Strangeness in Astrophysics and Cosmology

T Boeckel†, M Hempel†, I Sagert‡, G Pagliara†, B Sa’d†,
J Schaffner-Bielich§

† Institut für Theoretische Physik, Ruprecht-Karls-Universität, Philosophenweg 16,
69120 Heidelberg, Germany
‡ Institut für Theoretische Physik, Goethe Universität, Max-von-Laue-Str. 1,
60438 Frankfurt am Main, Germany
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E-mail: schaffner@thphys.uni-heidelberg.de

Abstract. Some recent developments concerning the role of strange quark matter
for astrophysical systems and the QCD phase transition in the early universe are
addressed. Causality constraints of the soft nuclear equation of state as extracted
from subthreshold kaon production in heavy-ion collisions are used to derive an upper
mass limit for compact stars. The interplay between the viscosity of strange quark
matter and the gravitational wave emission from rotation-powered pulsars are outlined.
The flux of strange quark matter nuggets in cosmic rays is put in perspective with a
detailed numerical investigation of the merger of two strange stars. Finally, we discuss
a novel scenario for the QCD phase transition in the early universe, which allows for
a small inflationary period due to a pronounced first order phase transition at large
baryochemical potential.

1. Introduction

There is no attempt in this contribution to discuss all the recent advances in the very
active research area of studying the impacts of strange quark matter in astrophysics
and cosmology. We refer to the other contributions of this conference for topics not
covered in this contribution to the proceedings. Signals for the QCD phase transition
to strange quark matter in core-collapse supernovae are addressed in the contribution
by Irina Sagert et al. (see also [1]). For the appearance of a new strange phase in the
evolution of proto-neutron stars we refer to the contribution by Giuseppe Pagliara et
al. (see also [2]). The issues of how to nucleate strange quark matter in astrophysical
systems has been studied in detail in the contribution of Bruno Mintz et al. (see also
[3]). Strange quark matter, colour superconductivity and the relation to quarkyonic
matter are discussed in the contribution by David Blaschke et al. (see also [4]).

In the following we give attention to a few other recent developments in the field.
First we reconsider the maximum mass constraint for neutron stars using causality

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arguments for the nuclear equation of state. Constraints on the nuclear equation of state using heavy-ion data, here subthreshold production of kaons, can be adopted to give a new maximum mass limit of about 2.7 solar masses. Then we are studying the gravitational wave emission from rotating neutron stars and the relation to the viscosity of strange quark matter. The recent simulation of the merger of two strange stars, the release of strange quark matter nuggets to the interstellar medium and the possible impact for the flux of strangelets in cosmic rays are another issue being highlighted. Finally, we are concerned with the cosmological QCD phase transition which happens around $10^{-5}$ seconds after the big bang. If one allows for an inflationary period at a strong first order phase transition, the early universe can actually pass through the QCD phase diagram at large baryochemical potential in contrast to the standard model of cosmology.

2. Maximum mass of neutron stars: constraints from heavy-ion data

Neutron stars are produced in core-collapse supernova explosions and are compact, massive objects with radii of 10–15 km and masses of 1–2 $M_\odot$. Pulsars are rotation-powered neutron stars and have been observed in binary systems, i.e. with a companion star, with a white dwarf or even with another neutron star. To create such a binary pulsar one starts with two ordinary stars, one with at least 8 $M_\odot$. The heavier star explodes first in a supernova and leaves a neutron star as a remnant. The neutron star is spun up by accreting matter from the companion star. Then also the companion star might become a white dwarf or another neutron star depending on its initial mass (see \[5\] for a review).

For binary pulsars masses can be pretty nicely determined. At present more than 1800 pulsars are known with 140 binary pulsars. From those binary pulsars, the pulsar PSR J1903+0327 is particular interesting \([6, 7]\). By measuring the post-Keplerian parameters from pulsar timing, here the Shapiro delay parameters $r$ and $s$ alone, constrain the mass to $M = (1.67 \pm 0.11)M_\odot$. Combined with the periastron advance $\dot{\omega}$ the mass is constraint to be $M = (1.67 \pm 0.01)M_\odot$. This mass measurement would put some severe constraints on soft nuclear equations of state which give a smaller maximum mass \([8]\).

