Mass Ejection by Strange Star Mergers and Observational Implications

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We determine the Galactic production rate of strangelets as a canonical input to calculations of the measurable cosmic ray flux of strangelets by performing simulations of strange star mergers and combining the results with recent estimates of stellar binary populations. We find that the flux depends sensitively on the bag constant of the MIT bag model of QCD and disappears for high values of the bag constant and thus more compact strange stars. In the latter case, strange stars could coexist with ordinary neutron stars as they are not converted by the capture of cosmic ray strangelets. An unambiguous detection of an ordinary neutron star would then *not* rule out the strange matter hypothesis.

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The strange matter hypothesis (SMH) considers the possibility that the absolute ground state of matter might not be formed by iron but by strange quark matter (SQM), a mixture of up, down, and strange quarks [1,2]. If true, stable objects consisting of this matter with baryon numbers from about 10^2 to 10^{57} might exist [3–5]. The latter end corresponds to strange stars (SS) with a mass and radius comparable to that of neutron stars (NS), where the upper mass limit is given by the inevitable collapse to a black hole (BH) [6,7]. In contrast to NSs these SSs are self-bound and do not have an overall inverse mass-radius relation.

One of the astrophysical consequences of the SMH is the possibility that collision events of two SSs lead to the ejection of strangelets, small lumps of SQM [8,9]. These strangelets would contribute to the cosmic ray flux. The pollution of the Galaxy with strangelets is speculated to convert all ordinary NSs to SSs. It was argued that all compact stars have become SSs in this scenario because already a tiny amount of strangelets is sufficient to trigger the transformation [7,10]. If this sequence of arguments was true, the unambiguous observation of a NS would rule out the SMH according to Refs. [8,9].

Estimates of the strangelet flux use results of NS-NS merger simulations [11], which are not necessarily reliable in the case of SQM. No detailed simulations of SS coalescence have been conducted so far, and the ejected mass is unknown. Only Newtonian simulations of SS-BH binaries, modeling the BH by a pseudorelativistic potential [12], were carried out by [13]. It was found that from this kind of mergers no matter is ejected. In order to shed light on the merger process of SS binaries we performed relativistic three-dimensional hydrodynamical simulations of the coalescence.

Several current and upcoming experiments have the potential to detect signatures of SQM. For instance, SQM might be produced directly in the Large Hadron Collider at CERN [14,15]. But also cosmic ray experiments like the Alpha Magnetic Spectrometer AMS-02 planned to be installed on the International Space Station in 2010 are designed to capture strangelets [16,17]. In addition, gravitational-wave detectors like LIGO and VIRGO might identify characteristic signals from SS mergers and SS oscillations or instabilities [5]. Also indirectly, the observation of compact stars can help to decide on the SMH especially by pinning down the mass-radius relation [3–5]. For a review on additional SQM searches, see [4,18].

The expectation that all NSs convert to SSs and that there is a measurable flux of strangelets as cosmic rays relies on the assumption that SS mergers or another source indeed eject SQM in a sufficient amount. Here we report that a pollution through SS mergers does not need not be present for all models describing absolutely stable SQM. In fact, we find that the amount of ejected matter depends on the so-called bag constant, which in the MIT bag model adopted here represents the pressure of the nonperturbative QCD vacuum. Therefore the determination of the mass flux of strangelets in cosmic rays could help to constrain this unknown parameter, which in turn gives the binding energy of SQM. Complementary insights in the equation of state (EOS) of SQM might come from the detection of gravitational waves (GWs) from SS coalescences, if some specific features distinguished them from those of merging NSs.

