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Letter to the Editor

On the initial progenitor masses of stellar mass black holes and neutron stars

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Abstract. We examine the information on the progenitor masses of stellar black holes that can be derived from the seven known black hole X-ray binaries with low- mass donor stars (Soft X-ray Transients- SXRs) in combination with stellar evolution considerations and observed properties of High Mass X-ray Binaries (HMXBs). It appears that several independent lines of evidence indicate that a considerable fraction of the stars more massive than 20 - 25 $M_{\odot}$ leave black holes as remnants while, on the other hand, t e neutron star in at least one HMXB had a progenitor more massive than 50 $M_{\odot}$. We argue that the only plausible explanation of these apparently contradicting facts is that in a certain mass range, probably between 20 and 50 $M_{\odot}$, the outcome of core collapse can either be a neutron star or the black hole, depending on additional stellar parameters, for example rotation and magnetic fields.

The high masses of the black holes in three soft X-ray Transients (6 - 13 $M_{\odot}$) and Cygnus X-1 (16 $M_{\odot}$) exclude the alternative explanation that in a limited mass range (e.g.20 - 40 $M_{\odot}$) stars leave black holes, and, due to very heavy stellar wind mass loss, stars more massive than about 40 $M_{\odot}$ leave neutron stars, just as stars between 8 and 20 $M_{\odot}$.

Key words: Black holes - neutron stars - stellar evolution - Black Hole mass limit - X-ray Binaries - Soft X-ray Transients

The seven recently discovered black hole soft X-ray transients (SXTs) with low-mass companion stars (G-,K- or M- dwarfs or subgiants, see Table 1) for first time yield a glimpse of the population of stellar-mass black holes in the Galaxy. Using evolutionary models and estimated lifetimes of low-mass X-ray binaries- which are a very rare end-product of massive binary evolution (van den Heuvel 1983; 1994) - the observed number of such systems within a few kpc from the Sun already allows one to estimate the Galactic stellar-mass black hole population to be at least of order 10^8 (van den Heuvel, 1992).

In this paper we consider the constraints that evolutionary considerations in combination with our knowledge of these systems and of High Mass X-ray Binaries (HMXB) set to the initial mass ranges of the stars from which black holes and neutron stars originate.

In an earlier paper (van den Heuvel and Habets, 1984) it was found that the progenitor of the black hole in the HMXB LMC X-3 must have had an initial mass $\geq 60\ M_{\odot}$, whereas the progenitor of the neutron star in the HMXB GX301-2/4U1223-624 (with its hypergiant companion Wray 977) had an initial mass $\geq 40 M_{\odot}$, which later was revised to $\geq 50\ M_{\odot}$ (Kaper et al. 1995).

Thus, assuming that there would be a simple mass cut below which stars leave neutron stars, and above which they become black holes, one would expect the lower mass limit for black hole formation to be $\geq 50\ M_{\odot}$ (Kaper et al. 1995). However, the situation may not really be that simple, because more recently, evidence has been accumulating indicating that black holes may also form from stars of lower mass. There are (at least) three independent lines of evidence indicating this, as follows:

(i) Maeder (1992) showed, on the basis of detailed population-synthesis calculations in which contributions from stellar winds, supernovae and planetary nebulae are included, that the heavy-element yields depend strongly on the lower mass limit M_{BH} for black hole formation (for M$\geq M_{BH}$ the heavy elements produced disappear into the black hole). He found that in order to obtain agreement between theoretically predicted yields and the observations, M_{BH} should not be larger than 20 to 25 $M_{\odot}$. A subsequent further analysis by Woosley&Weaver (1995) confirms this (see also Timmes et al. 1996). It should be noted that the massive-star evolution calculations by Woosley and Weaver (1995) indicate that there is a natural limiting mass close to 20 $M_{\odot}$, namely about 19 $M_{\odot}$. This mass limit separates pre-supernova stellar cores that burn carbon convectively

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Table 1. Observational data for BHC.The top seven system are SXT with low-mass companions. The lower 3 systems are High Mass X-ray Binaries.
Author names referring to the reference numbers are given at the bottom of the table.

