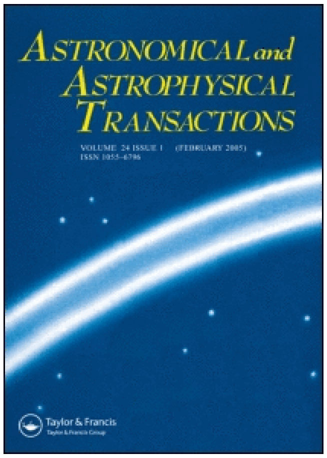

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MASSES OF NEUTRON STARS AND BLACKHOLES BORN IN CLOSE BINARY SYSTEMS

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The masses of some neutron stars (NSs), blackholes (BHs), radio and X-ray pulsars (PSRs) are known but with very different errors. We collected all of the considerably reliable mass values of these objects and we analysed these values. Using these data number-mass distributions of NSs and BHs are constructed. Among the 44 NSs none of them has a mass value $> 2M_{\odot}$. On the other hand, the average mass value for these NSs is very close to $1.4M_{\odot}$. The distribution of the number of NSs with respect to their initial masses has a maximum at a value close to $1.4M_{\odot}$. We investigated the possibility of explaining very high mass values ($\sim$ 6–$10M_{\odot}$) of BHs by accretion in close binaries. Accretion in binary systems by itself cannot result in considerable changes in masses of compact objects, and one can hardly explain the gap between the masses of NSs and BHs and cannot explain the large masses of BHs. Therefore, the masses of BHs when they were born must be predominantly greater than 3–$5M_{\odot}$.

KEY WORDS Masses of neutron stars and blackholes

1 THE MASSES OF NEUTRON STARS AND BLACKHOLES

In Table 1, a list of binary radio pulsars (PSRs) with both components with known masses is given. In column 1 the names of radio pulsars are given (in terms of RA(2000), Dec(2000)). Then come the orbital periods (in days), the masses of PSRs and their components in units of solar mass, the companions, the logarithm of PSRs' ages (years), and in the last column the references. The first eight pulsars and their companions given in the table have accurate mass values. These eight systems consist of 13 NSs with masses in the interval of 1.09–1.54 $M_{\odot}$. The average of the mass values of these 13 NSs is 1.37 $M_{\odot}$.

Table 1. Binary radio pulsars with components with known masses.

Names	P_{orb} *(days)*	M_{PSR} $(M_\odot)$	M_{com} $(M_\odot)$	*Component*	$\log\tau$ *(years)*	*Ref.*
J 0045−7319 (SMC)	51	1.4	8.8	B1 V	6.52	
J 1518+4904	8.63	1.54 (< 1.54)	1.09 (1.09)	NS	> 10.2	1, 8
J 1537+1155	0.421	1.32 (< 1.32)	1.36 (1.36)	NS	8.39	2, 8
J 1804−0735 (GC NGC 6539)	2.62	1.28 (< 1.28)	0.35		8.89	3, 8
J 1857+0943	12.327	1.27 (< 1.27) 1.36–1.76	0.23	WD	9.68	4, 8 5
J 1915+1606	0.32	1.44 (< 1.44)	1.39 (1.39)	PSR	8.04	6, 7
J 2130+1210C (GC M15)	0.34	1.35 (< 1.35)	1.36 (1.36)	NS	7.99	7, 8
J 2305+4707	12.34	1.5 (1.5)	1.46 (< 1.46)	NS	7.47	3, 8
J 0823+0159	1232	1.4–1.8	0.2–0.5	WD	8.12	9
J 1455−3330	76.2	1.4–1.8	0.26–0.36	WD	10.32	9
J 1640+2224	175	1.4–1.8	0.25–0.35	WD	10.24	9
J 1643−1224	147	1.4–1.8	0.14–0.34	WD	9.35	9
J 1713+0747	67.8	1.4–1.8	0.30–0.39	WD	9.95	9
J 1803−2712	407	1.4–1.8	0.16–0.41	WD	8.49	9
J 1955+2908	117	1.4–1.8	0.18–0.33	WD	9.52	9
J 2019+2425	76.5	1.4–1.8	0.31–0.46	WD	9.88	9
J 2033+1734	56.2	1.4–1.8	0.19–0.29	WD		9
J 2229+2643	93.0	1.4–1.8	0.13–0.32	WD	10.4	9
J 1012−5307	0.605	1.76–2.52 ≤ 2	0.14–0.18	WD	9.76	10 11

1. Nice *et al.* (1996), 2. Wolszczan (1991), 3. Thorsett *et al.* (1993), 4. Ryba and Taylor (1991), 5. Kaspi *et al.* (1994), 6. Taylor and Weisberg (1989), 7. Deich and Kulkarni (1996), 8.Van Paradijs (1998), 9. Glendenning (1997), 10. Van Kerkwijk *et al.* (1996), 11. Sarna *et al.* (1998).

