called *boiling* by analogy. In this paper, we argue that this process can provide a more efficient mechanism of heating the outer parts of the PNS (as compared with the neutrino-diffusion and convection mechanisms) and generate an additional pressure wave.

The paper is organized as follows. In Sec. 2, we give the basic thermodynamic description of the coexistence of various phases in the supernova matter after the bounce. In Sec. 3, we derive the criterion of boiling to occur, and, in Sec. 4, we provide our numerical estimates for the values involved in this criterion using the tabulated equation of state from [31]. In Sec. 5, we consider a simple model of the boiling mechanism and derive numerical estimates characterizing the efficiency of this process. We summarize and discuss our results in Sec. 6.

2. Phase Equilibrium

Just after the core bounce, the inward movement of the inner core significantly decreases, and the prompt shock wave moves outwards losing its energy mostly on the nuclear dissociation and the radiation of $\nu\bar{\nu}$-pairs. The material within and around the PNS approaches a state of mechanical equilibrium (while the velocities of the convective motion are much smaller than the appropriate first cosmic velocity). In contrast with the rapid collapse during the pre-bounce stage of contraction, the local thermal equilibrium is a good approximation for the post-bounce stage.

Because of the radial density gradient, the PNS at this stage has onion-like structure. The density of its inner core is higher than the nuclear saturation density, and the homogeneous matter phase is thermodynamically preferred. In the outer layers of the PNS, the density is much less than the nuclear saturation density, and matter exists in the form of ordinary nuclei. A number of intermediate phases can exist between these two shells. Adjacent phases are separated by the surfaces of coexistence. Here, we derive a simple condition of coexistence of phases applied to the situation under consideration.

We can consider a phase transition characterized by the fixed pressure p, temperature T, baryon number B, electric charge C, and lepton number L. The conservation laws of the last three quantities imply the existence of the corresponding chemical potentials: μ_{B}, μ_C, and μ_L. We can determine their values from the chemical potentials of supernova matter components (we suppose that the supernova matter consists only of neutrons, protons, electrons, and electron neutrinos):

$$\begin{array}{ll} \mu_n = \mu_{\rm B}\,, & \mu_p = \mu_{\rm B} + \mu_C\,, \\ \mu_e = \mu_L - \mu_C\,, & \mu_\nu = \mu_L\,. \end{array} \tag{1}$$

Since the number of particle species is greater than the number of independent charges, we have one more relation for the chemical potentials (the so-called beta-equilibrium condition):

$$\mu_p + \mu_e = \mu_n + \mu_\nu. \tag{2}$$

For fixed values of p and T, our thermodynamic system tends to a state with a minimum value of the Gibbs free energy (see, e.g., [32])

$$\Phi = \sum_i \mu_i N_i = \mu_{\rm B} B + \mu_C C + \mu_L L. \tag{3}$$

Since we are interested only in electrically neutral phases, we have

$$C \equiv 0 \tag{4}$$

and the second term in (3) vanishes. The third term, $\mu_L L$, does not change during the phase transition because the electron neutrinos interact with nuclear matter very weakly.

Finally, the condition of equilibrium between phases 1 and 2 is

$$\mu_{1n}\left(p_0,\ T_0,\ \mu_{\nu 0}\right) = \mu_{2n}\left(p_0,\ T_0,\ \mu_{\nu 0}\right), \tag{5}$$

where the subscript "0" marks the values of the parameters right on the interface between the two phases.

3. Criterion of Boiling

The local thermal equilibrium described in the previous section is continuously disturbed by the process of diffusion of electron neutrinos away from the central region of the PNS. This causes the inhomogeneous heating of the bulk of nuclear matter. If this heating is sufficiently strong, it can lead to the overheat of a particular phase, which may result in its *boiling* — the emergence of bubbles of the adjacent lighter phase in its bulk. These bubbles will then raise and grow, effectively transferring heat and lepton number. Boiling is a particular case of a non-equilibrium first-order phase transition. In this section, we derive a necessary condition of boiling in the form of a relation for the parameters of the supernova matter.

