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Study of measured pulsar masses and their possible conclusions

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ABSTRACT

We study the statistics of 61 measured masses of neutron stars (NSs) in binary pulsar systems, including 18 double NS (DNS) systems, 26 radio pulsars (10 in our Galaxy) with white dwarf (WD) companions, 3 NSs with main-sequence companions, 13 NSs in X-ray binaries, and one undetermined system. We derive a mean value of $M = 1.46 \pm 0.30\ M_\odot$. When the 46 NSs with measured spin periods are divided into two groups at 20 milliseconds, i.e., the millisecond pulsar (MSP) group and others, we find that their mass averages are, respectively, $M = 1.57 \pm 0.35\ M_\odot$ and $M = 1.37 \pm 0.23\ M_\odot$. In the framework of the pulsar recycling hypothesis, this suggests that an accretion of approximately $\sim 0.2\ M_\odot$ is sufficient to spin up a neutron star and place it in the millisecond pulsar group. Based on these estimates, an approximate empirical relation between the accreting mass (ΔM) of recycled pulsar and its spin period is proposed as $\Delta M = 0.43\ (M_\odot)(P/1\ \mathrm{ms})^{-2/3}$. If we focus only on the DNS, the mass average of all 18 DNSs is $1.32 \pm 0.14\ M_\odot$, and the mass averages of the recycled DNSs and the non-recycled NS companions are, respectively, $1.38 \pm 0.12\ M_\odot$ and $1.25 \pm 0.13\ M_\odot$. This is consistent with the hypothesis that the masses of both NSs in DNS system have been affected by accretion. The mass average of MSPs is higher than the Chandrasekhar limit $1.44\ M_\odot$, which may imply that most of binary MSPs form via the standard scenario by accretion recycling. If we were to assume that the mass of a MSP formed by the accretion induced collapse (AIC) of a white dwarf must be less than $1.35\ M_\odot$, then the portion of the binary MSPs involved in the AICs would not be higher than 20%, which imposes a constraint on the AIC origin of MSPs. With accreting mass from the companion, the nuclear matter composition of MSP may experience a transition from the "soft" equation of state (EOS) to a "stiff" EOS or even neutron to quark matter.

Key words. pulsars: general – stars: neutron

1. Introduction

Mass is one of the important parameters of a neutron star (NS), from which we can infer the stellar evolution of its progenitor, the nuclear matter composition of a compact object (e.g. Haensel et al. 2007) or its equation of state (EOS), and strength of gravitational field if the NS radius is known. In other words, the precise mass measurements can provide significant tests of studies of stellar evolution, nuclear physics of superdense matter, and Einstein's general relativity in the strong gravity regime (Lattimer & Prakash 2004, 2007; Kramer & Stairs 2008), as well as insight into binary evolution since NS masses are measured in binary systems.

A NS is one of the possible ends for a massive star with mass greater than $\sim$4–8 $M_\odot$. After having finished burning the nuclear fuel, a star undergoes a supernova (SN) explosion, and the central region of the star collapses under gravity to form a NS in the central supernova remnant (SNR) (Haensel et al. 2007). Hence, the NS mass statistics help the astronomers to infer the properties of its progenitor star, and its links to SN and SNR. However, unlike the other NS parameters, e.g. spin period and magnetic field, NS mass is only measured in the binary system (e.g. Freire et al. 2008a; Lorimer 2008; Lyne & Smith 2005). Therefore, the statistics of the measured NS masses may provide information about the NS accretion history in the binary phases (e.g. Stairs 2004; Manchester 2004; Bhattacharya & van den Heuvel 1991).

An accurate measurement of a NS mass in a pulsar binary system needs five relativistic post-Keplerian parameters, e.g., the periastron advance, time dilation, orbital shrinking rate, and Shapiro delays, which can in principle be measured. All of these relativistic parameters place constraints on the NS masses, and when three are measured, an accurate determination of NS masses becomes possible (e.g. Lorimer 2008; Freire 2004, 2008a,b, 2009). The NS masses have been measured precisely in double neutron-star (DNS) systems, such as the first discovered pulsar PSR B1913+16 (Hulse & Taylor 1975; Taylor & Weisberg 1982) and double pulsar system PSR J0737-3039 (Burgay et al. 2003; Lyne et al. 2004; Kramer & Stairs 2008), because the eccentric orbits of both systems provide well-measured relativistic parameters. Unlike DNSs, masses of millisecond pulsars (MSPs) are not easy to determine, since their binary orbits are so circular (or of such low eccentricity) that normally no sufficient relativistic effects can be used to provide extra equations to solve the masses (Freire 2000; Freire et al. 2004). Therefore, the masses of MSP systems are often measured with large errors, such as PSR J0514C4002A

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Table 1. Parameters of neutron stars in X-ray binaries.

