Preprint typeset using LaTeX

OBSERVATIONAL SIGNATURES OF STRANGE STARS

CURRAN D. MUHLBERGER
Department of Physics, Cornell University, Ithaca, New York 14853
December 15, 2009

Abstract

If the strange matter hypothesis is correct, compact objects thought to be neutron stars could in fact be strange stars. Such objects would differ from neutron stars in their normal modes of oscillation and their behavior during merger events. Therefore, by measuring the frequencies of quasi-periodic magnetar oscillations and the spectra of gravitational wave signals, we can infer the internal structure of compact stars. Additionally, the presence of strange quark matter in the cosmic ray flux would favor the existence of strange stars. Observations to date have been inconclusive, but experiments in the next five years should reveal the identity of these objects, thereby constraining the QCD equation of state.

Subject headings: cosmic rays — equation of state — gravitational waves — methods: numerical — stars: interiors — stars: neutron

1. INTRODUCTION

In 1984, E. Witten proposed that the ground state of matter might not be ^{56}Fe, but rather a mixture of up, down, and strange quarks [1]. If this "Strange Matter Hypothesis" is true, then collections of this bulk quark matter with baryon numbers between 10^2 and 10^{57} would be absolutely stable, even under zero pressure [2]. Objects at the low end of that mass range are called "strangelets," while those at the high end are strange stars.

Even if strange quark matter (SQM) is the ground state of matter, its presence in the universe is not guaranteed. Neutron star cores provide the most favorable conditions for its formation, however, and should SQM come in contact with a neutron star interior, it could convert the entire star to a lower-energy SQM state: a strange star. Therefore, it is conceivable that neutron stars do not exist at all or are merely a transient phase in the stellar life cycle between supernovae and strange stars.

If neutron stars and strange stars could be distinguished observationally, not only would it answer this question as to the ultimate fate of massive stars, but it would also provide constraints on the theory of quantum chromodynamics (QCD) at high densities. Unfortunately, the necessary observations are hardly trivial. Here we consider three avenues to inferring the true identity of compact objects.

First, in section 3 we examine the effects of SQM on the oscillation modes of the stellar crust, which could be excited during giant flares. Then in section 4, leaving the electromagnetic spectrum behind, we use the results of numerical simulations to look for unique features in the gravitational waves produced during compact star mergers. Finally, we turn to the direct detection of SQM in our local environment in section 5. All three of these approaches will be implemented in the near future, putting the answer to the strange matter question close at hand.

2. STRANGE MATTER AND STRANGE STARS

At extremely high densities it is possible for the quarks in baryons to become deconfined, forming bulk quark matter. As quarks are fermions, the energy needed to add additional quarks to a SQM object increases due to Pauli exclusion. However, each flavor of quark fills its own Fermi sea, and additional seas lower the overall energy. These seas only become available when the Fermi energy of quarks in the object is greater than the rest mass energy of the next quark flavor.

The up quark has a mass of 2.5 MeV [3] while the down quark has a mass of 5.0 MeV, making two-flavor quark matter accessible once deconfinement is overcome. The strange quark has a mass of 70 MeV–130 MeV, becoming accessible with sufficient baryon number. The charm quark, however, has a mass of 1.3 GeV and remains inaccessible. Under the high pressures found in neutron star cores, a deconfined quark state may be energetically favorable. However, regions of the rather uncertain QCD parameter space also allow the three-quark variant to be energetically stable at zero pressure, and it is this that we call SQM.

Even though it is absolutely stable, SQM is not likely to form spontaneously due to its high minimum baryon number. Approximately 100 simultaneous weak interactions would need to occur in the same place to convert ordinary matter without a progenitor [1]. However, intermediate states, like two-flavor quark matter or Λ particles, are accessible in the cores of neutron stars and may facilitate the formation of SQM. Alternately, a process called "neutrino sparking" may create SQM depending on the fates of s and $\bar{s}$ quarks in subsequent reactions. In this situation, a high-energy neutrino would deliver its energy to a nuclear quark, which would share that energy with numerous neighbors very rapidly.

