CAN THE MAXIMUM MASS OF NEUTRON STARS RULE OUT ANY EQUATION OF STATE OF DENSE STELLAR MATTER BEFORE GRAVITY IS WELL UNDERSTOOD?

DE-HUA WEN$^{1,2}$, BAO-AN LI $^{2,3}$, LIE-WEN CHEN$^4$

$^1$Department of Physics, South China University of Technology, Guangzhou 510641, P.R. China
$^2$ Department of Physics and Astronomy, Texas A&M University-Commerce, Commerce, Texas 75429-3011, USA
$^3$ Department of Applied Physics, Xi’an Jiao Tong University, Xi’an 710049, P.R. China
$^4$ Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, P.R. China

Draft version January 10, 2011

ABSTRACT

Probably No! As an example, using soft EOSs consistent with existing terrestrial nuclear laboratory experiments for hybrid neutron stars containing a quark core described with MIT bag model using reasonable parameters, we show that the recently discovered new holder of neutron star maximum mass PSR J1614-2230 of $1.97 \pm 0.04 M_\odot$ can be well described by incorporating a Yukawa gravitational correction that is consistent with existing constraints from neutron-proton and neutron-lead scatterings as well as the spectroscopy of antiproton atoms.

Subject headings: hybrid star, hyperon, quark, gravity

1. INTRODUCTION

What is gravity? Are there additional spacetime dimensions? These are among the Eleven Science Questions for the New Century identified by the Committee on the Physics of the Universe, US National Research Council (CPUNRC 2003). Interestingly, despite the fact that gravity is the first force discovered in nature, the quest to unify it with other fundamental forces remains elusive because of its apparent weakness at short-distance, see, e.g., refs. (Arkani-Hamed et al. 1998, Pea 2001, Hovy 2003, Long et al. 2003, Jean et al. 2003, Boehm et al. 2004a,b, Decca et al. 2005). In developing grand unification theories, the conventional inverse-square-law (ISL) of Newtonian gravitational force has to be modified due to either the geometrical effect of the extra spacetime dimensions predicted by string theories and/or the exchange of weakly interacting bosons, such as the neutral spin-1 vector $U$-boson (Fayet 2009), proposed in the super-symmetric extension of the Standard Model, see, e.g., refs. (Adelberger et al. 2003, 2009, Fischbach 1993, Newman 2009, Uzai 2003, Raynaud 2005) for recent reviews. The modified gravity has also been proposed as an explanation for the present period of cosmological acceleration, see, e.g., ref. (DeDeo et al. 2008). The search for evidence of modified gravity is at the forefront of research in several sub-fields of natural sciences including geophysics, nuclear and particle physics, as well as astrophysics and cosmology, see, e.g., refs. (Fujii 1974, Pea 2001, Hovy 2003, Arkani-Hamed et al. 1998, Long et al. 2003, Adelberger et al. 2009, Kapner et al. 2007, Nesvizhevsky et al. 2008, Kamyslykov et al. 2008, Azam et al. 2008, Geraci et al. 2010, Lucchesi et al. 2010). Various upper limits on the deviation from the ISL has been put forward down to femtometer range. Since the composition of neutron stars are determined mainly by the weak and electromagnetic forces through the $\beta$ equilibrium and charge neutrality conditions while their stability is maintained by the balance of strong and gravitational forces, neutron stars are thus a natural testing ground of grand unification theories of fundamental forces. Moreover, neutron stars are among the densest objects with the strongest gravity in the Universe, making them ideal places to test strong-field predictions of General Relativity (GR) (Psaltis 2008). The masses and radii of neutron stars are solely determined by both the strong-field behavior of gravity and the Equation of State (EOS) of dense stellar matter. However, there is no fundamental reason to choose Einstein’s equations over other alternatives and it is known that the GR theory itself may break down at the limit of very strong gravitational fields, see, e.g., ref. (Psaltis 2008) for a comprehensive review. In fact, effects of modified gravity on properties of neutron stars have been under intense investigation. As expected, results of these studies are strongly model dependent, see, e.g., refs. (Germani et al. 2001, Wisemans et al. 2002, Azam et al. 2008, Krivoruchko et al. 2009, Wen et al. 2009). Nevertheless, it is very interesting to note that alternative gravity theories that have all passed low-field tests but diverge from GR in the strong-field regime predict neutron stars with significantly different properties than their GR counterparts (DeDeo et al. 2003). Moreover, the deviations for neutron star properties from the GR predictions for these theories are larger than the uncertainty due to the poorly known EOS of dense matter in neutron stars. It was also clearly shown that the neutron star maximum mass alone can not distinguish gravity theories (DeDeo et al. 2003). Furthermore, in the endeavor of testing GR theory of gravity using properties of neutron stars, it is known that there is a degeneracy between the matter content and gravity. This degeneracy is tied to the fundamental Strong Equivalence Principle and can only be broken by using at least two independent observables (Yunes et al. 2010).