System	$M(M_\odot)$	$M_c(M_\odot)$	P_{orb}(d)	P_{spin}(ms)	Eccentricity	*type*	Refs.
4U 1538-52	$1.06^{+0.41}_{-0.34}$	$16.4^{+5.2}_{-4.0}$	3.73	5.28×10^5	0.08	HMXB	X1
SMC X-1	1.05 ± 0.09	15.5 ± 1.5	3.89	708	$<4 \times 10^{-5}$	HMXB	X2
Cen X-3	1.24 ± 0.24	19.7 ± 4.3	2.09	4814	$<8 \times 10^{-4}$	HMXB	X3
LMC X-4	1.31 ± 0.14	15.6 ± 1.8	1.41	1.35×10^4	<0.01	HMXB	X2
Vela X-1	1.88 ± 0.13	23.1 ± 0.2	8.96	2.83×10^5	0.09	HMXB	X4
	1.86 ± 0.16	23.8 ± 0.2	8.96	2.83×10^5	0.09	HMXB	X4
$4U1700 - 37^*$	2.44 ± 0.27	58 ± 11	3.41	No	0.2	HMXB	X5
Her X-1	1.5 ± 0.3	2.3 ± 0.3	1.70	1240	$<3 \times 10^{-4}$	XB	X6
4U1820-30	$1.29^{+0.19}_{-0.07}$	≤ 0.106	0.08	6.9×10^5	No	XB	X7
2A 1822-371	0.97 ± 0.24	0.33 ± 0.05	0.23	590	<0.03	LMXB	X8
XTE J2123-058	$1.46^{+0.30}_{-0.39}$	$0.53^{+0.28}_{-0.39}$	0.25	3.9	No	LMXB	X9
Cyg X-2	1.78 ± 0.23	0.60 ± 0.13	9.84	No	0.0	LMXB	X10
	1.5 ± 0.3	0.63 ± 0.16	9.84	No	0.0	LMXB	X10
V395 CAR/2S 0921ÍC630	1.44 ± 0.10	0.35 ± 0.03	9.02	No	No	LMXB	X11
Sax J 1808.4-3658	<1.4	<0.06	0.08	2.49	<0.0005	LMXB	X12
HETE J1900.1-2455	<2.4	<0.085	0.06	2.65	<0.005	LMXB	X13

Notes. $^{(*)}$ The compact object may be a black hole (Lattimer & Prakash 2007). LMXB – Low-mass X-ray binary, HMXB – High-mass X-ray binary.

References. X1 – van Kerkwijk et al. (1995) (M, M_c, P_{orb}, eccentricity); Robba et al. (2001) (P_s). X2 – van Kerkwijk et al. (1995) (P_{orb}, eccentricity); van der Meer et al. (2005) (M, M_c); van der Meer et al. (2007) (P_s). X3 – van Kerkwijk et al. (1995); Ash et al. (1999) (P_{orb}, eccentricity); van der Meer et al. (2005) (M, M_c); van der Meer et al. (2007) (P_s). X4 – Quaintrell et al. (2003) ($M = 2.27,1.88\ M_\odot$, M_c, P_{orb}, eccentricity, P_s); Barziv et al. (2001) ($M = 1.86\ M_\odot$). X5 – Clark et al. (2002) (M, M_c); Hammerschlag-Hensberge et al. (2003) (P_{orb}, eccentricity). X6 – Cheng et al. (1995) (P_{orb}, eccentricity); Reynolds et al. (1997) (M, M_c); Liu et al. (2000) (P_s); van der Meer et al. (2007) (P_s). X7 – Wang et al. (2010) (M, M_c, eccentricity, P_s); Shaposhnikov et al. (2004) (M, P_{orb}); Dib et al. (2005) (P_{orb}). X8 – Jonker & van der Klis (2001) (P_{orb}, eccentricity, P_s); Jonker et al. (2003) (M, M_c). X9 – Tomsick et al. (1999) (P_s); Tomsick et al. (2002) (M, M_c, P_{orb}, eccentricity). X10 – Cowley et al. (1979) (P_s); Orosz & Kuulkers (1999) (M, M_c, P_{orb}, eccentricity); Elebert et al. (2009a). X11 – Steeghs & Jonker (2007) (1.44 $M_\odot$); Shahbaz & Watson (2007) (1.370.13 $M_\odot$). X12 – Elebert et al. (2009b); Chakrabarty & Morgan (1998); Jain et al. (P_{orb}). X13 – Elebert et al. (2008); Kaaret et al. (2006) (P_{orb}).

(Freire et al. 2004), except in cases of high eccentricity. The observations of relativistic parameters in pulsar binary systems have presented the first application of general relativity and provided the most widely available laboratories for testing theories of gravitation (e.g. Hulse & Taylor 1975; Taylor & Weisberg 1982; Weisberg & Taylor 2003; Thorsett et al. 1993; Stairs et al. 2002).

Mass measurements are also possible in X-ray binaries, where a neutron star X-ray pulsar and an optical companion reside. Careful monitoring of the cyclical Doppler shifts of the pulse period and Doppler shifts of the spectral features of the optical companion can be used to determine the orbital period as well as the radial velocity, which provide/infer the mass function of the system. Both masses are known when the inclination angle of an eclipsing binary system can be measured (e.g. van Kerkwijk et al. 1995; Jonker et al. 2003). The accuracy of this method is not so high as that of measuring DNS mass, usually being affected by an error of about ∼10% or more (see Table 1).

Thorsett and Chakrabarty (TC99) presented the results of a statistical study of 19 NS binary systems, and obtained a Gaussian distribution of mass around 1.35 $M_\odot$, with a narrow deviation of 0.04 $M_\odot$. The sample has increased significantly since then. There are now about 61 NSs with measured (estimated) masses in various types of binary systems.

In this paper, we present a statistical analysis of the masses of NSs in binaries using the current data set, and investigate in particular the pulsar recycling hypothesis. We present a compilation of all NS mass observations in Sect. 2. In Sect. 3, we study the relation between the NS mass and its spin period. Our conclusions are given in Sect. 4.

