Is there Quark Matter in (Low-Mass) Pulsars?

Jürgen Schaffner-Bielich

Institut für Theoretische Physik/Astrophysik

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work done by:
Matthias Hempel, Giuseppe Pagliara, and Irina Sagert

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Phase Transitions in QCD

- early universe at small baryon density and high temperature
- neutron star matter at small temperature and high density
- first order phase transition at high density (not deconfinement)!
- probed by heavy-ion collisions with CBM@FAIR!
Nuclear Equation of State as Input in Astrophysics

- supernovae simulations: $T = 1–50 \text{ MeV}, \ n = 10^{-10}–2n_0$
- proto-neutron star: $T = 1–50 \text{ MeV}, \ n = 10^{-3}–10n_0$
- global properties of neutron stars: $T = 0, \ n = 10^{-3}–10n_0$
- neutron star mergers: $T = 0–175 \text{ MeV}, \ n = 10^{-10}–10n_0$
Hunting down strange quark matter in the heavens

Coming of age! Some suggestive signals:

- ’exotic’ mass-radius relation of compact stars
- rapidly rotating pulsars due to r-mode *stability* window
- enhanced cooling of neutron stars
- gamma-ray bursts by transition to strange quark matter (GRBs without a supernova, late x-ray emission, long quiescent times)
- gravitational wave signals of phase transitions
  - binary neutron star collisions
  - collapse of neutron star to a hybrid star
  - r-mode spin-down of hybrid stars
- core-collapse supernovae?
redshifted spectral lines measured (Cottam, Paerels, Mendez (2002))

analysis of Özel (Nature 2006): \( M \geq 2.10 \pm 0.28 M_\odot \text{ and } R \geq 13.8 \pm 1.8 \text{ km} \), claims: 'unconfined quarks do not exist at the center of neutron stars'!

reply by Alford, Blaschke, Drago, Klähn, Pagliara, JSB (Nature 445, E7 (2007)): limits would rule out soft equations of state, not quark stars or hybrid stars!
The EoS for Quark Matter
First order phase transition based on symmetry arguments!

- Phases of color superconducting quark matter in $\beta$ equilibrium: normal (unpaired) quark matter (NQ), two-flavor color superconducting phase (2SC), gapless 2SC phase, color-flavor locked phase (CFL), gapless CFL phase, metallic CFL phase

(Alford, Rajagopal, Wilczek, Reddy, Buballa, Blaschke, Shovkovy, Drago, Rüster, Rischke, Aguilera, Banik, Bandyopadhyay, Pagliara, ...
use toy model EoS for quark matter: \( p = a \cdot \epsilon \) with constant \( a = 1/3 \) and a given energy density jump

use RMF model (here set GM3) for the low-density nuclear EoS

phase transition close to the maximum: always unstable solutions for the quark core
(Giuseppe Pagliara and JSB, arXiv:0711.1119)

- change the critical energy density for the phase transition
- phase transition close to the maximum mass: unstable quark core
- onset of phase transition at moderate densities: stable quark core
Color-superconducting quark matter in the NJL model

\[ p = \frac{1}{2\pi^2} \sum_{i=1}^{18} \int_0^\Lambda dk k^2 |\epsilon_i| + 4K \sigma_u \sigma_d \sigma_s - \frac{1}{4G_D} \sum_{c=1}^{3} |\Delta_c|^2 \]

\[ -2G_S \sum_{\alpha=1}^{3} \sigma_{\alpha}^2 + \frac{1}{4G_V} \omega_0^2 + p_e \]

- use Nambu–Jona-Lasinio model for describing quark matter
- describes both dynamical quark masses (quark condensates \( \sigma \)) and the color-superconducting gaps \( \Delta \)
- so far 'best' model in the field (Rüster et al. (2005))
- parameters: cutoff, scalar and vector coupling constants \( G_S, G_V \), diquark coupling \( G_D \), 't Hooft term coupling \( K \)
- fixed to hadron masses, pion decay constant, free: \( G_D \) and \( G_V \)
Hybrid Star Matter

