Signals of the QCD Phase Transition in Compact Stars

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INT Program on Core Collapse Supernovae
Workshop on Probing the Supernova Mechanism by Observations
INT, University of Washington, Seattle, USA, July 16-20, 2012
Introduction: Nuclear Equation of State and Supernovae

Constraints on Quark Matter from Pulsar Masses

QCD Phase Transition and Supernovae

Summary
Introduction: Nuclear Equation of State and Supernovae
Nuclear Equation of State as Input in Astrophysics

- supernovae simulations: $T = 1–50$ MeV, $n = 10^{-10}–2n_0$
- proto-neutron star: $T = 1–50$ MeV, $n = 10^{-3}–10n_0$
- global properties of neutron stars: $T = 0$, $n = 10^{-3}–10n_0$
- neutron star mergers: $T = 0–100$ MeV, $n = 10^{-10}–10n_0$
New Equations of State for Supernovae

(Hempel, Fischer, JSB, Liebendörfer 2012, Steiner, Hempel, Fischer 2012)

- New equation of state for supernova simulations available
- Check with new pulsar mass limit
- Based on models for describing nuclear properties (nucleons only)
- Improvement in NSE (Hempel and JSB 2010)
Neutrino Luminosities for a 40 $M_\odot$ Progenitor

- neutrino luminosities for a 40 $M_\odot$ progenitor star
- collapse to a black hole within 1s
- collapse time depends on equation of state
- differences in particular in $\nu_\mu$ and $\nu_\tau$ spectra

(Hempel, Fischer, JSB, Liebendörfer 2012)
Correlation between maximum mass and collapse time

- relation between collapse timescale to a black hole and compact star masses
- cases for cold case (crosses), for constant entropy per baryon $S/A = 4$ (circles), and from simulation (boxes) for different EoS
- constant $S/A = 4$ describes maximum mass achieved in simulations quite well

(Hempel, Fischer, JSB, Liebendörfer 2012)
Profiles just before collapse (Hempel, Fischer, JSB, Liebendörfer 2012)

- radial profiles of density, abundances, entropy, temperature
- situation just before collapse to a black hole
- rather constant entropy per baryon of $S/A = 4$
- extremely high densities and temperatures (about 100 MeV!)
Early universe at zero 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 at GSI, Darmstadt (FAIR)
Structure of a Neutron Star  (Fridolin Weber)

- Absolutely stable strange quark matter
- Quark-hybrid star
- Hyperon star
- Strange star
- Nucleon star
- Traditional neutron star
- Neutron star with pion condensate

- $R \sim 10 \text{ km}$
- $M \sim 1.4 M_{\odot}$

- $10^6 \text{ g/cm}^3$
- $10^{11} \text{ g/cm}^3$
- $10^{14} \text{ g/cm}^3$
NASA news release 02-082:
“Cosmic X-rays reveal evidence for new form of matter”
— a quark star?
Selfbound Star versus Ordinary Neutron Star

(Hartle, Sawyer, Scalapino (1975!))

**Selfbound stars:**
- Vanishing pressure at a finite energy density
- Mass-radius relation starts at the origin (ignoring a possible crust)
- Arbitrarily small masses and radii possible

**Neutron stars:**
- Bound by gravity, finite pressure for all energy density
- Mass-radius relation starts at large radii
- Minimum neutron star mass: \( M \sim 0.1M_\odot \) with \( R \sim 200 \text{ km} \)
Hybrid Stars in the effective mass bag model

(Schertler et al. (2000))

- hybrid star: consists of hadronic and quark matter
- three phases possible: hadronic, mixed phase and pure quark phase
- composition depends crucially on the parameters as the bag constant $B$ (and on the mass)
Matching to low density EoS

Two possibilities for a first-order chiral phase transition:

- A weakly first-order chiral transition (or no true phase transition),
  $\Rightarrow$ one type of compact star:
  hybrid stars masquerade as neutron stars

- A strongly first-order chiral transition
  $\Rightarrow$ two types of compact stars:
  a new stable solution with smaller masses and radii
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 Quark Matter/Phase Transition?

