Neutron Stars and Pulsars: Challenges and Opportunities after 80 years
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H-cluster stars

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Abstract. The study of dense matter at ultra-high density has a very long history, which is meaningful for us to understand not only cosmic events in extreme circumstances but also fundamental laws of physics. In compact stars at only a few nuclear densities but low temperature, quarks could be interacting strongly with each other. That might produce quarks grouped in clusters, although the hypothetical quark-clusters in cold dense matter have not been confirmed due to the lack of both theoretical and experimental evidence. A so-called H-cluster matter is proposed in this paper as the nature of dense matter in reality.

Motivated by recent lattice QCD simulations of the H-dibaryons (with structure *uuddss*), we are therefore considering here a possible kind of quark-clusters, H-clusters, that could emerge inside compact stars during their initial cooling, as the dominant components inside (the degree of freedom could then be H-clusters there). We study the stars composed of H-clusters, i.e., H-cluster stars, and derive the dependence of their maximum mass on the in-medium stiffening effect, showing that the maximum mass could be well above 2 $M_\odot$ as observed and that the resultant mass-radius relation fits the measurement of the rapid burster under reasonable parameters. Besides a general understanding of different manifestations of compact stars, we expect further observational and experimental tests for the H-cluster stars in the future.

Keywords. pulsars: general, stars: neutron, equation of state

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1. Introduction

Compact objects, especially at density as high as nuclear matter density, are recognized by astronomers and physicists as a unique window on the relations between fundamental particle physics and astrophysics. Above the saturated nuclear matter density, ρ_0, the state of matter is still far from certain, whereas it is essential for the exploration of the nature of pulsars. In cold quark matter at realistic baryon densities of compact stars ($\rho \sim 2 - 10\rho_0$), the energy scale is far from the region where the asymptotic freedom approximation could apply. In this case, the interaction energy between quarks could be comparable to the Fermi energy, so that the the ground state of realistic quark matter might not be that of Fermi gas (see a discussion given in Xu 2003, 2010). It is then reasonable to infer that quarks could be coupled strongly also in the interior of quark stars, which could make quarks condensate in position space, to form quark clusters. The resulting quark stars could then be actually "quark-cluster stars".

Quark clusters may be analogized to hadrons. In our previous work about the quark-clusters stars, we first proposed a general form of equation of state, the polytropic model, to describe the clustering quark matter (Lai & Xu 2009a). Then we took the number of quarks inside each quark-cluster N_q as a free parameter, applying the Lennard-Jones interaction to model the inter-cluster potential (Lai & Xu 2009b, 2011). Here we specify the quark-clusters, under the light flavor symmetry, to be H-clusters (Lai *et al.* 2011).

2. In-medium stiffening

We suppose that the in-medium stiffening, i.e. the so called Brown-Rho scaling (Brown *et al.* 1991, Brown & Rho 2004), holds for nucleons, mesons and H-dibaryons, with the same coefficient of scaling α_{BR},

$$m_n^*/m_n = m_M^*/m_M = 1 - \alpha_{BR}\frac{n_n}{n_0}, \qquad m_H^*/m_H = 1 - \alpha_{BR}\frac{n}{n_0}, \tag{2.1}$$

where n_0 denotes the number density of saturated nuclear matter, n_n and n denote the nucleon number density and H-dibaryon number density, m_n and m_M denote the mass of neutrons and mesons, and the masses with and without asterisks stand for in-medium values and free-space values respectively. The decreasing of the mass of H-dibaryons with increasing densities could be equivalent to the increasing of binding energy of H-dibaryons, which makes H-clusters to be more stable.

3. Equation of state and mass-radius curves of H-cluster stars

The interaction between H-clusters has been studied under the Yukawa potential with σ and ω coupling (Faessler *et al.* 1997),

$$V(r) = \frac{g_{\omega H}^2}{4\pi}\frac{e^{-m_\omega^* r}}{r} - \frac{g_{\sigma H}^2}{4\pi}\frac{e^{-m_\sigma^* r}}{r}, \tag{3.1}$$

where $g_{\omega H}$ and $g_{\sigma H}$ are the coupling constants of H-clusters and meson fields. Assuming the localized H-clusters form the simple-cubic structure, we can get the interaction energy density $\epsilon_I \propto n \cdot V$, and then we can get the pressure $P = n^2 \frac{d}{dn}\left(\frac{\epsilon}{n}\right)$, where the total energy density is $\epsilon = \epsilon_I + m_H^* \cdot n$. By this way, we can derive the equation of state.

