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Pulsar Population

The Remnant Mass in Neutron Stars

Literature Report
in Galactic Astronomy
eingereicht von

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1 Pulsars and Neutron Stars

The first mention of the "Possible existence of a Neutron" was made by Chadwick in 1932. Shortly afterwards Landau anticipated a dense-compact star composed of neutrons. In 1934 Baade and Zwickey first mentioned the term "neutron star" and possible evolutionary paths produce a neutron star and put constraints on the mass and radius. The mass is one of the most important parameters of a neutron star. With the birth mass it is possible to infer information about the stellar evolution, core collapse and super nova mechanisms by testing previous studies about the stellar and binary evolution. The maximum mass outlines the low-mass limit for stellar black holes. Furthermore if the matter composition of a neutron star is well constrained by the equation of state it becomes possible to test nuclear physics of superdense matter. Additionally with the gravitational strength of the star it is possible to test Einstein's general relativity in the strong gravity regime.

Even before Baade and Zwickey Chandrasekhar in 1931 and Landau in 1932 calculated theoretical upper mass limits for white dwarfs at $0.91M_{\odot}$ and $1.5M_{\odot}$. Following this work and using formalism's by Tolman, Oppenheimer and Volkoff predicted and upper mass limit for neutron stars between $0.7M_{\odot}$ and $3.4M_{\odot}$. Since then many mass ranges have been heavily discussed in the literature. In 1994 Finn's attempt constrained the mass range to $1.3M_{\odot}$ and $1.6M_{\odot}$. A few years later in 1999 Thorsett and Chakrabarty found the very narrow mass distribution of $1.38^{-0.06}_{+0.10}M_{\odot}$ for the then observed pulsars. But recent observations of pulsars show significant deviations from the canonical value of $1.4M_{\odot}$. Therefore it has become important to find out how exactly the remnant mass of a neutron star is distributed, where the limits towards the white dwarfs and black holes are to predetermine the outcome of future super novae, study the nature of compact remnants and infer the number of neutron stars in the galaxy.

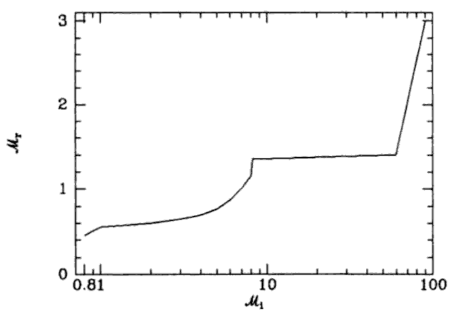

Figure 5.7 The remnant-mass–initial-mass relation. In the range $1 < \mathcal{M}/\mathcal{M}_{\odot} < 8$ the curve follows data published in Weidemann (1990) for solar-neighborhood white dwarfs. For larger masses the curve is more uncertain.

Figure 1.1: Binney, Merrifield - Galactic Astronomy - **Now Outdated**

1.1 Phenomenology

Pulsars are rapidly spinning, highly magnetized neutron stars. They follow the "lighthouse" model meaning the spin axis is not aligned with the symmetry axis of the magnetic field and can only be observed when it's symmetry axis is directed at the earth. The rotational period is normally around a few seconds but can also decrease down to milliseconds. A pulsar's spin is gradually slowing down and therefore increases it's period due to the radiation gradually carrying away the rotational kinetic energy.
The neutron star itself is one possible remnant of a main sequence star after a super nova explosion. The ZAMS mass is believed to be around $8-60M_{\odot}$. The radius of a typical neutron star is around $10km$ which makes the stars probably the most dense objects. This results in unusual high strengths of the magnetic field at the surface ($> 10^{10}T$). The gravitational field at the surface is about 10^{11} times stronger than on earth which should make it make it act like a gravitational lens.
Unlike the spin, period and the magnetic field of a pulsar the mass of the neutron star itself can only be measured in a binary system. This poses a problem because about 90% of all pulsars are isolated stars and therefore now mass measurement is possible.