According to Eq. (5), in the process of external heating, the heavier phase 1 becomes metastable with respect to its transition to the lighter phase 2 if the condition is reached such that

$$\mu_{1n}(p_0 + \delta p,\ T_0 + \delta T,\ \mu_{\nu 0} + \delta\mu_\nu) >$$

$$> \mu_{2n}(p_0 + \delta p,\ T_0 + \delta T,\ \mu_{\nu 0} + \delta\mu_\nu), \tag{6}$$

where the positive increments of the thermodynamic variables correspond to their radial gradients. From this, we obtain the condition

$$\left[\left(\frac{\partial \mu_{2n}}{\partial T}\right)_{p,\mu_\nu} - \left(\frac{\partial \mu_{1n}}{\partial T}\right)_{p,\mu_\nu}\right]\frac{dT}{dr} +$$

$$+ \left[\left(\frac{\partial \mu_{2n}}{\partial \mu_\nu}\right)_{p,T} - \left(\frac{\partial \mu_{1n}}{\partial \mu_\nu}\right)_{p,T}\right]\frac{d\mu_\nu}{dr} +$$

$$+ \left[\left(\frac{\partial \mu_{2n}}{\partial p}\right)_{T,\mu_\nu} - \left(\frac{\partial \mu_{1n}}{\partial p}\right)_{T,\mu_\nu}\right]\frac{dp}{dr} > 0. \tag{7}$$

In the important particular case of hydrostatic equilibrium, we have

$$\frac{dp}{dr} = -\rho_m g, \tag{8}$$

where ρ_m is the mean density, and g is the local free fall acceleration. Substituting this into (7), we obtain

$$\left[\left(\frac{\partial \mu_{2n}}{\partial T}\right)_{p,\mu_\nu} - \left(\frac{\partial \mu_{1n}}{\partial T}\right)_{p,\mu_\nu}\right]\frac{dT}{dr} +$$

$$+ \left[\left(\frac{\partial \mu_{2n}}{\partial \mu_\nu}\right)_{p,T} - \left(\frac{\partial \mu_{1n}}{\partial \mu_\nu}\right)_{p,T}\right]\frac{d\mu_\nu}{dr} >$$

$$> \left[\left(\frac{\partial \mu_{2n}}{\partial p}\right)_{T,\mu_\nu} - \left(\frac{\partial \mu_{1n}}{\partial p}\right)_{T,\mu_\nu}\right]\rho_m g. \tag{9}$$

4. Numerical Estimates

It remains to check whether the condition of boiling derived in the previous section can be realized in the usual supernova core-collapse. For this purpose, we estimate the values of the partial derivatives in (9) using the numerical simulations of the EoS of the supernova matter given in [31].

The authors of [31] tabulate all essential parameters describing the supernova matter in three phases: nuclei, cheesed phase, and homogeneous matter. In Table 1, we show the parameters which are required in our analysis. Because the required values of derivatives are not listed in [31], we try to obtain them by interpolation. Namely, we use the finite differences:

$$\mu_n(p_2,T_2,\mu_{\nu 2})-\mu_n(p_1,T_1,\mu_{\nu 1})\approx\frac{\partial\mu_n}{\partial p}(p_2-p_1)+$$

$$+\frac{\partial\mu_n}{\partial T}(T_2-T_1)+\frac{\partial\mu_n}{\partial\mu_\nu}(\mu_{\nu 2}-\mu_{\nu 1}), \tag{10}$$

neglecting the higher derivatives. For each phase, we solve a system of three equations for three unknown variables. The numerical values obtained in such a manner should be considered as estimates. They are presented in Table 2.

To check whether the conditions of boiling are realized, we use the conventional values of the other parameters. Numerical simulations (see, e.g., [19]) give the following estimates:

$$g\approx 1.0\times 10^{14}\ \mathrm{cm/s^2},$$

$$\frac{d\mu_\nu}{dr}\approx-(10-20)\ \mathrm{MeV/km},\quad \frac{dT}{dr}<0. \tag{11}$$

Using this data together with those in Table 2, we obtain the following conditions for boiling:
– for the transition between the nuclear and cheesed phase ($\rho_m\approx 0.8\times 10^{14}$ g/cm^3),

$$\frac{dT}{dr}<-(0.4-0.8)\mathrm{MeV/km}; \tag{12}$$

– for the transition between homogeneous matter and cheesed phase ($\rho_m\approx 1.6\times 10^{14}$ g/cm^3),

$$\frac{dT}{dr}>-(1.0\div 1.5)\mathrm{MeV/km}. \tag{13}$$

The difference in the inequality signs in estimates (12) and (13) is related to the difference in the signs of the coefficients of the temperature gradients in (7) or (9) for the two phase transitions under consideration. Note that conditions (12) and (13) are overlapping and complementary, so it is very likely that one of them is satisfied. We can expect, therefore, that the boiling of nuclear matter can take place inside the supernova core. However, this only demonstrates the possibility of principle, calling for an additional thorough investigation of this issue.

5. A Model

In this section, we construct the simplified model of a phase transition between the heavier phase 1 and the lighter phase 2 which are taken, for definiteness, to be the cheesed phase and the phase of nuclei, respectively.

