Pulsar Masses

The Remnant Mass distribution in Neutron Stars

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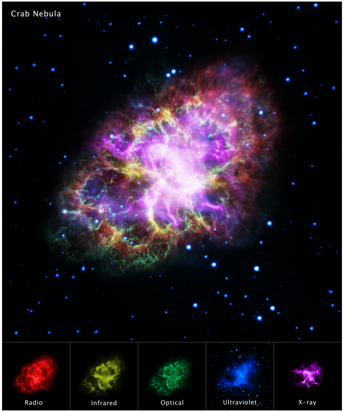

Figure: NASA, ESA, G. Dubner et al, 2017

History

- 1932 - Chadwick - Possible existence of a neutron
- shortly after - Landau - anticipates neutron composed dense-compact stars
- 1934 - Baade & Zwickey - introduce term "neutron star", mention evolutionary paths, mass and radii constraints

Why are these constraints important?

Masses

Mass one of the most important parameters

- Birth mass - Stellar evolution, core collapse, super novae
- Maximum mass - outlines black hole low-mass limit
- Equation of State - test nuclear physics of superdense matter
- Gravitation - test Einstein's general relativity in strong gravity regime

Over the years many mass constraints have been proposed

Pulsars

General information and values

Mass	investigated	$M_{ZAMS} \approx 8 - 60 M_{\odot}$
Radius	$r_{NS} \approx 12km$	
Period	$P \sim few\ s$	$\dot{P} \approx 10^{-15} s/s$
Millisecond pulsar	$P \sim few\ ms$	$\dot{P} \approx 10^{-20} s/s$
Lighthouse model		complicates detection
Magnetic field strength	$H > 10^{10}\,T$	no alignment with spin
Gravitational field	$g \approx 10^{11} g_{earth}$	possibility of Lensing

Measurements

Spin period, period decay measurable for every NS
Mass measurement only possible in a binary system

This poses a major problem
$\sim$ 90% of all NS are isolated stars

2 methods are currently used in two different frequency regimes:
Radio measurements with more precise model
X-ray - optical combination model

Possibility with gravitational waves from mergers (LIGO & LISA)

Radio and Post Keplerian Parameters

Normal Keplerian not suited due to effects of GR
2 parameters required to infer M_{psr} with high precision

1. Advancement of Periastron $\dot{\omega}(P_b, T_\odot, e, M_{tot})$
2. Orbital Period Decay $\dot{P}_b(P_b, T_\odot, e, M_{tot}, M_{psr}, M_{cmp})$
3. time dilation-gravitational redshift $\gamma(P_b, T_\odot, e, M_{tot}, M_{psr}, M_{cmp})$
4. Shapiro delay range $r(T_\odot, M_{cmp})$
5. Shapiro delay shape $s(P_b, T_\odot, a, M_{tot}, M_{cmp})$

Additional measured parameters provide consistency test method of strong field gravitational theories

X-Ray - optical method

Works in actively accreting binary system with optical companion

Accretion makes X-ray observation possible
Optical companion observed with optical spectroscopy

Orbital Period and v_{rad} can be determined from measuring:

- cyclical doppler shift of pulse period
- doppler shift in spectral features of optical companion

Parameters provide systems mass function
Inclination angle splits it into M_{psr} and M_{cmp}

Models typical mass errors of 10%

Binary Population

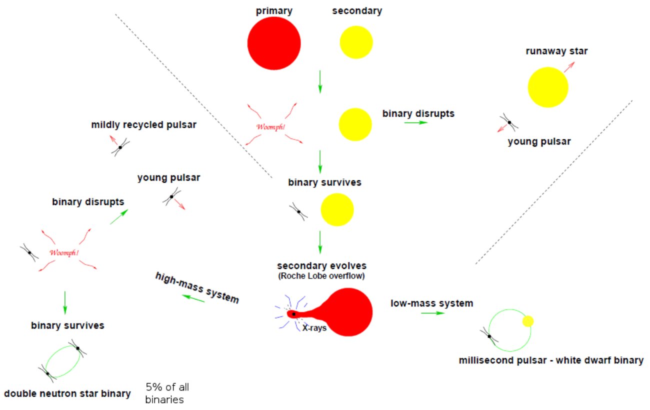

Figure: Lorimer (modified) - Binary evolutionary scenarios

Theoretical Mass Values

Birth mass infered from Chandrasekhar mass: $M_{ch} \approx 1.457 M_{\odot}$
Various corrections for not well understood evolutionary processes:
$M_{birth} \sim 1.06 - 1.57 M_{\odot}$

