Physics Letters B 733 (2014) 164–168

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Strange quark matter fragmentation in astrophysical events

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ARTICLE INFO

Article history:
Received 12 November 2013
Received in revised form 7 March 2014
Accepted 18 April 2014
Available online 24 April 2014
Editor: W. Haxton

Keywords:
Strange quark matter
Strangelets
Statistical multifragmentation model

ABSTRACT

The conjecture of Bodmer–Witten–Terazawa suggesting a form of quark matter (Strange Quark Matter) as the ground state of hadronic interactions has been studied in laboratory and astrophysical contexts by a large number of authors. If strange stars exist, some violent events involving these compact objects, such as mergers and even their formation process, might eject some strange matter into the interstellar medium that could be detected as a trace signal in the cosmic ray flux. To evaluate this possibility, it is necessary to understand how this matter in bulk would fragment in the form of *strangelets* (small lumps of strange quark matter in which finite effects become important). We calculate the mass distribution outcome using the statistical multifragmentation model and point out several caveats affecting it. In particular, the possibility that strangelets fragmentation will render a tiny fraction of contamination in the cosmic ray flux is discussed.

1. Introduction

Sometime after the papers of Bodmer [1] and Terazawa [2] put forward the idea of a quark ground state of strongly interacting matter, the wide and colorful discussion given by Witten [3] added considerable interest to the issue of what is now called the *Strange Quark Matter* (SQM) hypothesis.

The stability scenario has been systematically studied for the first time by Farhi and Jaffe [4] within the MIT bag model, where a wide parameter space for absolute stability to hold was established. More recently, it has been claimed that the preferred state would be when quarks form pairs, similarly to electrons in ordinary superconductivity, for it would allow an even lower energy per baryon number for the system due to the formation of the color condensate [5–7].

If the SQM hypothesis is valid, the low probability of a *simultaneous* decay of roughly a third of up and down quarks in a nuclei into strange quarks under everyday conditions would prevent the transition. However, it has been shown [8–10] that for nuclear systems at high density and moderate temperature, the transition could be favored. In this way, compact objects are naturally thought as niches for the existence of SQM. Among the predicted systems and phenomena, strange stars [11–14], compact stars where the transition to SQM happens in all the stellar interior, and strangelets [4,15,16], small lumps of strange quark matter, were discussed. The possibility of strangelets being a part of the cosmic ray flux, and likely involved in exotic events [17], naturally raised the question about the conditions for bulk strange quark matter to break apart, and with what mass and energy spectra the fragmentation into strangelets would ensue [18].

Starting with these early papers, some injection mechanisms for strangelets in astrophysical sites have been proposed: strange stars mergers [3,19], phase transition during type II supernovae [20,21,18], and acceleration in strange pulsar environment [22]. All these processes might lead to a measurable abundance of this component among the cosmic ray flux, although they have not been addressed in full detail yet. Considering this, a simple manner of testing the existence of strange matter in the interior of compact stars would be the detection by ground-based or in-orbit experiments of strangelets of astrophysical origin. In fact, some experiments claimed to have detected possible exotic components [23–26], though a live debate has taken place without a firm confirmation of the nature of the primaries.

On the other hand, the problem of fragmentation of nuclear matter during cooling/decompression has been studied for several decades (for a review, see for example [27]), with wide applicability to laboratory experiments (e.g., nuclei collision in accelerators). A range of r-process nuclei could be produced this way [28] and the analogous situation with SQM in the place of nuclear matter appears to be justified if the Bodmer–Witten–Terazawa conjecture is true. However, the production of strangelets and subsequent acceleration still lack a detailed general analysis. In particular, the predicted fluxes of strangelets among cosmic rays are based

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http://dx.doi.org/10.1016/j.physletb.2014.04.036

on plausible suppositions instead of refined calculations, and in general dismiss the possible decay of these particles into ordinary nuclei [29]. Moreover, the energy spectrum of strangelets to be injected in the interstellar medium is quite uncertain. In this way, supposing the Fermi mechanism will accelerate strangelets the same way it does with ordinary cosmic rays may pose some problems [30], since only particles with a non-thermal spectrum can be accelerated by shocks. The distribution of masses and energies at the injection site are then important ingredients for all these attempts to connect some events with the possible strangelet primaries arriving to earth [31].

Here we present an analysis for the fragmentation of strange quark matter within the statistical multifragmentation model. This model can be applied to a supernova explosion driven by the conversion of ordinary nuclear matter to strange quark matter, for example, being this scenario an alternative to the neutrino-driven ones that still face difficulties in explaining the explosion in numerical simulations. The conversion during the proto-neutron star phase could provide enough energy for the expelling of stellar material either in the form of a detonation wave or of a second neutrino wind [20,21]. The ejected outer layers could be contaminated by strangelets due to turbulent mixing effects [32]. As a general result, we shall show that a fragmentation into mass chunks having $A \leqslant 100$ may be expected, although significant uncertainties in the underlying physics remain, and in fact recent calculations do not obtain ejection of SQM [33]. Since the temperatures and other parameters are quite similar, scenarios of the merging of two strange stars [31] would follow a similar fragmentation pattern.

