ASYMMETRIC CORE COMBUSTION IN NEUTRON STARS AND A POTENTIAL MECHANISM FOR GAMMA-RAY BURSTS

G. LUGONES, C. R. GHEZZI, E. M. DE GOUEVIA DAL PINO, AND J. E. HORVATH
Instituto Astronómico e Geofísico, Universidade de São Paulo, Rua do Matão 1226—Cidade Universitária, 05508-900 São Paulo SP, Brazil; glugones@astro.iag.usp.br
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ABSTRACT

We study the transition of nuclear matter to strange quark matter (SQM) inside neutron stars (NSs). It is shown that the influence of the magnetic field expected to be present in NS interiors has a dramatic effect on the propagation of a laminar deflagration (widely studied so far), generating a strong acceleration of the flame in the polar direction. This results in a strong asymmetry in the geometry of the just formed core of hot SQM, which resembles a cylinder orientated in the direction of the magnetic poles of the NS. This geometrical asymmetry gives rise to a bipolar emission of the thermal neutrino-antineutrino pairs produced in the process of SQM formation. The $\nu\bar{\nu}$ annhilate into $e^+e^-$ pairs just above the polar caps of the NS, giving rise to a relativistic fireball, thus providing a suitable form of energy transport and conversion to $\gamma$-emission that may be associated to short gamma-ray bursts.

Subject headings: gamma rays: bursts — instabilities — MHD — stars: magnetic fields — stars: neutron

1. INTRODUCTION

The transition to strange quark matter (SQM) is expected to occur in neutron stars (NSs) if SQM has lower energy per baryon than ordinary nuclear matter (NM; Bodmer 1971; Terazawa 1979; Chin & Kerman 1979; Witten 1984). This has strong consequences in the astrophysics of compact stars since, if SQM is the true ground state of strongly interacting matter rather than $^{56}\text{Fe}$, compact objects could be strange stars (SSs) instead of NSs. Some tentative SS candidates are the compact objects associated with the X-ray bursters GRO J1744–28 (Cheng et al. 1998) and SAX J1808.4–3658 (Li et al. 1999a) and the X-ray pulsar Her X-1 (Dey et al. 1998). In addition, the observed high- and low-frequency quasi-periodic oscillations in the atoll source 4U 1728–34 have been shown to be more consistent with an SS nature (Li et al. 1999b). A number of different mechanisms have been proposed for NM to SQM conversion (Haensel & Madsen 1991) inside the star. All them are based on the formation of a “seed” of SQM inside the NS. A possible mechanism is the so-called strangelet contamination, where a seed of SQM from the interstellar medium enters an NS and converts it to an SS. In another possible scenario, a seed of SQM forms in the core of an NS as a result of the increase of the central density above the critical density for deconfinement phase transition. A way to do this is through mass accretion onto the NS in a binary stellar system. In a third mechanism, a seed of SQM may naturally form inside a newly born NS from a core-collapse supernova explosion after a deleptonization timescale (Lugones & Benvenuto 1998; Benvenuto & Lugones 1999). No matter which of these mechanisms are actually triggering the NS to SS transition, once the first seed of SQM is produced inside the NS, it will propagate as a combustion swallowing neutrons, protons, and hyperons. The transition to SQM inside the burning front has actually two stages. Deconfinement driven by strong interactions first liberates quarks confined inside hadrons. The just deconfined quark phase has a certain finite strangeness due to the presence of strange hadrons in NS matter. However, the composition of the just deconfined phase (with $u, d$, and $s$ quarks) is not in beta equilibrium, and consequently chemical equilibrium is reached by weak interactions. It is in this phase that a large amount of energy is released and then $\nu$’s are copiously produced.