MSP accretion mass
Typical accretion rates and angular momentum needed for spin up:
$\Delta M_{acc} \approx 0.1 - 0.2 M_{\odot}$

Expected mass order:
DNS $<$ accreating NS $<$ recycled NS $<$ recycled MSP

Maximum mass dependent on EoS
General relativity and causal limit: $M_{max} \sim 3.2 M_{\odot}$
Modern EoSs: $M_{max} \approx 1.5 - 2.2 M_{\odot}$

DNS

Zhang - simple gaussian approach
$M_{DNS} = 1.32 \pm 0.14 M_{\odot}$
heavier $M_{rcy} = 1.38 \pm 0.12 M_{\odot}$
lighter $M_{nrcy} = 1.25 \pm 0.13 M_{\odot}$
Mass ratio - orbital period relation?

Özel - likelihood modeled distribution
$M_{DNS} = 1.33 \pm 0.05 M_{\odot}$
faster $M_{psr} = 1.35 \pm 0.05 M_{\odot}$
slower $M_{cmp} = 1.32 \pm 0.05 M_{\odot}$

Kiziltan - $M_{DNS} = 1.35 \pm 0.13 M_{\odot}$

Özel & Freire - $M_{DNS} = 1.33 \pm 0.09 M_{\odot}$

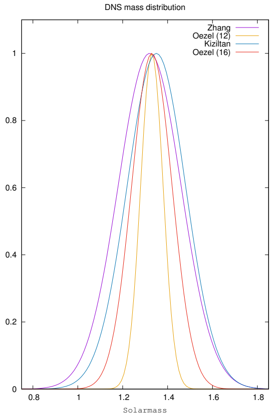

Figure: DNS distribution

Accreting NS/Slow Pulsar

Believed to be sightly above the Birth/DNS mass but wider distributed due to different times of accretion

Investigated by Özel

First approach did not confirm this
$M_{aNS} = 1.28 \pm 0.24 M_{\odot}$ (2012)

Second approach described the hypothesis
$M_{aNS} = 1.49 \pm 0.19 M_{\odot}$ (2016)

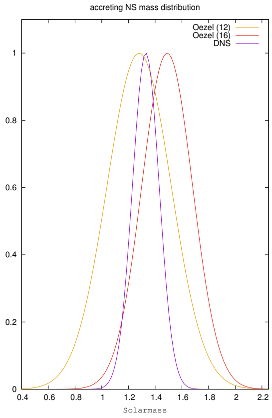

Figure: aNS distribution

NS-WD (recycled NS)

Özel - included MSP and low mass X-ray NS - $M_{rNS} = 1.48 \pm 0.20 M_{\odot}$

Radio method observations alone yielded - $M_{rNS} = 1.46 \pm 0.21 M_{\odot}$

Kiziltan - slightly heavier result - $M_{rNS} = 1.50 \pm 0.25 M_{\odot}$

Özel & Freire - update now even heavier - $M_{rNS} = 1.54 \pm 0.23 M_{\odot}$

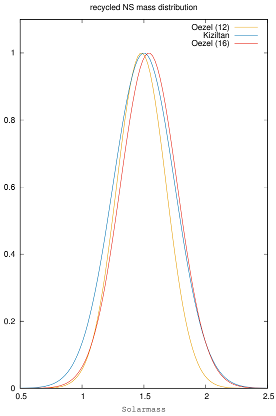

Figure: rNS distribution

MSP

Zhang - included every NS with spin period $< 20ms$ - $M_{MSP} = 1.57 \pm 0.35 M_{\odot}$
Significantly heavier than slow spinning pulsars $M_{MSP} = 1.37 \pm 0.23 M_{\odot}$
4 MSP with masses less than Chandrasekhar mass limit $M_{ch} = 1.44 M_{\odot}$ - AIC?