It is known that millisecond pulsars exist as a result of the first SN explosion in close binary systems. Their spin periods are continuously decreasing because of accretion on their surfaces. The accretion also increases the masses of millisecond PSRs, so that the masses of these PSRs when they were born are a little bit ($\sim 0.2\ M_\odot$, Alpar *et al.*, 1982) smaller than their present masses.

The age of the PSR in the system J 1518+4904 is very large. On the other hand, its spin period is small, $p = 0.041$ s. Because the component of this PSR is a NS, its progenitor was also a massive star and so the lifetime of the progenitor was small (absolutely less than the age of the PSR). The PSR's mass ($M = 1.54 M_\odot$) is greater than the mass of the NS ($M = 1.09 M_\odot$). All of these show that the NS was born due to a second SN. So, we can say that the mass of the NS did not change and that this mass is equal to its mass when it was born.

The periods of J 1537+1155 and J 2130+1210C are 0.038 s and 0.031 s, respectively. This means they have decreased during the accretion. There is no any other data showing that these PSRs were born after the first SNe in their systems. These two PSRs might have had smaller masses when they were born. These discussions are also true for the PSRs J 1804−0735 and J 1857+0943, because the periods of these PSRs are also small, 0.023 s and 0.005 s, respectively. Kaspi *et al.* (1994) give considerably large mass values, 1.36–1.76 $M_\odot$ for PSR J1857+0943.

The PSR J 1915+1606, which has a period of 0.059 s, was also born after the first SN, so that its mass was increased. The facts that the component of the PSR is a younger PSR ($\log \tau = 7.8$) and its period is ~ 1.6 s show that this is the case.

The period of the PSR J 2305+4707 is large, $p = 1.07$ s. The component of this PSR is a NS. So, the NS was born after the first SN and its mass increased a bit due to the accretion. The young PSR J 0045−7319 was also born after the first SN, its component is still on the main sequence and there is no evidence for an increase in its mass. The upper limits for the masses of NSs just after the first SN explosion are given in brackets.

It is shown above that the average mass of 13 NSs with well-known masses is close to 1.4 $M_\odot$. Naturally, the masses of some of these NSs have increased a bit due to accretion. Although a small number of statistical data does not lead to a very reliable result, we can say the data of these 13 NSs show that the number distribution of NSs with respect to their masses when they were born has a maximum at about 1.4 $M_\odot$; and there is no observational data that the mass of a NS can be $> 1.5 M_\odot$ when it is born.

The observational data of the next 10 systems given in Table 1 are not enough to obtain exact values for the masses of the components. Because of this, the same mass values, 1.4–1.8 $M_\odot$, were given for the millisecond PSRs in these systems and using these values the masses of WDs were roughly obtained (Glendenning, 1997). The mass values obtained like this for WDs are close to the mass values of the components of the PSR J 1804−0735 and the PSR J 1857+0943. The last system in Table 1, J 1012−5307, in which the millisecond PSR has a large age value and a short orbital period, contains the WD with the smallest mass value, $\sim$ 0.14–0.18 $M_\odot$. It is highly probable that the mass value of the PSR J 1012−5307 is $\sim$ 1.8–2.5 $M_\odot$ (Van Kerkwijk *et al.*, 1996). Naturally, large amounts of mass exchange took place in this system and we may assume that the initial mass of the NS was also $< 2\ M_\odot$. Sarna *et al.* (1998) derived a value of 2 $M_\odot$ for the maximum value of the gravitational mass of the NS, a value of $1.5 \pm 0.2\ M_\odot$ for the progenitor of the WD and a mass value of 0.16 $M_\odot$ for the WD in this system. All of these show that masses of NSs are not $> 2\ M_\odot$.

In Table 2, a list of binary X-ray sources which contain NSs or BHs is given. In column 1 the names of the sources are given. In columns 2 and 3 the names and the spectral types of the optical companions are presented, respectively. The next two

Table 2. Masses of neutron stars and blackholes.