1.2 Measurements

The precise measurement of the mass is only possible due to the orbital motion in a binary system. There are two different methods in two different observational regimes. The first more common and precise method uses timing measurements in the radio regime. The pulsar's orbit can be described in classical gravity with the five Kelperian parameters. The mass function only needs the binary period P_b, the semi major axis a and the inclination angle i between the orbital angular momentum and the line of sight.

$$f_{mass} = \frac{(M_{cmp}\,sin\,i)^3}{(M_{psr}+M_{cmp})^2} = (\frac{2\pi}{P_b})^2\frac{(a\,sin\,i)^3}{G} \tag{1.1}$$

If the effects of general relativity are measurable these five parameters are not enough. Then the gravitational influence can be measured with the post-Keplerian parameters: $\dot{\omega}$ advance of periastron, $\dot{P}_b$ orbital period decay, γ time dilation-gravitational redshift, r range of Shapiro delay and s shape of Shapiro delay.

$$\dot{\omega} = 3 * (\frac{P_b}{2\pi})^{-5/3}(T_{\odot}M)^{2/3}(1-e^2)^{-1} \tag{1.2}$$

$$\dot{P}_b = \frac{-192\pi}{5} * (\frac{P_b}{2\pi})^{-5/3}(1+\frac{73}{24}e^2+\frac{37}{96}e^4)(1-e^2)^{-7/2}T_{\odot}^{5/3}m_{psr}m_{cmp}M^{-1/3} \tag{1.3}$$

$$\gamma = e * (\frac{P_b}{2\pi})^{1/3} T_\odot^{2/3} M^{-4/3} m_{cmp}(m_{psr} + 2m_{cmp}) \tag{1.4}$$

$$r = T_\odot m_{cmp} \tag{1.5}$$

$$s = a * (\frac{P_b}{2\pi})^{-2/3} T_\odot^{-1/3} M^{2/3} m_{cmp}^{-1} \tag{1.6}$$

With eccentricity e, longitude and time of periastrom passage ω, $T_\odot$ from classical Keplerian. If two of these post-Keperian parameters are measured the individual masses of the pulsar m_{psr} and companion m_{cmp} can be derived. Even more measured parameters present a method to test the consistency of the strong field gravitational theories.

The other significant but not equally precise method only works in a X-ray binary system. In these systems we have an X-ray emitting pulsar and an optical companion. Be measuring the cyclical doppler shifts of the pulse period and the doppler shifts in the spectral features of the optical companion it is possible to infer the masses of both stars. this method has an typical error of about 10%.

Mixing both methods in an analysis about the mass distribution could lead to an additional systematic error besides the normal statistical one and should be handled carefully. Because of the very small sample size choosing the right statistical approach to determine the distribution becomes also very important. A simple Gaussian may yield a good result, but it has to be handled carefully. A better method is the Bayesian approach which reviews the overall likelihood for distribution parameters provided by a Monte Carlo Markov Chain.

1.3 Types and Population

The type of neutron star is closely linked to the initial mass of the system and each follows specific evolutionary paths.

But as mentioned before it is very unlikely to find a neutron star in a binary system after a super nova explosion due to the very high probability that it is kicked out of the binary system from the blast. Unless this happens in a globular cluster where the star can find a new binary system it will last as an isolated star and now mass measurements are possible.

The general evolutionary path for a neutron star in a binary system starts with its own super nova explosion. After the binary system survives the violent conditions of this disruption the neutron star will start to accrete matter from its evolving companion star in an Roche Lobe overflow. During this phase the neutron stars get the simple name of "accreting neutron star" or "slow pulsar" and when observed they are near their birth masses.

