Solid Bare Strange Quark Stars

Renxin Xu

School of Physics, Peking University, Beijing 100871, China

Abstract. The reason, we need three terms of ‘strange’, ‘bare’, and ‘solid’ before quark stars, is presented concisely though some fundamental issues are not certain. Observations favoring these stars are introduced.

1. Hadronic stability: why strange?

Strange (quark) stars are quark stars with strangeness. What’s strangeness? Some peculiar cosmic ray events were discovered in 1947, with a strange nature of “being produced rapidly in pairs, but decaying slowly independently”. These particles were thus called “strange” particles, and a new quantum number, “strangeness” ($S$), was introduced. In the standard model of particle physics, it is known that the strangeness represents actually the existence of a new kind of quarks, the strange quark, $s$. In this model, a neutron is composed of three valence quarks (one up and two down quarks), sea quark pairs ($u\bar{u}, d\bar{d}, s\bar{s}$), and gluons, i.e., $n = \{udd, u\bar{u}d\bar{u}, ds\bar{s}, g\}$; a proton $p = \{uud, u\bar{u}d\bar{u}, ss\bar{s}, g\}$. A neutron (or proton) does not have strangeness because of $S(s) = -1$ and $S(\bar{s}) = 1$. Hadrons with three valence quarks are called baryons (e.g., protons and neutrons).

And then, how to produce strangeness in a star if it is the remains of an evolved main sequent star? Atomic nuclei in normal stars are made only of the two nucleons (proton and neutron), without strangeness. Two scenarios are outlined for creating strangeness in dense stellar matter. (1) The first one is in the hadronic degrees of freedom (i.e., hadrons as quasiparticles). Hyperons are baryons with strangeness, in which one or more valence quarks are replaced by $s$-quarks (e.g., $\Lambda = \{usd\}, \Xi = \{sss\}$). Nucleons with high enough Fermi energy (e.g., in traditional neutron stars) may decay into hyperons by weak interactions. Such nuclear matter with strangeness is called as strange hadronic matter, and the corresponding neutron stars are named as hyperon stars. The study of hypernuclei may help us to understand the hyperon stars. (2) The second one is in the quark degrees. Suppose that quarks within hadrons are deconfined in high density (to form quark-gluon plasma, or called quark matter), one may expect that 2-flavor quark matter (i.e., $u$ and $d$) appears in “neutron” stars. However, in case of $s$-quark mass being smaller than the Fermi energy of $u$- and $d$-quarks, the system may become more stable via weak-interaction, decaying into 3-flavor quark matter. A further radical speculation is that bulk 3-flavor quark matter is absolutely stable (the Bodmer-Witten’s conjecture); strange stars (e.g., Xu 2002a) are accordingly made of such strange quark matter (SQM) with nearly equal numbers of the light quarks. Note: an SQM core and outer nuclear matter may coexist over macroscopic scale if bulk SQM is metastable (mixed stars).

And then, can hadrons (e.g., neutrons) in “neutron” stars be deconfined? The underlying theory of the interaction between quarks is believed to be quan-
tum chromodynamics (QCD), based on which it is proved that the interaction is asymptotically free in the smaller scale (another property of QCD could be color confinement in the larger scale, which has not been proved yet). Short distance on average between quarks is possible by two methods: (a) creating virtual quark pairs in relativistic heavy ion collisions, (b) crowding hadrons in compact stars. The former is of temperature-dominated, and the later baryon-density-dominated. Therefore, possible quark-deconfinement in compact stars might be a straightforward consequence of asymptotic freedom.

In summary, the exist of strange stars (SSs), a special kind of quark stars, could be quite natural if bulk SQM is an absolutely stable state of 3-flavor color interaction system, though heavy quark (charm, top, and bottom quarks) degrees could be excited if the chemical potential is much high (e.g., in an SS core where the density is very high). It is still not certain that pulsar-like stars observed are neutron or strange stars. No solid evidence for pulsars being neutron stars (NSs) yet (though many authors believe this conventionally)!