Recently, using the general relativistic Shapiro delay the mass of PSR J1614-2230 was precisely measured to be $1.97 \pm 0.04 M_\odot$ (Demorest et al. 2010), making it the new holder of the maximum mass of neutron stars. Comparing with mass-radius relations predicted from solving the TOV equation using various EOSs within GR theory of gravity, it was shown that the mass of PSR J1614-
2. NON-NEWTONIAN GRAVITY AND MODEL EOS OF HYBRID STARS

Fujii (Fujii 1971) first proposed that the non-
Newtonian gravity can be described by adding a Yukawa
term to the conventional gravitational potential between
two objects of mass $m_1$ and $m_2$, i.e.,

$$V(r) = -\frac{Gm_1 m_2}{r} \left(1 + \alpha e^{-r/\lambda}\right),$$

where $\alpha$ is a dimensionless strength parameter, $\lambda$ is
the length scale and $G$ is the gravitational constant. In
the boson exchange picture, $\alpha = \pm g^2/(4\pi G m^2)$
where $\pm$ stands for scalar/vector bosons and $\lambda = 1/\mu$ (in
natural units). The $g^2$ and $\mu$ are the boson-baryon
coupling constant and the mass respectively. The light and
weakly interacting $U$-boson is a favorite candidate mediating the extra interaction (Fayet 2009; Krivoruchenko et
al., 2009; Zhu 2007). Similar to the degeneracy between matter content and gravity, there appears to be a duality of incorporating effects of the
Yukawa term in either the TOV equation or the input
EOS. Nevertheless, according to Fujii (Fujii 1988), the
Yukawa term is simply part of the matter system in general
relativity. Therefore, only the EOS is modified and the
TOV equation remains the same. Within the mean-
field approximation, the extra energy density due to the
Yukawa term is (Long et al. 2003; Krivoruchenko et
al. 2009)

$$\varepsilon_{UB} = \frac{1}{2V} \int \rho(\vec{x}_1) \frac{g^2}{4\pi} \frac{e^{-\mu r}}{r} \rho(\vec{x}_2) d\vec{x}_1 d\vec{x}_2 = \frac{g^2}{2} \frac{\rho^2}{\mu^2},$$

where $V$ is the normalization volume, $\rho$ is the baryon
number density and $r = |\vec{x}_1 - \vec{x}_2|$. Assuming a constant
boson mass independent of the density, one obtains
the corresponding addition to the EOS $P_{UB} = \frac{1}{2} \frac{\rho^2}{\mu^2}$,
which is just equal to the additional energy density. As it
was emphasized by Fujii (Fujii 1988), since the new

2230 can rule out almost all soft EOSs especially those
associated with hyperon or boson condensation. While
conventional quark stars with soft EOSs are also ruled
out by this observation, neutron stars with strongly inter-
acting quark cores are allowed (Demorest et al. 2010;
Ozel et al. 2010; Lai et al. 2010). It was further shown
that a transition to quark matter in neutron star cores
can occur at densities comparable to the nuclear satu-
ration density $\rho_0$ only if the quarks are strongly inter-
acting and are color superconducting (Ozel et al. 2010).
The mass of PSR J1614-2230 was then used to constrain
the interacting parameters of quarks. It was also shown
that neutron stars with interacting quark clusters in their
cores or solid quark stars can be very massive. Using the
Lennard-Jones potential for interactions between quark
clusters, the mass of the PSR J1614-2230 was used to
constrain the number of quarks inside individual quark
clusters (Lai et al. 2010). In this work, using soft nuclear
EOSs for hybrid stars containing a quark core described
by the MIT bag model with reasonable parameters, we
show that the mass of PSR J1614-2230 is readily ob-
tained by incorporating a Yukawa gravitational correction
that is consistent with existing constraints from ter-
restrial nuclear laboratory experiments.

