What can compact stars really tell us about dense QCD matter?

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Chair: Andreas Schmitt

David Blaschke  
(Wroclaw Univ., JINR Dubna)

Wynn Ho  
(Southampton Univ.)

Jürgen Schaffner-Bielich  
(Heidelberg Univ.)

Fiorella Burgio  
(INFN, Catania)

Josef Pochodzalla  
(Mainz Univ.)

Wolfram Weise  
(Munich, Tech. Univ.)
What can compact stars really tell us about dense QCD matter?

① Appearance of hyperons in NS matter
Strong effects on the maximum mass!
Need of more information on NY and YY interaction. Link to hypernuclei physics.

② Onset of quark matter
The transition to quark matter in NS looks likely, but the amount of quark matter depends on the quark matter model.

③ EoS of quark matter
The observation of large mass NS (above 2 solar mass) gives access to the quark matter EoS, which requires additional repulsion with respect to “naive” quark models. The observational data on NS can also be used to constrain parameters which eventually appear in quark phase models, e.g. the Field Correlator Method.

④ Interplay between RHIC, LHC data and NS observations.
How to link these two different regimes of density/temperature?
Observing Quark Matter in the Sky

Two different types of modification from high-density QCD matter

- equation of state, phase transition(s):
  - mass-radius relation (third family of compact stars?)
  - dynamics of core-collapse supernovae (second shock wave?)
  - proto-neutron star evolution (collapse to a black hole?)
  - neutron star merger (gravitational wave signal)

- transport properties:
  - bulk and shear viscosity (r-mode instability)
  - neutrino reactions (cooling of (proto-) neutron stars)

x-ray satellites (NuSTAR, eRosita, ATHENA?), optical (JWST), radio (SKA), gravitational wave (Advanced LIGO, eLISA/NGO?) and neutrino detectors (Super-K, IceCube)
Strange nuclear systems

**Relevance**
- Equation of state at high density
- Neutron star composition
  
  *If really no hyperons in NS, why?*
- Strange dibaryons – *to be or not to be?*

**Baryon-baryon interaction**
- charge symmetry breaking $N-N$, $Y-N$?
- Three baryon forces $N-N-N$, $Y-N-N$?
- Charge symmetry of 3B force?
- $Y-Y$ interaction?

**Need precision observables and theoretical tools with predictive power** for regimes where experimental information is not directly available

- **Scattering experiments with hyperons** feasible but difficult → JPARC, PANDA
- Precision ground state mass spectroscopy → MAMI
- Precision nuclear excited state spectroscopy → JPARC
- Double hypernuclei ground state decays → JPARC, PANDA
- Double hypernuclear excited state spectroscopy → PANDA
- $\Lambda$ production and $\Lambda\Lambda$ correlations in HI reactions → SIS18, ALICE, CBM...
- **Exotic systems (S=3)** in Heavy Ion Reactions → STAR, ALICE, CBM
- Precision nuclear many body calculations with realistic forces ($\chi$EFT) in SU3?
- Linking nuclear structure to Lattice QCD?
- QCD systems at high density? Short range B-B interaction? → LQCD?
What can compact stars really tell us about dense QCD matter?

Two-solar-mass neutron star sets strong constraints:

- “Stiff” equation-of-state required

- “Conventional” EoS works best
  (nuclear physics + effective field theory + advanced many-body methods)

- Central baryon densities in neutron stars are not extreme
  (do not exceed 3 - 4 times the density of normal nuclear matter)

- Change of paradigm?
  “Exotic” forms of matter (kaon condensates, quark matter with first-order phase transition, . . .) unlikely to exist in n-star cores?

- Strangeness and hyperons in dense baryonic matter?
  Small admixtures still possible, but only with strongly repulsive short-range hyperon-nucleon and hyperon-hyperon interactions (see Lattice QCD)
J1614-2230 Shapiro delay measurement: $M = 1.97 \pm 0.04 \, M_{\odot}$

**NEUTRON STAR MATTER**

Equation of State

- Low-density (crust) + ChEFT (FKW)
- Constrained extrapolation (polytropes)
- Akmal, Pandharipande, Ravenhall (1998)

**NEUTRON STAR**

Density Profile

- T. Hell et al. (2012)
- Core density less than 4 times $\rho_0$ (nucl. matter)

- $M = 2 \, M_\odot$
- $R = 11.9 \, \text{km}$

Nuclear physics constraints $M(R)$

Astrophysics constraints $\epsilon(P)$
Roundtable: Compact Star Constraints on Dense Matter

1. Observational evidence for quark/strange stars or exotic matter
   × RX J1856.5-3754 – small radius but blackbody
   × Cassiopeia A – small radius but blackbody or H atmosphere
   ? PSR J1614-2230 – two solar mass is not too high
   ? 3C 58 and CTA 1 – too cold for standard neutrino cooling

2. Extremes of dense nuclear matter
   • state of matter: equation of state, core composition, symmetry energy
   • high temperature superfluidity and superconductivity

3. (Distinct) observational signatures of exotic matter or stars
   ? mass-radius
   • supernova explosion and elemental abundances
   • pulsar glitches
   • stellar oscillation modes, ie r-modes
   • ?
   • ?
Implications of PSR J1614-2230 (Demorest) & CasA for structure and cooling of compact stars

High maximum mass → stiff EoS
Stiffer EoS → lower central density

Modern cooling theories are crucially sensitive to density dependence of emissivities etc. → pairing gaps!

Quark matter cores can accelerate the cooling, but they exist only for EoS with low critical densities $n_c \sim 3-4\, n_0$

Masquerade problem of phase transition constructions ! Unified description of quark-hadron matter needed ...

Lattimer & Prakash, arxiv:1012.3208

Stiffer nuclear EoS → lower central density → slower cooling → pairing gaps important

Sufficiently stiff hadronic EoS (APR-based):
Demorest & CasA both: hadron or hybrid star
\[ M_{\text{CasA}} = 1.463 \, M_\odot \quad M_{\text{CasA}} = 1.640 \, M_\odot \]

Stiffer hadronic EoS (DD2-based): Hadronic star cools too slow (unless gaps changed), hybrid OK
\[ M_{\text{CasA}} = 2.426 \, M_\odot \quad M_{\text{CasA}} = 1.674 \, M_\odot \]
Discussion

• What does the $M = 1.97 \, M_\odot$ star tell us?

• What does the cooling curve of Cas A tell us?

• Baryon-baryon interactions (and baryonic superfluidity):
  
  What can we learn...
  
  ... from compact stars?
  
  ... from experiments?
  
  ... from theory?

• Deconfined quark matter in a compact star?
  
  – How to distinguish from nuclear matter?
  
  – Color-superconducting quark matter?
  
  – Are quark stars conceivable?
Outlook

• What new input would we like to have from theory?

• What compact star observables would we like to measure (more precisely)?