Source names	*Optical stars*	*Spectral Type*	M_X ($M_\odot$)	M_{opt} ($M_\odot$)	*Type*	*Ref.*
0115−737 (SMC X-1)	SK 160	BO Ib	1.2–1.6	15–16	Pulsar	1, 2
0532−664 (LMC X-4)	SK 6566	O7 III–V	1.4–1.6	14–17	Pulsar	2, 3, 4
0535−668 (LMC)	Star Q	B2 III–IVe	1	12	Pulsar	5, 6
0538−641 (LMC X-3)	Star 1	B3Ve	> 7		Blackhole	7
J 0538−6906 (LMC)	Star R 140	WN 4.5	> 2.5		Blackhole (possible)	5, 6
0540−697 (LMC X-1)	Star 32	O7-9III	> 3		Blackhole	8, 9
0900−403	HD 77581	B0.5 Iab	1.4–1.9	23	Pulsar	2, 10, 11
1119−603	V 779 Cen	O 6.5 II–III	1.07	19	Pulsar	2, 12
1538−522	QV Nor	B0 Iab	1.1–1.8	17–20	Pulsar	2, 13, 14
1700−377	HD 153919	O 6.5	1.4–2.6	30–53	Pulsar	15, 16
1956+350	HD 226868	O 9.7 Iab	>7–10	18	Blackhole	17
2030+407	V 1521 Cyg	WR	17	7–13	Blackhole	18–19
2138+568			1.4	10	Pulsar	20, 21
J 0422+32	V 518 Per	M0–2 V	3–6 (4–14)	< 0.5	Blackhole	22, 23, 24, 50
0620−003	V 616 Mon	K 4–5 V	3–7	0.4–0.8	Blackhole	25, 26, 50
0748−676	UY Vol		∼ 1.4			27
0921−630	V 395 Car	G III	1.4	0.6		5, 6
1124−684	XN Mus	K 3–5 V	6 (5–8)	0.6–1.1	Blackhole	28, 29, 50
1254−690	GR Mus		1.4	0.5		30
1455−314	V 822 Cen	K 5–7 V	0.5–2.1	< 0.7		31, 32
1617−155	V 818 Sco X-1		1.3	0.8–1.2		33

columns contain the masses of the X-ray and the optical components, respectively. Next come the types of the compact sources, and in the last column the references are given. The first 13 sources are high-mass X-ray binaries (HMXBs), and the last 20 sources are low-mass X-ray binaries (LMXBs) in this table.

Let us now discuss the NSs and BHs in X-ray binaries. The total number of known HMXBs is 78 (Guseinov *et al.*, 1998). Among these binaries 35 X-ray PSRs and five possible PSRs, four BHs and one possible BH (J 0538−6906 in LMC) were found. We presented those 13 HMXBs for which the mass values of the compact sources are known in Table 2. Five of these 13 HMXBs are in the LMC, one of them is in the SMC and seven of them are in the Galaxy. There are eight X-ray pulsars and four BHs and one possible BH (all of these BHs may have masses greater than

Table 2. (Contunued). Masses of neutron stars and blackholes.

Source names	*Optical stars*	*Spectral Type*	M_X $(M_\odot)$	M_{opt} $(M_\odot)$	*Type*	*Ref.*
1636−536	V 801 Ara		1.4	0.2		34
J 1655−40		F 3–6	4–7 (7)	2.3	Blackhole	35, 36, 50
1656+354	HZ Her	A8–BO	1–1.3	2.2	Pulsar	2
1705−250	V 2107 Oph	K3 ?	6 (5–8)	> 0.15	Blackhole	37, 38, 50
J 1744−28			1.4	0.07–0.14	Pulsar	39
1822−371	V 691 CrA	G–M	1–2	0.3–0.6		40, 41
1915+105		Be ?	> 5		Blackhole	28, 42, 43
2000+251	QZVul	K 3–7 V	> 6 (6–18)	0.4-0.7	Blackhole	44, 50
2023+338	V 404 Cyg	K0 IV	6–14 (10–14)	0.3–0.6	Blackhole	26, 32, 45, 50
2127+119 (GC M15)	AC 211		1.4	0.47		46, 47
2129+470	V 1727 Cyg	F 7–8 V	0.6–1	0.4–0.6		48, 49
2142+380	V 1341 Cyg	F 0 IV	1.3–1.9	0.4–0.7		49