Kaons are produced by associated production: $NN \rightarrow NAK$ and $NN \rightarrow NKK$ in elementary collisions. In the medium as generated in central heavy-ion collisions new processes emerge through rescattering as $\pi N \rightarrow AK, \pi A \rightarrow NK$ so that kaons can be even produced below the (elementary) threshold bombarding energy. In heavy-ion collisions of 1–2 AGeV nuclear matter can compressed up to $3n_0$. As kaons have a long mean-free path, they can escape the high density region serving as a messenger of the properties of high-density nuclear matter (for a review see e.g.\([9]\)). One defines the double ratio as the multiplicity of produced kaons per mass number for Au+Au collisions relative to the one for C+C collisions. This observable turns out to be rather insensitive to input parameters but strongly dependent on the nuclear equation of state (to be more precise
the in-medium potential of nucleons which can be related to the nuclear equation of
state). Using a simple Skyrme parametrization, only simulations with a compression
modulus of $K_N \approx 200$ MeV \cite{10, 11} can describe the energy dependence of the kaon
production data as measured by the KaoS collaboration \cite{12, 13}. Hence, the nuclear
equation of state would be soft around 2–3 $n_0$.

Causality arguments can then be adopted to constrain the maximum possible mass
of neutron stars. Above a fiducial density as determined from the data analysis of the
KaoS data the stiffest possible equation of state is taken which gives the maximum
pressure for a given energy density allowed. Causality demands then that at most
$p = \epsilon - \epsilon_c$ above the fiducial density $\epsilon_f$ (see \cite{14, 15}). There is a general scaling relation for
the maximum possible mass of compact stars which is given by $M_{\text{max}} = 4.2 M_\odot \left(\epsilon_0 / \epsilon_f\right)^{1/2}$
where $\epsilon_0$ is the energy density of normal nuclear matter (the numerical prefactor depends
slightly on the low-density nuclear equation of state, see \cite{16}). For a fiducial density
of $\epsilon_f = 2\epsilon_0$ as provided by the heavy-ion data the upper mass limit is about $2.7 M_\odot$
\cite{17, 18}.

3. Gravitational wave emission from rotating neutron stars: the viscosity of
strange quark matter

There exists a special class of binary neutron stars, so called x-ray burster. In these
astrophysical systems, the neutron star is accreting matter from an ordinary star or
a white dwarf. A low-mass x-ray binary (LMXB) is a neutron star with a low mass
companion star or a white dwarf. The accreting matter falls onto the neutron star
surface and thereby releases x-rays in a burst. The neutron star surface is heated up to
typical temperatures of $T = 10^{-100}$ keV.

For rotating neutron stars, there exists an instability, the r-mode instability. Oscillations brings the neutron star matter out of $\beta$-equilibrium which is restored by
weak processes affecting the bulk and shear viscosity \cite{19}. The viscosity of nuclear matter
is quite low in certain regions of frequency and temperature so that the oscillations will
not be damped, gravitational waves are emitted and the star’s rotation slows down. The contributions from quarks increase the stability window in temperature and frequencies
substantially. In color-superconducting phases the viscosity of quark matter can be
dramatically different \cite{20, 21, 22, 23, 24}. In the 2SC phase, with the pairing of two quark
flavours and two colours, there are still unpaired quarks left and one obtains similar
results compared to the free case \cite{25, 26}. Both cases are compatible with the data on
low-mass x-ray binaries. On the contrary, quarks of all color and flavor are paired in the
CFL phase. The reaction rates are suppressed, the instability window is considerably
broader which could leave an observable impact on the evolution of young pulsars and
accreting neutron stars. Recently, it was also found that there is a new process which
takes away the energy from the r-mode oscillations by the emission of neutrinos. It
acts effectively as a viscosity which would help in damping the r-mode instability by a
substantial factor \cite{27}.
4. Strange star mergers: the flux of strangelets in cosmic rays