Özel & Freire - reference paper of Antoniadis et al.(2016) - Double peak population
$M_{AIC?} = 1.388 \pm 0.058 M_{\odot}$
$M_{rMSP} = 1.814 \pm 0.152 M_{\odot}$

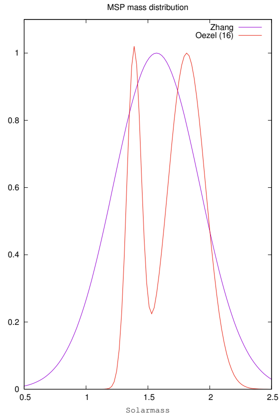

Figure: MSP distribution

Accretion mass

Zhang - infered from accretion mass - spin period relation

$$M = M_{birth} + M_{caracc}(P/ms)^{-2/3}$$

Characteristic accretion mass $M_{caraacc} = 0.43 \pm 0.23 M_{\odot}$

with very low confidence level

Confirmed mass for MSP to be $\Delta M \approx 0.2 M_{\odot}$

Özel - derive formula with spin frequency and moment of inertia

$$\Delta M = 0.034(\frac{\nu_s}{300Hz})^{4/3}(\frac{M}{1.48 M_{\odot}})^{-2/3}(\frac{I}{10^{45} gcm^2})M_{\odot}$$

M not specified and no calculations done

Birth mass

Zhang - infered from relation of accretion mass - spin period
$M = M_{birth} + M_{caracc}(P/ms)^{-2/3}$
$M_{birth} = 1.40 \pm 0.07 M_{\odot}$

Kiziltan - more diverse sample with more rigorous testing needed

Özel - never mentioned one value
$M_{DNS} = 1.33 \pm 0.05 M_{\odot} (1.33 \pm 0.09 M_{\odot})$
$M_{aNS} = 1.28 \pm 0.24 M_{\odot} (1.49 \pm 0.19 M_{\odot})$

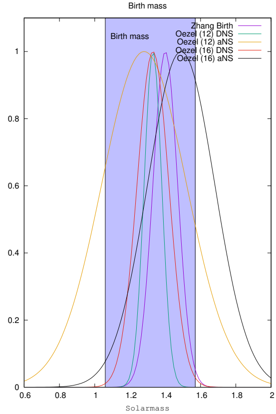

Figure: Birth mass

Maximum mass

Latest maximum mass measured with a good precision $M = 2.01 \pm 0.04 M_\odot$

Higher masses due to 1PK parameter or X-ray - optical

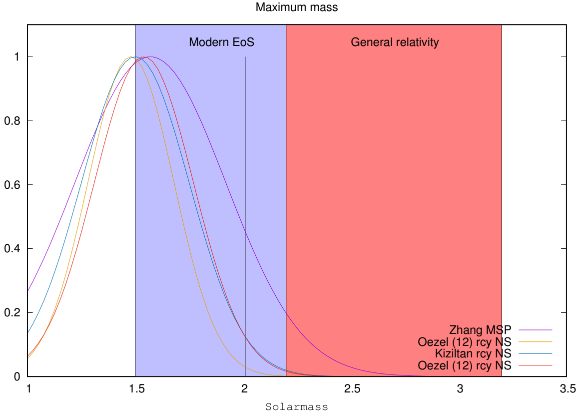

Figure: Maximum mass and EoS limits

Zhang et al.

- Accreting mass for MSP $\sim 0.2M_\odot$
- DNS mass lower than slow NS mass $\Rightarrow$ difference in mass formation or evolutionary history?
- DNS mass ratio - orbital period
- AIC formation rate $< 20\%$ (4/22)

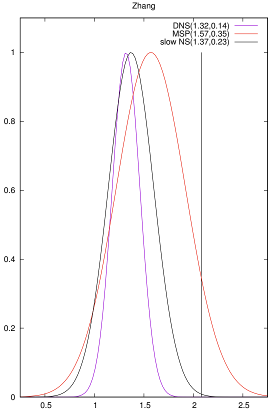

Figure: Zhang distribution

Özel et al.

- Difference: DNS $\not\Leftrightarrow$ other binarys
- Narrow DNS difficult to account for
  Wide distribution by SN fallback
  $\Rightarrow$ evolutionary history to formation
- rNS $0.2 M_\odot$ heavier than aNS/slow pulsars $\Rightarrow$ enough for MSP
- Surprised that $M_{rNS} \ll 2 M_\odot$
  Refine low-mass X-ray binary models
- Some reach comparable $M_{max,NS}$
  collapse into undetected low mass BH

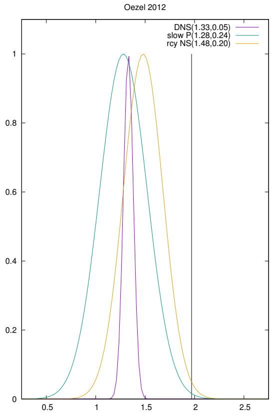

Figure: Özel distribution

Kiziltan et al.