1. Bonnet Bidaud and Van der Klis (1981), 2. Van Kerkwijk *et al.* (1995), 3. Levine *et al.* (1991), 4. Pietsch *et al.* (1995), 5. Van Paradijs (1995), 6. Guseinov *et al.* (1998), 7. Ebisawa *et al.* (1993), 8. Cowley *et al.* (1995), 9. White and Van Paradijs (1996), 10. Sato (1986), 11. Bulik *et al.* (1995), 12. Van Paradijs and McClintock (1995), 13. Cominsky and Moraes (1991), 14. Reynolds *et al.* (1992), 15. Heap and Corcoran (1992), 16. Haberl *et al.* (1989), 17. Herero *et al.* (1995), 18. Tarasowa and Nakamura (1995), 19. Shmutz *et al.* (1996), 20. Schulz *et al.* (1995), 21. Mihara *et al.* (1991), 22. Kato *et al.* (1995), 23. Callanan *et al.* (1996), 24. Orosz and Bailyn (1995), 25. Shahbaz *et al.* (1994b), 26. Shahbaz *et al.* (1994a), 27. Van Paradijs *et al.* (1988), 28. Orosz *et al.* (1996), 29. Greiner *et al.* (1994), 30. Motch *et al.* (1987), 31. Whitlock *et al.* (1990), 32. Shahbaz *et al.* (1994c) 33. Petro *et al.* (1981), 34. Cowley *et al.* (1988), 35. Crary *et al.* (1996), 36. Bailyn *et al.* (1995), 37. Martin *et al.* (1995), 38. Remillard *et al.* (1996), 39. Finger *et al.* (1996), 40. Mason *et al.* (1982), 41. Cowley *et al.* (1982), 42. Chen *et al.* (1997), 43. Mirabel *et al.* (1997), 44. Filippenko *et al.* (1995), 45. Harlaftis *et al.* (1996), 46. Dotani *et al.* (1990), 47. Naylor and Charles (1989), 48. Horne *et al.* (1986), 49. Casares *et al.* (1998), 50. Bailyn *et al.* (1998).

2.5 $M_\odot$) among these HMXBs. In 10 of these 13 systems the masses of the optical companions are known and all of them have mass values greater than 7 $M_\odot$.

In these systems, the masses of the eight NSs are in the range 1–2 $M_\odot$ and the average value of them is 1.43 $M_\odot$. But the masses of the four BHs and the possible BH lie in the interval $2.5M_\odot < M < 17M_\odot$. Although there are huge differences between the masses of NSs and BHs there is no difference in their progenitors' masses (see Table 2).

There are 138 known LMXBs (Guseinov *et al.*, 1998); eight pulsars and two possible PSRs, eight BHs and 10 possible BHs were found among these sources. We

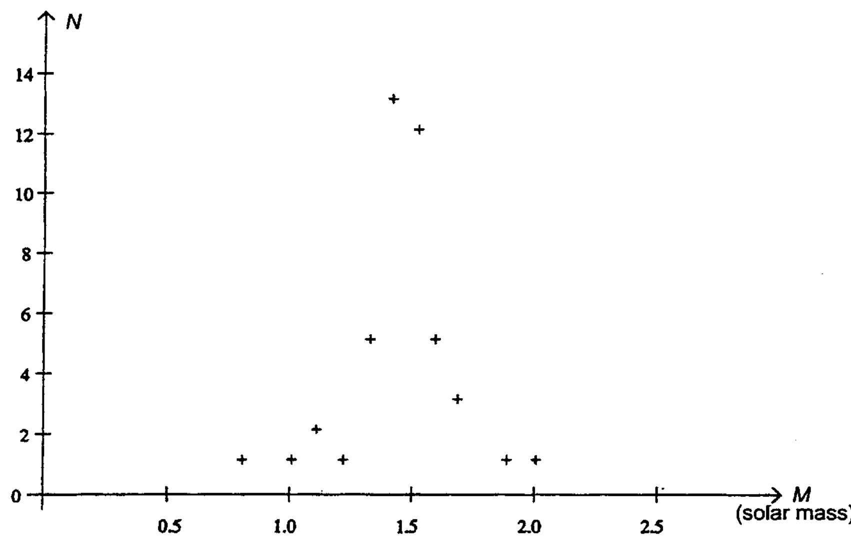

Figure 1 Number–mass distribution of NSs in binary systems.

do not know the masses for all possible BHs; there are only indirect indications for existence of these BHs, e.g. the hardness of the X-ray spectrum.

For 20 of the 138 LMXBs the masses of the compact objects are known and they are presented in Table 2. All of these 20 sources, among which there are two pulsars and eight BHs, are in the Galaxy. For the remaining 10 LMXBs the masses of the compact sources are $< 2\ M_{\odot}$ so that all of them must be NSs. Therefore, in 12 of these 20 systems the compact objects are NSs and the remaining eight are BHs. For these 12 systems the average masses of the NSs are $< 1.4\ M_{\odot}$. In the other eight systems the masses of the BHs are between 3 and 14 $M_{\odot}$ and the average mass for them is $\sim 6M_{\odot}$.