In order to describe the EOS of absolutely stable SQM we employ the MIT bag model [19,20]. Within this model, quarks are considered as a free or weakly interacting Fermi gas and the nonperturbative QCD interaction is simulated by a finite pressure of the vacuum, the bag constant B. The small current masses of up and down quarks allow us to treat them as massless particles, whereas for the strange quark we adopt the value of $m_s = 100$ MeV [21]. For our study we consider free quarks, which corresponds to a range of the bag constant of $57 \lesssim B \lesssim 84\ \mathrm{MeV/fm^3}$. The lower limit of B is given by the fact that baryons do not convert spontaneously to a two flavor quark phase, while the upper limit is determined by the requirement of absolutely stable SQM (energy per baryon at zero pressure, E/A, lower than the corresponding value of 930 MeV for nuclear matter). These limits can be altered for other choices of m_s or by considering the interactions among quarks. The values of $60\ \mathrm{MeV/fm^3}$ ($E/A = 860$ MeV) and $80\ \mathrm{MeV/fm^3}$ ($E/A = 921$ MeV) for the bag constant have been chosen to represent the extreme cases of the underlying microphysical model, which we refer to as MIT60 and MIT80. This choice of parameters yields a maximum mass of bare cold SSs of $1.88 M_\odot$ for MIT60 and $1.64 M_\odot$ for MIT80 with corresponding radii of 10.4 and 9.0 km, respectively. For given mass the stellar radii for MIT80 are in general slightly smaller than those for MIT60. A possible nuclear crust of SSs is neglected because of its small mass ($\sim 10^{-5} M_\odot$), which makes it irrelevant for the dynamics of the system.

We performed SS merger simulations with the code described in [22]. A three-dimensional relativistic smoothed particle hydrodynamics scheme (SPH) is combined with an approximate treatment of general relativity (GR) employing the conformal flatness condition, supplemented by a method accounting for the backreaction of GW emission on the fluid [22]. Magnetic fields are not included, because they can be considered as unimportant for the dynamical behavior as long as the initial field strength inside the compact star is below $\sim 10^{16}$ G [23].

The models of our simulations are chosen such that they cover the whole potential mass range of compact star binaries. The gravitational masses of the stars vary between $0.9 M_\odot$ and roughly the maximum SS mass for each EOS. The simulations start after a relaxation phase from a quasiequilibrium orbit about two revolutions before the actual merger. SQM has a shear viscosity comparable to that of nuclear matter [24] (and with color-superconducting phases even lower [25]), which is expected to be too low to yield tidally locked systems [26]; therefore, we consider irrotational configurations. Thermal effects are also taken into account as these were shown to be important for merger simulations with nuclear EOSs, in particular, when the ejection of mass is of interest [22].

In total we discuss results of 29 simulations for MIT60 and 19 for MIT80 with a resolution of about 130 000 SPH particles. Using nonuniform particle masses we achieve a mass resolution of roughly $10^{-5} M_\odot$ in these runs. The results were tested for convergence by additional simulations with higher resolution.

There are two possible outcomes of SS mergers. For relatively high masses of the binary components, the merged object collapses promptly to a BH shortly after the stars come in contact. The forthcoming formation of a BH is indicated by a steep decrease of the lapse function. Also the central density increases within a fraction of the sonic time scale to values of twice the maximum density of a single nonrotating SS and thus exceeds the maximum density of stable, uniformly rotating "supermassive" SSs. If the masses are lower, the merger remnant can be transiently supported against collapse mainly by differential rotation. Such a "hypermassive object" (HMO) [27] emits a characteristic GW signal, which is sensitive to the total mass of the binary and the EOS (see [28] for NS mergers). This will be analyzed in a separate publication. Since the system mass is much larger than the mass limit of supermassive SSs for the given EOS, the remnant collapses to a BH after the angular momentum has been redistributed [27].

Figure 1 gives an overview of the simulated binary mass configurations and their outcome. Filled circles indicate prompt collapse to a BH while open circles correspond to the formation of a HMO. M_1 and M_2 refer to the gravitational masses of the SSs in isolation.

To estimate the amount of matter that becomes gravitationally unbound, we use the criterion defined in [22]. It considers the energy of a fluid particle in a comoving frame and applies if pressure forces are small in comparison to gravitational forces, which is well fulfilled for particles leaving the merger site. In addition, we cross-checked these results by a simple criterion that monitors how much matter expands away from the merger site. The ejecta estimates agree within a factor of less than 2. Ejecta from HMOs originate from the tips of tidal tails that develop on time scales longer than the time scale of prompt collapse to a BH. In the case of such a prompt collapse no angular momentum can be redistributed from the center to the outer parts of the merged object because the matter in the inner part is swallowed quickly by the BH [22]. Thus, particles potentially forming an accretion torus around the BH have no chance to end up in tidal tails and to gain enough energy to become unbound.