- More diverse sample tested with more rigorous statistics required
- Distribution shows no truncation for high mass NS
  $\Rightarrow$ evolutionary constraint driven limit
- $2M_\odot$ minimum for maximum M_{NS}
  but: typical accretion rates during LMXB phase can't form them
  $\Rightarrow$ non standard evolutionary channels or standard scenario needs revision

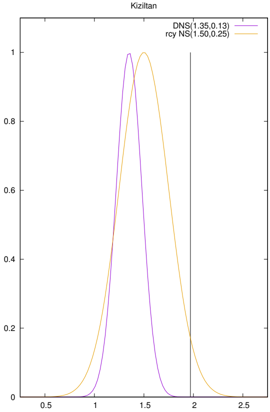

Figure: Kiziltan distribution

Özel and Freire

- Mass not main topic of paper
- Narrowness of DNS stands out but new measurments suggest wider distribution
- Current highest precise mass
  $M = 2.01 \pm 0.04 M_\odot$
  but: see possibility for heavier NS

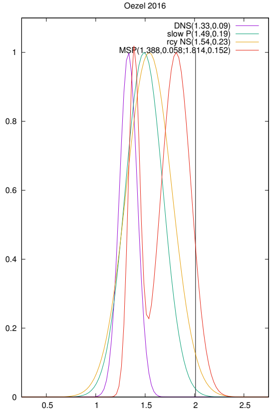

Figure: Özel distribution

Conclusions

- Kiziltan et al. right - two few masses known ($\approx$ 65 of $\sim$ 250)
  Özel and Freire - large increase in upcoming years
- Expected mass increase is shown
  DNS $<$ accreating NS $\leqslant$ recycled NS
- Two MSP types - recycled NS and AIC from WD
- $0.2 M_{\odot}$ enough for MSP creation
- Current max mass known but no clear cut off found

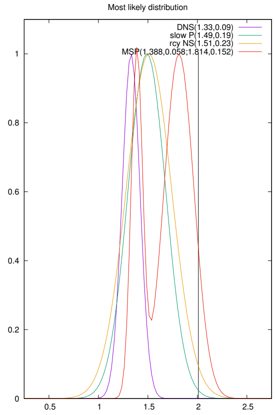

Figure: Likely distribution

Questions

- Birth mass still now well constrained - Possibility for different Birth masses for DNS and other binaries?
- DNS - unusual narrow distribution - evolutionary mechanism, orbital period relation or random statistics?
- How are the heavy NS created? High birth mass, even longer or higher accretion or other evolution?

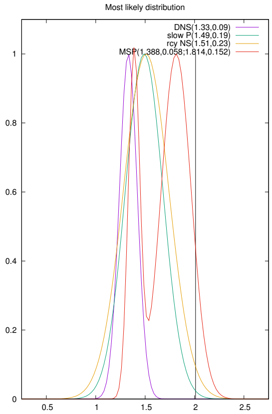

Figure: Likely distribution

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Thank you for your attention!

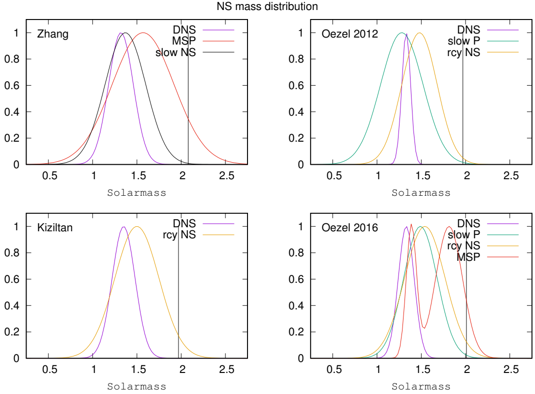

Figure: Mass distribution

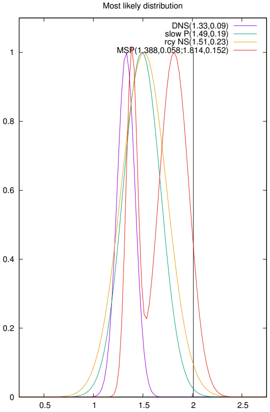

Figure: Likely distribution