In a recent paper, Biswas and collaborators [34] used the statistical multifragmentation model to analyze the fragmentation of strange quark matter in a scenario of strange stars mergers, concluding that the mass spectrum results in low mass fragments and shows an exponential decay with A and also presenting an estimate for the strangelet flux based on cosmic ray diffusion properties. However, their analysis dismissed important contributions to the energy of the fragments and assumed some physical properties (discussed at length in [35]) that may significantly alter the results. These are related to the dependency of the fragment energy on the strange quark mass (assumed negligible) and also on the possibility of pairing between quarks, as will be described in the next section.

2. Statistical multifragmentation model

Among the several proposals formulated to deal with the fragmentation problem, the statistical multifragmentation model (SMM) (see [27] and references therein) has provided consistent results when applied to the bulk nuclear matter → nuclei transition.

When we proposed using the SMM to treat the fragmentation of strange quark matter [36], we initially employed it to treat fragmentation in a supernova driven by the conversion of nuclear matter into SQM scenario. Recent works have shown that in the collision of two strange stars, matter achieve high temperatures [37] (of order ∼ tens of *MeV*), which are high enough to comply with the hypotheses of the statistical multifragmentation model. Specifically, the critical condition involving the excitation energy per baryon number for the occurrence of the break-up (which must be comparable to the total binding energy, ensuring thermal and dynamical equilibrium) is satisfied. Therefore, in both scenarios the fragmentation should proceed similarly. Also, in Ref. [36], we used an approximate treatment for the strangelet energy taking mean values instead of considering the full dependence of the surface and curvature energies on temperature and baryonic number, which is certainly important for the matter, and considered strange quark matter without pairing. We found in Ref. [36] some inconsistencies regarding the position of the fragmentation peak, as we shall discuss bellow, and the present treatment is the result of this analysis.

We based our analysis on a simplified version of the SMM [38] in which the system is studied in the grand canonical ensemble, rendering neat analytical solutions when the thermodynamical limit is taken. Generally speaking, an exponential behavior for the partition function is predicted for high masses.

We have started from the partition function of a single fragment with A nucleons

$$\omega_A = V\left(\frac{mTA}{2\pi}\right)^{3/2} e^{-f_A/T}, \tag{1}$$

where f_A is the internal free energy of the fragment

$$f_A = -WA + \sigma A^{2/3} + CA^{1/3}, \tag{2}$$

and W represents the volume binding energy per baryon number of SQM, σ and C being the internal free energy of a fragment with baryon number A, rest mass m and chemical potential μ corresponding to the surface and curvature contributions, respectively; and T is the bulk SQM temperature.

From the definition of pressure in the grand canonical ensemble,

$$p(T,\mu) = T \lim_{V\to\infty} \frac{\ln \mathcal{Z}(V,T,\mu)}{V}, \tag{3}$$

where $\mathcal{Z}$ is the Laplace transform of the grand canonical partition function, the pressures for both phases are obtained from the singularities of the isobaric partition function (for details, see [38] and references therein).

The liquid and gas pressures are given by

$$p_g(T,\mu) = T\left(\frac{mT}{2\pi}\right)^{3/2}\left\{z_1 e^{\frac{\mu-bp_g}{T}} + \sum_{A=2}^{\infty} A^{3/2} e^{[(\nu-bp_g)A-\sigma A^{2/3}-CA^{1/3}]/T}\right\}, \tag{4}$$

$$p_l(T,\mu) = \frac{\nu}{b}, \tag{5}$$

where $\nu = \mu + W$ is the (shifted) chemical potential.

The fragmentation spectrum, $\mathcal{P}_g$, can be then obtained (considering chemical equilibrium between bulk matter and the fragments) by taking the derivative of the gas pressure, p_g, with respect to the chemical potential of the fragments, μ_A,

$$\mathcal{P}_g(A) = \frac{\partial}{\partial \mu_A} p_g = \left(\frac{m_0 T}{2\pi}\right)^{3/2} A^{3/2} e^{[(\mu+W-bp_g)A-\sigma A^{2/3}-CA^{1/3}]/T}, \tag{6}$$

In the model, the parameter b represents the repulsive interactions in a simple Van der Waals approximation.

We have considered strange quark matter within the MIT bag model framework, in the color-flavor-locked (CFL) state [5,6,39]. The energy of each fragment was calculated by employing the multiple reflexion expansion formalism as in [40], thus presenting the necessary dependence on the temperature, baryonic number, gap parameter, bag constant, and strange quark mass.

When obtaining the mass number for which the fragment distribution reaches its maximum in the coexistence region, we have checked that the peak is always obtained for strangelets with mass