2. Statistics of pulsar masses

2.1. NS mass distribution

In Tables 1–3, we list all known NSs with measured and estimated masses, including their binary parameters when available. In Table 1, we list the 13 systems consisting of X-ray NSs with low or high mass post-main-sequence star companions. In Table 2, we first list the 18 DNSs that have masses with high accuracies, then 16 radio pulsars with WD companions, 3 radio pulsars with the main-sequence star companions and one uncertain system. In Table 3, we also list the 10 Galactic radio pulsars with WD companions.

To illustrate all NS mass distributions, a histogram of NS masses is plotted in Fig. 2, where a fitted Gaussian distribution function is shown with a mean mass of 1.40 $M_\odot$ and a small uncertainty of 0.19 $M_\odot$, that is slightly higher than the previous statistical mean value of 1.35 ± 0.04 $M_\odot$ by TC99. About ∼67% (∼90%) of all NSs are within the range of 1.2 $M_\odot$–1.6 $M_\odot$ (1.0 $M_\odot$–1.8 $M_\odot$). The NSs with masses over 1.8 $M_\odot$ represent about ∼10% of all samples. The maximum and minimum values of NS masses are, respectively, 2.74 ± 0.2 $M_\odot$ (J1748-2021B) and 0.97 ± 0.24 $M_\odot$ (2A 1822-371).

It is interesting to investigate why the present NS mass average is higher than that measured ten years ago. The data of NS

Table 2. Parameters of radio binary pulsars.

System	$M(M_\odot)$	$M_c(M_\odot)$	P_{orb}(d)	P_{spin}(ms)	Eccentricity	type	Refs.
J1518+4904	$1.56^{+0.20}_{-1.20}$	$1.05^{+1.21}_{-0.14}$	8.63	40.9	0.249	DNS	R1
J1811-1736	$1.5^{+0.12}_{-0.4}$	$1.06^{+0.45}_{-0.1}$	18.8	104.2	0.828	DNS	R2
J1829+2456	$1.15^{+0.1}_{-0.25}$	$1.35^{+0.46}_{-0.15}$	1.176	41.0	0.139	DNS	R3
B1534+12	1.33 ± 0.0020	1.35 ± 0.0020	0.421	37.9	0.274	DNS	R4
B1913+16	1.44 ± 0.0006	1.39 ± 0.0006	0.323	59.0	0.617	DNS	R5
B2127+11C	1.35 ± 0.080	1.36 ± 0.080	0.335	30.5	0.681	DNS	R6
J0737-3039A(B)	1.34 ± 0.010	1.25 ± 0.010	0.102	22.7 (2773)	0.088	DNS	R7
J1756-2251	$1.40^{+0.04}_{-0.06}$	$1.18^{+0.06}_{-0.04}$	0.320	28.5	0.181	DNS	R8
J1906+0746$^{@}$	1.25	1.37	0.166	144	0.085	DNS	R9
J0437-4715	1.58 ± 0.18	0.24 ± 0.017	5.74	5.76	1.9×10^{-5}	NSWD	R10
J0621+1002	$1.70^{+0.59}_{-0.63}(^{+0.32}_{-0.29})$	$0.97^{+0.43}_{-0.24}(^{+0.27}_{-0.15})$	8.32	28.9	0.003	NSWD	R11
J0751+1807	1.26 ± 0.14	0.19 ± 0.03	0.263	3.48	3×10^{-6}	NSWD	R12
	$2.1^{+0.4}_{-0.5}$(corrected)	0.19 ± 0.03	0.263	3.48	3×10^{-6}	NSWD	R12
J1012+5307	1.7 ± 1.0	0.16 ± 0.02	0.605	5.26	$<10^{-6}$	NSWD	R13
	1.64 ± 0.22	0.16 ± 0.02	0.605	5.26	$<10^{-6}$	NSWD	R13
J1045-4509	<1.48	0.13	4.08	7.47	$<10^{-5}$	NSWD	R14
J1141-6545	1.27 ± 0.01	1.02 ± 0.01	0.198	394	0.172	NSWD	R15
	1.3 ± 0.02	0.986 ± 0.02	0.198	394	0.172	NSWD	R15
J1713+0747	$1.53^{+0.08}_{-0.06}(1.6 \pm 0.24)$	0.33 ± 0.04	67.83	4.75	7.5×10^{-5}	NSWD	R16
B1802-07	$1.26^{+0.15}_{-0.67}$	$0.36^{+0.67}_{-0.15}$	2.62	23.1	0.212	NSWD	R17
J1804-2718	<1.73	0.2	11.1	9.34	4×10^{-5}	NSWD	R18
B1855+09	$1.58^{+0.10}_{-0.13}$	$0.27^{+0.010}_{-0.014}$	12.33	5.36	2.2×10^{-5}	NSWD	R19
J1909-3744	1.44 ± 0.024	0.20 ± 0.0022	1.53	2.95	10^{-7}	NSWD	R20
J2019+2425	<1.51	0.32–0.35	76.5	3.93	1.1×10^{-4}	NSWD	R21
B2303+46	1.34 ± 0.10	1.3 ± 0.10	12.34	1066	0.658	NSWD	R22
J0437-4715	1.76 ± 0.20	0.25 ± 0.018	5.74	5.76	1.918×10^{-5}	NSWD	R23
J1023+0038	1.0–3.0	0.14–0.42	0.198	1.69	$\leq 2 \times 10^{-5}$	NSWD	R24
J1738+0333	1.6 ± 0.2	0.2	0.354	5.85	1.1×10^{-6}	NSWD	R26
J0045-7319	1.58 ± 0.34	8.8 ± 1.8	51.17	926	0.808	NSMS	R27
J1740-5340	1.53 ± 0.19	>0.18	1.35	3.65	$<10^{-4}$	NSMS	R28
J1903+0327	1.67 ± 0.01	1.05	95.17	2.15	0.437	NSMS	R29
J1753-2240	~ 1.25	~ 1.25	13.64	95.1	0.304	uncertain	U