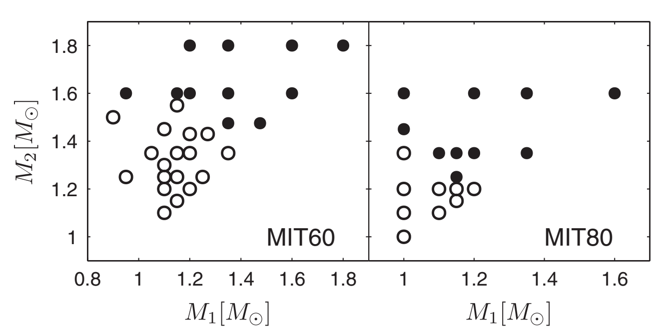

FIG. 1. Computed models for MIT60 and MIT80 in the M_1-M_2 plane of the gravitational masses of the SS binaries. Filled circles denote prompt collapse to a BH, while open circles indicate the formation of a HMO.

Figure 2 shows the estimated amount of unbound matter for given mass ratios $q = M_1/M_2$ and total binary masses $M_{\mathrm{tot}} = M_1 + M_2$ computed for MIT60 and MIT80 by means of our ejecta criterion. Above a certain M_{tot} value we cannot determine any amount of ejecta (see white lines in Fig. 2). If M_{tot} is below this limit, we obtain a steep rise of the ejecta mass in a narrow region of the M_{tot}-q plane in both EOS cases for $q \lesssim 0.85$. For MIT60 the region where more than $0.01 M_\odot$ of matter become unbound is located around a total mass of about $2.5 M_\odot$. For MIT80 significantly lower total masses are required to obtain unbound matter and the ejected masses are lower as well. This dependence on the bag constant originates from the fact that MIT80 leads to more compact stars with correspondingly smaller radii, which impedes the tidal disruption.

Since the ejected mass is very low in comparison to the system mass, we found a dependence on the chosen resolution and the initial setup of the SPH particles. The values of the ejected mass are uncertain within a factor of ~ 2. However, our conclusion that some configurations do not eject matter relies on the occurrence of a prompt collapse to a BH. This is a safe result of our simulations within the employed approximations. Therefore the border between systems that eject matter and those that do not can be considered as well determined (see Fig. 2). Only for equal-mass binaries the borderline includes configurations that do not collapse promptly and still do not eject matter, because such systems do not form pronounced tidal arms (see [22] for NS mergers).

Population synthesis studies [29] provide probability distributions of compact star binaries dependent on their system parameters (e.g., q and M_{tot}). Folding our results for the ejecta masses with these probability distributions allows us to estimate the ejected mass per merger event averaged over the whole population. These numbers can be used to derive more accurately the expected flux of strangelets in a detector like AMS-02 [11]. Assuming that the results of [29] hold also for SSs and not only for NSs, we compute for MIT60 a population-averaged ejecta mass of $8 \times 10^{-5} M_\odot$. The uncertainties due to the limited resolution and the criterion for determining ejecta masses can change this result up to a factor of ~ 4. For MIT80 we do not find any ejecta because only configurations not present in the adopted population eject matter.

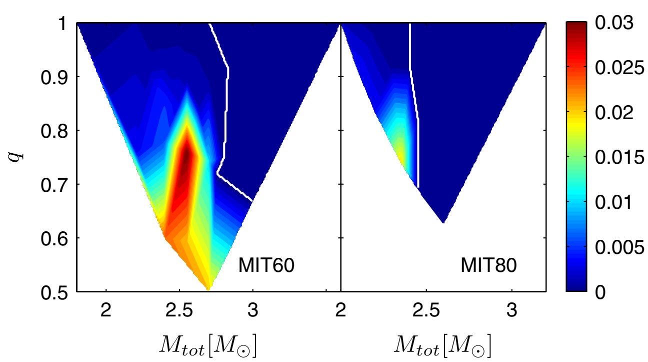

FIG. 2 (color online). Ejected mass per merger event, color-coded and measured in $M_\odot$, as function of the mass ratio $q = M_1/M_2$ and the total system mass $M_{\mathrm{tot}} = M_1 + M_2$ of the binary configurations for the MIT60 and MIT80 EOSs. The white line separates binary mergers with and without ejecta.