We assume the spherical symmetry of the PNS, so that the cheesed phase is located in a spherical shell with the radial coordinate from $R-H$ to R. The free fall acceleration on the upper boundary of this region is equal to

$$g=\frac{GM}{R^2}=$$

$$=1.33\times 10^{14}\left(\frac{M}{M_\odot}\right)\left(\frac{10\ \mathrm{km}}{\mathrm{R}}\right)^2\ \mathrm{cm/s^2}, \tag{14}$$

where M is the total mass inside the sphere of radius R.

We can estimate H using the condition of hydrostatic equilibrium

$$\rho g H\approx\Delta p, \tag{15}$$

where Δp is the dimension of the pressure interval, in which the cheesed phase exists. According to Table 1, this pressure interval is approximately equal to 0.83 MeV/fm^3. We thus have

$$H\approx\frac{\Delta p}{\rho g}\approx 1.0\times\left(\frac{\Delta p}{0.83\ \mathrm{MeV/fm^3}}\right)\left(\frac{10^{14}\ \mathrm{g/cm^3}}{\rho}\right)$$

$$\times\left(\frac{1.33\times 10^{14}\ \mathrm{cm/s^2}}{g}\right)\ \mathrm{km}. \tag{16}$$

If we assume that the boiling takes place in the whole volume of phase 1, then the total mass of the boiling

Table 1. Parameters from [31] used in the estimate of the partial derivatives in (9)

Phase	n_B, fm^{-3}	μ_n, MeV	p, MeV/fm^3	T, MeV	μ_ν, MeV
Nuclei	0.02	−2.230	0.1807	4.00	81.613
	0.04	−1.953	0.4556	4.88	105.363
	0.05	−1.837	0.6111	5.17	114.092
	0.06	−1.818	0.7738	5.44	121.699
Cheesed	0.05	−2.660	0.5615	5.07	114.149
	0.07	−2.189	0.9086	5.65	127.934
	0.09	−1.967	1.2726	6.08	139.143
	0.10	−2.093	1.4432	6.23	144.213
Homog.	0.10	−2.536	1.4241	6.18	144.530
	0.11	−1.202	1.7203	6.64	147.952
	0.12	0.154	2.2267	7.09	169.312
	0.16	7.525	4.227	8.84	188.917

Table 2. Results for the partial derivatives

Phase	$\left.\frac{\partial\mu_n}{\partial p}\right\|_{T,\mu_\nu}$, fm^3	$\left.\frac{\partial\mu_n}{\partial T}\right\|_{p,\mu_\nu}$	$\left.\frac{\partial\mu_n}{\partial\mu_\nu}\right\|_{p,T}$
Nuclei	−1.353	−2.626	0.125
Cheesed	0.666	5.182	−0.201
Homogeneous	2.87	1.289	−0.0317

matter can be estimated as[1]

$$M_b \approx 4\pi\rho R^2 H \approx 6.1 \times 10^{-2} \left(\frac{\Delta p}{0.83 \text{ MeV/fm}^3} \right) M. \quad (17)$$

The densities of phases 1 and 2 are related by ρ_1 and $\rho_2 = \rho_1(1-\epsilon)$, where $\epsilon \ll 1$. According to [34], ϵ is equal to 0.1 for the phase transition between the cheesed phase and the homogeneous matter phase and to 0.2 for the transition between nuclei and the cheesed phase. Lower estimates for ϵ are present in [31]: it equals to 0.07−0.08 for both phase transitions if the entropy per baryon (which is conserved in the simulations) $S/A = 1.0$; for $S/A = 1.5$, the value $\epsilon = 0.05$ is obtained for the transition between nuclei and the cheesed phase, and $\epsilon = 0.01$ for the transition between the cheesed phase and homogeneous matter. To be conservative, we use the lowest estimate in this paper, namely, $\epsilon = 0.01$.

The maximum acceleration which can be reached by a raising bubble (neglecting the liquid resistance) is

$$a_{\max} = \frac{\epsilon GM}{R^2}. \quad (18)$$

The maximum velocity that can be reached by the bubble is then

$$v_{\max} \sim \left(\frac{2\epsilon \Delta p}{\rho} \right)^{1/2} = 5100 \left(\frac{\epsilon}{10^{-2}} \frac{\Delta p}{0.83 \text{ Mev/fm}^3} \right)^{1/2} \times$$

$$\times \left(\frac{10^{14} \text{ g/cm}^3}{\rho} \right)^{1/2} \text{ km/s}. \quad (19)$$

Matter in the boiling volume will convectively move in both directions. We can expect that roughly a half of matter moves upwards (the bubbles and the surrounding matter) and the other half moves downwards with the same average velocity (from the momentum conservation). Therefore, the “convective boiling” overturn will be established. We can try to estimate the maximum efficiency of this overturn.

