Two types of glitches in a solid quark star model

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Outline

Motivation
- Challenges to the theories on pulsar glitches

The model
- Bulk-variable starquake
- Bulk-invariable starquake

The result
- Two types of starquakes corresponds to two types of glitches in observation

D & C
- Discussion
- Conclusion

2015/1/13
Pulsar = Neutron Star??

- Wiki tells us “Pulsar is highly magnetized rotating Neutron star”. But not exactly!

Up: An imaginary model of magnetized rotator model for ‘pulsar’

Twinkle, twinkle, little star
How I wonder what you are

Down: An observed profile in the radio telescope, which is ‘a pulsar’.
Pulsar ≠ Neutron star

• Different EoS models for pulsars (Xu 2014)

Hadron star: quarks confined gravity-bound
Quark star: quarks de-confined self-bound on surface
Hybrid/mixed star: quarks de-con./con. gravity-bound
Quark-cluster star: quarks localized self-bound on surface

conventional Neutron Star
light flavour symmetry: Strange Star
Puzzling Pulsar Inside: EoS...

- Nucleus and Quark-cluster star: differences and similarities

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Quark-cluster star</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron</td>
<td>Proton</td>
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</table>

**Self-bound**: by strong int.

- $l \sim \text{fm}$: electrons outside
- $l > \lambda_e$: electrons inside

- 2-flavour symmetry: isospin
- 3-flavour symmetry: strangeness

- Light clusters: $p(uud)$, $n(udd)$
- Heavy clusters: 6(H), 9, 12, 18

- Quantum gas/liquid
- Solid condensed matter at low-$T$

Xu, 2014 Presentation in CSQCD IV
Neutron Star vs. Quark Star

• From observational point of views:

  ➢ The absence of spectrum lines in pulsar spectrums
    Neutron Star: crust with mostly iron atoms. remark: 1E 1207.4-5209
    Quark Star: bare, no atomic structure
  ➢ The binding energy
    Neutron Star: gravity/em bound on the surface
    Quark Star: self bound on the surface
  ➢ The iron core collapse model of Type II supernova
    Quark Star: optically thin for neutrino
  ➢ Glitches
    to be discussed today...
Pulsar glitch

- An important phenomenon to help us understand the EoS of dense matter.
- Normal glitch / Slow glitch / Anti glitch ...
- The mechanism is still a matter of debate.

Glitch: sudden spin up of pulsars.
First observed on Vela pulsar (1969)
A 195ns decrease in the spin period was detected by Radhakrishnan & Manchester
Pulsar Glitch

The quadratic signature of the timing residuals during the glitch (glitch detectors)

Espinoza et al. 2012

Observational parameters of pulsar glitch
Pulsar glitch

Two types of glitches in a solid quark star model

**Challenge 1**
Radiative quiet glitches of Vela pulsar
\[ \frac{\delta \nu}{\nu} \sim 10^{-6} \]
negligible energy release in observations
(Helfand et al. 2001)

**Challenge 2**
Radiative loud glitches of AXP/SGRs
\[ \sim< \frac{\delta \nu}{\nu} \sim 10^{-6} \]
X-ray bursts & radiative anomaly
(Dip & Kaspi 2014)

As the development of glitch observations, more and more challenges to the previous theories remain to be solved.
Starquake models in Solid quark stars

Quakes in solid quark stars
Zhou A Z, et al. 2004 Astro-Particle Journal

Pulsar slow glitches in a solid quark star model
Peng & Xu 2008 MNRAS

Two types of glitches in a solid quark star model
The model – bulk variable starquake

The M-R relation for solid quark stars

Physical scenario
Self-bound (low mass) $M \sim R^3$
Gravity-bound (high mass) $M \uparrow R \downarrow$

Exceeding the $R_m$ by accretion will make a solid star accumulate elastic energy and induce a starquake which can be seen as a global reduce of the radius

Guo et al. 2014
Bulk variable starquake

Type II starquake can be treated as a global decrease in \( R \).