- delayed collapse of a proto-neutron star to a black hole (Thorsson, Prakash, Lattimer, 1994)
- spontaneous spin-up of pulsars (Glendenning, Pei, Weber, 1997)
- mass-radius relation: rising twins (Schertler et al., 2000)
- rapidly rotating pulsars due to r-mode stability window
- enhanced cooling of neutron stars
- collapse of a neutron star to the third family? (gravitational waves, γ-rays, neutrinos)
- gravitational wave signals of phase transitions from neutron star mergers?
- secondary shock wave in supernova explosions (Sagert, Fischer et al. 2009)
similar masses and radii, cooling, surface (crust), ... but look for

- extremely small mass, small radius stars (includes strangelets)
- strange dwarfs: small and light white dwarfs with a strange star core (Glendenning, Kettner, Weber, 1995)
- super-Eddington luminosity from bare, hot strange stars (Page and Usov, 2002)
- quark novae with modified r-process nucleosynthesis (Jaikumar, Meyer, Otsuki, Ouyed 2007)
- gamma-ray bursts by conversion to strange quark matter (GRBs without a supernova, late x-ray emission, long quiescent times)

...
Constraints on quark matter from pulsar masses
spin rate from PSR B1937+21 of 641 Hz: \( R < 15.5 \) km for \( M = 1.4 M_{\odot} \)

Schwarzschild limit (GR): \( R > 2GM = R_s \)

causality limit for EoS: \( R > 3GM \)

mass limit from PSR J1614-2230 (red band): \( M = (1.97 \pm 0.04)M_{\odot} \)
Quark Star Masses: Unpaired Case

Use free gas of quarks with a term from interactions and from a vacuum energy:

\[ \Omega_{QM} = \sum_{i=u,d,s,e} \Omega_i + \frac{3\mu^4}{4\pi^2}(1 - a_4) + B_{eff} \]

- Effective model with an expansion in the chemical potential \( \mu \)
- Two parameters: effective bag constant \( B_{eff} \) and interaction parameter \( a_4 \)
- 2-flavour constraint: nuclei do not collapse to (u,d) quark matter!
- 3-flavour constraint: strange (u,d,s) quark matter shall be more stable than nuclear matter, so that selfbound quark stars dubbed strange stars can exist
Kepler line: mass shedding limit for 716 Hz (highest observed pulsar frequency)

- green region: allowed parameter space from maximum pulsar mass
- corrections from interactions are needed \((a_4 < 1)\) to be compatible with observations!
Add to a free gas of quarks terms from interaction, from pairing and from an vacuum energy:

\[
\Omega_{CFL} = \frac{6}{\pi^2} \int_0^\nu dp \frac{p^2}{p^2(p - \mu)} + \frac{3}{\pi^2} \int_0^\nu dp \frac{p^2}{\sqrt{p^2 + m_s^2} - \mu} \]

\[
+ (1 - a_4) \frac{3\mu^4}{4\pi^2} - \frac{3\Delta^2\mu^2}{\pi^2} + B_{\text{eff}}
\]

where \( \nu = 2\mu - \sqrt{\mu^2 - m_s^2/3} \).

- \( \Delta \): gap energy of the color-superconducting phase
  (normally \( \Delta \leq 100 \text{ MeV} \))
- fix strange quark mass to \( m_s = 100 \text{ MeV} \)
- set for simplicity \( a_4 = 0 \)
Quark Star Masses: effects of quark pairing

(Weissenborn, Sagert, Pagliara, Hempel, JSB 2011)

- two constraints on quark matter: 2-flavour and 3-flavour line
- green region: allowed parameter space from maximum pulsar mass
- a gap of at least $\Delta = 20 \text{ MeV}$ is needed to be compatible with observations
- pulsar masses above $1.9M_\odot$ start to constrain QCD parameters!
- additional interactions needed for pulsar masses well above $2.3M_\odot$
Hybrid Stars with a stiff nuclear EoS

- nuclear phase: relativistic mean field model with parameter set NL3 (fitted to properties of nuclei)
- match with Gibbs (lines) or Maxwell construction (shaded area)
- solid lines: pure quark matter cores, dashed lines: mixed phase cores
Hybrid Stars with a soft nuclear EoS

- Nuclear phase: relativistic mean field model with parameter set TM1 (fitted to properties of nuclei)
- Match with Gibbs (lines) or Maxwell construction (shaded area)
- Solid lines: pure quark matter cores, dashed lines: mixed phase cores
- No pure quark cores compatible with data for a soft nuclear EoS