The first effect to be discussed is the heat transfer. If the bubbles fill a half of the boiling volume, the heating rate at the surface of the boiling layer is

$$\dot{Q}_{\max} \sim \frac{1}{2} \times 4\pi R^2 v_{\max} q =$$

$$= 7.7 \times 10^{52} \left(\frac{R}{10 \text{ km}} \right)^2 \left(\frac{v_{\max}}{5100 \text{ km/s}} \right) \times$$

$$\times \left(\frac{q}{0.015 \text{ MeV/fm}^3} \right) \text{ erg/s}. \quad (20)$$

Here, q is the specific volume heat of evaporation, and its value is estimated as $q = 0.015\,\text{MeV/fm}^3$ from [25]. The value of (20) is comparable to the neutrino luminosity. This is, in principle, the upper estimate of the heating rate which corresponds to the maximal workload of the “boiling machine.” In reality, the boiling heat transfer should work together with diffusion and/or convection below and above the boiling shell, by increasing the *net* heat transfer rate.[2] This should lead to an increase in pressure behind the shock wave, providing more efficient conditions for the shock revival.

The second effect is the momentum transfer. The maximum mechanical pressure that the bubbles can exert is estimated as

$$p_{\max} \sim \rho v_{\max}^2 = 2\epsilon\Delta p = 1.7 \times 10^{-2}\,\text{MeV/fm}^3, \quad (21)$$

where the numerical value corresponds to the cheesed phase. This is much smaller than Δp since $\epsilon \ll 1$; therefore, including this contribution to the pressure does not seriously affect our previous calculation. But it can provide an additional barrier for the infalling matter to reach the inner core, reducing the final mass of the neutron star.

We should admit that most of the above estimates represent upper limits corresponding to the maximal workload of the “boiling machine.” In a subsequent paper, we will discuss these processes in more details.

6. Summary and Conclusions

In this paper, we have demonstrated the possibility of the boiling of a nuclear liquid in the supernova core after the bounce. If it occurs, it can lead to effects increasing the efficiency of the neutrino-driven mechanism of supernova explosions. Among these effects are the following:

[1]Recent simulations [33] show that the total mass of different phases between nuclei and homogeneous nuclear matter (collectively called “pasta phases” in [33]) inside the supernova just *before* the bounce can amount to 0.13−0.30 $M_\odot$. This estimate somewhat differs from that in (17) because, before the bounce, one deals with *small* pressure gradients in an (almost) free-falling matter, while, after the bounce, we have the matter close to the hydrostatic equilibrium with its large pressure gradients. It is possible, in principle, that the *pre-bounce* boiling, if it occurs, can affect the propagation of a prompt shock wave, but we do not consider this issue here.

[2]This can be compared with an electric circuit with a series of resistances. As one of the resistances in the series is shortened out, the total current increases.

– The increase of the heat transfer rate from the inner core to the neutrinosphere. This increases the mean neutrino energy, making the delayed-shock mechanism more efficient.
– The increase of the pressure in the boiling region. It provides an additional barrier between the infalling matter and the inner core, thereby reducing the mass of the neutron-star remnant.

We expect that taking the effect of boiling in the conventional delayed-shock/acoustic mechanism into account is important and will enable one to explain the energetics of the supernova explosions in a simpler self-consistent way.

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КИПІННЯ ЯДЕРНОЇ РІДИНИ У ВИБУХАХ НАДНОВИХ З КОЛАПСОМ ЯДРА

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Р е з ю м е

Досліджується можливість нестійкості відносно кипіння ядерної рідини у внутрішньому ядрі прото-нейтронної зірки, утвореної в результаті колапсу ядра наднової типу II. Виведено простий критерій кипіння. Використовуючи цей критерій для одного з найкраще описаних рівнянь стану ядерної речовини, зроблено висновок про можливість кипіння в умовах, що реалізуються у прото-нейтронній зірці. Обговорюються наслідки цього процесу, такі, як збільшення швидкості переносу тепла і тиску в області кипіння. Очікується, що врахування цього ефекту у загальноприйнятому механізмі вибухів наднових типу II – у затриманій ударній хвилі, що підживлюється потоком нейтрино, – може збільшити енергію вибуху і зменшити масу залишкової нейтронної зірки.