In a high mass system the companion star can also evolve into a super nova and if the binary system can also survive the second disruption it will be called a "double

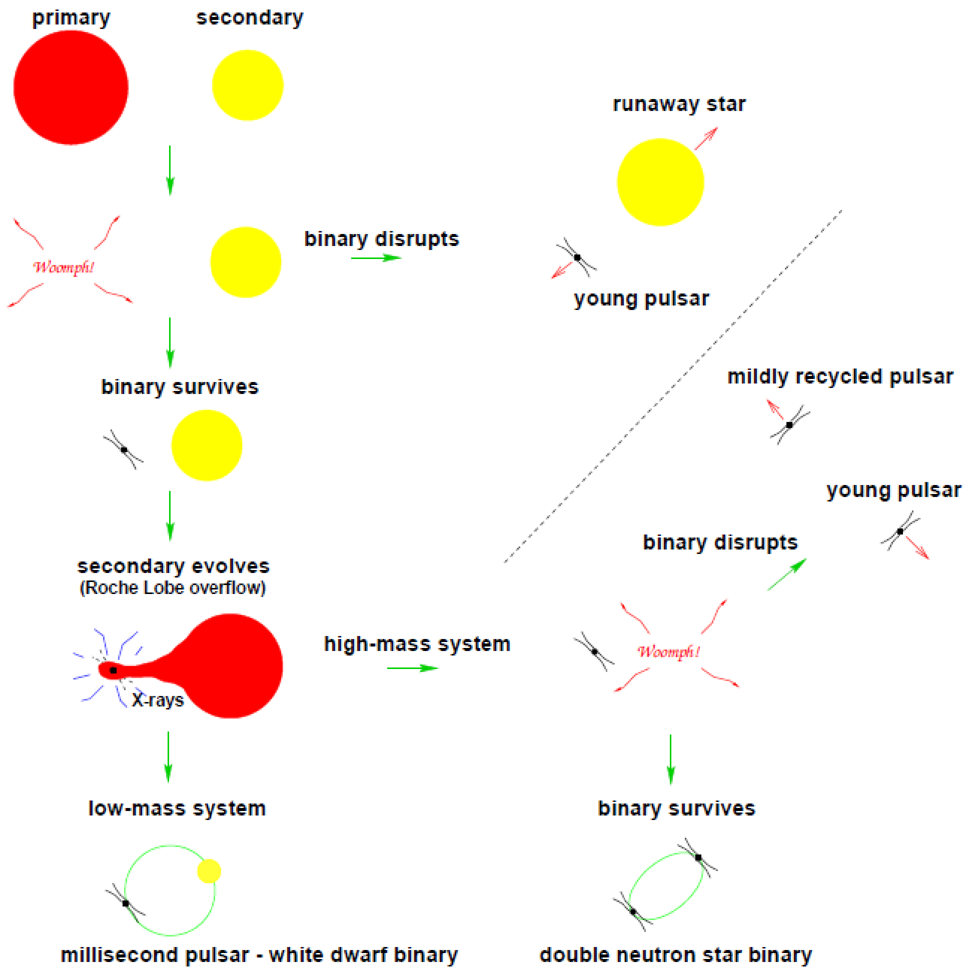

Figure 1.2: Lorimer - Evolutionary scenarios involving binaries

neutron star" system (DNS). Because of the two disruptions of the binary these are quite rare and make up for about 5% of the binary systems. Due to only a short accretion phase both stars will be close to the birth mass of neutron stars with the older one having a little more mass.

In a low mass binary system the neutron star becomes a "recycled neutron star" due to the extended mass accretion from his companion through winds, a disk or a common envelope. The mass accretion turns the system into the observable x-ray binary. After the accretion phase the companion star turns into a white dwarf making the binary a so called "white dwarf-neutron star" system (WDNS).

Depending on the accreted mass and by that the transferred angular momentum the neutron stars period can reach the millisecond regime making it one of the "millisecond pulsars" (MSP). These millisecond pulsars not only have a very fast rotation bur also a very stable one. The Period-Period decay diagrams suggest that about 30% of the millisecond pulsars are produced through non-standard evolutionary channels. One possible channel are "accretion induced collapses" (AIC) where white dwarfs accrete mass until they reach the Chandrasekhar mass and then go trough a core collapse turning them into neutron stars.

