“Black widow” binary systems

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Once upon a time the idea of a single mass scale was firmly rooted in the community.

Figure from Clark et al. A&A 392, 909 (2002)

Consistent with $1.4 \, M_\odot$
However, the newest evidence points towards a much wider range of masses.

Sample compiled by Lattimer et al 2012, available at

http://www.stellarcollapse.org/nsmasses
Bayesian analysis (Valentim, Rangel & Horvath, MNRAS 414, 1427, 2011) points out that one mass scale is unlikely, the distribution is more complex. Within a double gaussian scenario, two masses are present: 1.37 and 1.73 M⊙

Is the high value related to the size of the Fe core? (jump @ 18 M⊙) Are some of them born as such, massive? Accretion role important? Stay tuned...

Other works finding the same pattern:

Özel et al., ApJ 757, 55, 2012 (1.33 and 1.48 M⊙)
Kiziltan, Kottas & Thorsett, arXiv:1011.4291 (1.35 and 1.5 M⊙)
Demorest et al 2010: a NS with $M \sim 2 \, M_\odot$ measuring the Shapiro delay
1982: Backer et al. discovered the first member of the *ms* pulsar class. **RECYCLED BY ACCRETION?**

1988: Fruchter, Stinebring & Taylor (Nature 333, 237, 1988) found an eclipsing pulsar with a very low mass companion, the hypothesis of ablation wind quickly follows

Original sketch of the PSR 1957+20 system

Composite Image from *Chandra* (2012)
“Black widow” pulsars

Relatives of the accreting X-ray binaries...

LMXRB and others

Many ms pulsars in binaries
M. Roberts, arXiv:1210.6903 and this conference
Last members of the zoo:

**PSR J1719-1438** (Bailes et al., Science 333, 1717, 2011)
Extremely low mass companion, yet high mean density $\rho > 23 \text{ g cm}^{-3}$ for it.

Similar system, but with extremely low hydrogen abundance for the donor $n_H < 10^{-5}$.
How are these ultra-compact systems formed?

*(Benvenuto, De Vito & Horvath ApJL 753, L33, 2012)*

\[ M_1 \quad \text{primary (NS)}, \quad M_2 \quad \text{secondary (donor)} \]

Onset of Roche Lobe Overflow (RLOF), Paczynski

\[ R_L = 0.46224 \, a \left( \frac{M_2}{M_1 + M_2} \right)^{1/3} \]

\[ \dot{M}_1 = -\beta \dot{M}_2 \]

Accreted by the NS, always

\[ \dot{M}_{\text{Edd}} = 2 \times 10^{-8} \, M_\odot \, \text{yr}^{-1} \]
In general, $\beta < 1$ and angular momentum is lost from the system. The exact value of $\beta$ is not critical.

1st ingredient
(Ritter, A&A 202, 93, 1988)

$$\dot{M}_{2, \text{RLOF}} = -\dot{M}_0 \exp \left( \frac{R_2 - R_L}{H_P} \right)$$

Evaporating wind

2nd ingredient
(Stevens et al., MNRAS 254, 19, 1992)

$$\dot{M}_{2, \text{evap}} = -\frac{f}{2v_{2,\text{esc}}^2} L_P \left( \frac{R_2}{a} \right)^2$$

with

$$L_P = 4\pi^2 I_1 P_1 \dot{P}_1$$

Irradiation feedback

3rd ingredient
(Bunning & Ritter, A&A 423, 281, 2004
Hameury)
All three effects incorporated into an adaptative Henyey code, solving simultaneously structure and orbital evolution (Benvenuto & De Vito, 2003; De Vito & Benvenuto, 2012)

\( (M_1, M_2, P_i) \) must be in the “right” range to explain the observed systems.

If \( P_i \) is too short (< 0.5 d), the mass transfer would start at ZAMS. If \( P_i \) is too long (> 0.9 d), the orbit widens and a ~0.3 Mo not the observed state!

If \( M_2 \) is too small, mass transfer would be > age universe.

If \( M_2 \) is too high, mass transfer is unstable (Podsiadlowski et al).

Started calculations right after the NS formation.

CAVEAT !!!, just an hypothesis.

\( M_1 = 1.4M_\odot \), \( M_2 = 2M_\odot \)
Low-inclination solutions acceptable

At slightly larger initial periods, the secondary detaches at high mass and do not produce “black widow” systems.
The system goes back and forth from accretion to ablation when the donor becomes semi-degenerate. 

*Not* a numerical instability.
PSR J1311-3430: similar but VERY hydrogen-free~ \(10^{-5}\)


When the donor star becomes fully convective, \(M_2=0.053M_\odot\)
the central abundance can be zero (pure He star) provided \(P_\text{i} > 0.86\) d

If \(P_\text{i}\) is shorter, it still produces a “black widow” but hydrogen is present

(Benvenuto, De Vito & Horvath MNRAS Letters, in the press)

\[ \frac{M_{\text{psr}}}{M_2} \sim 70 \] (through spectral lines, radial velocity)

\[ M_{\text{psr}} = 2.4 \pm 0.12 \, M_\odot \]

\[ (M_{\text{psr}} > 1.66 \, M_\odot \text{ firm}) \]

Romani et al. (ApJ 760, L36, 2012) found three high values for the neutron star in PSR J1311-3430, depending on the interpretation \[ M_{\text{psr}} > 2.1 \, M_\odot \text{ up to } \sim 3 \, M_\odot \]
Self-consistent calculations of the PSR J1311-3430 system require such high values to reach the observed state.

Calculations for several values of the initial period, and fixed accretion efficiency $\beta$ of 50%.
Conclusions

* Ultra-compact “black widow” pulsar systems result from a bifurcation in parameter space, in this sense they are a new evolutionary path. Hydrogen-free companions result from very tight initial conditions.

* The role of winds+irradiation is crucial: RLOF alone would not produce anything like PSR J1719-1438 or PSR J1311-3430. The full parameter space needs exploration, but we can state that PSR masses emerging are consistently very large.

* We have results for the original black widow, just the radius comes out wrong, but the opacities were extrapolated and it should not be a surprise, meanwhile period, mass ratio, OK.