On the minimum mass of neutron stars

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collaboration with
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~10km (~40min w/ metro & bus)

Kyoto Station

Kyoto University

Long-term workshop “Multi-messenger astrophysics in the GW era”
incl. YKIS conference
Pulsar number is increasing

compiled data from ATNF pulsar catalog and P. Freire’s table
The most recent measurements of neutron-star masses. Double neutron stars (Figure 2), bursters (SAX J1802.7-2017, SAX J1748.9-2021), and slow pulsars (cyan) are included. Although clearly not representative of NSs as a whole, as it was once thought (Thorsett & Freire 2016), the DNSs, previously believed: the recycled pulsar has a mass of 1.559 (5) M☉ for the slow pulsars. A recent study also raised the possibility of two peaks within the system, one for the recycled MSP population, with the first peak at 1.0 1.1 M☉ and a second peak appearing at 2.6 M☉, which would not arise if it had slowly evolved to a massive WD.

Finding the maximum mass of NSs is of particular interest in mass measurements because of its potential for probing the fundamental physics of neutron stars. There are also some studies of a particular class of MSPs called black widows (and their cousins redbacks) that have suggested higher NS masses (e.g., van Kerkwijk et al. 2011). These MSPs among these inferred distributions, the narrowness of the DNS distribution stands out. The likelihood distributions for these systems in a narrow range. Recent discoveries, such as the DNS J0453+1559c, B2127+11Cc, and J1946+3417, have shown that the masses of NSs in these systems are relatively narrow. However, there are difficulties in obtaining accurate measurements from these ablated companions. Even when using spectroscopy (to measure the mass ratio) of the companion star, there are many uncertainties.

Mass measurements of NSs

* >2600 pulsars have been found in the Galaxy
* 10% in the binary system → mass measurement possible
* 15 double NSs so far [Tauris+ 2017]

http://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html
Massive NSs tell us nuclear physics

\[ 1.97 \pm 0.04 M_{\odot} \]

NB) mass estimation was updated by Arzoumanian+ 2018 as \( 1.908 \pm 0.016 M_{\odot} \)

Another massive NS was reported by Antoniadis+ (2013), J0348+0432, \( 2.01 \pm 0.04 M_{\odot} \)
So, what does a small NS tell?
**Double NSs**

![Graph showing neutron-star masses](image)

The graph illustrates the most recent measurements of neutron-star masses, with double neutron stars (magenta), recycled pulsars (gold), bursters (purple), and slow pulsars (cyan) included. The masses concentrate within a small range, indicating a tight distribution of neutron-star masses in those systems.
First asymmetric DNS system

First asymmetric DNS system

$M_p = 1.559 \pm 0.005 M_\odot$

$M_c = 1.174 \pm 0.004 M_\odot$

Martinez+ 2015
A low-mass NS

* $M_{NS} = 1.174 M_\odot$! (NB, it’s gravitational mass, baryonic mass is ~1.28 $M_\odot$)

* Is it a white dwarf? Maybe no
  - a large eccentricity ($e = 0.112$) is difficult to explain by slow evolution into a WD

* How to make it?
  - a small iron core of massive star? (typically $M_{Fe} \approx 1.4\text{–}1.8 M_\odot$)
  - getting rid of mass from a NS?

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Sukhbold+ 2018

![Graph showing iron core mass vs. ZAMS mass](image)
**A path toward a low mass NS?: Ultra-stripped SN**


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![Diagram of stellar evolution and SN explosion](image)

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**Figure 7.**

- **Evolutions of the radius of shocks.**
- **Figure 5.**
  - **Ultra-stripped SN:**
  - **Type Ic SN 2005ek:**
  - **We obtained light trans-iron elements in the ultra-stripped SN model:**
  - **for more massive CO cores:**
  - **These compositional differences could:**
  - **produce distinctive spectral features.**
  - **The identification of ultra-stripped SN:**
  - **may be left behind:**
  - **CO15 model to the solar abundance:**
  - **The red and black lines correspond:**

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**Notes.**

- **(b) CO15 model to the solar abundance:** The red and black lines denote the ratios.
- **Ic SNe to the solar abundance:** The red and black lines correspond.
- **survives the CE phase,** it consists of a NS orbiting a helium star.
- **especially if the eccentricity is large:**
- **BH: black hole.**
- **supernova; NS: neutron star; HMXB: high-mass X-ray binary; CE: common envelope;**
- **Note that this model is marginally exploding.**
- **The Ni mass at:**
- **The baryonic mass of NS at:**
- **not small iron core itself,** which can rapidly accelerate shock, would
  - **be overestimated due to the existence of preferable direction of NS**
  - **axial symmetry is assumed in our simulations,** the kick velocity may
  - **be underestimated because of the missing proton-rich component in**
  - **We obtained light trans-iron elements in the ultra-stripped SN model:**
  - **for modeling ultra-stripped Type Ic SNe:** We have found that all
  - **cores and explosion simulations for the end product of the CO cores**
  - **generally lead to small kick velocity due to too short time for SASI**
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When does a core collapse?

**Graph:**
- **Y-axis:** Mass
- **X-axis:** Time till collapse

**Lines:**
- **Red line:** \( M_{\text{Chandra}} \)
- **Blue line:** \( M_{\text{core}} \)

**Collapse Point:**
- The point where both lines intersect, indicating the time till core collapse.
**Modified Chandrasekhar mass**

* Chandrasekhar mass *without* temperature correction

\[ M_{Ch0}(Y_e) = 1.46M_\odot \left( \frac{Y_e}{0.5} \right)^2 \]

* Chandrasekhar mass *with* temperature correction

\[ M_{Ch}(T) = M_{Ch0}(Y_e) \left[ 1 + \left( \frac{s_e}{\pi Y_2} \right)^2 \right] \]

\[ s_e = 0.5\rho_{10}^{-1/3}(Y_e/0.42)^{2/3}T_{MeV} \]

Baron+ 1990; Timmes+ 1996

* To make a small core, *low* \( Y_e \) and *low* entropy are necessary
$M_{ch}$ vs. $M_{core}$

**Explosion simulations and NS masses**


<table>
<thead>
<tr>
<th>Model</th>
<th>$M_{CO}$ ($M_\odot$)</th>
<th>$M_{ZAMS}$ ($M_\odot$)</th>
<th>$M_{Fe}$ ($M_\odot$)</th>
<th>$M_{NS,b}$ ($M_\odot$)</th>
<th>$M_{NS,g}$ ($M_\odot$)</th>
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</thead>
<tbody>
<tr>
<td>CO137</td>
<td>1.37</td>
<td>9.35</td>
<td>1.280</td>
<td>1.289</td>
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<tr>
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<td>9.5</td>
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<tr>
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<td>9.75</td>
<td>1.277</td>
<td>1.376</td>
<td>1.245</td>
</tr>
</tbody>
</table>

$M_{NS,b}-M_{NS,g}=0.084M_\odot(M_{NS,g}/M_\odot)^2$

(Lattimer & Prakash 2001)
Discussion


$M_{NS,b}$ $M_{NS,g}$
(M☉) (M☉)

~1.32 ~1.20

ONeMg core -> electron-capture SN

~1.37

~1.42

Fe core -> core-collapse SN

$M_{CO}$ (M☉)
Summary

* A low-mass NS of $M_{\text{NS}, g} = 1.174M_\odot$ was found

* Q: Is it possible to make such a low-mass NS with standard modeling of SN?

* A: Yes, it is.
  - The minimum mass is $\sim 1.17M_\odot$.
  - If a new observation finds even lower mass NS, we cannot make it. Something wrong.