The main parameter in a Type II starquake: \( \delta R \)

\[ \delta E = \left( \frac{3GM^2}{5R} - \frac{L^2}{I} \right) \frac{\delta R}{R} \]

- Gravitational energy of a spheroid + kinetic energy
- Conservation of the angular momentum

\[ \frac{\delta \omega}{\omega} = -\frac{\delta I}{I} = -\frac{2\delta R}{R} \]

- The moment of inertia of a spheroid

Result

\[ |\delta E| = \frac{3GM^2 \delta \nu}{10R} \frac{\delta \nu}{\nu} \sim 10^{47} \text{ erg} \left( \frac{M}{1.4M_\odot} \right)^2 \left( \frac{R}{10^6 \text{ cm}} \right)^{-1} \left( \frac{\delta \nu}{\nu} / 10^{-6} \right) \]

- The gravitational energy is much larger than the kinetic energy

two types of glitches in a solid quark star model

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The model – bulk invariable starquake

The stable shape of a rotating star will be ellipsoid instead of spheroid.

\[ E_{\text{total}} = E_k + E_g + E_{el} = E_0 + \frac{L^2}{2I} + A\varepsilon^2 + B(\varepsilon - \varepsilon_0)^2. \]

The key parameter in a Type I starquake: \( \varepsilon = (I - I_0)/I_0 \)

For a rotating star with certain density \( \rho \), the relation between ellipticity and angular velocity is

\[ \Omega^2 = 2\pi G\rho\left[\frac{\sqrt{1-e^2}}{e^3}(3-2e^2)\sin^{-1} e - \frac{3(1-e^2)}{e^2}\right] \]

Remark: Jacobi ellipsoid for extremely fast spinning pulsars
The model – bulk invariable starquake

The evolution between two glitches

\[ t=0 \]
Solidification or the end of previous glitch

- No elastic energy

\[ t=0 \sim t=t_1 \]
Normal spin down phase

- The difference between \( \varepsilon \) and \( \varepsilon_{mac} \)
- Elastic energy accumulated

\[ t=t_1-0 \]
The glitch epoch

- Elastic energy reaches the critical value

\[ t=t_1+0 \]
Glitch

- The elastic energy is released and the pulsar can be treated as fluid
- The shape changes and a new equilibrium is set up at the end of the glitch
The model – bulk invariable starquake

\[ \delta E \text{ w.r.t } \delta \varepsilon \]
\[ E_{\text{ela}} < \frac{B}{2(A+B)} |\delta E_k| (\varepsilon_0 - \varepsilon_1) \]

- The condition of quasi-equilibria during the normal spin down: \( \frac{\partial E}{\partial \varepsilon} = 0 \)

\[ \frac{\delta \Omega}{\Omega} = -\frac{\delta I}{I} = -\frac{\delta \varepsilon}{1 + \varepsilon} \]

\[ \delta \varepsilon \ll \varepsilon \ll 1 \]
- Conservation of angular momentum

\[ \varepsilon_1 - \varepsilon_0 = -\frac{A \delta \Omega}{B \Omega} \]
- The evolution of \( \varepsilon \)

\[ \delta E \sim 4 \times 10^{36} \text{ erg} \left( \frac{t}{10^6 \text{ s}} \right) \left( \frac{\delta \nu}{\nu} / 10^{-6} \right) \]

- Note that the spin down power and interval between two glitches also affect the energy released
- The observational data of Vela is applied
The result

EoS by
Lai & Xu 2009

Parameters set to fit the observation of Vela
The result

Helfand et al. 2001

\[ \Omega \]

Contributes to energy release but not the spin up effect

Contributes to energy release as well as the spin up effect

\[ 4 \times 10^{36} / (3 \times 10^6) = 1.3 \times 10^{30} \text{ erg/s} \]

Zhou et al. 2014

two types of glitches in a solid quark star model
Discussion

- AXP/SGRs: observational hints of accretion (Wang et al. 2006)
  slow rotators (~10s)
  fall back disc + quark star model (Tong & Xu 2011)
  implies Type II

- Vela like pulsars: no hints for accretion
  fast rotators (~<1s)
  implies Type I

- Possible mechanism for Anti-glitches?

\[ \text{two types of glitches in a solid quark star model} \]
Discussion

• The neutron star crust cracking model (Baym & Pines 1976) failed to explain the glitch on Vela because of the short intervals (~1 month, for largest glitches ~1 year)

$$t_{\text{interval}} = \frac{2(A + B) \left( \frac{A}{B} \right) \left( \frac{\Delta \Omega}{\Omega} \right)}{I \Omega \dot{\Omega}}.$$

For quark stars it’s no longer a problem because the entire star is in solid state, what matters is the initial ellipticity when the pulsar became solid.

Suggesting that the initial ellipticity for Vela is 0.01 (P~4ms), there could be 10^4 glitches with $\Delta \Omega/\Omega \sim 10^{-6}$ during the lifetime of Vela, which is coincident with the observation.
Conclusion

• There should be two types of starquakes in a solid quark star model: Type I (bulk invariable) & Type II (bulk variable)
• We figure out the energy release of the two types of starquakes, and find out that Type II starquake is much more energetic than Type I.
• Considering other observational features, we think that the two types of glitches in a solid quark star model can account for the two types of glitches in observation.
• Thanks!