Perhaps the most likely source of SQM, however, is the merger of two strange stars. Because SQM is stable over a wide range of baryon number, matter shed in this process would take the form of strangelets and propagate through the ISM. If such a strangelet were to come in contact with the interior of a neutron star, its offering of lower energy would convert the neutron star into a strange star. Therefore, aside from the details of QCD, the strangelet flux in galaxies is crucial in determining whether or not all compact stars are strange stars [2].

The equation of state for SQM is quite different than that for nuclear matter, and this results in a very distinct mass-radius relation for strange stars, shown in Figure 1. Since SQM has a preferred density for lower baryon numbers, $M \propto R^3$ for much of the curve, and the overall correlation is positive. This is in stark contrast to nuclear equations of state, such as those by Shen and Lattimer & Swesty, which have an inverse

curran@astro.cornell.edu

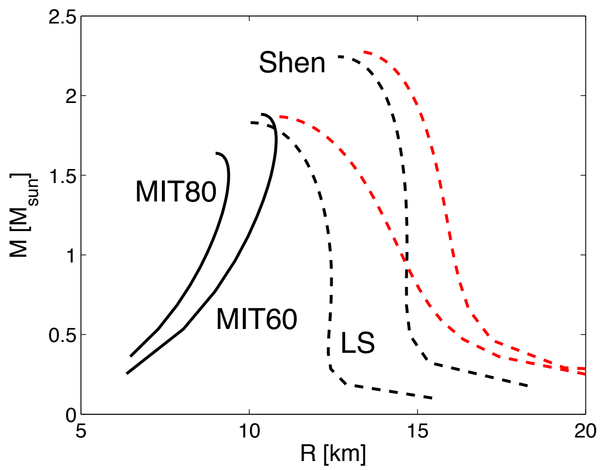

FIG. 1.— Mass-radius relation for Shen, LS, and MIT equations of state. From Bauswein et al. [4].

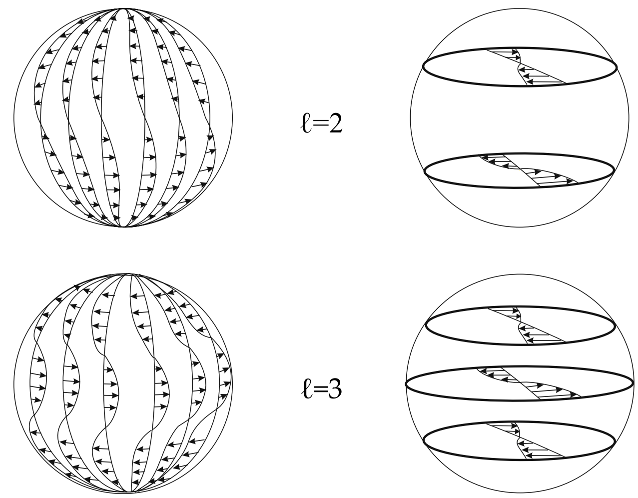

FIG. 2.— Illustration of global torsional modes. From Bastrukov et al. [9].

relationship between mass and radius.

When compared to softer equations of states, like that of Shen, SQM equations of state (here computed with the MIT bag model) support more compact strange stars with a smaller maximum mass. However, there is a region of QCD configuration space, parameterized by the MIT bag constant B, where strange stars can have compactnesses comparable to neutron stars with stiff equations of state like that of Lattimer & Swesty. Therefore, a single precision M,R measurement would be insufficient to resolve the strange matter hypothesis unless $M > 2M_\odot$.

The crusts of strange stars are another source of uncertainty. It is possible for strange stars to have a bare quark surface [1], and if they do feature a crust, it will be significantly smaller ($\sim 10^{-5}M_\odot$) than those of neutron stars [2]. Two models for strange star crusts exist. Due to a strong electric field just above the quark surface, the star may be able to support a thin crust of nuclear matter. However, the size of such a crust is limited – once the crust reaches sufficient pressures for neutron drip, the neutral free neutrons will not feel the Coulomb barrier and will come into contact with and convert into SQM [1]. A more recent model suggests that the crust could be made up of a lattice of SQM "nuggets" in an electron background [5].