(Giuseppe Pagliara and JSB, arXiv:0711.1119)

- fix the pressure in vacuum ($B_0$) or at the chiral phase transition ($B_*$)
- first case: phase transition to CFL quark matter (left plot)
- second case: two phase transition to 2SC then to CFL phase (right plot)
phase transition directly to CFL phase: unstable first then stable branch

two phase transitions: two kinks in curve, also two stable solutions

new stable solution possible \(\rightarrow\) third family of compact stars!

two phase transitions can be present in compact star matter: implications for supernovae?
third solution to the TOV equations besides white dwarfs and neutron stars, solution is stable!

generates stars more compact than neutron stars

possible for any first order phase transition!
Signals for a Third Family/Phase Transition?

- mass-radius relation: rising twins (Schertler et al., 2000)
- spontaneous spin-up of pulsars (Glendenning, Pei, Weber, 1997)
- collapse of a neutron star to the third family? (gravitational waves, \(\gamma\)-rays, neutrinos)
- r-mode instabilities: millisecond pulsars, gravitational wave burst (Drago, Pagliara, Berezhiani, 2006), . . .
- gamma-ray bursts with late x-ray emission, long quiescent times (Drago and Pagliara, 2007), . . .
- secondary shock wave in supernova explosions?
- gravitational waves from colliding neutron stars?
The hot EoS for Supernovae
Composition of Supernova Matter (Low Densities)

need thermodynamic consistent low-density EoS

gas of nucleons, nuclei and electrons (plus Coulomb-lattice)

here: supernovae matter for a proton fraction $Y_p = 0.4$ and $T = 5\ MeV$

broad distribution, many exotic nuclei $\rightarrow$ relation to FAIR physics!
start of the mixed phase at quite low densities due to $\beta$-equilibrium, strange quark matter is more stable than nucleon matter (using RMF model TMA)

even lower critical densities for isospin-asymmetric matter (low proton fraction $Y_p$) due to asymmetry energy for nucleons

quark matter favoured in hot matter due to the QCD phase diagram

production of quark matter in supernovae at bounce possible!
plot of the phase transition line of temperature versus chemical potential

phase transition nearly independent on the proton fraction $Y_P$

phase transition line bends towards low chemical potentials for large $T$
presence of quark matter can change drastically the mass-radius diagram
third family of solution for certain bag constants
unique feature: small radii for moderate neutron star masses!
Summary

- the phase transition to quark matter leads to a rich variety of astrophysical signals involving compact stars and supernovae.
- do not look for supermassive neutron stars!
  - supermassive neutron stars well above $2.3M_\odot$: hard to achieve with any realistic modern EoS
  - maximum mass around $2M_\odot$: can be normal nuclear matter or a hybrid star with quark matter
  - maximum mass of $1.5M_\odot$ (well below $2M_\odot$): must involve exotic matter, hyperons or quarks!
- look for light pulsars and measure the radius!
- quark matter likely to be formed in core collapse supernovae!
- opportunities for a cross-check between heavy-ion physics and relativistic astrophysics!
Back-Up Slides
Phase Transition Density to Quark Matter for HICs

(Irina Sagert and Giuseppe Pagliara)

- no $\beta$-equilibrium (just up-/down-quark matter)
- large critical densities in particular for isospin-symmetric matter (proton fraction $Y_p = 0.5$)
- production of ud-quark matter unfavoured for HICs at small $T$ and high density
Phase Transition Line to Quark Matter for HICs

Phase transition line for ud-quark matter

Phase transition is at larger chemical potentials for ud-quark matter

'quasi-consistent' picture for freeze-out parameters at low energies:

SIS: $\mu_{f.o.} = 700 - 800$ MeV, $T_{f.o.} = 50 - 70$ MeV

AGS: $\mu_{f.o.} \sim 500$ MeV, $T_{f.o.} \sim 120$ MeV

(Irina Sagert and Giuseppe Pagliara)
plot of the *chiral* phase transition line within the NJL model

phase transition is at small chemical potentials, in particular for $Y_p = 0.5$

2SC phase likes symmetric matter, as only u- and d-quarks pair
(CFL phase is at higher densities)
measurement of periastron advance of the pulsar PSR J1748-2021B

inclination angle $i$ of orbital plane unknown

statistical analysis (for angle $i$):
$M = 2.74 \pm 0.21 M_\odot$ ($1\sigma$) and $M > 2.0 M_\odot$ (99% c.l.)

two neutron stars with $M \sim 1.4 M_\odot$ 'unlikely' but possible for $i = 4 - 5$ degrees

measurement of a second GR effect needed to draw firm conclusions!
Probes Using X–Ray Bursts

- X-ray bursts from accreting neutron stars originating from the surface spectral profile is modified from space-time warpage → gives a model independent mass and radius!
- Constellation-X will determine the mass-radius ratio to within 5%!

(Bhattacharyya et al. 2004)

(Strohmayer (2004))
Supernova Explosions

- stars with a mass of more than 8 solar masses end in a (core collapse) supernova (type II)
- new generation of simulation codes: 3D, Boltzmann neutrino transport

‘...the models do not explode. This suggests missing physics, possibly with respect to the nuclear equation of state ...’!
stars with a mass of more than 8 solar masses end in a (core collapse) supernova (type II)

new generation of simulation codes: 3D, Boltzmann neutrino transport


SASI: standing accretion shock instability, the models do explode!

(Janka, GSI Theory Seminar, July 11, 2007)
Masses of Pulsars (Stairs, 2006)

- more than 1600 pulsars known

- best determined mass: 
  \[ M = (1.4414 \pm 0.0002) \, M_\odot \]
  for the Hulse-Taylor pulsar (Weisberg and Taylor, 2004)

- smallest known mass: 
  \[ M = (1.18 \pm 0.02) \, M_\odot \]
  for pulsar J1756-2251 (Faulkner et al., 2005)
Massive Neutron Stars in Pulsar–White Dwarf Systems?

(Nice, Splaver, Stairs (2003))

- shaded area: from theoretical limits for white–dwarf companion

- Nice et al. (2005):
  \[ M = 2.1 \pm 0.2M_{\odot} \ (1\sigma) \] and
  \[ M = 1.6 - 2.5M_{\odot} \ (2\sigma) \]

- David Nice and Ingrid Stairs, private communication (2007):
  \[ M = 1.14 - 1.40M_{\odot} \]
two-component blackbody: small soft temperature, so as not to spoil the x-ray
this implies a rather LARGE radius so that the optical flux is right!
lower limit for radiation radius: \( R_\infty = R/\sqrt{1 - 2GM/R} \approx 17 \text{ km} \) (d/140 pc)
redshift \( z_g \approx 0.22: \, R \approx 14 \text{ km} \) and \( M \approx 1.55M_\odot \)
largest uncertainty in distance d
improved hydrogen atmosphere: adjusted surface gravity $g_s$ (solid blue lines, 90% c.l.) vs. fixed $g_s$ (pink dotted lines)

for fixed radius of 10 km:
\[ M = 2.20^{+0.03}_{-0.16} M_\odot \text{ (90\% c.l.)} \]

for fixed mass of $1.4M_\odot$:
\[ R = 14.5^{+1.8}_{-1.6} \text{ km (90\% c.l.)} \]

nearly no constraint on the mass for $R \approx 14 \text{ km}$!

any mass from $0.5M_\odot$ to $2.3M_\odot$ allowed!
spectral modelling of neutron stars in M13 (dotted blue line) and ω Cen (solid red line) and X7 in 47 Tuc (dash-dotted green line) all 99% c.l.

mass-radius curve has to pass through all three regions: data from M13 demands a small mass
The EoS from Heavy-Ion Data versus Astro Data
Kaon production in heavy-ion collisions

- Kaons produced by associated production:
  \[ NN \rightarrow N\Lambda K, \quad NN \rightarrow NNK\bar{K} \]

- In-medium processes (rescattering):
  \[ \pi N \rightarrow \Lambda K, \quad \pi \Lambda \rightarrow N\bar{K} \]

- Nuclear matter is compressed up to \( 3n_0 \)!