So, the 24 NSs shown in Table 1, the eight X-ray pulsars in HMXBs, and the 12 NSs in LMXBs (see Table 2), totalling 44 NSs with known masses, do not show that the masses of NSs can be $> 2\ M_{\odot}$. In Figure 1 the number–mass distribution of the 44 NSs from Table 1 and Table 2 is represented. As we can see, there exists a very sharp maximum at very close to 1.4 $M_{\odot}$. As is well known and discussed above, in close binary systems the masses of NSs can increase a bit because of accretion. On the other hand, the average of the masses of these 44 NSs is $< 1.4\ M_{\odot}$. When they were born the mass values of some of these NSs were less. So, this leads us to the following result: the number distribution of NSs with respect to their masses when they were born has a maximum at a value very close to 1.4 $M_{\odot}$.

From Table 2 we saw that there is a large gap between the mass values of NSs and BHs. This is true for both HMXBs and LMXBs. In Figure 2 the number–mass distribution of BHs among the HMXBs and LMXBs from Table 2 is represented. The arrows indicate the lower limits for the masses of BHs. The gap for the LMXBs

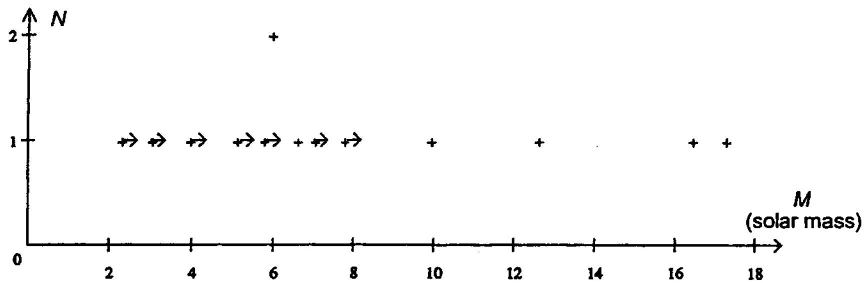

Figure 2 Number–mass distribution of BHs (arrows indicate the lower limits for the masses of BHs).

was discussed by Bailyn *et al.* (1998); yet, they gave large mass values for BHs (see the data given in brackets in Table 2).

The LMXBs containing BHs and for which the masses of both components are estimated are relatively close to us, so they are less concentrated in the direction of the Galactic centre than other BHs. But these eight systems are not concentrated in the star formation regions and the Galactic arms. Because of this and the distribution of the LMXBs which contain BHs we can surely say that the masses of the companions (in the main sequence stage) of the BHs in LMXBs were $< 5\ M_\odot$. Most of the HMXBs, 34 out of 62 Galactic sources, contain X-ray pulsars and only in four of them are there BHs.

The number of BHs in LMXBs is a factor of 2–3 more than the number of BHs in HMXBs. One may think that this is due to results of accretion, that maybe a NS transforms into a BH. But to explain the gap between the masses of NSs and BHs by accretion is very difficult and it is not possible to explain the high masses of BHs by accretion. As we saw above, NSs are born with masses $< 2\ M_\odot$. The masses of the optical companions in all of the LMXBs are $< 5\ M_\odot$ on the main sequence as seen from observations, and only some part of the mass of the companion can be accreted onto the surface of the NS. Then, how can one explain the BHs' masses of 6–10 $M_\odot$? It is also very difficult to explain those high masses of BHs in the case of HMXBs by accretion. It is necessary to remember that millisecond pulsars have passed the stage of LMXB but their masses are not different from the masses of younger NSs.

2 DISCUSSIONS AND CONCLUSIONS

(1) The number distribution of NSs with respect to their masses when they were born has a sharp maximum at a value very close to 1.4 $M_\odot$. Practically, masses of NSs do not exceed 2 $M_\odot$.
(2) Accretion in binary systems by itself can hardly explain the gap in the masses of NSs and BHs and cannot explain the large masses of BHs. In fact BHs are born with high masses.

The first conclusion does not exclude the possibility that NSs may have masses of 2–5 $M_\odot$, but in the catalogues there is no radio PSR and X-ray source in binary systems with masses in the range of 2–2.5 $M_\odot$ except HMXB 1700-377 for which the NS may have a mass value of 1.4–2.6 $M_\odot$.

The X-ray luminosity of a binary system does not depend on whether the compact object is a NS or a BH. So that one cannot say that the accretion rate in a binary system containing a BH is higher than a binary system which contains a NS. On the other hand, transient phenomena do not depend on whether the compact object in the system is a NS or a BH. So, we can say that the average accretion rate is similar to each other in both cases and large masses of BHs are not due to accretion. If we can rely on the above conclusions and discussions and the masses of the BHs then we can say that the masses of BHs when they were born must be > 3–$5\ M_\odot$.

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