vector boson contributes to the EOS only through the
combination $g^2/\mu^2$, while both the coupling constant $g$
and the mass $\mu$ of the light and weakly interacting
bosons are small, the value of $g^2/\mu^2$ can be large. On
the other hand, by comparing with the $g^2/\mu^2$ value of
the ordinary vector boson $\omega$, Krivoruchenko et al. have
pointed out that as long as the $g^2/\mu^2$ value of the $U$
boson is less than about 200 GeV$^{-2}$, the internal structures
of both finite nuclei and neutron stars will not
change (Krivoruchenko et al., 2009). However, global
properties of neutron stars can be significantly modified
(Krivoruchenko et al., 2009; Wen et al. 2009). One of
the key characteristics of the Yukawa correction is its compo-
sition dependence, unlike Einstein’s gravity. Thus, ideally
one needs to use different coupling constants for various
baryons existing in neutron stars. Moreover, to our
best knowledge, it is unknown if there is any and what
might be the form and strength of the Yukawa term in the
hadron-quark mixed phase and the pure quark phase.
Nevertheless, instead of introducing more parameters,
for the purpose of this exploratory study, we assume that the
$P_{UB}$ term is an effective Yukawa correction existing in
all phases with the $g$ considered as an averaged coupling
constant.

Including the Yukawa term the EOS becomes $P = P_0 + P_{UB}$
where $P_0$ is the conventional pressure inside
neutron stars. For the latter, we use typical model EOSs
for hybrid stars containing a quark core covered by
hyrons and leptons. The quark matter is described by
the MIT bag model with reasonable parameters widely used
in the literature (Chodos et al. 1974; Heinz et al. 1986).
The hyperonic EOS is modelled by using an extended
isospin- and momentum-dependent effective interaction
(MDI (Das et al. 2003)) for the baryon octet with pa-
rameters constrained by empirical properties of symmet-
ric nuclear matter, hyper-atoms, and heavy-ion reactions
(J. Xu et al. 2010). In particular, the underlying EOS of
symmetric nuclear matter is constrained by compar-
ing transport model predictions with data on collective
flow and kaon production in relativistic heavy-ion colli-
sions (Danielewicz et al. 2000; Li et al. 2008). Moreover,
3. MAXIMUM MASS OF HYBRID STARS WITH NON-NEWTONIAN GRAVITY

As an example, shown in Fig. 4 is the mass-radius relation of hybrid stars with the bag constant $B^{1/4} = 170$ MeV and varying values of $g^2/\mu^2$. First of all, without the Yukawa contribution (black solid line) the maximum stellar mass supported is only about $1.46M_\odot$. Including the Yukawa term, as the EOSs are increasingly stiffened with larger values of $g^2/\mu^2$, the maximum stellar mass increases. With $g^2/\mu^2 = 50$ GeV$^{-2}$ the maximum mass of $1.97M_\odot$ is just in the middle of the measured mass band of PSR J1614-2230. The corresponding radius is about 12.4 km. To see more clearly relative effects of the

Fig. 4.— (Color online) Constraints on the strength and range of the Yukawa term from terrestrial nuclear experiments in comparison with $g^2/\mu^2 \approx 40 - 50$ GeV$^{-2}$.

bag constant B and the Yukawa term, shown in Fig. 3 are the maximum stellar masses as a function of $g^2/\mu^2$ with $B^{1/4} = 170$ MeV and $B^{1/4} = 180$ MeV, respectively. As expected, with $B^{1/4} = 180$ MeV a smaller value of $g^2/\mu^2 = 40$ GeV$^{-2}$ is needed to obtain a maximum mass consistent with the observed mass of PSR J1614-2230.