- Long mean-free path of kaons: kaons can escape high density matter

Sturm et al. (KaoS collaboration), PRL 2001
Fuchs, Faessler, Zabrodin, Zheng, PRL 2001
Confirmed KaoS data analysis: the nuclear EoS is soft!

The **KaoS** Collaboration

- kaon production ($K^+$) in heavy-ion collisions at subthreshold energies
- double ratio: multiplicity per mass number for C+C collisions and Au+Au collisions at 0.8 AGeV and 1.0 AGeV (rather insensitive to input parameters)
- only calculations with a compression modulus of $K_N \approx 200$ MeV can describe the data (Hartnack, Oeschler, Aichelin, PRL 2006; KaoS collaboration, 2007)

$\text{\Rightarrow the nuclear equation of state is SOFT!}$
Ansatz for the energy per particle:

\[
\frac{\epsilon}{n} = m_N + E_{0}^{kin} + \frac{A}{2} \cdot u + \frac{B}{\sigma + 1} u^\sigma + S_0 \cdot u^\alpha \cdot \left(\frac{n_n - n_p}{n}\right)^2
\]

where \( u = n/n_0 \). The parameters \( A, B, \sigma \) are fixed by nuclear matter properties \( n_0, E/A \), and the compression modulus \( K \), the asymmetry term by the asymmetry energy \( S_0 \) at \( n_0 \), \( \alpha \) varies between 0.7 and 1.1 (B.-A. Li et al. 2007).

The pressure is determined by the thermodynamic relation

\[
P = n^2 \frac{d}{dn} \left(\frac{\epsilon}{n}\right)
\]

EoS used as input in transport model calculations.

(Note: the equation of state can become acausal for \( \sigma > 2 \).)

Check: are low compressibilities ruled out by neutron star masses?
Empirical Nucleon-Nucleon Interaction: Maximum Masses

(Irina Sagert)

- small variation of the maximum mass with the compression modulus $K$ and the asymmetry energy for normal density dependence $\alpha = 1.0, 1.1$
- strong dependence on the compression modulus $K$ for $\alpha = 0.7$
- maximum mass $M \geq 1.6M_\odot$ for $K_0 > 160$ MeV!
- maximum mass $M \geq 2M_\odot$ for $K_0 > 160$ MeV and $\alpha = 1.0, 1.1$!
slight dependence on asymmetry energy $S_0$, up to $\Delta M = \pm 0.1M_\odot$ for low $K$

maximum central density $n_c = (7 \div 8)n_0$ for $\alpha = 1.0, 1.1$ and $10n_0$ for $\alpha = 0.7$

EoS causal up to $K_0 = 340$ MeV ($M = 2.6M_\odot$) for $\alpha = 1.0, 1.1$, and up to $K = 280$ MeV for $\alpha = 0.7$

$\Rightarrow$ A $2M_\odot$ pulsar mass is compatible with a ‘soft’ EoS!
Hot Nuclear Equation of State

- Taken into account nucleons, electrons and all nuclei
- Input: 2003 update of nuclear mass data
- State-of-the-art (relativistic) nuclear model for unknown nuclear masses
- Coulomb, shell-effects, pairing, axial deformations included!
phase transition to quark matter in the MIT bag model

onset of mixed phase appears between \((1 - 2)n_0\) even for large values of the bag constant

sufficiently high densities reached in the core for a \(1.3M_\odot\) neutron star to have quark matter
Hybrid Stars (Schertler et al. (2000))

- hybrid star: consists of hadronic and quark matter
- three phases possible: hadronc, mixed phase and pure quark phase
- composition depends crucially on the parameters as the bag constant \( B \) (and on the mass!)