In addition to influencing seismic oscillations and glitches, crustal composition is important when considering strangelet seeding as a creation mechanism for strange stars. In particular, the strange nugget model would provide an additional source of strange matter likely to become unbound during a merger event. Furthermore, neutron star crusts might prevent strangelets from reaching their cores, resisting conversion to strange stars. For neutron stars older than one month, only strangelets with baryon numbers $\gtrsim 10^{39}$ are predicted to survive the impact with the crust.

3. QUASI-PERIODIC OSCILLATIONS

Because strange star crusts are so different from those of neutron stars, and because the composition of strange star crusts is still undetermined, observables dependent on properties of the crust are powerful tools for testing the strange matter hypothesis. In particular, because these crustal models have very different shear speeds and thicknesses, they will exhibit distinct modes of oscillation. These modes could be excited during starquakes following giant flares, and their signature may be present in electromagnetic signals from the event.

In 1998 and 2004, giant flares with luminosities as high as 10^{46} erg/s were detected from magnetars SGR $1900+14$ and SGR $1806-20$ using the Rossi X-Ray Timing Explorer (RXTE) and Ramaty High Energy Solar Spectroscopic Imager (RHESSI) satellites [6, 7, 8]. Quasi-periodic oscillations (QPOs) were present at frequencies ranging from 18 Hz to 625 Hz [5]. By attributing these to seismic oscillations of the crust, we can judge the ability of each crustal model to reproduce these spectra.

A. Watts and S. Reddy have studied simplified models of potential magnetar crusts and computed the frequencies of their normal modes [5]. Because $P/\rho g \ll R$, they assume a plane-parallel (slab) geometry and a constant, uniform B-field. Furthermore, they assume that the crust is decoupled from the core. Though this is clearly not the case in magnetars, the coupling is not expected to alter the frequencies very much. They then quantize the toroidal shear modes with no compression or radial displacement in terms of periodic dependencies of the form $e^{i\omega t}$. Similar modes are visualized in Figure 2.

With no radial node present, the frequencies of the $n=2$ modes scale with ℓ as $\sqrt{(\ell+2)(\ell-1)}$. With this scaling, the observed sets of frequencies are best fit with a fundamental of ~ 30 Hz. Lower frequencies are attributed to global Alfvén modes. When a radial node is added ($n=1$), the frequencies become much higher, and these overtones are the best candidates for the 625 Hz QPO observed in SGR $1806-20$. Neutron star crusts can reproduce these frequencies for a range of realistic neutron star parameters. Strange stars, on the other hand, have more trouble.

For the thin nuclear crust, the $n=0$ modes are largely independent of both temperature and B-field strength. Because there is no radial mode, they also do not depend heavily on the thickness of the crust, ΔR. However, the $n=1$ mode does depend strongly on the magnetic field. Furthermore, because of the radial node, it is very dependent on the crust thickness and has a higher frequency for thinner crusts. Because high temperatures thin the crust due to melting, these frequencies also increase with temperature. These dependencies are plotted in Figure 3. Unfortunately, for all physically relevant strange star parameters, both the fundamental $n=0$ mode and the $n=1$ overtone have frequencies that are too high to fit the

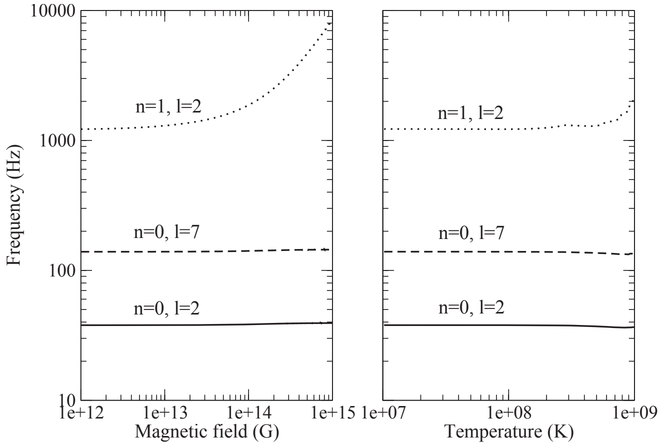

FIG. 3.— Fundamental and overtone frequencies for a thin nuclear crust around a $1.4 M_\odot$ strange star. From Watts & Reddy [5].