According to the Bodmer-Witten hypothesis absolutely stable strange quark matter would be more bound than ordinary nuclear matter. If one allows for absolutely stable strange quark matter, then strange stars will exist which are compact stars consisting of absolutely stable strange quark matter being bound by strong interactions (selfbound) and not by gravity as ordinary neutron stars. Strange stars can coexist with neutron stars, but in principle a neutron star would collapse to strange star in a spectacular astrophysical event. Recently, the collisions of two strange stars have been simulated in 3D relativistic smoothed particle hydrodynamics with approximate treatment of effects from General Relativity [28]. Typical timescales involved are milliseconds, so that matter is in $\beta$-equilibrium. The simulations have been performed for two bag constants of $B = 60$ and $80$ MeV/fm$^{-3}$, in both cases one gets absolutely stable strange quark matter, and for different initial masses of the two strange stars. In principle, two different scenarios have been found: either there is an immediate collapse to a black hole or a hypermassive object stabilized by differential rotation is formed. The implications of these results are quite striking: the ejected mass of strange quark matter (strangelets) released to the interstellar medium are estimated to be $(1.4-2.8) \cdot 10^{-4} M_\odot$ for the lower bag constant and zero for the larger one. As strange star mergers are considered to be the prime source for strangelets in cosmic rays, the latter result opens the possibility that no strangelets are seen in cosmic rays although strange stars exist. The Alpha Magnetic Spectrometer AMS will measure the strangelet flux in cosmic rays (planned to be installed at the International Space Station ISS in 2010). Interestingly, the gravitational wave pattern of compact star mergers can be used to distinguish between neutron star and strange star mergers [29].

5. Early universe: phase transition from strange quark matter

Let us briefly outline the history of the early universe. In a radiation dominated universe the temperature scales inversely with the scale parameter $a$. Big-bang nucleosynthesis happens at times of $t = 1s$ to 3 minutes which corresponds to temperatures of $T = 1$ to $0.1$ MeV. The QCD phase transition occurs at a temperature of about $T \approx 170$ MeV, i.e. at a time of $t \approx 10^{-5}$ s after the big bang. The early universe passes through the electroweak phase transition at $t \approx 10^{-10}$ s ($T \approx 100$ GeV). In the standard cosmology, one knows from the measurement of the microwave background radiation with WMAP and from the observed light element abundance from the big bang nucleosynthesis that the ratio of the number of baryons to the number of photons (which is related to the total entropy of the universe) is tiny:

$$n_B/s \sim n_B/n_\gamma \sim \mu/T \sim 10^{-9}$$

Note that the baryon number per entropy is a conserved quantity throughout the evolution of the universe unless there is a non-equilibrium process as a first order phase transition. From the above considerations one concludes that the early universe evolves...
Along \( \mu \sim 0 \) which implies that the early universes crosses the QCD phase transition in a region of the QCD phase diagram where one expects a crossover transition as seen in recent lattice gauge calculations. A crossover transition implies that there is nothing spectacular happening, as one expects no cosmological signals from such a kind of transition.

The Friedmann equation for radiation dominated universe reads
\[
H^2 = \frac{8\pi G}{3} \rho \sim g(T) \frac{T^4}{M_p^2}
\]
where \( g(T) \) is effective number of relativistic degrees of freedom at a given temperature \( T \) and \( M_p \) is the Planck mass. The Hubble time is defined by the Hubble parameter and is related to the true time by \( t = 3t_H \) for a radiation dominated universe. By using the Friedmann equation one finds that \( t_H = 1/H \sim g^{-1/2} M_P / T^2 \) so that there is a simple relation between the time after big bang and the temperature of the radiation dominated early universe
\[
\frac{t}{1 \text{ sec}} \sim \left( \frac{1 \text{ MeV}}{T} \right)^2
\]
We see that if the number of degrees of freedom changes smoothly with the temperature, as it would be the case for a crossover phase transition, the temperature changes continuously with time.

The interesting question is what would happen if the early universe passes through a first order phase transition? We argue in the following that this is a viable scenario for the QCD phase transition and not in contradiction to our present knowledge of QCD. Furthermore, we demonstrate that it would leave an observable imprint on the gravitational wave background [30].

A first order phase transition in general allows for a false metastable vacuum state where the universe could be trapped for some time. For a constant vacuum energy,
one arrives at the de Sitter solution of the Friedmann equations which results in an (additional small) inflationary period:

\[ H = \dot{a}/a \sim M_p^{-1} \rho_v^{1/2} = H_v = \text{const.} \implies a \sim \exp(H_v \cdot t) \]

Remarkably, just a few e-folds are enough (standard inflation needs \( N \sim 50 \)) for our purposes. The baryon to photon ratios before and after the inflationary period should scale with the ratio of the scale parameters cubed as entropy is produced during reheating while baryon number is conserved so that

\[ \left( \frac{\mu}{T} \right)_i \approx \left( \frac{a_i}{a_f} \right)^3 \left( \frac{\mu}{T} \right)_i \]

The final ratio should be \( 10^{-9} \) as observed so that we need just a boost of \( N = \ln (a_f/a_i) \sim \ln(10^3) \sim 7 \), i.e. seven e-folds, to get an initial ratio of \( (\mu/T)_i \sim O(1) \).