The type of diffusion-driven combustions studied so far by several authors (Olinto 1991; Heiselberg, Baym, & Pethick 1991) actually correspond to laminar deflagrations (slow combustions). Whether the conversion process remains forever as a deflagration, either laminar or turbulent, or jumps to the detonation regime, thus driving an explosive transient (Horvath & Benvenuto 1988; Benvenuto & Horvath 1989; Benvenuto, Horvath, & Vucetich 1989; Lugones, Benvenuto, & Vucetich 1994), has been debated in the literature. The situation is closely analogue to the much more studied thermonuclear combustions leading to Type Ia supernovae. In addition to the lack of detailed studies on the model(s) of combustion (laminar/turbulent deflagration or detonation), there is (to the best of our knowledge) no calculation of the influence of ubiquitous magnetic fields expected to be promptly generated or already present in the NS as a fossil. We shall consider hereafter an initially laminar deflagration in the presence of a $B$-field. As stated, previous works (Olinto 1991; Heiselberg et al. 1991) have calculated the velocity of the laminar deflagration by considering the diffusion of $s$-quarks as the main agent for the progress of the conversion. Given that the combustion is idealized to happen near the $T = 0$ limit (which is small when compared with the chemical potential of quarks), these diffusion-limited “cold” models are reasonable for this purpose. The general result, which also holds when temperature corrections and full nonlinearity are considered, is that the laminar velocity of the front is relatively slow ($v_{\text{lam}} \lesssim 10^4 \text{ cm s}^{-1}$), although this speed may be uncertain by several orders of magnitude (Olinto 1991). This velocity is a direct consequence of both the timescale for weak decays that create $s$-quarks ($10^{-8} \text{ s}$) and the physics of the diffusion process.

2. INSTABILITIES AND ASYMMETRIES

A nuclear flame that starts as a laminar deflagration propagating outward rapidly enters the wrinkled flamelet regime owing to the action of several hydrodynamic instabilities, such as the Landau-Darrieus (LD) and Rayleigh-Taylor (RT). For the largest scales (those much greater than the thickness of the flame), the RT instability dominates over LD (see Ghezzi, de
Gouveia Dal Pino, & Horvath 2001 for details). It is possible to identify distinct regimes in the deflagration stage, and we will apply the fractal model of combustion (Timmes & Woosley 1992; Niemeyer & Hillebrandt 1995; Niemeyer & Woosley 1997; Ghezzi et al. 2001) for all those regimes. The wrinkled surface $A$ behaves like a fractal with $A \sim R^d$, where $d$ is the fractal dimension of the surface, with $2 \leq d < 3$, and $R$ is the mean radius of the wrinkled surface (Filyand, Sivashinsky, & Frankel 1994). Numerical simulations (Filyand et al. 1994) and laboratory experiments involving different gas mixtures (Gostintev, Istratov, & Shulenin 1988) show that the fractal growth actually increases the velocity of the combustion front because of the change in the transport mechanism from a laminar to a fully turbulent burning. The burning of NM to SQM has been studied so far in the absence of any magnetic RT instability (Jun, Norman, & Stone 1995) reinforces the results of asymmetry here reported and also reveals a tendency for its amplification as the magnetic pressure $B^2/8\pi$ is not relevant, the B-field quenches the growth of RT instabilities in the equatorial direction, acting as a surface tension, while it is innocuous in the polar one, where on average we have $v_p \times B = 0$. More specifically, $B$ modifies the minimum RT instability scale, and since the turbulent flame velocity is related to RT growth, this results in a different velocity of propagation along each direction. Since the density of the products of combustion (SQM) is comparable to the fuel (NM), $\rho \sim 10^{28} \text{g cm}^{-3}$, and using the values for $v_{\text{lam}}$ found in previous works (Olinto 1991; Heiselberg et al. 1991; $\approx 10^4 \text{cm s}^{-1}$), we find that $B^2/4\pi > \rho v_{\text{lam}}^2$ for relatively low values of $B$ (i.e., $\approx 10^{12} - 10^{13}$ G), so that for $D \approx 2.5$ (which is in good agreement with numerical studies; Blinnikov, Sasorov, & Woosley 1995), $\xi$ scales linearly with the field to a good approximation. So,

$$\xi = 10(B/10^{13})G(10^{15} \text{g cm}^{-3}/\rho)^{1/2}(10^4 \text{ cm s}^{-1} v_{\text{lam}}),$$

(2)

and large asymmetries can be produced even for moderate values of $B$. Next, we evaluate the time that the polar front needs to reach the surface $[\tau_p = Rh v_p = R(\xi \theta)]$:

$$\tau_p \approx 10 \text{(R/10 km)(10^{13} G/\rho)}(10^{15} \text{ g cm}^{-3})^{1/2}.$$  

(3)