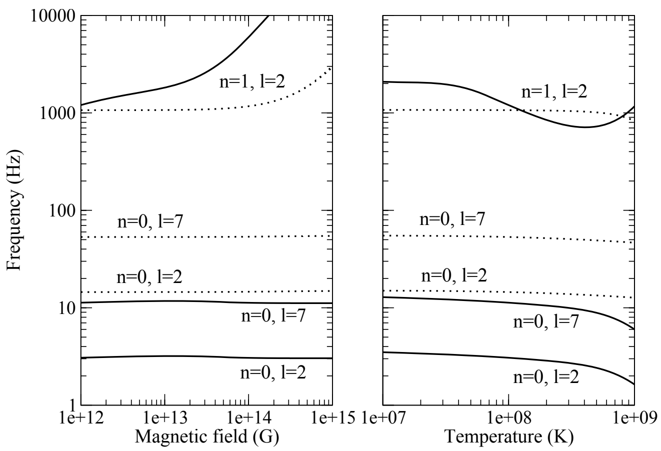

FIG. 4.— Fundamental and overtone frequencies a SQM nugget crust around a $1.4 M_\odot$ strange star. Solid curves correspond to a strange quark mass of $m_s = 150\,\mathrm{MeV}$, while dotted lines represent $m_s = 250\,\mathrm{MeV}$. From Watts & Reddy [5].

observations.

Crusts containing SQM nuggets, on the other hand, have fundamental frequencies that are too low. The shear speed of the crust increases with the mass of the strange quark, but even at the upper limit of m_s the $n = 0$ frequencies are well below the desired 30 Hz. Even the dotted curves in Figure 4, which correspond to an unphysically large $m_s = 250\,\mathrm{MeV}$, are not high enough in frequency to conveniently fit the measured mode sequences. Additionally, the $n = 1$ overtone frequencies are still too high and exhibit a strong dependence on temperature. This clashes with the observation that the QPOs have long coherence times (hundreds of seconds), during which time the temperature may vary widely.

These calculations strongly favor neutron stars as the identities of these magnetars. However, they are limited by several severe instructions. The calculations were conducted in Newtonian gravity, as relativistic models currently lack B-fields [10]. Even given the simplifications of Newtonian gravity, though, these models still neglected the global geometry of the neutron star and the configuration of its B-field. The assumption that global modes will share the same frequency spectra introduces further uncertainty. Finally, even if these models prove accurate, it is possible that the observed QPOs are not seismic in origin. Therefore, while strange stars find no support in this study, the jury is still out on their existence.

4. GRAVITATIONAL WAVES

If electromagnetic signals are insufficient to distinguish between neutron stars and strange stars, we can soon turn to gravitational wave astronomy for a new view. Detectors like LIGO and VIRGO are sensitive to frequencies expected during the merger of two stellar-mass compact objects, and confident detections are expected in the near future. Unfortunately, mapping gravitational waveforms back to physical quantities requires matching them against predictions produced by computationally expensive numerical simulations.

There are two primary strategies for simulating relativistic fluids. In the Eulerian picture, fluid quantities like density and velocity are evaluated at points on a fixed grid. The grid specification fixes a spatial resolution. Quantities of interest can then be evolved using finite difference, finite volume, or spectral methods. Alternately, one can take the Lagrangian approach, implemented as smoothed particle hydrodynamics (SPH). Here, fluid elements are represented by co-moving "particles" whose coordinates are evolved in time.

The Max Planck Institute for Astrophysics has developed a SPH code for modeling neutron star and strange star mergers [11]. However, their code can only treat general relativity in the conformally flat approximation. In the conformally flat formalism, the number of spatial degrees of freedom in the metric is reduced from 6 to 1, facilitating simpler solution methods. However, this comes at the cost of gravitational radiation and black holes, neither of which exist in a conformally flat metric. Gravitational wave extraction and backreaction must be treated separately by adding additional post-Newtonian contributions.

