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## Is There a Crisis in Neutron Star Physics?

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### 1 Introduction

Sometimes it becomes difficult for people not following the development of a field to judge the advances and ongoing changes. Neutron star physics is no exception to this rule. As a specific example of how long-lasting concepts and results can be fundamentally changed, we may quote the standard statement in all textbooks and even scientific articles up to the beginning of the 21st century which reads: neutron star masses are compatible with a single scale of  $1.4M_{\odot}$ . Mounting evidence for massive and light neutron stars was considered as unreliable and unconfirmed. And despite the possible width of this “single-distribution”, the belief that nature had some robust mechanism to produce quasi-identical neutron stars was strong and is still present.

However, the situation changed dramatically in the last years, when reliable new evidence become available. On the one hand, very precise reports using different methods [1, 2] have demonstrated the existence of objects with  $\sim 2M_{\odot}$ . On the other, low masses have been reported for a few systems [3], even below the absolute minimum expected theoretically for any neutron star formed in a supernova, although systematic errors can not be completely controlled as yet.

We shall show in this report that the theoretical evolution of a particular class of systems containing a neutron star, the so-called “black widow” binaries, suggest masses above the  $\sim 2M_{\odot}$ , a fact that would bring serious concerns about the right description of the equation of state above the saturation density. Moreover, so far the actual determinations of masses for these systems consistently give values above  $2M_{\odot}$ , reinforcing the quandary. In this sense, and given that the confirmation of these ideas would create problems for the microphysical description, we argue that a crisis could be “in the works” in neutron star physics.

## 2 Stellar Evolution and Masses

It is now quite apparent that there are neutron stars with masses above and below the “canonical” value of  $1.4M_{\odot}$ . A few recent works using the database by Lattimer, Steiner and collaborators [19] have concluded that at least two different scales are present [4, 5, 6, 7], although the exact values and physical origins remain controversial. The suggestion by van den Heuvel [20] that massive neutron stars may arise from massive cores developed by stars with  $M \geq 18M_{\odot}$  (also present in the calculations of Timmes, Woosley and Weaver [8]) could be related to a “direct” channel of formation. Naturally, accretion histories in LMXB and related objects can also contribute to produce heavy objects. The celebrated detection of a  $\sim 2M_{\odot}$  by direct measurement of the Shapiro delay by Demorest et al. [1] stands firm, but not unique, among the high-end numbers (see below).

After the discovery of the first “millisecond” pulsar in 1982 [9], another striking discovery came to enlarge the variety of neutron star systems [10] with the addition of the first member of the “black widow” class. These systems were rapidly identified as ablating the matter from the companions, and therefore killing them much in the same way the homonymous spiders do. In fact, low masses were measured for the latter, and the presence of matter coming out of the system confirmed the basic picture. The latest additions to the group include the system PSR J1719-1438 in a 2.2 h orbit featuring a Jupiter-mass companion [11] and PSR J1311-3430, discovered in gamma-rays first by Pletsch et al. [12] and almost completely devoid of hydrogen. However, it did not become clear how these systems are formed, since their evolutionary paths could not be identified or calculated with certainty. Black widows (and their cousins in which the donors have higher masses, named after the Australian “red backs”, see [21]) were loosely identified as relatives of the LMXB, but their exact relationship remained obscure. The follow-up of these ideas by actual numerical calculations recently gave an unexpected bonus as we shall see below.

### 3 Calculations

We have performed numerical calculations to understand the conditions of formation of these black widow systems. A full description of the Henyey code solving simultaneously the stellar structure + stellar orbit equations is given in Benvenuto & De Vito (2003). The application to these specific systems has taken into account 1) the detailed behaviour of the Roche Lobe region; 2) the evaporating wind  $\propto L_P(R_2/a)^2$  (with  $R_2$  the radius of the donor,  $L_P$  the luminosity of the pulsar and  $a$  the semiaxis of the orbit, see [18]) although irradiation feedback was discarded because of simplicity. We have generated several tracks starting from a quite narrow period interval (otherwise, the orbit could widen immediately and a black widow will not be produced, see [14]) and several choices of the initial donor mass within accretion stability limits. By hypothesis, we have chosen to start with a just-formed neutron star of  $1.4M_\odot$  and assumed a fixed value of the transfer efficiency  $\dot{M}_1 = -\beta\dot{M}_2$ , although this parameter is not really crucial for the outcome.