2. Formation and evolution: why bare?

Because of the significant mass differences between s- and u- (or d-) quarks, electrons in SQM maintain global charge neutrality. The electrons occupy a larger space ($\sim 10^8$ fm in radius) than that of quarks since the electromagnetic interaction is weaker than the color one. This results in a strong magnetic field ($\sim 10^{17}$ V/cm) just above the quark surface. The field could repulse (or support) positively charged nuclei, and a crust with mass $\sim 10^{-5} M_\odot$ ($\sim 10^2$ m thickness) may cover the SQM. No difference between the surfaces of crusted SSs and NSs.

In case of existence of SSs, radio pulsars were not supposed to be bare SSs (BSSs) until Xu & Qiao (1998) addressed that BSSs can do as radio pulsars, with 3 advantages. Can the quark surface be exposed to the cosmos? If can, the quark surface could be used to identify an SS (Xu 2002b). (1) A crust can hardly survive the detonation flame during a combustion of nuclear matter into quark matter, because of rapid energy release and high temperature. (2) Unless the spin period is $> 10^3$ s and the accretion rate is $> \text{the Eddington one}$, an isolate SS could not be covered by a crust through accretion during its lifetime.

3. Their astrophysical appearances: why solid?

Condensation in momentum space (e.g., 2SC, CFL, LOFF states) is currently focused on in the study of quark matter with high density but low temperature. However, can condensation in position space occur? No such a competition (i.e., condensation in momentum vs. position spaces) happens in the electric superconductivity due to the strong Coulomb repulsion between electrons.

Quantum effects dominate in an ideal gas if the thermal de Broglie wavelength is larger than the mean distance between particles, but the case is different if strong interactions participate. The interaction may favor a condensation in position space (Xu 2003), which results in the formation of $n$-quark clusters in SQM (Note: these clusters are not bag-like color singlet hadrons; if so, the Bodmer-Witten’s conjecture is violated). The mean distance between $n$-quark clusters is $l \sim \left[n/(3n_b)\right]^{1/3}$ for SQM with density $n_b$. The distance $l \sim 1$ fm for $n = 1$ and $n_b = 2n_0$, where $n_0 = 0.16$ baryons per fm$^3$ is the nuclear saturation density. The interaction between quark clusters could be of a well potential, the depth of which should be $V_0 > \sqrt{(hc/\lambda)^2 + mc^2} - mc^2$, with $m$ the mass
of the clusters, in order to describe classically the cluster gas. Furthermore, if the thermal excitation is not enough, \( \sqrt{(hc/l)^2 + m^2c^4 - mc^2 + kT} \ll V_0 \), with \( T \) the temperature, the clusters might be localized to form a solid state. In the non-relativistic (NR) approximation, this means \( h^2/(2ml^2) + kT \ll V_0 \). Assuming the interaction is of Lennard-Jones potential, \( V(r) = -A/r^6 + B/r^{12} \), we have \( l = (2B/A)^{1/6} \) and \( V_0 = -V(l) = A^2/(4B) \). Therefore the condition for a solid state of SQM in the NR case is \( A^2/(4B) - h^2/(2m)(A/2B)^{1/3} - kT \gg 1 \).

Recent experimental evidence for multi-quark \( (n > 3) \) particles (e.g., Bai et al. 2003), although still not being understood in QCD (e.g., Jaffe & Wilczek 2003), may increase the possibility of quark clustering in SQM. These multiquark hadrons may decay rapidly by strong interaction; nonetheless, such clusters could be stable in SSs since their decay into hadrons would be suppressed or forbidden if the Bodmer-Witten’s conjecture is correct.

Actually, there may be a few observational hints of such a solid quark state.  

**Thermal spectra without atomic features** — Atomic lines are not detected definitely yet in the thermal radiation (Xu 2002c). It is natural to understand the thermal spectra observed in a model of SSs with solid quark surfaces, where the thermal radiation could be analogous to that of metals, for RXJ1856 (Zhang et al. 2003) as well as for other sources (Zhu et al. 2003, in preparation).

