Physics Letters B 777 (2018) 184–190

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Numerical simulation of the hydrodynamical combustion to strange quark matter in the trapped neutrino regime

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ARTICLE INFO

Article history:
Received 17 June 2017
Received in revised form 12 December 2017
Accepted 12 December 2017
Available online 13 December 2017
Editor: W. Haxton

Keywords:
Neutron stars
Nuclear matter aspects of neutron stars
Quark deconfinement quark–gluon
Plasma production phase-transition

ABSTRACT

We simulate and study the microphysics of combustion (flame burning) of two flavored quark matter (u,d) to three flavored quark matter (u,d,s) in a trapped neutrino regime applicable to conditions prevailing in a hot proto-neutron star. The reaction–diffusion–advection equations for (u,d) to (u,d,s) combustion are coupled with neutrino transport, which is modeled through a flux-limited diffusion scheme. The flame speed is proportional to initial lepton fraction because of the release of electron chemical potential as heat, and reaches a steady-state burning speed of (0.001–0.008)c. We find that the burning speed is ultimately driven by the neutrino pressure gradient, given that the pressure gradient induced by quarks is opposed by the pressure gradients induced by electrons. This suggests, somewhat counter-intuitively, that the pressure gradients that drive the interface are controlled primarily by leptonic weak decays rather than by the quark Equation of State (EOS). In other words, the effects of the leptonic weak interaction, including the corresponding weak decay rates and the EOS of electrons and neutrinos, are at least as important as the uncertainties related to the EOS of high density matter. We find that for baryon number densities $n_B \leq 0.35$ fm^{-3}, strong pressure gradients induced by leptonic weak decays drastically slow down the burning speed, which is thereafter controlled by the much slower burning process driven by backflowing downstream matter. We discuss the implications of our findings to proto-neutron stars.

1. Introduction

The Bodmer–Terazawa–Witten hypothesis (BTWH) [1–3] of absolutely stable quark matter made of up, down, and strange quarks ((u,d,s) matter) is of much astrophysical and fundamental interest. One consequence of the BTWH is a large binding energy release associated with the conversion of a neutron star to a quark star. Since (u,d,s) matter has, by design of the BTWH, lower energy/baryon than hadronic matter, this conversion can release up to $\approx 10^{53}$ ergs. The energetics and timescale of this conversion can be important for many high-energy astrophysical phenomena, e.g., Type II Supernovae, Gamma-Ray Bursts, and Superluminous Supernovae [4–13]. While energetically feasible and entropically favored, the dynamics of the conversion is quite complex and deserves further investigation.

But how does one describe the microscopic dynamics of the conversion of hadronic to quark matter? One way is by modeling the conversion as a combustion process with a well defined front, where the hadronic "fuel" is burnt into a (u,d,s) "ash" [14]; for a recent review of the literature about hadron-quark combustion, see Furusawa et al. [15]. The length of the reaction zone is determined by the leptonic and non-leptonic weak interaction and pressure gradients, and is of the order of centimeters [16]. This length scale is six orders of magnitude smaller than the radius of a neutron star (~ 10 km), which makes the problem computationally intensive. One is usually restricted to studying either the microphysics of the simulated ($\sim$ cm size) conversion zone [14,17,16,15], or reducing the combustion zone into a sharp discontinuity and propagating it as a turbulent deflagaration [18,19]. In the latter scenario, typically, one assumes the combustion is a supersonic, shock-driven process (e.g. [13]), or a subsonic, deflagration process (e.g. [14,15]), ignoring the fact that the burning speed must arise naturally from the nonlinear reactive–diffusive–advective processes that govern it. Niebergal et al. [16] (henceforth Paper I), modeled the microphysics of the combustion process by numerically solving the reaction–diffusion–advection equations in the vicinity of the conversion front between two flavor (u,d) quark matter and

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https://doi.org/10.1016/j.physletb.2017.12.027
0370-2693/

three flavor (u,d,s) matter. In this approach, nothing is assumed about the burning speed *a priori*, instead, the reaction–diffusion–advection equations are solved numerically including non-linear feedback effects between the weak decay rates, fluid transport, and the EOS.

An important result emerging from Paper I is that neutrino cooling (which was implemented in that work with an energy leakage scheme) generates thermal pressure gradients that slow down the burning speed. Furthermore, Paper I confirmed that for a given amount of neutrino cooling, the front could halt.[1] Thus, for typical neutrino emission rates, the resulting cooling dominates the dynamics of the flame. Paper I clearly showed the significance of leptonic weak decays in the overall dynamics of the flame. Given that leptonic weak decays may be as important to the dynamics of the flame as the poorly constrained details of the EOS at high density, we present in this paper an improved study of the conversion dynamics that includes neutrino transport, going beyond a leakage prescription.