Notes. DNS – double neutron star; NSWD – pulsar-white dwarf binary; NSMS – neutron star/main-sequence binary; $^{(@)}$ The recycled NS should be the companion because of the strong magnetic field of PSR J1906+0746 $\sim 10^{12}$ G.

References. R1 – Nice et al. (1995) (P_{orb}, P_s, eccentricity); TC99 (M, M_c); Janssen et al. (2008) ($m_p < 1.17$ and $m_c > 1.55\ M_\odot$). R2 – Lyne et al. (2001) (P_{orb}, P_s, eccentricity); Lorimer et al. (2008) (M, M_c); Breton (2009) (M, M_c). R3 – Champion et al. (2004) (P_{orb}, P_s, eccentricity); Lorimer et al. (2008) (M, M_c); Breton et al. (2009) (M, M_c). R4 – Wolszczan (1991) (P_{orb}, P_s, eccentricity); Stairs et al. (2002) (M, M_c). R5 – Hulse & Taylor (1975) (P_{orb}, P_s, eccentricity); Weisberg & Taylor (2003) (M, M_c). R6 – Anderson et al. (1990) (P_{orb}, P_s, eccentricity); Jacoby et al. (2006); TC99 (M, M_c). R7 – Burgay et al. (2003) (P_{orb}, P_s, eccentricity); Lyne et al. (2004) (M, M_c). R8 – Manchester et al. (2001) (P_{orb}, P_s, eccentricity); Faulkner et al. (2005) (M, M_c). R9 – Lorimer & Stairs (2006) (P_{orb}, P_s, eccentricity); Kasian et al. (2008); Lorimer et al. (2008) (M, M_c); Breton et al. (2009) (M, M_c). R10 – Johnston et al. (1993) (P_{orb}, P_s, eccentricity); van Straten et al. (2001) (M, M_c). R11 – Camilo et al. (1996) (P_{orb}, P_s, eccentricity); Splaver et al. (2002) (M, M_c). R12 – Lundgren et al. (1995) (P_{orb}, P_s, eccentricity); Nice et al. (2004) (M, M_c); Nice et al. (2005), Nice et al. (2008) (M, M_c). R13 – Nicastro et al. (1995) (P_{orb}, P_s, eccentricity); van Kerkwijk et al. (1996), (2005; Callanan et al. (1998); TC99 (M, M_c). R14 – Bailes et al. (1994) (P_{orb}, P_s, eccentricity); TC99 (M, M_c). R15 – Kaspi et al. (2000) (P_{orb}, P_s, eccentricity); Burgay et al. (2003) (M, M_c); Bailes et al. (2003); Bhat & Bailes, (2008) (M, M_c). R16 – Foster et al. (1993 (P_{orb}, P_s, eccentricity); Splaver et al. (2005) (M, M_c). R17 – D'Amico et al. (1993) (P_{orb}, P_s, eccentricity); TC99 (M, M_c); Lorimer et al. (2008) (M, M_c); Breton et al. (2009) (M, M_c); Freire (2000). R18 – Lorimer et al. (1996) (P_{orb}, P_s, eccentricity); TC99 (M, M_c); Breton et al. (2009) (M, M_c). R19 – Segelstein et al. (1986) (P_{orb}, P_s, eccentricity); Nice et al. (2003) (M, M_c). R20 – Jacoby et al. (2003) (P_{orb}, P_s, eccentricity); Jacoby et al. (2005) (M, M_c). R21 – Nice et al. (1993) (P_{orb}, P_s, eccentricity); Nice et al. (2001) (M, M_c). R22 – Dewey et al. (1985) (P_{orb}, P_s, eccentricity); Kerkwijk & Kulkarni (1999) (M, M_c). R23 – Johnston et al. (1993) (P_{orb}, P_s, eccentricity); van Beveren et al. (2008) (M, M_c). R24 – Archibald et al. (2009) (P_{orb}, P_s, eccentricity, M, M_c). R26 – Jacoby, PhD Thesis, (2004); Freire PhD Thesis, (2000). R27 – Bell & Bessell et al. (1995) (M, M_c); Kaspi et al. (1996) (P_{orb}, P_s, eccentricity). R28 – Kaluzny et al. (2003) (P_{orb}, M); D'Amico et al. (2001) (P_s, eccentricity, M_c). R29 – TC99 (P_{orb}, P_s, eccentricity, M_c). R29 – Champion et al. (2008) (P_{orb}, P_s, eccentricity, M, M_c); Freire et al. (2009). U – uncertain companion type, Keith et al. (2009a,b) (P_{orb}, P_s, eccentricity, M, M_c).

Table 3. Parameters of Galactic cluster pulsars.