(Weissenborn, Sagert, Pagliara, Hempel, JSB 2011)
Hybrid Stars with a NJL model

uses Nambu-Jona-Lasinio model for quark matter
matches to nuclear EoS with hyperons (RMF with set NL3)
2SC quark matter below green line
\( \delta = \frac{R_{CFL}}{R} \): amount of CFL quark matter

(Bonanno and Sedrakian 2011)
\[ p = \frac{1}{2\pi^2} \sum_{i=1}^{18} \int_0^\Lambda \frac{1}{2} k^2 |\epsilon_i| + 4K \sigma_u \sigma_d \sigma_s - \frac{1}{4G_D} \sum_{c=1}^{3} |\Delta_c|^2 \\
- 2G_S \sum_{\alpha=1}^{3} \sigma_{\alpha}^2 + \frac{1}{4G_V} \omega_0^2 + p_e \]

- use Nambu–Jona-Lasinio model for describing quark matter
- describes both dynamical quark masses (quark condensates \( \sigma \)) and the color-superconducting gaps \( \Delta \) (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 \( G_V \)
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, . . .)
QCD Phase Transition and Supernovae
Historical Notes:

- De Rujula 1987: May a supernova bang twice? (two neutrino peaks from SN1987A delayed by 5 hours)
- Hatsuda 1987: formation of a strange star within 1s!
- Gentile et al. 1993: hydro simulation with a phase transition (second shock wave, but no neutrinos included)
- Drago and Tambini 1999: prompt bounce by strange quark matter formation
- Nakazato, Sumiyoshi, Yamada 2008: SN simulation for $100\,M_\odot$ with phase transition (no second shock wave)
standard lore for the onset of the quark phase in core-collapse supernovae: during evolution of the proto-neutron star

timescale for quark matter to appear (see volume fraction $\chi$): typically $(5 - 20)$s (due to a large bag constant, $B^{1/4} > 180$ MeV!)

supernova collapse timescale: milliseconds (with SASI 600 ms?)

quark matter appears well after bounce?
quark matter appears at low density due to $\beta$-equilibrium for a bag constant of $B^{1/4} = 165$ MeV

low critical density for low $Y_p$ due to nuclear asymmetry energy

quark matter favoured at finite temperature
quark matter appears at low density due to $\beta$-equilibrium for a bag constant of $B^{1/4} = 165$ MeV

low critical density for low $Y_p$ due to nuclear asymmetry energy

quark matter favoured at finite temperature

production of quark matter in supernovae at bounce possible!
presence of quark matter can change drastically the mass-radius diagram

maximum mass: $1.56 M_\odot \ (B^{1/4} = 162 \text{ MeV})$, $1.5 M_\odot \ (B^{1/4} = 165 \text{ MeV})$
→ too low! need $\alpha_s$ corrections!
Check: Phase Transition for Heavy-Ion Collisions

(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
- no contradiction with heavy-ion data!
velocity profile of a supernova for different times (around 250ms)
formation of a core of pure quark matter produces a second shock wave
Implications for Supernovae – Explosion!

(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2009)

- velocity profile of a supernova for different times (around 250ms)
- formation of a core of pure quark matter produces a second shock wave
velocity profile of a supernova for different times (around 250ms)

formation of a core of pure quark matter produces a second shock wave

leads to an delayed explosion
Implications for Supernova – Neutrino-Signal!

- temporal profile of the emitted neutrinos out of the supernova
- thick lines: without, thin lines: with a phase transition
- pronounced second peak of anti-neutrinos due to the formation of quark matter
- peak location and height determined by the critical density and strength of the QCD phase transition

(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2009)
Supernova Explosion – Parameter dependence

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<th>Prog.</th>
<th>B</th>
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<th>$M_Q$</th>
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$^a$ moment of black hole formation  
$^b$ black hole formation before positive explosion energy is achieved

(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2009)

- supernova simulation runs for different parameters
- appearance of the quark core at $t_{pb} = 200$ to $500$ ms
- results ($t_{pb}$, baryonic mass and explosion energy) are significantly sensitive to the location of the QCD phase transition (bag constant)
- problem: so far explosion only for cases with too low a maximum mass!
Detection of neutrinos from a SN with SuperK (left) and IceCube (right)
mostly sensitive to antineutrinos by inverse $\beta$ decay reactions ($\bar{\nu}_e P \rightarrow n e^+$)
take spectrum from supernova simulation, SN at distance of 10 kpc
highly sensitive to second burst from QCD phase transition!
The Future: CBM@FAIR and NICA

