

Disassembly Model for the Production of Astrophysical Strangelets

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Determination of the baryon number (or mass) distribution of the strangelets, that may fragment out of the warm and excited strange quark matter (SQM) ejected in the merger of strange stars (SSs) in compact binary stellar systems of the Galaxy, is attempted by using a statistical multifragmentation model (SMM). Finite mass of strange quarks is taken into account in the analysis. Strangelet charge and the resulting Coulomb corrections are included to get a realistic mass distribution of galactic strangelets at their source.

Key Words : SQM; Galactic Strangelets; Statistical Multifragmentation Model; Primary Cosmic Rays

Introduction

SQM, containing roughly equal numbers of up, down and strange quarks enclosed in a MIT bag, may be the true ground state of hadronic matter (Witten, 1984; Farhi and Jaffe, 1984). Finite sized lumps of SQM, i.e., the strangelets, could also be more stable than the normal nuclei (Farhi and Jaffe, 1984). Possible scenario for the formation of galactic strangelets is the fragmentation of bulk SQM ejected in tidal disruption of SSs in compact binary stellar systems (Madsen, 2005). Simulations of SS merger (Bauswein *et al.*, 2009) show clumpy structures in SQM ejecta that are possibly the signatures of initial formation of strangelet-clusters. Further fragmentation and separation of those lumps, as the ejected material approaches its thermodynamic and chemical equilibrium, may ultimately yield a strangelet mass distribution that contributes to the primary cosmic rays (PCR) (Madsen, 2005; Biswas *et al.*, 2012). We here determine that mass spectrum

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of strangelets at their source by taking finite mass of strange quarks into account and by invoking SMM (Bondorf *et al.*, 1995).

The Disassembly Model

In SMM, the bulk SQM ejected in SS merger evolves in thermodynamic equilibrium and undergoes disassembly after reaching the freeze-out volume at a temperature T in which the strong interactions between fragments cease to exist (Biswas *et al.*, 2012). Here, we choose the values of T in the range (0.01-1.0) MeV (Rosswog and Bruggen, 2007; Oechslin *et al.*, 2007)) representing possible distribution of temperatures in the regions in which strangelets may form. The multiplicity ω_i of the strangelets of species ‘ i ’ with baryon number A_i is (Bondorf *et al.*, 1995; Biswas *et al.*, 2012).

$$\omega_i = \frac{\mathcal{V}}{\Lambda_i^3} e^{(\bar{\mu}_i - F_i)/T}. \quad (1)$$

Here, u and d quarks are considered massless (i.e. $m_u = m_d = 0$), while the mass of the strange quarks is taken as $m_s = 150$ MeV. \mathcal{V} is the available volume, i.e., the freeze-out volume minus the volume of the produced fragments. In Eq. (1), $\bar{\mu}_i = \sum_f \mu_f N_f^i$ is the chemical potential of the i^{th} species. Here, the quark chemical potential is μ_f (f indicating a particular quark flavour) and $N_f^i = -\frac{\partial \Omega_i^f}{\partial \mu_f} \Big|_{V_i, T}$ is the number of quarks of the f^{th} flavour in the i^{th} species with Ω_i^f being the thermodynamic potential of the species corresponding to the quarks of that particular flavour. The mass of the species of baryon number A_i is $m_i = 874A_i + 77A_i^{2/3} + 232A_i^{1/3}$ MeV (Madsen, 1999) and their thermal de-Broglie wavelength is $\Lambda_i = h/\sqrt{2\pi m_i T}$, h being the Planck’s constant. Here, $F_i = \Omega_i + \bar{\mu}_i + E_i^c$ is the Helmholtz free energy of the i^{th} species; Ω_i and E_i^c are its thermodynamic potential and its Coulomb energy respectively. Thus $F_i = \Omega_i^{\text{tot}} + \bar{\mu}_i$ with $\Omega_i^{\text{tot}} = \Omega_i + E_i^c$. Eq. (1) yields

$$\omega_i = \frac{\mathcal{V}}{\Lambda_i^3} e^{-\Omega_i^{\text{tot}}/T}. \quad (2)$$

We will use Eq. (2) to determine the multiplicities of various fragments after we define the thermodynamic quantities pertaining to a single strangelet in the fragmenting complex.