For a rough assessment of the uncertainties associated with the theoretical population synthesis studies, we employed a second data set based on observations of massive progenitor stars in double systems [30]. Using theoretical results for the mass relation between NSs and progenitor stars [31] and ignoring complications due to binary evolution effects, we derive a probability distribution function of compact binaries. Taking into account uncertainties in the determination of stellar masses, we obtain an average ejecta mass per event of $(1.4\text{–}2.8) \times 10^{-4} M_\odot$ for MIT60 and again a vanishing ejecta mass for MIT80.

The bag constant B is the only parameter varied between the EOSs and determines the mass-radius relation of SSs as the crucial property for the merger dynamics [22,32]. For intermediate values of B we expect smaller ejecta masses than MIT60 but higher than MIT80. The border line between models with and without ejecta would then be shifted to an intermediate location as well.

QCD perturbative corrections can be absorbed in an effective bag constant that can be chosen to yield mass-radius relations which agree well with the bag models we used [33]. Color superconductivity has only a small effect on the EOS [34,35]. However, quark interactions change the B window for absolutely stable SQM [5,20,36,37].

Our findings have important observational implications. The mass-radius relation (in our study determined by the bag constant) strongly affects the amount of matter ejected from SS mergers. Therefore a measured mass flux of strangelets would constrain this relation if quark star mergers were the main source of strangelets. A relatively high flux would be an indicator for less compact SSs, while no or only a low flux would only be consistent with more compact SSs. This would also put limits on the bag constant and so the binding energy of SQM. Assuming a Galactic merger rate of SS binaries of 10^{-5}–10^{-4} yr^{-1} [29], our population-averaged ejecta mass of $\sim 10^{-4} M_\odot$ for MIT60 yields a Galactic strangelet production rate of $\dot{M} = (10^{-9}\text{–}10^{-8}) M_\odot\ \mathrm{yr}^{-1}$. Since the flux of strangelets near Earth depends linearly on $\dot{M}$, we derive a 10–100 times larger value than in [11].

Even more relevant are the consequences if there are no other production mechanisms of strangelets. Our results for MIT80 imply that the SMH cannot be ruled out but would only be compatible with compact SSs, if experiments like AMS-02 could not find any evidence for a nonzero strangelet flux. A strangelet flux below a critical limit would mean that no or not all NSs might have converted to SSs by capturing a strange nugget. SSs might then still form by nucleation of SQM drops, e.g., during stellar core collapse and explosion or by mass accretion of NSs in binaries when the central conditions reach some critical threshold for the phase transition to quark matter [4,5,10,38]. In this scenario there is a limiting mass above which SSs are formed while NSs exist below (see also [39]). Thus in the case of a large bag constant NSs and SSs could be in coexistence. In the light of our simulations the unambiguous observation of a NS would not rule out the SMH, contrary to the suggestion in [8,9].

We stress that these conclusions from our simulations hold only if SS mergers are the only efficient sources of strangelet ejection. In fact, several other suggestions have been made, e.g., core-collapse supernova explosions [40] or the ejection by electric fields from the surface of a SS [41] if SQM nuggets were embedded in the crust [42]. Despite the remaining uncertainties of our simulations like the approximate treatment of GR, which also does not allow us to follow the formation of the BH, the limited mass resolution, the simplified EOS, and the omission of magnetic fields and a nuclear crust, we expect that a more sophisticated approach will only yield quantitative shifts, changing the exact values of the ejecta masses and possibly insignificantly moving the border between configurations with and without ejecta.

Our results might also apply to other forms of self-bound matter like pion-condensed nucleon matter [5,43] provided the stellar properties are similar.

Future investigations, which should preferably be done in full GR, should consider EOSs including quark interactions and color superconductivity, or should use descriptions beyond the MIT bag model. Also SS-BH mergers should be reexamined in the GR framework. Finally, GW signals from mergers besides the stellar cooling behavior [4,44] may be promising means to decide on the SMH or other forms of self-bound matter, once wave measurements will become possible.

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