There are, in fact, some efforts to understand the thermal spectra in the conventional model of NS atmospheres. (1) The featureless spectra was suggested to be an indication of the vacuum polarization effect (Ho & Lai 3002), but a satisfactory fit is not done in the model with the inclusion of the polarization effect. (2) A hypothetical plasma phase condensation transition was suggested (Lai & Salpeter 1997) for NS atmospheres with high \( B \) or low \( T \), and was applied to interpret the featureless thermal spectrum of RXJ1856 (Turolla, Zane & Drake 2003). However a consistent study of the phase transition in thermodynamics is still not done yet. (3) Rapid rotating of an NS may smear a spectral line, but such an NS may hardly become radio “death” (i.e., below death lines). Additionally, a problem could be inherent in all of these efforts: *How to calm down the magnetospheric activities* (e.g., AXP/SGR-like persistent and burst X-ray emission, radio emission due to pair-plasma instabilities, etc.) for such an NS with strong field or high spin frequency?

**Pulsar glitching and free-precession** — The current model for glitches involves neutron superfluid vertex pinning and the consequent fluid dynamics. However, the pinning should be much weaker than predicted by the model at least for two radio pulsars (PSR B1828-11 and PSR B1642-03), otherwise the vortex pinning will damp out the precession on timescales being much smaller than observed. In addition the picture, that an NS core containing coexisting neutron vertices and proton flux tubes, is also inconsistent with observations of freely precessing pulsars (Link 2003). Theoretically, a definitive conclusion on the nature of vertex pinning has not been reached yet due to various uncertainties in the microscopic physics. This discrepancy could be circumvented if radio pulsars are solid: no damping in free-precession of solid stars, and glitches reflecting the behaviors of global starquakes. The stresses, which trigger a starquake, develop due to the spindown or, possibly, to the frame-dragging effect.

The global starquake can also results in an exponential recovery of post-glitches. For a solid star, the angular frequency \( \Omega(t) \) and the moment of inertia...
$I(t)$, as functions of time $t$, are governed by $\{d(I\Omega)/dt = -\alpha, \dot{I} = -\kappa(I - I_0), I_0 = I_0(\Omega)\}$, where $\alpha$ is the external braking torque which is known for a star with certain magnetic momentum, $I_0$ is the inertia moment of the star in force-free equilibrium (i.e., no stress there), and the recovery of the inertial moment $\dot{I}$ is assumed to be at a rate being proportional to $(I - I_0)$. These equations are closed if the function $I_0(\Omega)$ is given, which can be well approximated by calculating the Maclaurin configurations since the density of an SS with mass $< 1.4M_\odot$ is almost uniform. If we temporarily neglect $\alpha$, $I_0$ is a constant. One then has $\delta I \equiv I - I_0 = -\Delta I \exp[-\kappa t]$ from the second equation, if a glitch occurs at $t = 0$, with $\Delta I$ the initial departure of inertia moment after the glitch (Note: $I(0) < I_0$). Therefore we have a glitch recover behavior of the form $\Omega(t) - \Omega(0) \sim \exp[-\kappa t]$, the postglitch relaxation observed. It is worth noting that the superfluid vortex pinning and unpinning could also work during a starquake if, besides quark-clusters localized, superfluid free quarks exist too.

**Others** — (1) Pulsars with submillisecond spin periods? Rotating fluid stars are subject to $r$-mode instability, which results in temperature-dependent minimum spin periods for SSs (Madsen 2000), but a solid star can spin more fast. Solid SSs can be identified if discovering pulsar spin frequency beyond the $r$-mode critical one. (2) Starquake-induced magnetic reconnection or the strange planet’s collision could be responsible to the bursting X-ray radiation of AXP/SGRs, while propeller accretion results in their persistent X-ray emission.

4. **Conclusions**

The time for “neutron” star study hasn’t been passed although it’s been over 70 years since the related idea appeared. Such a kind of compact stars may not just be boring big “nuclei”, but could be composed by matter of a new state — quark-gluon plasma. Recent observations challenge the conventional NS models, and should reveal valuable information of the quark matter state.

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