Observational Signatures of Strange Stars

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Background

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2 Oscillations

3 Gravitational Waves

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The Strange Matter Hypothesis

The ground state of matter might not be ^{56}Fe, but a bulk mixture of up, down, and strange quarks.

Properties of Strange Matter

- Absolutely stable for baryon numbers of 10^2–10^{57}
- If $\epsilon_F > m_s$, up and down quarks will weakly convert to strange quarks, forming a 3-flavor Fermi gas
- PDG: $m_s \in$ 70-130 MeV
- Electrons ensure charge neutrality

Strange Star Formation

Strange matter is unstable for low baryon number ($\lesssim 100$), so spontaneous conversion of nuclei requires ~ 100 simultaneous weak interactions.

Formation/Conversion Mechanisms

- Intermediate states at high density (2-flavor QM, Λs)
- Neutrino sparking (depends on $s, \bar{s}$ balance)
- Strangelet seeding ($A \gtrsim 10^{39}$ if older than 1 month)

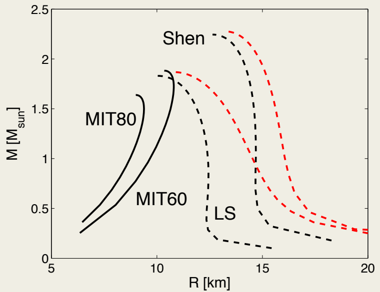
Strange Star Structure

SSs are composed of a SQM core with either a bare surface, a thin nuclear crust, or a "nugget crust."

Crust Properties

- Low-mass ($\sim 10^{-5} M_{\odot}$)
- Nuclear: nuclei repulsed by E-field; limited in size because high pressure produces free neutrons, absorbed by core
- Nugget: lattice of SQM nuggets in electron background

Mass-Radius Relation



[Bauswein, Oechslin, & Janka]

- Opposite *M*-*R* relationship from NSs
- More compact (*M*/*R*) than NSs
- Lower maximum mass than NSs
- Mass, radius inferred via seismic modes
- Possible overlap with NS configuration space

Oscillations

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SGR Observations

QPOs in giant flares from magnetars may reflect seismic vibrations of compact star crusts.

Giant Flares

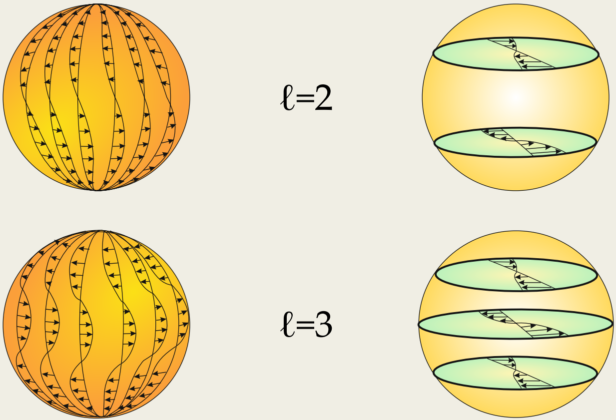
- Observatories: RXTE and RHESSI
- Luminosities: 10^{44}–10^{46} erg/s
- SGR 1900+14 (1998): 28, 53, 84, 155 Hz
- SGR 1806−20 (2004): 18, 26, 30, 92, 150, 625 Hz

Modeling Seismic Oscillations

Assumptions (Watts & Reddy)

- Plane-parallel (slab) geometry ($P/\rho g \ll R$)
- Constant, uniform B-field
- No coupling to core (global modes expected for magnetars, but frequencies might be similar to crust-only case)
- Pure toroidal shear modes (incompressible, no radial displacement) with periodic time dependence ($e^{i\omega t}$)

Global Torsional Modes



[Bastrukov et al.]

Mode Assignments

Frequencies of $n = 0$ modes scale as $\sqrt{(l+2)(l-1)}$, requiring a fundamental of $\sim 30\,\mathrm{Hz}$ to fit mode sequence.

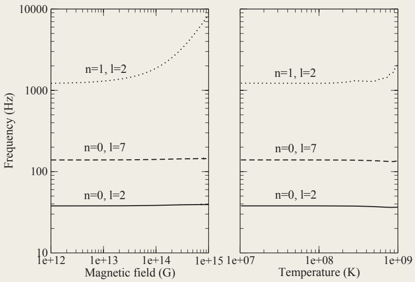
- Assume lower frequencies are from global Alfvén modes
- Assume highest frequencies are from $n = 1$ modes (one radial node)

NS models match observations very well.

Thin Nuclear Crust

Fundamental too high for reasonable SS masses, overtone too high for magnetar B-fields.