System	$M(M_\odot)$	$M_c(M_\odot)$	$P_{\rm orb}$(d)	$P_{\rm spin}$(ms)	Eccentricity	*type*	Refs.
J0024-7204I(B0021-72I)	1.44	0.15	0.23	3.49	6.3×10^{-5}	GC	G1
J0024-7204H(B0021-72H)	$1.61^{+0.04}_{-0.04}$	$0.18^{+0.086}_{-0.016}$	2.380	3.21	0.071	GC	G1
J1518+0204B(B1516+02B)	2.08 ± 0.19	>0.13	6.860	7.95	0.14	GC	G2
J1911-5958A	$1.40^{+0.16}_{-0.10}$	0.18	0.837	3.48	$<10^{-5}$	GC	G2
J1802-2124	1.21 ± 0.1	>0.81	0.699	12.65	3.2×10^{-6}	GC	G3
J1824-2452C	<1.367	>0.26	8.078	4.158	0.847	GC	G4
J0514-4002A	<1.52	>0.96	18.79	4.99	0.888	GC	G5
J1748-2021B	2.74 ± 0.2	>0.11	20.55	16.76	0.57	GC	G6
J1748-2021I(Ter 5 I)	$1.87^{+0.04}_{-0.07}$	0.24	1.328	9.57	0.428	GC	G7
J1748-2021J(Ter 5 J)	$1.73^{+0.07}_{-0.13}$	0.38	1.102	80.34	0.35	GC	G7

Notes. GC – Globular cluster pulsars.

References. G1 – Manchester et al. (1991); Freire et al. (2003); Lorimer et al. (2008). G2 – Wolszczan et al. (1989); Bassa et al. (2006); Cocozza et al. (2006); Freire et al. (2007); Lorimer et al. (2008); Freire et al. (2008b). G3 – Lorimer et al. (2008); Lorimer et al. (2008); Faulkner et al. (2004); Ferdman et al. (2010) (1.24 ± 0.11 $M_\odot$). G4 – Freire (2009). G5 – Freire & Ransom (2007). G6 – Freire & Ransom (2008); Freire et al. (2008a); Freire (2009). G7 – Ransom et al. (2005); Lattimer & Prakash (2007) (see also `www.naic.edu/~pfreire/GCpsr.html`).

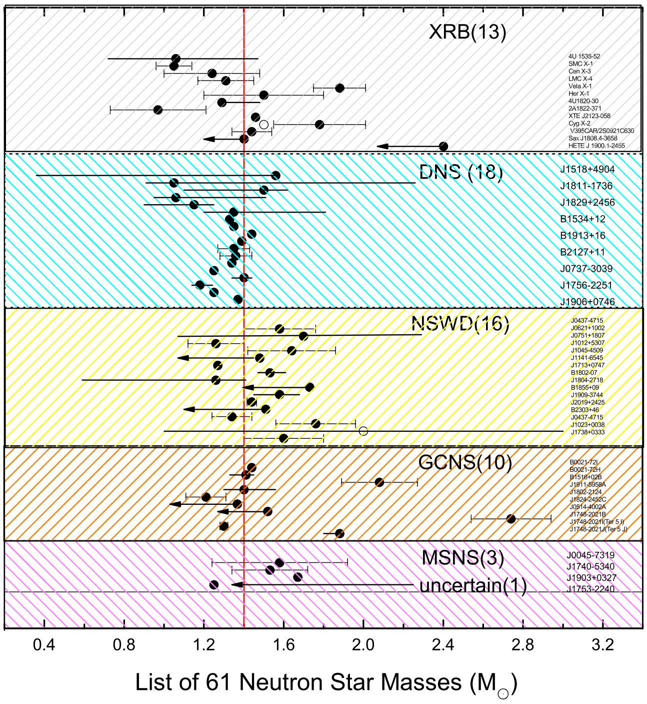

Fig. 1. List of 61 measured NS masses in the different types of NS binary systems. Their details and references can be seen in Tables 1–3. Vertical line $M = 1.4\ M_\odot$ delineates the mass mean value inferred from Gaussian fitting.

masses by TC99 are based on the DNSs, which are generally less than the canonical value of 1.4 $M_\odot$. The present NS mass data includes all types of binary systems with different evolutionary histories. In particular, there are many NSWD systems, which have significantly high NS masses as shown in Tables 1–3.

It is generally assumed that MSPs are formed from the spin-up of a magnetic neutron star caused by accretion in a binary system (e.g. Alpar et al. 1982; Bhattacharya & van den Heuvel 1991; van den Heuvel 2004). If the neutron stars were born with the standard pulsar type fields $\sim 10^{12}$ G, it has to be assumed that the field decays to $\sim 10^{8-9}$ G by accretion as well. The MSPs are understood to be evolutionarily linked to the long-lived LMXBs (e.g. van den Heuvel 2004). The evidence of a MSP that is linked to an LMXB was found with the discovery of the first accretion-powered X-ray pulsar SAX J 1808.4-3658 (spin frequency of 401 Hz, Wijnands & van der Klis 1998). A consequence of the re-cycling hypothesis for the origin of MSPs is that the mass of a MSP should be higher than that of non-recycled pulsar. It has long been believed that a MSP should possess a higher mass than the canonical value of 1.4 $M_\odot$, e.g. ~1.8 $M_\odot$, because of the significant amount of accretion (e.g. van den Heuvel & Bitzaraki 1995a,b; Burderi et al. 1999; Stella & Vietri 1999). Thus, if this relation between MSP mass and accretion exists, we may expect to see it in NS mass statistics taken over different spin period ranges.