After  $\sim$  few *Gyr* transfer the orbit shrinks when the donor star becomes semi-degenerate and the wind from the pulsar ablates matter until short period/low masses systems, as the ones observed follow. However, the most relevant result for our discussion here is the final NS mass. Fig.1 displays the evolution of both the donor and the NS masses along the evolutionary history of the system for a fixed value of  $\beta = 1/2$ . We see that a good amount of accretion onto the NS is in fact very important for the evolution of the systems, otherwise they could not occupy the region of short period/low masses as observed. Therefore, and unless an actual calculation with variable  $\beta(t)$  prove otherwise, even a modest amount of efficiency would drive the NS above the  $2M_\odot$  value. This is quite striking but sound, since a long history of accretion with episodes of ablation must have an effect on the accretor after all.

It was not then unexpected that very recent work combining photometry and spectroscopy for the system PSR J1311-3430 [17] rendered high values for the NS mass, namely  $2.15 \pm 0.11M_\odot$ ,  $2.68 \pm 0.14M_\odot$  or even  $2.92 \pm 0.16M_\odot$ , depending on the interpretation of the light curve. It is also important to remark that the “original” black widow, PSR 1957+20 NS mass has been estimated as  $2.4 \pm 0.12M_\odot$  before [15], in complete agreement with the theoretical calculations. While there may be still a fine adjustment of the final masses, we may have to consider seriously the existence of masses even larger than the Demorest et al. (2012) determination.

### 4 Discussion

Is there a crisis in NS physics after all? If the emerging values of the black widow NS are confirmed, the answer will be “yes”. After many years standing on the  $1.4M_\odot$ , the evidence for larger masses seems overwhelming, and the work on the black widow sys-

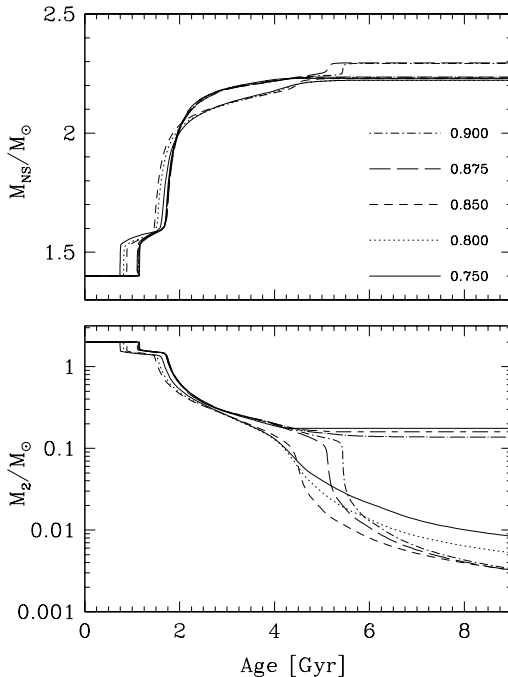


Figure 1: The mass of the neutron star in the system PSR J1311-3430 (upper panel) and its companion (lower panel). Several *Gyr* are needed to place the system in the observed orbit with the observed value of the donor mass, and if the efficiency of accretion is not absurdly low, this history will also produce a massive neutron star.

tems push the maximum value to “uncomfortable” levels. The answer will not come easily, although the recent work on the hyperon sector suggest there is unexpected repulsion hidden there, leading to consider a variety of models in which hyperons could stand masses  $> 2M_{\odot}$  instead of turning the stellar sequences downwards. The exotic models resorting to quark matter, even in its extreme SQM version would also be insufficient since in both popular versions (MIT bag and NJL, both with CFL-type pairing) the mass cannot be increased indefinitely by tuning the parameters [16].

We must add here that there is a real possibility that rapidly rotating neutron stars could increase their masses by  $\sim 20\%$  near Keplerian frequency. However, the very fast rotation of both quoted black widow pulsars ( $2.5ms$  for PSR J13113430 and  $1.6ms$  for PSR 1957+20) are still fast from this extreme condition (see, for example, Weber, Orsaria and Negreiros, these Proceedings), and their “extra” mass is not larger than a few percent for any type of equation of state.

We shall witness a new round of theoretical work to see how large masses are accommodated after all, although nature surely knows how as shown by the plain observations.

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