- $n = 0$ modes independent of B, T, ΔR
- $n = 1$ modes strongly dependent on B
- For $n = 1$, ν increases as ΔR decreases
- As T increases, ΔR decreases (melting)

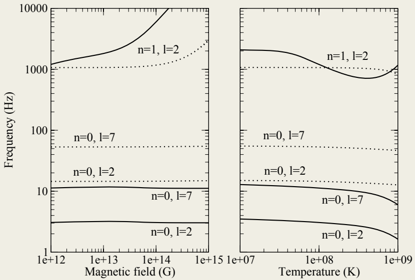


[Watts & Reddy]

Nugget Crust

Fundamental now too low, overtone still too high.

- Dotted lines assume $m_s = 250\,\text{MeV}$, which is probably too large
- Overtone frequency is very T-dependent, yet QPOs have long coherence times



[Watts & Reddy]

Limitations

- Assumes constant Newtonian gravity (current relativistic studies lack B-fields)
- Neglects B-field configuration, global geometry
- Assumes global modes will mimic axial crust modes
- Presupposes seismic origin of QPOs

Gravitational Waves

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Numerical Simulations

Eulerian (FD, Spectral)

- Evolve density, velocity on a fixed grid
- Limited spatial resolution

Lagrangian (SPH)

- Evolve coordinates of comoving "particles"
- Limited mass resolution

Conformal Flatness

Currently no fully (general) relativistic SPH code. Can approximate GR by assuming spatial metric is conformally flat.

Motivation

- Reduce number of DoFs
  - Newtonian: $\nabla\Phi$
  - GR: $g_{\mu\nu} \rightarrow \alpha, \beta^i, \gamma_{ij}$
  - CF: $\gamma_{ij} = \psi^4 \delta_{ij}$

Limitations

- No gravitational radiation (waves, backreaction)
- Cannot treat black holes

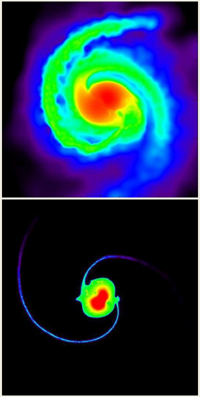
Qualitative Differences

Neutron Stars

- Dilute halo/torus
- Higher mass prompt collapse

Strange Stars

- Sharp surface
- Thin tidal arms
- Thin, fragmented disk



[Bauswein, Oechslin, & Janka]

Frequency Signatures

GW frequencies are functions of compactness (M/R).

- SSs have higher maximum inspiral frequency
- SSs have higher ringdown frequency
- LS, MIT60 can be similarly compact and thus indistinguishable below 1 kHz
- Future detectors (Einstein Telescope) will be more sensitive above 1 kHz

Luminosity Signatures

When frequency measurements cannot distinguish EoSs, luminosity characteristics potentially can, even without waveform models.

- $\Delta E_{\mathrm{pm}} / \Delta E_{\mathrm{in}}$ higher for SSs than for NSs
- SS remnant radiates energy away faster than NS
- Frequency "gap" before peak more prominent with LS EoS than MIT60

Limitations / Future Directions

- Conformal flatness
- No SS crust
- No B-fields
- Simplified EoS
- Limited mass resolution ($10^{-5}M_{\odot}$)
- Should also consider SS-BH mergers

Strangelets

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Significance

- Sufficient strangelet pollution would convert all NSs to SSs – a single fragment of SQM reaching a NS core converts the whole star (Ice-9).
- Even if SMH is true, NSs may not convert to SSs on their own. Therefore, NSs and SSs could coexist if strangelet flux is low enough.
- If strangelet ejection in mergers depends on EoS, then the observed strangelet flux could constrain QCD.

Origins

- Asymmetric mergers (tidal tails)
- Core-collapse supernovae
- Crust nugget ejection by E-fields
- Particle accelerators

Note

BH-SS mergers and SS-SS mergers that promptly collapse to a BH do not eject strangelets.

Results

An unambiguous detection of a NS would not rule out the existence of SSs.

- Mass ejected depends strongly on MIT bag constant
- For $B = 60\,\mathrm{MeV\,fm^{-3}}$, population-averaged ejecta mass is $\sim 10^{-4} M_\odot$ per compact star merger
- For $B = 80\,\mathrm{MeV\,fm^{-3}}$, no strangelets are ejected

Limitations

- Same simplifications as GW simulations
- Lack of crust makes fate of crust nuggets uncertain

Direct Detection

Past terrestrial and accelerator experiments have neither found nor ruled out SQM.

Alpha Magnetic Spectrometer (AMS-02)

- Launch date: July 29, 2010
- To be installed on ISS
- Measures charge-to-mass ratio of cosmic rays (no nucleus has $Z/A < 0.3$)

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Present and Future

Currently, QPOs disfavor the SMH, but there is no conclusive evidence on either side. Observations in the next 5 years should tip the balance one way or the other.

Timeline

- Now: Enhanced LIGO, LHC, Fermi
- July 29, 2010: AMS-02 launch
- 2014: Advanced LIGO

The End

Questions?

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