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THE EFFECTS OF NUCLEAR FORCES ON THE MAXIMUM MASS LIMIT OF NEUTRON STARS*

by

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Recently the problem of the maximum mass limit of a stable neutron star has drawn the attention of many people, because it may seriously affect the models of pulsars and other phenomena which are most likely caused by the presence of neutron stars. In this brief report I wish to compare the neutron star models by various groups, including the most recent results I am aware of, those by the Cornell group (Boozer-Salpeter) and those by the Kyoto group (S. Ikeuchi, T. Mizutani, S. Nagata, R. Tamagaki, and C. Hayashi).

In Figure 1, the curve marked IDEAL represents the models with no nuclear interactions, originally constructed by Oppenheimer and Volkoff.[1] The models by Harrison, Thorne, Wakano and Wheeler[2] approximately lie on the same curve in the neutron star region. The dotted curves marked V_β and V_γ are the models constructed by Tsuruta and Cameron[3] and subsequently used by Thorne and others at CIT[4] in their calculations of the moments of inertia of neutron stars, etc. I decided to show these curves also, because these results (especially the V_γ models) have been used by Ostriker and others[5] in their pulsar studies. The solid curves show neutron star models

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constructed after the pulsar discovery. The curve (1) is by Cohen et al.[6], (2) is by the Cornell group (Boozer-Salpeter), (3) is by Wang et al.[7], and the curves (4) through (7) are obtained by the Kyoto group.

In all models shown here except the first (those marked IDEAL), nuclear interactions are taken into account. In the models marked as V_β and V_γ, the nuclear potentials of V_β and V_γ type, respectively, by Levinger and Simmons[8] are used. In the models (1), the modified Levinger-Simmons neutron gas models are used. Boozer and Salpeter (the curve (2)) made use of the neutron gas calculations (2b) by Nemeth and Sprung[9] with the soft-core Reid potentials. Wang et al. (the curve (3)) took the average of the soft-core Reid potentials and several other potentials, but they all give the similar equations of state. The results by the Kyoto group are obtained in the following way. For densities ρ less than $\rho_0 \simeq 8 \times 10^{14}$ gm/cm^3 where the neutron matter calculations from the concept of "nuclear potential" becomes unreliable, the one-boson exchange hard-core potentials constructed by Kishi were used in the models (4), called OBEP-K, and the one-pion exchange potentials with a Gaussian type soft core constructed by Tamagaki were used in the models (5) called OPEG-T. For $\rho > \rho_0$ in these models, the equation of state obtained in this manner was parabolically extrapolated in the logarithmic scale. In the models (6) and (7), the equation of state $P = \epsilon/3$ and $P = \epsilon$, respectively, (where ϵ is the energy density) were used for $\rho > \rho_1 \simeq 5 \times 10^{15}$ gm/cm^3 where the Zel'dovich type scalar or vector interactions are assumed to become applicable, the method (4) was used for $\rho \lesssim \rho_0$, and the intermediate regions have been interpolated. Similar results are obtained if the OPEG-T or the Hamada-Johnston potentials are used for $\rho \lesssim \rho_0$.

We see, first of all, that drastically different masses are obtained depending on how the inter-particle interaction problem is treated. In the models (2) and (3) the calculations are terminated where the nuclear potential approach is thought to become unreliable. If the calculations are extended to higher densities, the curve (2) reaches the mass peak of about 1 $M_\odot$, similar to the curves (4) and (5) by the Kyoto group. Near the breakdown point, ρ_0, the models (3), (4), (5), (6) and V_β have small mass values of only around 0.2-0.4 $M_\odot$, while the other models shown in the figure have larger masses. At the mass peak, the curve (7) reaches almost $3M_\odot$. It may be pointed out that these models obtained by different methods nevertheless possess a few common points as mentioned below. As the mass increases from the minimum value to approximately $0.2M_\odot$, the corresponding radius decreases quickly from about 300 km to about 10 km or so. This occurs a little below or around the nuclear density, depending on the models. For densities of around 10^{15} gm/cm^3 the radius is around 10 km, and for densities of around 10^{16} gm/cm^3 the radius is around 5 km. Our studies also show that the effects of the presence of hyperons and protons on the mass limit are much smaller than the effects of nuclear forces, if the interactions among all baryons are basically similar. It will be hard to draw definite conclusions from the above results, but the following comments may be valid.

In the regions where the concept of "nuclear potential" is still valid (for approximately $\rho \lesssim 10^{15}$ gm/cm^3), using realistic potentials alone is not enough. For instance, quite different results are obtained in the models (2) and (3), even though the both groups used the similar potentials (the soft-core Reid potentials). In this respect (of applying realistic potentials in a realistic way), I feel that the models (5), the OPEG-T, are the best recommended (among the models shown here). However, it may be noted that many-body interactions are generally neglected and that the nuclear potential term is treated non-relativistically in the work done so far. The net effect of the corrections to these approximations seems to lower the densities and increase the masses near the mass peak. Thus the V_γ models used already in various pulsar studies seem to be not far from reality.