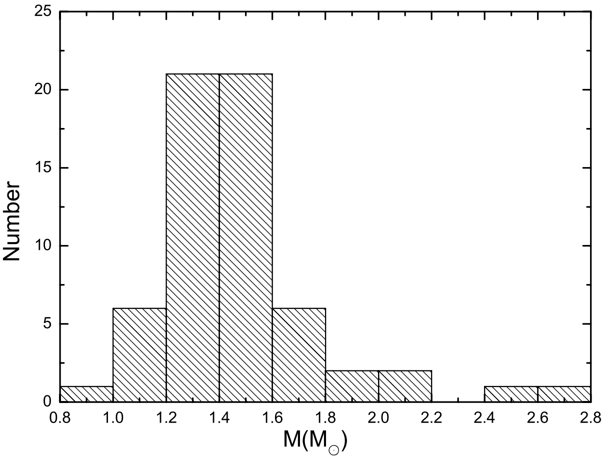

Fig. 2. Histogram of 61 measured NS masses. A Gaussian fitting curve is superimposed on the histogram plot, with the mass mean value 1.40 $M_\odot$ and standard deviation 0.18 $M_\odot$.

We first divided all NS samples into two groups, those with spin periods longer than and equal to or shorter than 20 ms. The 20 ms dividing line was taken somewhat arbitrarily as the period below which a pulsar would be classified as a MSP. We find that the mass averages of MSPs and less recycled NSs are 1.57 ± 0.35 $M_\odot$ and 1.37 ± 0.23 $M_\odot$, respectively. The expected trend is therefore clearly seen in the data. The above trend can also be seen in Fig. 3. The mass systematically decreases with the spin

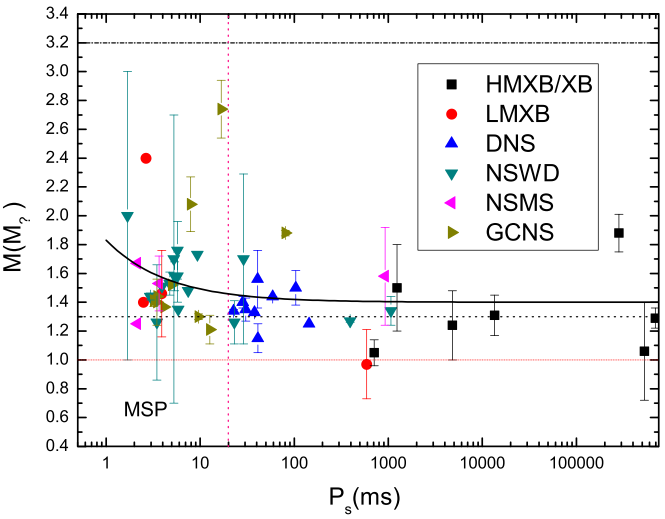

Fig. 3. Diagram of mass versus spin period for 39 NSs. The horizontal line $M = 1\ M_\odot$ ($3.2\ M_\odot$) stands for the measured minimum mass (theoretical maximum mass, see Rhoades & Ruffini 1974). The vertical line at 20 ms separates the samples into two groups, MSP (<20 ms) and less recycled NS (>20 ms). It is found that the mass averages of two groups are, respectively, $1.57 \pm 0.35\ M_\odot$ and $1.37 \pm 0.23\ M_\odot$. The solid curve stands for the relation between accretion mass and spin period of recycled pulsar as described in Eqs. (1) and (2), $M = 1.40 + 0.43(\frac{P_s}{\mathrm{ms}})^{-2/3}\ (M_\odot)$.

period, or alternatively, spin-up is associated with an increase in mass of NS.

By dividing the pulsars into three groups, the mass averages are, respectively, $M = 1.57 \pm 0.35\ M_\odot$ ($P < 20$ ms), $M = 1.38 \pm 0.23\ M_\odot$ (20 ms $< P <$ 1000 ms), and $M = 1.36 \pm 0.24\ M_\odot$ ($P >$ 1000 ms). Here, we note that the average mass of the recycled pulsar increases with the stellar spin-up. In general, the spin periods and magnetic fields (B) of recycled pulsars are just below the spin-up line in B-P_s diagram of pulsars (e.g. Bhattacharya & van den Heuvel 1991; Lorimer 2008), where the B-P_s correlation is given by $P_s \sim B^{6/7}$ from the accretion-induced magnetic evolution model for recycled pulsars (Zhang & Kojima 2006), the magnetic field and accretion mass correlation for recycled pulsars is given approximately by $B \sim \Delta M^{-7/4}$, which infers a relation as $\Delta M \sim P_s^{-3/2}$. On the basis of the above estimates and arguments, we propose an empirical relation between the accreting mass (ΔM) of recycled pulsar and its spin period as

$$\Delta M = M_a(P/\mathrm{ms})^{-2/3}, \tag{1}$$

where M_a is a characteristic accretion mass when a pulsar is spun-up to one millisecond. The mass of recycled pulsar (M) increases with accretion and is roughly expressed as,

$$M = M_0 + \Delta M, \tag{2}$$

where M_0 is the mass of NS at birth while NS spin period is as long as those of HMXBs.

Exploiting Eqs. (1) and (2) to fit the NS mass and spin period data as shown in Fig. 3, we find that $M_0 = 1.40 \pm 0.07\ M_\odot$ and $M_a = 0.43 \pm 0.23\ M_\odot$. Because of the broadness of the initial NS mass distribution and the large errors in measuring NS mass, the fitting COD is as low as 0.07.