From the equation of state we can get the mass M and radius R of an H-cluster star, from the hydrostatic equilibrium condition in general relativity. The results are shown in Figure 1. Our results are consistent with both the mass of a binary millisecond pulsar PSR J1614-2230 (Demorest *et al.* 2010) and the mass-radius measurement of the neutron star in the Rapid Burster MXB 1730-335 (at least at 2 σ; Sala *et al.* 2012).

4. Conclusions

We propose that, if the light flavor symmetry is restored, the strong interaction between quarks inside compact stars could render quarks grouped into a special kind of quark-clusters, H-clusters, leading the formation of H-cluster stars. The equation of state of H-cluster stars is derived by assuming the Yukawa form of H-H interaction under meson-exchanges, and the in-medium effect from Brown-Rho scaling law of meson-masses is also taken into account. H-cluster stars are self-bound objects, and they could be very low masses as well as very high masses (well above $2M_\odot$).

Finally, we would clarify two questions and answers, which should be beneficial to make sense about the conclusions presented in this paper. (1) *Why does not an H-particle on the surface decay into nucleons?* The reason could be similar to that why a neutron does not decay into proton in a stable nucleus. Landau (1938) demonstrated that significant gravitational energy would be released if neutrons are concentrated in the core of a star. It is now recognized, however, that fundamental color interaction is more effective and stronger than gravity to confine nucleons. The equality condition of chemical potentials at the boundary between two phases applies for gravity-confined stars (Landau 1938), but may not for self-bound objects by strong interaction. (2) *Why can hardly normal matter be converted into more stable H-cluster matter in reality?* We know ^{56}Fe is most stable

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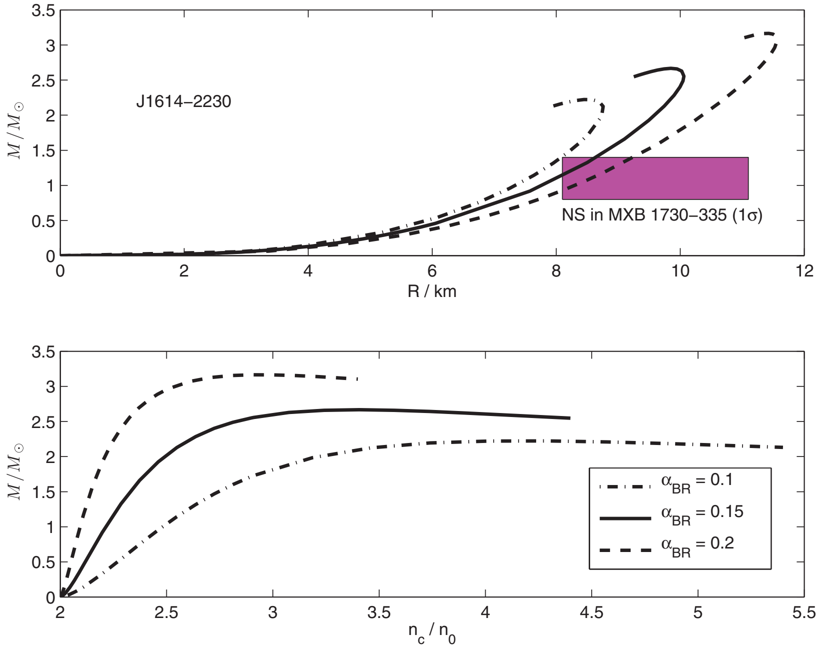

Figure 1. The mass-radius curves and mass-central density (rest-mass energy density) curves, in the case $\rho_s=2\rho_0$, including $\alpha_{BR}=0.1$ (dash-dotted line), $\alpha_{BR}=0.15$ (solid line) and $\alpha_{BR}=0.2$ (dashed line). The blue line shows the mass of PSR J1614-2230 (Demorest *et al.* 2010), the red region shows the mass/radius (1σ) of the neutron star in MXB 1730-335 (Sala *et al.* 2012).

nucleus, but it needs substantial thermal kinematic energy to make nuclear fusion of light nuclei in order to penetrate the Coulomb barrier. Strong gravity of an evolved massive star dominates the electromagnetic force, compressing baryonic matter into quark-cluster matter in astrophysics. This is expensive and rare.

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