(Klähn, Blaschke, Weber 2011)

- left: equation of state and flow constraints,
- right: compatible mass-radius relations and astrophysical constraints
- higher baryon densities achieved at higher bombarding energy
- probing densities beyond $2 - 3n_0$
Summary

• QCD phase transition can occur in the core of neutron stars
  ⇒ new family of compact stars possible, explosive phenomena

• transition can be present during a supernova, shortly after the first bounce
  ⇒ second shock forms, visible in a second peak in the (anti-)neutrino signal, gravitational waves (?), r-process nucleosynthesis (?) . . .

• to stimulate your fancies: color superconducting phase change transport properties – implications for SN neutrino spectra?
X-Ray burster EXO 0748–676 and Quark Matter

- analysis of Özel (Nature 2006): \( M \geq 2.10 \pm 0.28 M_\odot \) 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 rule out soft equations of state, not quark stars or hybrid stars!

- multiwavelength analysis of Pearson et al. (2006): data more consistent with \( M = 1.35 M_\odot \) than with \( M = 2.1 M_\odot \)
Fits to X-Ray Burster Spectra

(Suleimanov, Poutanen, Revnivtsev, Werner 2011)

- x-ray burster with photospheric radius expansion
- assume (color-corrected) black-body emission and Eddington flux at 'touch-down' (Ozel 2006): simple model fit fails above a certain distance!
- large correction from model atmosphere composition
Mass-Radius Constraints from X-Ray Burster and Binaries

(Steiner, Lattimer, Brown 2011)

- fit to three x-ray burster data with photospheric radius expansion and three quiescent x-ray binaries (from previous analysis)
- relax constraint at 'touch-down' to be on the surface \( r_{ph} \gg R \)
- strong constraint on radius relation (left: combined fit, right: separate fits)
isolated neutron star, pulses in x-rays

phase space resolved x-ray spectroscopy

fit to geometry of hot spot etc. including redshift $z$

resulting compactness: $(M/M_\odot)/(R/\text{km}) = 0.087 \pm 0.004$

indication for a stiff equation of state
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: $R_\infty = R/\sqrt{1 - 2GM/R} = 17 \text{ km (d/140 pc)}$
from parallax measurement: distance $d = 123(+11,-15)pc$
(Walter, Eisenbeiss, Lattimer, Kim, Hambaryan, Neuhaeuser 2011)
neutron star merger simulation with 3D smoothed particle hydro code using conformal flatness approximation

strong correlation with peak frequency in gravitational waves and neutron star radius rather insensitive to masses of neutron stars

measurable with advanced LIGO in a few years

(Bauswein and Janka, 2012)
Strangeness in Supernova Matter: Hyperons


- supernova matter for $Y_c = 0.4$ with constant entropy/baryon ratio S/B
- hyperon fraction at bounce $T \sim 20$ MeV: about 0.1%
- thermally produced strangeness, hyperons are in $\beta$-equilibrium!
Nucleation Timescales for strange quark matter


- nucleation of strange quark matter via fluctuations in strangeness
- timescales for different surface tensions and densities
  (quark EoS used: \( p = (1 - c) \mu_i^4 / (4\pi^2) \))
- bubble nucleation within 1 km\(^3\) within 100 ms for \( \sigma < 20 \text{ MeV fm}^{-2} \)
amplitude of gravitational wave signal from collapsing neutron stars at 10 kpc above sensitivity of present (LIGO, VIRGO) and well above future (Advanced LIGO) detector

- events in Virgo cluster (20 Mpc) needs probably third generation detectors
Phase transitions in neutron stars generate gravitational waves (blue band, for anisotropic neutrino emission: solid blue line)

background of such gravitational waves detectable with future space detectors!

signal larger than the one for conventional type II Supernovae (dashed line) and from inflation (dash-dotted lines)
Gravitational wave signals from hybrid stars

(Oechslin, Uryū, Pogosyan, Thielemann 2004)

- Fourier spectra of gravitational waves
- Increasing initial mass from top to bottom
- Solid line: neutron star, dashed line: hybrid star
- Different spectra for hybrid stars!