1.4 Theoretical Mass Values

Since the first mention of neutron stars multiple mass constraints have been calculated and proposed.

One of particular interest is the birth mass. The previous canonical mass of $1.4M_\odot$ is an approximation for the critical mass beyond which the remnant core will lose gravitational stability and collapse into a neutron star. The critical mass is more precisely defined through the Chandrasekhar mass $M_{ch} = 5.83Y_e^2 = 1.457M_\odot$ with the electron fraction $Y_e = n_p/(n_p + n_e) = 0.5$. This value has to be corrected to a smaller value because of a more reasonable smaller electron fraction, general relativistic implications, surface boundary pressure and a reduction of pressure from the Coulomb interactions at high pressure. But the electrons of the progenitor material are not completely relativistic leading to an increase of required mass to reach the gravitational potential that collapses the star. Also finite entropy corrections and rotational effects lead to a higher stable mass. These processes are not well understood and the different evolutionary paths lead to uncertainties of about 20%. As this is the baryonic mass we also have to apply a quadratic correction to obtain the actual measured effective gravitational masses, therefore $M_{birth} \sim 1.08 - 1.57M_\odot$ according to Kiziltan and $M_{birth} \sim 1.06 - 1.22M_\odot$ to Özel.

The actual mass then depends on the amount of fallback of stellar matter during the super nova explosion and the length of the time of stable accretion. Meaning DNS and slow pulsars should both be around their birth mass due to only short or still ongoing accretion phases. With typical accretion rates of $\dot{m} \sim 10^{-3}\dot{M}_{Edd}$ and estimations on the amount of angular momentum needed to spin up the neutron star to millisecond periods the accretion mass is proposed to be $\Delta m_{acc} \approx 0.1 - 0.2M_\odot$.

The maximum mass of a neutron star highly depends on its composition and is directly linked to equation of state (EOS). The composition is hard to study leading to wide range of very different theoretical EOS. But upper limits can be found by numerically integrating the Oppenheimer-Volkoff equations which lead Rhoades & Ruffini to an extreme upper bound reasoned by general relativity at $M_{max} \sim 3.2M_\odot$ in 1974. More modern EOSs give a new range $M_{max} \approx 1.5 - 2.2M_\odot$ by Thorsson(1994) and Kalogera & Baym (1996).

2 Mass Distribution

2.1 General approach

The general approach used by each group is important to evaluate the obtained results and understand the flaws.
The first paper in question was published in 2011. Zhang et al. started with a simple statistical mass analysis of all neutron stars in binaries. The Gaussian distribution fitted onto the data yielded $M = 1.4 \pm 0.19 M_{\odot}$ which coincides with the canonical mass value. But they acknowledged the drawback of using neutron stars in different types of evolutionary stages. Therefore their investigation concentrated on the pulsar recycling hypothesis and divided their sample depending on the spin period of the pulsar.
In 2012, Özel et al. questioned the work of Schwab (2010). Schwab used a bimodal distribution which for double neutron stars which yielded two very narrow mass peaks with errors of $0.008 M_{\odot}$ and $0.025 M_{\odot}$. Özel raised the question if double neutron stars are a representative sample for the birth mass of neutron stars. Therefore they modeled distributions for different subgroups of neutron stars based on the spin and companion nature to find the most likely parameter values. Hence they also included measurements not only of the pulsar timing method but also based on the X-ray method.
One year later Kiziltan et al. wanted to derive useful quantities like the birth mass, accreted mass and a maximum mass. They thought a single homogeneous population would be over-simplistic because of the increasing number of mass measurements that evidently differ from the canonical value especially in globular clusters. So they divided the neutron stars into a group of double neutron stars and white dwarf neutron star binaries and searched for the most likely parameters with a Monte Carlo Markov Chain.
At last Özel et al. took another look at the latest mass measurements in DNS and WD-NS systems, combined them with radii measurements to draw conclusions about the EOS. These latest used masses with low uncertainties from pulsar timing were in a range of $1.17 - 2.01 M_{\odot}$. In the case of unresolved masses and more inaccurate measurements from the X-ray regime these range can be exceeded.