The exact behavior in the regions above about 10^{15} gm/cm^3 seems to be beyond the knowledge of present-day physics. Since the maximum mass of some of the models lie in these high density regions, it is hard to answer the question of how high masses stable neutron stars can have. It will be fortunate if such a question can be answered rather from the observational side. Will it be an impossible dream, if one contemplates that more detailed pulsar observations might help the break-through of the difficulties facing us today in particle physics and some other fields?

In the pre-pulsar discovery periods, I did not see much sense in going beyond our V_β and V_γ models of neutron stars. But, today, with more observations of pulsars becoming available, better theoretical work with the cooperation of experts in various fields, including the effort to construct more realistic neutron star models, seems very desirable.

I wish to thank Professors Hayashi, Nagata, Salpeter and Tamagaki, and Messrs. Boozer, Ikeuchi and Mizutani, for giving me the results of their calculations[10] before publications.

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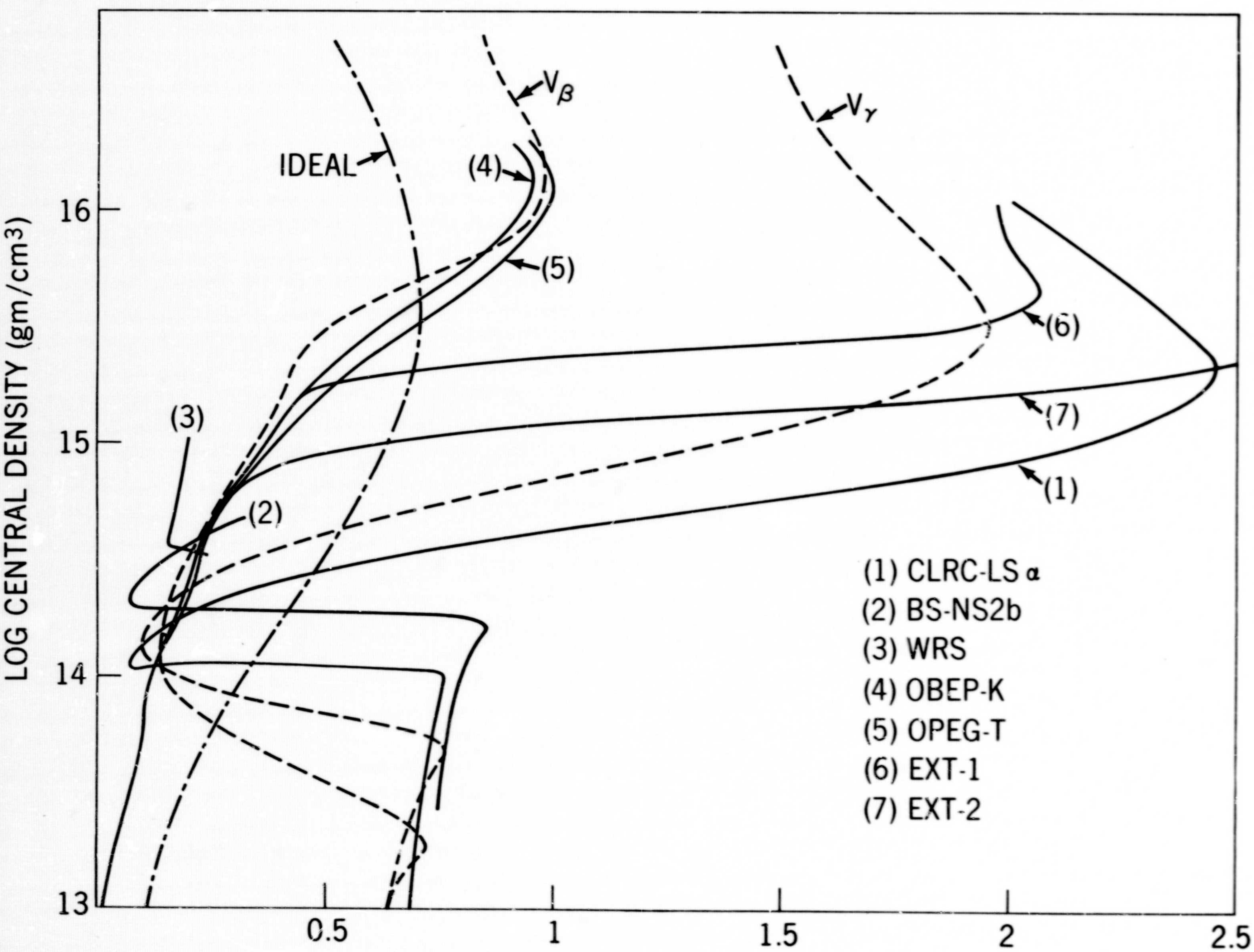

LOG CENTRAL DENSITY (gm/cm3)
MASS (M/M⊙)
13
14
15
16
0.5
1
1.5
2
2.5
IDEAL
V_β
V_γ
(1)
(2)
(3)
(4)
(5)
(6)
(7)
(1) CLRC-LS α
(2) BS-NS2b
(3) WRS
(4) OBEP-K
(5) OPEG-T
(6) EXT-1
(7) EXT-2

Figure 1