Specifically, we couple neutrinos to the hydrodynamics of the conversion, extending the microphysical approach of Paper I to the trapped lepton-rich regime. We implement neutrino transport through a flux-limited diffusion scheme and choose the physical conditions expected in proto-neutron stars as initial conditions, that is, high lepton fraction $Y_{\rm L} \geq 0.2$ and $T = 20$ MeV for initial temperature. Although some studies ([20,21]) argued that neutrino trapping inhibited quark nucleation (and thus, subsequent combustion) in a proto-neutron star given that neutrinos raise the critical density required for deconfinement, there is a parameter window where quark nucleation is possible within the first seconds of a Supernova Type II explosion [22,9]. We use an updated version of the code originally used in Paper I called Burn-UD. Our results clearly show that leptonic weak decays are at least as important for the flame dynamics, if not more so, than the details of the high density EOS, because the pressure gradients generated by quarks are canceled out by the pressure gradients generated by electrons, making the final burning speed a function of pressure gradients induced by neutrinos. Therefore, our finding suggests that studies of the combustion front require a treatment of leptonic weak decays, including neutrino transport.

This paper is structured as follows: In Sec. 2, we list the system of equations for the combustion of (u,d) to (u,d,s). In Sec. 2.1, we explain the physical effects that quarks, electrons, and neutrinos have on the hydrodynamics of the combustion flame. In Sec. 3, we present the numerical techniques that we used to solve the equations enlisted in Sec. 2; we also present the results of our simulations for the burning speed and discuss a semi-analytic model for the electron gradient induced instability. We discuss the astrophysical perspective of our results with concluding remarks in Sec. 4.

2. Combustion in lepton-rich matter

To ignite the combustion, we assume a strange quark matter seed has already been nucleated as an initial condition. As shown in Paper I, hadronic matter can begin to spontaneously combust into (u,d,s) matter provided a critical fraction of strange quarks diffuse across the interface (i.e., boundary of the seed) between hadronic and quark matter. Following a similar approximation done in Paper I, we assume that hadrons have already dissolved into (u,d) matter and simulate the subsequent combustion of (u,d) to (u,d,s) matter. The combustion process of (u,d) to (u,d,s) to quark matter in the lepton-rich trapped neutrino regime, where neutrino absorption is important, is driven by the following leptonic and non-leptonic weak interactions:

$$u + e^- \leftrightarrow s + \nu_e \tag{1}$$

$$u + e^- \leftrightarrow d + \nu_e \tag{2}$$

$$u + d \leftrightarrow u + s \tag{3}$$

Reactions involving positrons and electron anti-neutrinos are not relevant to combustion in the lepton-rich regime in a proto-neutron star because they are exponentially suppressed by the degenerate leptons. Although neutrinos of other flavors (e.g. μ, τ) arise through neutrino-pair bremsstrahlung, their energy density is orders of magnitude smaller than electron neutrinos [23]. Other weak interactions that are relevant are neutrino-quark scattering and neutrino-electron scattering, which influence the transport of neutrinos across the interface.

The current version of Burn-UD solves reaction–diffusion–advection equations in 1D

$$\partial U/\partial t = -\nabla F(U) + S(U) \tag{4}$$

where U are the fluid variables as expressed in [16], with the addition of lepton number conservation. $F(U)$ are the advective–diffusive terms and $S(U)$ are the source (chemical reaction) terms.[2] This work extends the system of equations 1–4 in Paper I by including the equations of neutrino transport:

$$\frac{\partial n_{\nu_e}}{\partial t} + \nabla \cdot (\mathbf{v} n_{\nu_e}) + \nabla \cdot \left(\nabla D_{\nu_e} n_{\nu_e}\right) = \Gamma_1 + \Gamma_2 \tag{5}$$

$$T\frac{\partial s}{\partial t} = \frac{d\epsilon_{\nu_e}}{dt} - \frac{dn_{\nu_e}}{dt}\mu_{\nu_e}, \tag{6}$$

where n_{ν_e} is the number density of electron neutrinos, ϵ_{ν_e} is their internal energy density given as a function of n_{ν_e}, $\partial s/\partial t$ is the entropy density change due to electron neutrinos, μ_{ν_e} is neutrino chemical potential, T is temperature, and Γ_1, Γ_2 are reaction rates for (1) and (2) which are taken from [11]. D_{ν_e} is flux limited in such a way that neutrinos do not travel faster than the speed of light. Effectively, $D_{\nu_e} = c\Lambda/\lambda_{\nu_e}$,where Λ is a function given by equation (28) in Levermore et al. [24], and λ_{ν_e} is the mean free path for neutrinos. We use analytic expressions for λ_{ν_e} originally derived by [23]. Since neutrinos are degenerate, we may reasonably assume that only neutrinos with energy $E_{\nu_e} = \mu_{\nu_e}$, are scattered or absorbed at the interface. We close the above equations with the thermodynamic Bag Model EOS for quark matter as elaborated in Paper I, where hadrons were treated as dissolved two-flavor quark matter.

2.1. Hydrodynamical effects

In the BTWH, combustion of hadrons implies transport of strange quarks into hadronic matter, propagating the conversion. As noted in Paper I, the transport of strange quarks will be affected by pressure gradients that determine flow velocities. In the hydrodynamic approach, there are many forces acting upon the

[1] We define the process of halting as in Paper I. Namely that pressure gradients induce a back-flow that advects the s-quarks away from the interface and the downstream fuel. However, that does not mean that burning completely stops, given that the same back-flow causes downstream fuel to advect into the interface, converting it into deconfined (u,d,s) matter. In other words, halting means that the burning speed is nonzero, but order of magnitudes slower than if s-quarks were not advected backwards.

[2] Paper I gives explicit forms for $F(U)$ and $S(U)$ in terms of relevant quark diffusion coefficients and weak decay rates.