Thermodynamics of a Strangelet

Radius of a spherical strangelet is $R_i = r_o^i A_i^{1/3}$, r_o^i being the radius parameter. Volume, surface and curvature of the strangelet are $V_i (= \frac{4}{3}\pi R_i^3)$, $S_i (= 4\pi R_i^2)$ and $C_i (= 8\pi R_i)$ respectively. Total thermodynamic potential for the i^{th} species is

$$\Omega_i = \Omega_V^o V_i + \Omega_S^o S_i + \Omega_C^o C_i + B V_i, \quad (3)$$

where, Ω_V^o , Ω_S^o and Ω_C^o are the corresponding thermodynamic potential densities, the detailed expressions of which will be published elsewhere. Here, the bag pressure is $B = (145)^4 \text{ MeV}^4$. At freeze-out, the strangelet-complex is in chemical equilibrium so that the effective quark chemical potential μ of the quarks of arbitrary flavour is the same in all the fragments. The local chemical potential μ_f is averaged over its maximum and minimum values within the strangelet such that $\mu_f = \mu - q_f \frac{\Delta\mu}{2}$; q_f being the charge (in units of e) of the quark of f^{th} flavour and $\Delta\mu = \frac{m_s^2}{4\mu}$. Charge (in units of e) of a strangelet of the i^{th} species with Debye screening length λ_D ($\sim 5 \text{ fm}$) is (Heiselberg, 1993)

$$Z_i = \frac{1}{\alpha} R_i \Delta\mu \left(1 - \frac{\tanh(R_i/\lambda_D)}{(R_i/\lambda_D)} \right) \quad (4)$$

and its Coulomb energy is (Heiselberg, 1993)

$$E_i^c = \frac{(\Delta\mu)^2}{2\alpha} R_i \left[1 - \frac{3 \tanh(R_i/\lambda_D)}{2 (R_i/\lambda_D)} + \frac{1}{2} (\cosh(R_i/\lambda_D))^{-2} \right] \quad (5)$$

with $\alpha = 1/137$. The total energy of the strangelet is given by

$$\begin{aligned} E_i &= T\mathcal{S}_i + \bar{\mu}_i + \Omega_i^{tot} \\ &= T\mathcal{S}_i + \bar{\mu}_i + \Omega_i + E_i^c \end{aligned} \quad (6)$$

with its entropy being $\mathcal{S}_i = -\frac{\partial\Omega_i}{\partial T} \Big|_{V_i, \mu}$. The number of u quarks in the species is $N_u^i = A_i + Z_i$. Strangelets are in mechanical equilibrium so that $P_i^{ext} = -\left(\frac{\partial\Omega_i^{tot}}{\partial V_i}\right) \Big|_{T, \mu}$ is the external pressure on the strangelet of the i^{th} species that arises due to the surrounding electrons maintaining overall charge neutrality of the fragments. This pressure is calculated in the Wigner-Seitz (WS) approximation (Shapiro and Teukolsky, 2004) to yield

$$\begin{aligned} P_i^{ext} &= (3\pi^2)^{1/3} \left[\frac{(n_{e_i})^{4/3}}{4} \right] + \left(\frac{\pi^2}{6} \right) \left[\frac{T^2}{(3\pi^2)^{1/3}} \right] (n_{e_i})^{2/3} \\ &\quad - \left(\frac{3}{10} \right) \left(\frac{4\pi}{3} \right)^{1/3} \frac{\alpha Z_i^2}{(V_{ws_i})^{4/3}}, \end{aligned} \quad (7)$$

where, V_{ws_i} is the volume of the WS cell associated with the i^{th} species whose value is calculated to be $5V_i$ and n_{e_i} is the number density of electrons in that WS cell.

Mass Spectra of Strangelets

Eqs. (2)-(7), with the added condition for the conservation of the initial baryon number A_b , namely (Biswas *et al.*, 2012)

$$A_b = \sum_i A_i \omega_i, \quad (8)$$

allow to evaluate the mass distribution of strangelets. The available volume $\mathcal{V} = 5V_b$; $V_b = \frac{4\pi}{3}r_b^3 A_b$ is the volume of the initial bulk SQM with $r_b \approx 0.94$ fm. For the initial baryon number, we choose $A_b = 1.2 \times 10^{53}$ corresponding to an average tidally released SQM mass $\sim 10^{-4} M_\odot$ per SS merger (Bauswein *et al.*, 2009).

Results

Figure 1 displays the multiplicity distribution at the extremes of the range of temperatures considered. Tendency towards the suppression of heavier fragments and enhanced production of lighter fragments with increasing temperature is noticed that is usual in SMM (Pal *et al.*, 1996).