Using this code, A. Bauswein, R. Oechslin, & H.-T. Janka have compared mergers of neutron stars to those of strange stars [4]. The merger process and remnant are quite different for the two cases, but more importantly these differences manifest themselves in gravitational waves observable from Earth. When compact stars merge, the remnant may either promptly collapse to a black hole or may support itself for some time through differential rotation. In the latter case, matter may be ejected from the binary constituents via tidal forces, providing another distinguishing observable.

Qualitatively, neutron star remnants are left with a dilute halo or torus or matter surrounding the resulting differentially rotating hypermassive object. Furthermore, neutron star mergers require higher mass binary constituents in order to initiate a prompt collapse to a black hole. Strange star remnants, on the other hand, exhibit a sharp surface with matter shed from the stars forming a thin, fragmented disk and thin tidal arms. These differences are primarily due to the fact that SQM remains self-bound even at low baryon numbers, allowing it to be shed in coherent "blobs" instead of becoming diffuse like normal matter. The contrast between the two cases is clearly shown in Figure 5.

In terms of the gravitational waves emitted during these events, the frequencies of such waves are primarily governed by the compactness (M/R) of the star. This would be sufficient to distinguish between strange stars and softer neutron star equations of state. However, as shown in Figure 1, other equations of state can produces neutron stars with compactnesses comparable to neutron stars. In this case, gravitational wave frequencies alone might not be able to distinguish the two given current detectors. Future instruments, though, like the Einstein Telescope, will be more sensitive to frequencies above 1 kHz where additional differences between the two signals become visible. In particular, a gap appears in the neutron star

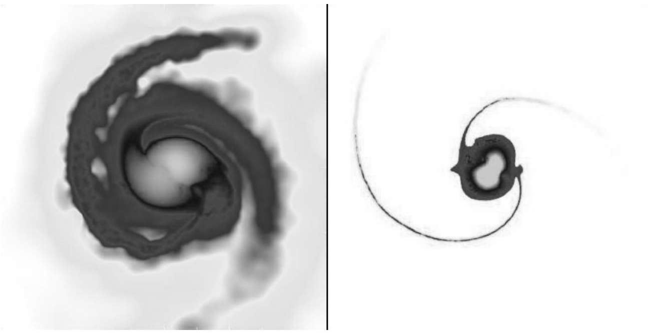

FIG. 5.— Tidal tails surrounding unequal-mass merger remnants for neutron stars (left, log scale) and strange stars (right, linear scale). From Bauswein et al. [4].

frequency spectrum just prior to the peak frequency.

Fortunately, we can also consider the luminosity characteristics of gravitational waves, even without a precise waveform model. Assuming that the time of coalescence is known, we can compute the total gravitational wave energy emitted by the ringdown of the post-merger remnant and compare it to the energy released during the last moments of inspiral. This ratio is consistently higher for strange stars than for neutron stars. Furthermore, strange star remnants radiate their excess energy away faster than their neutron star counterparts, which is visible when computing the total ringdown energy emitted as a function of time since merger.

These simulations do have some limitations. They assume conformal flatness, contain no stellar crusts or B-fields, use simplified equations of state for SQM, and are limited to a mass resolution of $10^{-5}M_{\odot}$. Future simulations would also want to consider the case of compact stars merging with black holes. Still, their present work may very well be sufficient to reach a conclusion on the strange matter hypothesis when the first definitive gravitational wave signals are detected.

5. STRANGELETS

A more direct approach to the strange matter question is to look SQM in our local environment. If sufficiently common in the cosmic ray flux, strangelets would almost certainly convert all neutron stars to strange stars. However, if the strangelet flux is low enough, neutron stars and strange stars could coexist, meaning that the unequivocal detection of one would not rule out the other. Finally, if we can relate the strangelet flux to the SQM equation of state, measurement of the flux could help constrain QCD given confident knowledge of merger rates.

Strangelets could form though a variety of cosmic mechanisms. The bulk of their flux would most likely come from mass ejection in unequal-mass mergers of strange stars, such as the tidal tails visible in Figure 5. Black hole–strange star mergers and mergers that promptly collapse would not contribute, however. Additionally, if strange star crusts are composed of strangelet nuggets, these could be ejected by electric fields. Core-collapse supernovae are yet another possibility [2]. Finally, there is a chance that strangelets could be produced in particle accelerators on Earth, though past terrestrial searches have been inconclusive.