2.2 Mass results

2.2.1 Double Neutron Stars

Zhang et al. averaged the mass of all neutron stars in DNS systems with a simple Gaussian at $M_{DNS} = 1.32 \pm 0.14 M_{\odot}$. Additionally he looked separately at the higher mass recycled ($M_{rcy} = 1.38 \pm 0.12 M_{\odot}$) and lower mass non-recycled ($M_{nrcy} = 1.25 \pm 0.13 M_{\odot}$) neutron stars and derived a mass ratio close to unity ($q = 0.91$) with two outliers which conincidentally are also the only systems with orbital periods around 10 days while the others are around or less than a day. Statistically there can not be drawn any conclusion from this.
Özel et al. (2012) on the other hand modeled the distribution and came nearly to the same result with an even smaller dispersion $M_{DNS} = 1.33 \pm 0.05 M_{\odot}$. They divided the neutron stars by their pulsar timing with the faster one being the "pulsar" ($M_{psr} = 1.35 \pm 0.05 M_{\odot}$) and the slower as the "companion" ($M_{cmp} = 1.32 \pm 0.05 M_{\odot}$). Therefore their mass ratio is even closer to unity ($q = 0.98$). In a final step they compared the predicted cumulative distribution for neutron star pairs independently drawn from a single Gaussian and a double Gaussian with the observed systems. The single Gaussian described the overall distribution because the double Gaussian favored mass ratios closer to unity.
With a similar modeling approach Kiziltan et al. determined the mass of a neutron star in a DNS system. Their result was very similar with $M_{DNS} = 1.35 \pm 0.13 M_{\odot}$. For their paper they did not divide the stars into two further subgroups.
At last Özel et al. (2016) updated their general mass result with a slightly bigger diviation $M_{DNS} = 1.33 \pm 0.09 M_{\odot}$ because of new measurements of DNS systems with significant lower mass ratios of $q = 0.75$.

2.2.2 Accreting NS / Slow Pulsar

Zhang et al. and Kiziltan et al. did not look at this population thus the only result was yielded by Özel et al from high mass binaries and slow pulsars. As these stars are believed to be close to their birth mass like the stars in DNS systems but were significantly wider distributed the most likely modeling value was shifted a bit and had a significantly higher dispersion ($M_{NS} = 1.28 \pm 0.24 M_{\odot}$). They improved this result by combining it with the numerical results of Rawls et al. about eclipsing X-ray pulsar binaries (2011) and got $M_{NS} = 1.24 \pm 0.20 M_{\odot}$ as a result.
In 2016 found a new result with $M_{NS} = 1.49 \pm 0.19 M_{\odot}$ which would describe the ongoing accretion in a better fashion due to the higher mass compared to the DNS system masses.

2.2.3 White Dwarf - Neutron Star System (Recycled)

As Zhang et al. divided the pulsars by spin period they had no explicit look at recycled neutron stars in a WDNS system. In this group Özel et al. included also the Millisecond Pulsars and low mass X-ray binaries which are still undergoing accretion. Their most likely value was yielded at $M_{rNS} = 1.48 \pm 0.20 M_\odot$. Because of the inclusion of the larger uncertainties of spectroscopic measurements from the X-ray binaries they did the same modeling also without these stars and found a very similar value $M_{rNS} = 1.46 \pm 0.21 M_\odot$.
A year later Kiziltan et al. used the similar likelihood modeling which resulted in a slightly increased mass of $M_{rNS} = 1.50 \pm 0.25 M_\odot$ and when Özel et al. revisited these stars he got an even higher distribution $M_{rNS} = 1.54 \pm 0.23 M_\odot$.