In Fig. 2, we examine the energy per baryon (E_i/A_i) of each species of the fragments against its baryon number A_i at $T = 1$ MeV. The condition $E_i/A_i < 930$ MeV (Madsen, 1999) of absolute stability of strangelets is easily satisfied for $A_i \gtrsim 10$.

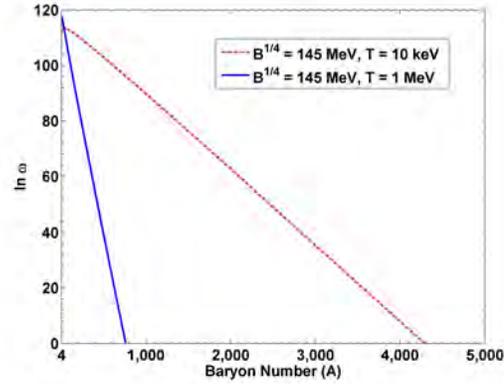


Fig. 1: Variation of the logarithm of multiplicity ($\ln \omega$) of strangelets with the variation in their baryon number (A) for two different temperatures at freeze-out

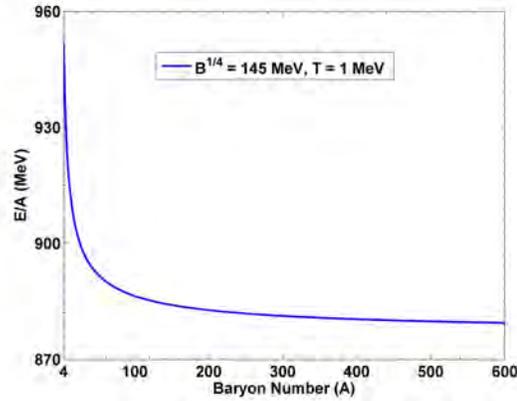


Fig. 2: Energy per baryon (E/A) vs. baryon number (A) of strangelets

Discussion

We are now in the process of using the determined mass distribution as an input in realistic galactic propagation models to estimate the strangelet flux at solar neighbourhood. This work would provide useful prediction of strangelet flux in PCR as a guidance to the ongoing experiments like the AMS-02 experiment (Kounine, 2010). Potential detection of strangelets in PCR would validate the strange matter hypothesis (Witten, 1984; Farhi and Jaffe, 1984).

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References

1. Bauswein A, Janka HT, Oechslin R, Pagliara G, Sagert I, Schaffner-Bielich J, Hohle MM and Neuhauser R (2009) Mass ejection by strange star mergers and observational implications *Phys Rev Lett* **103** 011101(1-4)
2. Biswas S, De JN, Joarder PS, Raha S and Syam D (2012) Multifragmentation model for astrophysical strangelets *Phys Lett* **B715** 30-34
3. Bondorf JP, Botvina AS, Iljinov AS, Mishustin IN and Sneppen K (1995) Statistical multifragmentation of nuclei *Phys Rep* **257** 133-221
4. Farhi E and Jaffe RL (1984) Strange matter *Phys Rev* **D30** 2379-2390
5. Heiselberg H (1993) Screening in quark droplets *Phys Rev* **D48** 1418-1423
6. Kounine A (2010) Status of the AMS experiment (Report number C117). In: *XVI International Symposium on Very High Energy Cosmic Ray Interactions* (ISVHECRI 2010), Batavia, IL, USA, arXiv:1009.5349 [astro-ph.HE]
7. Madsen J (1999) Physics and astrophysics of strange quark matter *Lect Notes Phys* **516** 162-203, arXiv:astro-ph/9809032
8. Madsen J (2005) Strangelet propagation and cosmic ray flux *Phys Rev* **D71** 014026(1-9)
9. Oechslin R, Janka HT and Marek A (2007) Relativistic neutron star merger simulations with non-zero temperature equations of state, I. variation of binary parameters and equation of state *Astron and Astrophys* **467** 395-409
10. Pal S, Samaddar SK and De JN (1996) The effect of flow on nuclear multifragmentation in a quantum statistical model *Nucl Phys* **A608** 49-62
11. Rosswog S and Bruggen M (2007) Introduction to High-Energy Astrophysics. Cambridge University Press
12. Shapiro SL and Teukolsky SA (2004) Black Holes, White Dwarfs and Neutron Stars: The Physics of Compact Objects. WILEY-VCH Weinheim
13. Witten E (1984) Cosmic separation of phases *Phys Rev* **D30** 272-285.