4. COMPARISON WITH TERRESTRIAL CONSTRAINTS ON NON-NEWTONIAN GRAVITY AT SHORT DISTANCE

As mentioned earlier, significant efforts have been devoted to constrain the possible non-Newtonian gravity using terrestrial experiments. These experiments have established a clear trend of increased strength $\alpha$ at shorter length $\lambda$. In the short range down to $\lambda \approx 10^{-14} - 10^{-8}$ m, neutron-proton and neutron-lead scattering data as well as the spectroscopy of antiproton atoms have been used to set upper limits on the value of $g^2/\mu^2$ (or equivalently the $|\alpha|$ vs $\lambda$). It is thus interesting to compare the values of $g^2/\mu^2$ necessary to support the PSR J1614-2230 within the model presented above with
the constraints extracted from terrestrial experiments. While the range parameter $\lambda$ is expected to be much larger (smaller) than the radii of finite nuclei (neutron stars), the maximum mass of neutron stars alone is not sufficient to set separate constraints on the values of $\alpha$ and $\lambda$. Shown in Fig. 4 is a comparison with the terrestrial constraints.\cite{Kamyshkov2008,Barbieri2003}.

1975; Pokotilovski 2006; Nesvizhevsky et al. 2008) in the trial constraints (Kamyshkov et al. 2008; Barbieri et al. $\lambda$ is larger (smaller) than the radii of finite nuclei (neutron stars) require a comprehensive understanding of both gravity and the EOS of dense stellar matter. Because strong-field gravity is well understood, it is unlikely that the maximum mass of neutron stars alone can rule out any EOS. As an example, using soft nuclear EOSs consistent with existing terrestrial experiments for hybrid stars containing a quark core described by the MIT bag model with reasonable parameters, the maximum mass of PSR J1614-2230 is readily obtained by incorporating the Yukawa gravitational correction that is consistent with existing constraints from terrestrial nuclear laboratory experiments.

We thank W.Z. Jiang, W. G. Newton, A.W. Steiner and Y. Zhang for useful discussions. D.H. Wen is supported in part by the National Natural Science Foundation of China under Grant No.10947023 and the Fundamental Research Funds for the Central University, China under Grant No.20092M0193. B.A. Li is supported in part by the US National Science Foundation under grant PHY-0757839, the National Aeronautics and Space Administration under grant NNX11AC41G issued through the Science Mission Directorate and the Texas Coordinating Board of Higher Education under grant No. 003565-0004-2007. L.W. Chen is supported in part by the National Natural Science Foundation of China under Grant Nos. 10675082 and 10975097, MOE of China under project NCET-05-0392, Shanghai Rising-Star Program under Grant No. 06QA14024, the SRF for ROCS, SEM of China, the National Basic Research Program of China (973 Program) under Contract No. 2007CB815004.

5. CONCLUSIONS
Among all fundamental forces, gravity remains the most uncertain one despite being the first discovered in nature. Neutron stars are natural testing grounds of grand unification theories of fundamental forces. In particular, they are ideal places to test GR predictions at the strong-field limit. Interpretations of observed properties of neutron stars require a comprehensive understanding of both gravity and the EOS of dense stellar matter. Before strong-field gravity is well understood, it is unlikely that the maximum mass of neutron stars alone can rule out any EOS. As an example, using soft nuclear EOSs consistent with existing terrestrial experiments for hybrid stars containing a quark core described by the MIT bag model with reasonable parameters, the maximum mass of PSR J1614-2230 is readily obtained by incorporating the Yukawa gravitational correction that is consistent with existing constraints from terrestrial nuclear laboratory experiments.