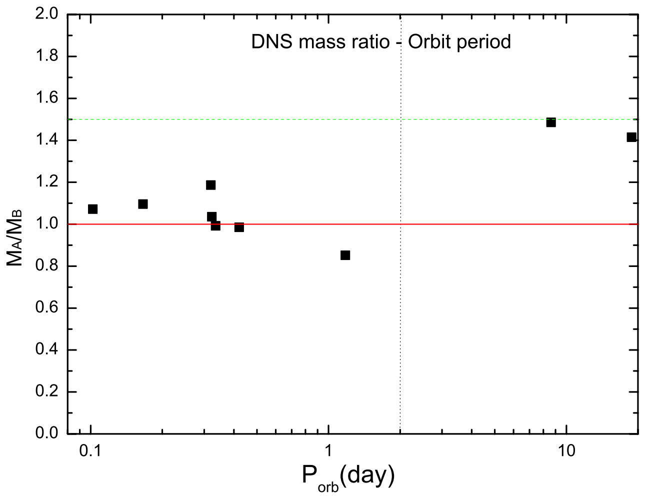

Fig. 4. Mass ratio versus orbital period diagram for 9 pairs of DNSs, where the vertical axis M_A/M_B represents the mass ratio of the recycled NS to non-recycled one.

2.2. Special DNS mass spectrum

The mass average of all eighteen DNSs in nine systems is $1.32 \pm 0.14\ M_\odot$, which is systematically lower than that of the less recycled NS ($M = 1.37 \pm 0.23\ M_\odot$). The mass averages of the nine recycled and non-recycled DNSs are, respectively, $1.38 \pm 0.12\ M_\odot$ and $1.25 \pm 0.13\ M_\odot$, where the mass of recycled NS is generally higher than that of non-recycled one, which may be the indication that either the accretion induces the mass increase for the recycled NS or the evolution of DNS progenitors makes the mass of non-recycled NS low. However, we cannot derive how much mass is accreted into these systems, since for two systems (J1811-1736 and J1518+4904) both NS pair masses have large differences with large errors, e.g., PSR J1811-1736 with $1.5^{+0.12}_{-0.4}\ M_\odot$ and $1.06^{+0.45}_{-0.1}\ M_\odot$ (see Table 2).

The mass ratios of seven DNSs are close to unity and those of the other two with longer orbital periods are higher than unity, as shown in Fig. 4. It is too early to draw conclusions about any ratio gap, separated by the orbital period at 2 days, since fewer DNS samples are not sufficient to infer a warranty statistical result. The cause of the systematically lower mass values of DNS systems than the typical $1.4\ M_\odot$ remains unknown. We propose that the evolution of the DNS progenitors may influence or interact each other, which may be responsible for the particular mass spectrum distributions shown above.

2.3. On AIC mechanism for MSP formation

Although we have focussed on the standard formation model (recycled NS) of MSPs which involves accretion, associated field decay and spin up, other models are possible (e.g. Kiziltan & Thorsett 2009, 2010a,b). These include the often discussed possibility of the accretion induced collapse (AIC) of a white dwarf onto a neutron star (e.g. van den Heuvel 1994; Verbunt 1990; Fryer et al. 1999; van Paradijs et al. 1997; Ferrario & Wickramasinghe 2007). In this model, a white dwarf of mass $>1.2\ M_\odot$ consisting O, Ne, and Mg (e.g. Nomoto & Yamaoka 1992) collapses onto a white dwarf because of the accretion of matter during the course of binary evolution, where a NS is assumed to be born as weakly magnetic and rapidly spinning as those observed MSPs.

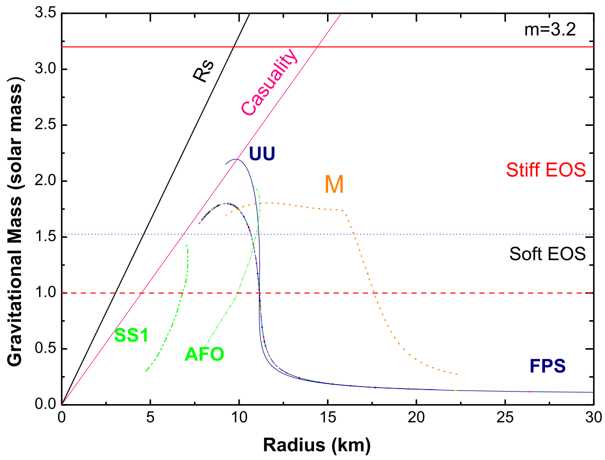

Fig. 5. NS mass versus radius plot. The EOS curves and straight lines follow the same meanings as those of Lattimer & Prakash (2004, 2007) and Miller (2002), where SS1 and AFO stand for EOSs of the quark matters. For most NSs with measured masses of 1.0–2.0 $M_{\odot}$, their nuclear matter compositions are difficult to distinguish as those of either neutrons or quarks, since NS radii cannot be precisely measured in general using present-day observations (e.g. Truemper et al. 2004).

Hurley et al. (2010) presented a comparative study of the expected properties of binary MSPs (BMSPs) born by means of NS recycling and AIC. They concluded that both processes produce significant populations of BMSPs that could potentially be identified with BMSPs. Furthermore, prior to the detached BMSP phase at the end of binary evolution, both the NS recycling and AIC binary systems may have experienced significant phases of accretion. Nevertheless, the AIC systems are likely on average to have accreted less mass.