Note that for standard inflation one needs about \( N = 50 \) e-folds, so that the little inflation at the QCD phase transition can not replace it but could be present as an additional small inflationary period in the early universe.

So our scenario is as follows: the early universe is initially at large baryochemical potentials \( \mu/T \sim 1 \). Such a large value is possible for e.g. Affleck-Dine baryogenesis which involves scalar supersymmetric fields carrying baryon number. The early universe reaches the first order phase transition line of QCD at high baryochemical potentials and is trapped in the false vacuum. Now the inflationary period starts with supercooling and dilution with \( \mu/T = \text{const.} \). The decay to the true vacuum state will release latent heat so that the universe is reheated to \( T \sim T_c \). Afterwards, the final baryon to photon ratio is given by \( \mu/T \sim 10^{-9} \) due to the entropy produced during the transition. Finally, the universe evolves along the standard cosmological path to big-bang nucleosynthesis and so on. The path through the QCD phase diagram is depicted in Fig. 1.

However, there are observable differences to the standard model of cosmology. The first order phase transition produces perturbations, scalar and tensor ones, by colliding bubbles. The tensor modes correspond to gravitational waves with a frequency scale given by the (redshifted) horizon scale at the transition point

\[ \nu_{\text{peak}} \sim H \cdot T_{\gamma,0}/T_{\text{QCD}} \sim T_{\text{QCD}}/M_p \cdot T_{\gamma,0} \sim 10^{-7} \text{ Hz} \]

The maximum amplitude of the gravitational waves is then given by the ratio of the scale factors today and at the QCD phase transition and is \( h \sim a_{\text{QCD}}/a_0 \sim 10^{-12} \). For superhorizon modes \( \nu < H \) the amplitude scales as \( h(\nu) \propto \nu^{-1/2} \) which corresponds to white noise. The modes within the horizon \( \nu > H \) are determined by multi bubble collisions and could scale as \( h(\nu) \propto \nu^n \) where \( n \) is between \(-1\) and \(-2 \). The gravitational waves from a first-order QCD phase transition are observable with pulsar timing, as with the Parkes Pulsar Timing Array and in the future with the Square Kilometre Array SKA (see figure 2).

Other cosmological implications of a first-order QCD phase transition are that the cold dark matter density is diluted by the same factor as the baryon number density, i.e. by up to a factor \( 10^{-9} \). To explain the present cold dark matter relic density within
Figure 2. The gravitational wave spectrum from a first order QCD phase transition. The Parkes Pulsar Timing Array PPTA already gives limits on the maximum amplitude of those gravitational waves. In the future the Square Kilometre Array SKA will push these limits down by a few orders of magnitude. For a flat spectrum at high frequencies, LISA would be also sensitive.

the standard WIMP scenario, one needs a different WIMP annihilation cross section $\sigma_{\text{ann}}$ as the cold dark matter density scales as $\Omega_{\text{CDM}} \sim \sigma_{\text{weak}}/\sigma_{\text{ann}}$ or by a substantially larger WIMP mass. Both cases can be probed by the LHC! The large-scale structure power spectrum responsible for galaxy and galaxy cluster formation would be modified up to a mass scale of $M \sim 10^9 M_\odot$ which is the typical mass scale of dwarf galaxies. Without QCD inflation, effects can be only up to the horizon mass $\sim 10^{-9} M_\odot$ at the phase transition point. Also, seeds of (extra)galactic magnetic fields can be generated by charged bubble collisions during the phase transition. The observed magnetic field today in our galaxy is $B \sim 10^{-5} \text{G}$, extragalactic ones are in the range of $B \sim 10^{-7} \text{G}$. One needs primordial seed fields of $B = 10^{-30} \ldots 10^{-10} \text{G}$. As the electroweak phase transition is a crossover for large Higgs masses, a first order QCD phase transition in the early universe would provide then a possible explanation of those cosmological magnetic fields within the standard model again (see [33] for a detailed calculation).

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