Note that equation (3) gives actually an upper bound to $\tau_p$ because we have approximated $v_p$ by $v_{\text{lam}}$. An asymmetry in the $\nu$-emission will be possible only if $\tau_p < \tau_s$ that is, if $\tau_s$ is smaller than the typical diffusion timescale $\tau_s$ through NM in the equatorial direction ($\tau_s$ is at least 30 s; Pons et al. 1999). Only in this case can we assume that the lateral sides of the cylinder are opaque and almost all the $\nu$ are emitted through the polar caps. Otherwise, we will still have a strong asymmetry in the shape of the SQM region, but this will not yield an asymmetry in the $\nu$-emission structure. The minimum $B$ for which $\tau_p < \tau_s$ is satisfied is obtained from equation (3):

$$B_{\text{min}} = 3 \times 10^2 \text{G}(\rho/10^{15} \text{ g cm}^{-3})^{1/2}(R/10 \text{ km}).$$  

(4)

In other words, for $B < B_{\text{min}}$ we recover the isotropy of the neutrino emission (see below).

When the polar front reaches the stellar surface, the equatorial front will have traveled only $\delta = R/\pi = 1 \text{ km}(R/10 \text{ km}) \times (10^{13} G/\rho)(10^{15} \text{ g cm}^{-3})^{1/2}(v_{\text{lam}}/10^4 \text{ cm s}^{-1})$, and therefore the SQM region will begin to emit its neutrino content mainly through a cylinder aligned with the poles with a radius $\delta \approx 1 \text{ km}$ and a height $2R = 20 \text{ km}$ (see Fig. 1). Notice that if $B > 10^{17}$ G, $\delta$ is very small and the total energy released by the SQM conversion is negligible in this asymmetric stage. An estimate for the ratio of the neutrino flux in the equatorial and the polar directions is found by comparing the flux through the opaque NS matter in the equatorial direction with the free-streaming flux of neutrinos emitted from the polar caps, namely,

$$\frac{F^e/F^p}{\Delta t} = \left[-c_\lambda x_3(\partial e_\lambda/\partial r)\right]/\left[c_\lambda_3/\Delta r\right],$$

(5)

where $\Delta x$ is the difference between the radius of the star and the equatorial radius of the SQM core; $\lambda_3 = 3 \times 10^3 \text{ cm} \times (\rho/10^{19} \text{ g cm}^{-3})/10 \text{ MeV}/e_\lambda$ is the mean free path of neutrinos diffusing from the surface of the SQM core in the equatorial direction (Shapiro & Teukolsky 1983). This $\lambda_3$ is mainly due to neutral-current elastic scattering off neutrons. For typical values of $\lambda_3$ and a highly asymmetric SQM region, we have $F^e/F^p \sim 10^{-2}$ to $10^{-4}$. Thus, once the polar front reaches the surface, almost all $\nu$’s are released through the polar caps. This is due to the fact that the flux in the equatorial direction is quenched owing to the high $\lambda_3$ while $\nu$’s in the polar surface escape freely.

The neutrino transport inside the SQM cylinder can be described by $\partial e_\lambda/\partial t = \partial \partial e_\lambda (\lambda_{\text{SQM}}/3)\partial \lambda/\partial x$, with the boundary conditions $e_\lambda(0,t)/\partial x = H_0(0,t)$, $e_\lambda(l,t)/\partial x = H_0(l,t)$, and the initial condition $e_\lambda(x,0) = e_{\lambda 0}$, $e_{\lambda}(x,t)$ being the neutrino density. We should note that, although the present work is based solely on a linear analysis, three-dimensional numerical simulations of the development of the magnetic RT instability (Jun, Norman, & Stone 1995) reinforces the results of asymmetry here reported and also reveals a tendency for its amplification in the nonlinear regime.
These luminosities are shown in Figure 2. We find that 90% of the $e^+e^-$ pairs are injected inside small cylinders located just above the polar caps (with radius $\delta$ and height 0.4$R$) in a timescale of $\tau_i \approx 0.2$ s almost independently of the initial temperature.