2.2.4 Millisecond Pulsar

Zhang et al. counted every pulsar with a spin period lower than 20ms as a MSP. Their mass was averaged at $M_{MSP} = 1.57 \pm 0.35 M_\odot$ and was significantly higher than the mass of all the slower rotating neutron stars. This proved the association of the spin-up with the increased mass. 4 of the MSP had masses less than the Chandrasekhar mass limit of $1.44 M_\odot$. They argued that these are possible "Accretion Induced Collapse" candidates but acknowledge the possibility of a really low birth mass.
The other groups did not investigate the MSP population any further but Özel et al. mention in their last paper the work of Antoniadis et al. (2016) about the millisecond pulsar distribution who found a possibility of two peaks in the population. Those peaks appeared at $M_{MSP} = 1.388 \pm 0.058 M_\odot$ and $M_{MSP} = 1.814 \pm 0.152 M_\odot$.

2.3 Deduced Masses

2.3.1 Birth Mass

Zhang et al. based their birth mass on a accretion mass - spin period relation:

$$M = M_{birth} + M_{ca}(P/ms)^{-2/3} \tag{2.1}$$

with the spin period P and a characteristic accretion mass M_{ca} when a pulsar is spun-up to one ms. This resulted in a birth mass of $M_{birth} = 1.40 \pm 0.07 M_\odot$ but with a very low confidence level. On the other hand Özel et al. avoided to mention one value and always referenced the mass of the neutron stars in DNS systems ($M_{DNS} = 1.33 \pm 0.05 M_\odot$) and slow pulsars ($M_{NS} = 1.28 \pm 0.24 M_\odot$).

2.3.2 Accretion Mass

With (2.1) Zhang et al. had a general solution with low confidence level for the accretion mass - spin period relation. The characteristic accretion mass turned out to be $M_{ca} = 0.43 \pm 0.23 M_{\odot}$. For the accretion mass needed to create a MSP they look at the mass difference of the two period regimes which yields $\sim 0.2 M_{\odot}$. Özel et al. agreed with this value and the sufficiency to create MSPs with this kind of mass. Additionally they proposed another formula to calculate the mass required to spin-up the pulsar:

$$\Delta M = 0.034 (\frac{\nu_s}{300 Hz})^{4/3} (\frac{M}{1.48 M_{\odot}})^{-2/3} (\frac{I}{10^{45} gcm^2}) M_{\odot} \tag{2.2}$$

with spin frequency ν_s and moment of inertia I.

2.4 Further Results

The following is still work in progress and only contains some incomplete or obsolete notes

No reliable determination possible if NS or QS - note terminology NS does not implay any details of nuclear matter composition (z)
high mass NS favor a stiff EOS, low mass a soft EOS - recycling could change the EOS and make a phase transition of nuclear matter possible (z)
Discussion of birth masses, increased dispersion of neutron star masses for DNS expected, Accreting and slow pulsars mass who are believed to be near birth mass are in agreement with expectations of core collapse (ö1)
Test if the method can detect a potential truncation at the high mass end, none is found - high mass end driven by evolutionary constraints, not general relativity of EOS (k)
mass of 2M minimum secure limit for maximum NS mass, all EOS with max NS mass lower 2M ruled out (k)
Evolution Problem for NS-WD, Peaks between DNS and NS-WD are consistent with accretion mass 0.15M but typical accretion rate during LMXB cannot form 2M NS, would require long term stable active accretion at unusually high rates - non standard evolutionary channel creates unusual distribution width (k)
standard recycling scenario needs revision (k)
Every theoretical EOS can be modeled into a mass-radius relation, NS mass and radius can place strong constraints on the properties and interactions of cold ultradense matter (ö2)
maximum mass at 2.01+-0.04(check maximum masses from other papers) (ö2)

possibility of more massive NS when it irradiates their low-mass companion, no convincing result yet (ö2)
EOS constraint by minimal max mass, combining with radii measurements yields smaller allowed confidence regions in the EOS parameters (ö2)

3 Conclusion

Just a few first notes and there will be more about the masses and what this will mean for the evolution and the different systems

Right now at the start of constraining the mass distribution with the first mass measurements, many more surveys will start observing with higher precision and many more NS will be found
Results are first indicator for specific mass values and ranges and help to understand the evolution of stars a little better

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