In Fig. 3, four of twenty-two BMSPs have masses of less than 1.35 $M_{\odot}$, which are less than Chandrasekhar mass limit 1.44 $M_{\odot}$, that may be candidate AIC MSPs. Of course, for a NS with initial mass of 1.1 $M_{\odot}$, a recycled process will also work by accreting 0.25 $M_{\odot}$ from its companion. If we assume the four MSPs to be the candidate AICs, then a constraint on the production of AIC can be derived that no more than 20% (~4/22) of BMSPs are involved in the AIC processes.

2.4. Pulsar: neutron star or quark star?

From the updated measured pulsar masses, we have insufficient information to clearly infer the nuclear matter compositions inside the central compact objects, since we require measurements of the stellar radii to determine the nuclear matter properties given in Fig. 5, a mass-radius plot of compact object. Theoretically, pulsars may consist of hadronic matter only (Menezes & Providência 2004a), hadronic and quark matter (hybrid stars) either bearing or not a mixed phase (Menezes & Providência 2004b; Panda et al. 2004; Tatsumi et al. 2003) or quark matter only (Menezes et al. 2006a; Ivanov et al. 2005; Li et al. 1999). All calculations depend on choosing of appropriate equations of state based on nuclear physics and thermodynamics requirements, which enter as input to the Tolman-Oppenheimer-Volkoff equations. The output are a family of stars, for instance, with certain gravitational and baryonic masses, radii, and central energy. The maximum gravitational mass and the associated radius are important constraints on the equations of state. Generally speaking, the hadronic matter equation of state (EOS) produces maximum masses higher than hybrid stars, which in turn, give slightly higher masses than quark stars. Radii are usually smaller for quark stars. However, these results are very model dependent as can easily be seen from the references mentioned above.

Therefore, based on the present results we cannot determine reliably whether the pulsar is a NS or a quark star (QS) in this paper. However, we note that the usage of the terminology NS to denote the central object of a pulsar is traditional and does not imply any detail of its nuclear matter composition.

Theoretically, the NS maximum mass limit of 3.2 $M_{\odot}$ was proposed by Rhoades & Ruffini (1974). The measured pulsar masses are then far below this limit, which would exclude many known EOS models for the behavior of matter at supra-nuclear densities. The possible existence of high mass NS observations favors a stiff EOS (e.g. Ozel 2006; on the NS stiffness see Stergioulas 2003). The "soft" EOS models predict lower pressures for a given density, corresponding to a less massive star, e.g. <1.5 $M_{\odot}$. Recycled NSs in binary systems should find that the stiffness increases, and that the phase transition of nuclear matter may occur (e.g. Glendenning & Weber 2001; Menezes et al. 2006b).

The fraction of NSs with masses outside range 1.2 $M_{\odot}$–1.8 $M_{\odot}$ is less than 20%, which would provide useful information about their progenitor properties in most cases.

3. Summary and conclusions

We have studied the statistical distributions of the updated measurements of pulsar masses in binary systems, and the following conclusions and implications are obtained:

(1) For 61 reliably measured (estimated) pulsar masses, a mass average of $M = 1.46 \pm 0.3$ $M_{\odot}$ is obtained, which is higher than found (1.35 $M_{\odot}$) in 1999 by TC99.

(2) Our statistics indicate that the mass average of the more rapidly rotating MSPs ($M = 1.57 \pm 0.35$ $M_{\odot}$ for $P_s < 20$ ms) is higher than that of the less recycled ones ($M = 1.37 \pm 0.23$ $M_{\odot}$ for $P_s > 20$ ms). This implies that the NS masses increase in the accreting spin-up binary systems, while a MSP accreting about ~0.2 $M_{\odot}$ from its companion appears to be present. The relation between the accretion mass (ΔM) of recycled pulsar and its spin period is proposed to be $\Delta M = 0.43\ (M_{\odot})(P/1\ \mathrm{ms})^{-2/3}$.

(3) The statistics of 18 DNSs indicate that their mass average $M = 1.32 \pm 0.14$ $M_{\odot}$ is systematically lower than the typical mass value of the less recycled PSRs, which seems to imply that the mass formation or evolution history of DNS should differ from those of the other binary systems.

(4) Apart from the standard recycled processes for the formation of MSPs, the mechanism by AIC of accreting white dwarfs is investigated by the MSP mass distribution, since AIC needs the mass of MSP to be less than the Chandrasehkar mass limit 1.44 $M_{\odot}$. If the AIC explodes after accreting ~0.1 $M_{\odot}$ of crust, then fewer than 20% of BMSPs are inferred to be in the AIC processes, which provide a quantitative constraint on the formation rates of AIC MSPs.

(5) The nuclear matter compositions of the less massive DNSs and heavier MSPs may be different. During accretion, the matter phase transition from the "soft" EOS to "stiff" EOS, or even the matter transition between the neutron and quark may be possible (Menezes et al. 2006b), which would provide classifications of the nuclear matter inside DNSs and MSPs.

Moreover, the recent accurately measured mass 1.97 ± 0.04 $M_{\odot}$ of a MSP PSR J161−2230 with a spin period of 3.15

milliseconds seems to hint that either MSP accretes more mass from its companion or a high mass of pulsar is brought in born (Demorest et al. 2010).

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