The merger simulations conducted by Bauswein et al. suggest that the cosmic flux of strangelets due to mergers is critically dependent on the equation of state used to model SQM [2]. In particular, an MIT bag constant of $60\,\mathrm{MeV\,fm^{-1}}$ results in an average of $\sim 10^{-4}M_{\odot}$ of strange matter ejected per merger, while a bag constant of $80\,\mathrm{MeV\,fm^{-1}}$ results in no strangelets being ejected. Though the lack of strange star crust modeling limits the certainty of these conclusions (the entire crust is below the mass resolution of the simulation), a negative result in a cosmic search for strange matter might not rule out the strange matter hypothesis, and a positive detection of a neutron star might not rule out strange stars either.

Such a cosmic search will be underway in under a year when the Alpha Magnetic Spectrometer (AMS-02) will be installed on the international space station. The instrument is scheduled to launch on July 29, 2010 and will measure the charge-to-mass ratio of cosmic rays above the Earth. Since no nucleus has a ratio of $Z/A < 0.3$, such a measurement would be a strong indicator of the presence of strange matter [12].

6. CONCLUSIONS

The strange matter question has been open for more than two decades now with no strong evidence on one side or the other. However, compact stars provide probably our best opportunity to probe this uncertainty in QCD. Simplified models of seismic modes suggest that neutron stars, and not strange stars, were the objects behind giant magnetar flares exhibiting QPOs, but the assumptions of the study are too great to be confident in this assessment. Furthermore, some regions of QCD parameter space would allow the coexistence of neutron stars and strange stars.

Fortunately, observations in the next five years should tip the balance of evidence one way or the other. Instruments like Enhanced LIGO, the Fermi satellite, and the LHC, all currently online, provide new opportunities to search for gravitational wave signatures, oscillation modes, and strange matter itself. Within a year, AMS-02 will take the question above our atmosphere. And by 2014, Advanced LIGO should be operational, ushering in a new era of gravitational astronomy. These near-term observational advances should bring the data on-par with the theory discussed here, likely providing an answer to this long-standing question while certainly generating new ones to pursue.

REFERENCES

[1]C. Alcock, E. Farhi, and A. Olinto, ApJ **310**, 261 (Nov. 1986).
[2]A. Bauswein, H.-T. Janka, R. Oechslin, G. Pagliara, I. Sagert, J. Schaffner-Bielich, M. M. Hohle, and R. Neuhäuser, Physical Review Letters **103**, 011101 (2009).
[3]C. Amsler et al., Physics Letters B **667**, 1 (2008), ISSN 0370-2693, review of Particle Physics.
[4]A. Bauswein, R. Oechslin, and H. Janka, ArXiv e-prints(Oct. 2009), arXiv:0910.5169.
[5]A. L. Watts and S. Reddy, MNRAS **379**, L63 (Jul. 2007), arXiv:astro-ph/0609364.
[6]G. L. Israel, T. Belloni, L. Stella, Y. Rephaeli, D. E. Gruber, P. Casella, S. Dall'Osso, N. Rea, M. Persic, , and R. E. Rothschild, ApJ **628**, L53 (2005).
[7]T. E. Strohmayer and A. L. Watts, ApJ **632**, L111 (2005).
[8]A. L. Watts and T. E. Strohmayer, ApJ **637**, L117 (2006).
[9]S. I. Bastrukov, H. Chang, I. V. Molodtsova, E. Wu, G. Chen, and S. Lan, Ap&SS **323**, 235 (Oct. 2009), arXiv:0902.0840.
[10]L. Samuelsson and N. Andersson, MNRAS **374**, 256 (Jan. 2007), arXiv:astro-ph/0609265.
[11]R. Oechslin, H.-T. Janka, and A. Marek, A&A **467**, 395 (may 2007).
[12]J. Sandweiss, Journal of Physics G: Nuclear and Particle Physics **30**, S51 (2004)