### 3. APPLICATION TO GAMMA-RAY BURSTS

Gamma-ray bursts (GRBs) appear to fall into at least two distinct categories, namely, the short-duration bursts ($\approx 0.2$ s) and the long-duration ones ($\approx 20$ s) (for a review, see Piran 2000). Recent works have explored the idea that the conversion of NM into SQM in NSs may be an energy source for GRBs (Alcock, Farhi, & Olinto 1986; Ma & Xie 1986; Haensel et al. 1991; Cheng & Dai 1996; Bombaci & Datta 2000; Wang et al. 2000; Ouyed 2002). These models addressed spherically symmetric conversions of the whole NS giving isotropic $\gamma$-emission. We show here that if a conversion to SQM actually begins near the center of an NS, the presence of a moderate magnetic field $B$ ($\approx 10^{13}$ G) will originate a prompt asymmetric $\gamma$-emission, which will be observed as a short, beam GRB.

Given that all pairs contributing to equation (7) will annihilate into $\gamma$-rays, we are led to the conclusion that an asymmetric short GRB can be generated by this process. The energy injected in $\gamma$-rays is $E_\gamma \geq 10^{51}$ ergs, comparable to the ones derived for long GRBs. The asymmetry crucial for this conclusion is controlled by the quotient of the field $B$ to the laminar velocity $v_{\text{lamin}}$ (eq. [1]). Had the latter been larger by a few orders of magnitude, no significant asymmetry would be produced by realistic magnetic fields. It should be remarked that we have not shown that the turbulent deflagration will be the actual propagation mode but rather assumed its realization all the way down to the stellar surface. Actually, a possible deflagration to detonation transition (DDT) mode (in close analogy with the DDT in white dwarf combustions) may be achieved (Horvath & Benvenuto 2002; Benvenuto & Horvath 2009; Lugones et al. 1994), depending on the behavior of the microphysics. However, if a substantial asymmetry has already been produced when the DDT is achieved, the polar flow will detonate before the equatorial one.

Basic requirements for associating asymmetric SQM burning to (short) GRBs are the absence of a large amount of matter above the polar regions and a rate per galaxy high enough ($\approx 10^{-3}$ yr$^{-1}$) to compensate for the collimation of the emission. It is unclear whether both can be achieved, but in any case, it is clear that further studies of the hydrodynamics and statistics
of the events are desirable. However, and quite independently of the specific astrophysical setting, the result of NM to SQM conversion in the presence of $B \sim 10^{13}$ G will produce an asymmetry in the neutrino emission and an enhanced annihilation to $\gamma$'s. However, the observational outcome and the rate of the events will depend on the type of system in which the NS is being burned. For example, in transitions produced by accretion-induced collapse of a white dwarf, the energy is deposited in a region that contains a low baryon loading. So, this collimated emission has an advantage over the isotropic one, where $B = 0$, in that the total baryon loading “seen” by the beamed burst is small enough to allow for a relativistic expansion of the fireball with very high Lorentz factors and is sufficient to explain apparent burst luminosities $L_\nu$ up to more than $\sim 10^{52}$ erg s$^{-1}$ for burst durations of $t \approx 0.2$ s. NSs in low-mass X-ray binaries are also likely candidates for the conversion to SQM because mass accretion may raise the central density of the NS above the critical density for transition. These NSs have “weak” magnetic fields in their surface ($B = 10^8 - 10^9$ G), which are generally understood as the result of mass accretion. Since this affects in principle only the field in the surface, the field in the interior of the NS would be in the range of values that leads to an asymmetric short GRB. Note also that if the emission is beamed it would be difficult to explain the observed rate of GRBs by conversions in binary systems alone. For transitions in newly born proto-NSs, the presence of the supernova envelope makes it necessary to explain how the $\gamma$-emission produced by the central proto-NS traverses the young expanding ejecta (one clue may have been provided by the GRB 980425/SN 1998bw association). In any case, we may expect emission of quasi-thermal X-ray flashes with rates per galaxy $\eta 10^2$ yr$^{-1}$, $\eta$ being the unknown fraction of proto-NSs with fields $B \sim 10^{13}$ G from the events. Other consequences for the ejected envelopes may include asymmetries of the envelope itself due to the nonisotropic injection of energy.

We plan to discuss these issues thoroughly in a future work.

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2 We should note that according to recent calculations of proto-NS evolution, convective instabilities occur within the first second of NS formation (Janka, Kifonidis, & Rampp 2001). Since the transition to SQM is not expected to occur immediately after the proto-NS formation, but after a sensible fraction of the deleptonization timescale (Lugones & Benvenuto 1998; Benvenuto & Lugones 1999), it is very likely that convection will have stopped well before the start of the burning, therefore not affecting the asymmetric scenario described in this work.

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