REFERENCES

Adelberger, E. G., Heckel, B. R., & Nelson, A. E. 2003, Annu. Rev. Nucl. Part. Sci., 53, 77
Adelberger, E. G., Gundlach, J. H., Heckel, B. R., Hoedl, S., & Schlamming S. 2009, Prog. Part. Nucl. Phys., 62, 102
Aklal, A., Pandharipande, V. R. and Stocker, H., & Greiner, W. 1986, Nucl. Phys., 12, 1237
Aoki, H., Dimopoulos, S., & Dvali, G. 1998, Phys. Lett. B, 429, 263; Phys. Rev. D, 59, 086004
Azam, M., Sami, M., Unnikrishnan, C. S., & Shiromizu, T. 2008, Phys. Rev. D, 77, 101101
Barbieri, R., & Ericson, T. 1975, Phys. Lett. B, 57, 270
Baym, G., Pethick, C., & Sutherland, P. 1971, ApJ, 170, 299
Boehm, C., Hooper, D., Silk, J., Casse, M. & Paul, J. 2004, Phys. Rev. Lett., 92, 101101
Boehm, C., & Fayet, P. 2004, Nucl. Phys. B, 683, 291
Chodos, A., Jaffe, R. L., Johnson, K., Thorn, C. B., & Weisskopf, V. F. 1974, Phys. Rev. D, 9, 12
Committee on the Physics of the Universe, National Research Council 2003, Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century (The National academies Press)
Danielewicz, P., Lacey, R., & Lynch, W. G. 2000, Science, 298, 1592
Das, C.B., Das Gupta, S., Gale, C., & Li, B. A. 2003, Phys. Rev. D, 67, 034061
Decca, R.S., Lópezo, D., Chan, H. B., Fischbach, E., Krause, D. E., & Jamell, C. R. 2005, Phys. Rev. Lett.94, 240401
DeDeo, S., & Psaltis, D. 2003, Phys. Rev. Lett., 90, 141101
DeDeo, S., & Psaltis, D. 2008, Phys. Rev. D, 78, 064013
Demorest, P., Pennucci, T., Ransom, S., Roberts, M., & Hesses, J. 2010, Nature, 467, 1081
Fayet, P. 2009, Phys. Lett. B, 675, 267
Fischbach, E., & Talmadge, C. L. 1999, The Search for Non-Newtonian Gravity(Springer-Verlag, New York, Inc.)
Fujii, Y. 1971, Nature, 234, 5
Fujii, Y. 1988, in Large Scale Structures of the Universe, page 471-477 (Eds. J. Audouze et al., International Astronomical Union.)
Geraci, A. A., Papp, S. B., & Kitching, J. 2010, Phys. Rev. Lett., 105, 101101
Germani, C., & Maartens, R. 2001, Phys. Rev. D, 64, 124010
Glendenning, N.K. 2001, Phys. Rep., 342, 393
Heinz, U., Subramanian, P. R., Stocker, H., & Greiner, W. 1986, Nucl. Phys., 12, 1237
Hoyle, C. D. 2003, Nature, 421, 899
Jean, P., et al. 2003, A&A, 407, L55
Kamyshkov, Y., Tithof J., & Vysotsky, M. 2008, Phys. Rev. D, 78, 114029
Kapner, D.J., Cook, T. S., Adelberger, E. G., Gundlach, J. H., Heckel, B. R., Hoyle, C. D., & Swanson, H. E. 2007, Phys. Rev. Lett., 98, 021101
Krivovorchenko, M.I., Sinkovice, F., & Faessler, A. 2009, Phys. Rev. D, 79, 125023
Lai, X. Y., & Xu, R. X., 2010, [arXiv:1011.0526]
Li, B. A., Chen, L. W., & Ko, C. M. 2008, Phys. Rep., 464, 113
Long, J. C., et al. 2003, Nature, 421, 922
Lucchesi, D. M., & Person R. 2010, Phys. Rev. Lett., 105, 231103
Nesvizhevsky, V. Y., et al. 2008, Phys. Rev. D, 77, 054020
Newman, R. D., Berg, E. C., & Boynton, P. E. 2009, Space Science Review, 148, 175
Özel, F., Psaltis, D., Ransom, S., Demorest, P., & Alford, M, 2010, [arXiv:1010.5799v1], ApJL in press.
Pease, R. 2001, Nature, 411, 986
Pokotilovski, Yu. N. 2006, Phys. Atom. Nucl., 68, 924
Psaltis, D. 2008, Living Reviews in Relativity, 11, 9
Reynaud, S., & Jaekel, M. M. 2005, Int. J. Mod. Phys. 20, 2294
S. Zhu, S. H. 2007, Phys. Rev. D, 75, 115004
Xiao, Z.G., et al., 2009, Phys. Rev. Lett. 102, 062502
Xu, J., Chen, L. W., Ko, C. M., & Li, B. A. 2010, Phys. Rev. C, 81, 055803
Xu, C., Li, B. A., & Chen, L. W. 2010, Phys. Rev. C, 82, 054607
Yunes, N., Psaltis, D., Özel F., & Loeb, A. 2010, Phys. Rev. D, 81, 064020
Zhu, S. H. 2007, Phys. Rev. D, 75, 115004