Source	Mass function	$M_x/M_\odot$	i	P_{orb}(hrs)	$M_s/M_\odot$	References
Nova Muscae 1991	3.1±0.4	>4.45±0.46	77^0	10.4	0.7	RMB (1)
A0620-00	3.18±0.16	3.3-4.24	$66^0.5$ -$73^0.3$	7.75	0.15-0.38	MRW (2)
GS2000+25 (QZ Vul)	4.97±0.1	6.04-13.9	47^0 - 75^0	8.3	0.26-0.59	HHF (3)
V404 Cyg (GS2023+338)	6.3±0.3	6-12.5	56^0	155.3	0.6	SRZ (4)
Nova Ophiuchi 1977	4.0±0.8	6±1	60^0 -80^0	-	0.7	ROM (5)
GRO J0422+32	1.21±0.06	3.57±0.34	48 $\pm 3^0$	5.08	0.39±0.02	FMH (6)
GRO J1655-40	3.24±0.09	7.02±0.22	69.5 $\pm 0.08^0$	62.4	2.34±0.12	OB (7)
Cyg X-1	0.24±0.01	$\approx 16 \pm 5$		134.4	≈ 33	GS (8, 9)
LMC X-3	2.3±0.3	> 7	$\approx 50^0$ -60^0	40.8	B3V	C (10)
LMC X-1	0.14±0.05	$> 2.6 \approx 6$	$< 60^0$	101.3	O7-9III	H (11)

(1) Remillard et al. (1992); (2) Marsh et al. (1994); (3) Harlaftis et al. (1996); (4) Sanwal et al. (1996); (5) Remillard et al. (1996); (6) Filippenko et al. (1995); (7) Orosz and Baylin (1997); (8) Gies and Bolton (1982); (9) Gies and Bolton (1986); (10) Cowley et al. (1982); (11) Hutchings et al. (1987).

from those that produce less carbon and burn radiatively. In consequence, there is an abrupt jump in pre-SN iron core masses around $19M_\odot$. As a result either a bimodal distribution of neutron star masses with peaks around $1.3M_\odot$ and $1.7M_\odot$ will be produced or, alternatively, for soft equations of state or weak explosion energies, the neutron stars in the second peak will collapse to black holes which may rapidly accrete and absorb much of the mass of the collapsing star.

(ii) Recent binary population synthesis calculations by Portegies Zwart et al. (1997), including Common Envelope evolution to produce low-mass X-ray binaries, show that if one uses a M_{BH}-value of 40 - 50 $M_\odot$, the formation rate of black hole low-mass X-ray is some two orders of magnitude lower than the rate inferred from the observations of SXTs. To overcome this discrepancy, M_{BH} has to be lowered to about 20 - 25 $M_\odot$.

(iii)The observed short orbital periods of most of the soft X-ray transients (four of the seven systems in Table 1 have P $<10.4^H$) are impossible to attain with M_{BH}>25 $M_\odot$. The basic reason for this is that, following Common-Envelope evolution, the pre-collapse cores of stars ≥ 25 $M_\odot$ are massive helium stars which undergo considerable stellar-wind mass loss before they collapse to black holes. Our calculations show that this wind mass loss widens the post-Common Envelo bits so much that the subsequent orbital narrowing (after the formation of the black hole) by gravitational radiation losses and magnetic braking can never reduce the orbital periods to $< 10.4^H$ within a Hubble time.

The first two of the above three independent lines of evidence indicate that a high fraction (of order 80 to 90 per cent or more) of all stars more massive than 20-25 $M_\odot$ must leave black holes as remnants.

On the other hand, as mentioned above, there is at least one pulsating HMXB where the progenitor of the neutron star was a star with an initial mass $>$ 50 $M_\odot$. Such a star left a helium core $>$ 20 $M_\odot$, and apparently such cores may still leave neutron star as remnants. We can envisage only two possible ways in which these apparently contradictory types of evidence might be reconciled, i.e.: either: (1) black holes form from a limited mass range, for example 20 to 40 $M_\odot$, with stars outside this range leaving neutron stars (i.e.: stars between 8 and 20 $M_\odot$, and $> 40M_\odot$), or (2) in the mass range $\geq$ 20 $M_\odot$ there are additional stellar parameters that influence whether the stellar core collapses to a neutron star or to a black hole. These parameters could for example be rotation and magnetic field, which in general - with only a few exceptions (Müller and Hillebrandt 1979; Symbalisti 1984) - are not included in the core collapse calculations, or: certain instabilities in the collapse process itself.

We will now discuss the viability of these two possible alternatives, (1) and (2).

Case (1): A limited mass range for stellar black hole formation ($\sim$ 20 - 40 $M_\odot$). For stars in the mass range 8 - 20 $M_\odot$ stellar winds are so weak during most of the evolution that wind loss is of little evolutionary significance (Chiosi and Maeder 1986). On the other hand, for very massive stars (VMS) $\geq$ 40 $M_\odot$, wind mass-loss rates are so high that these stars lose their entire hydrogen-rich envelopes during their lifetimes and turn into Wolf-Rayet stars (helium stars). These WR-stars also have very high stellar wind mass-loss rates, which increase with stellar mass (Maeder 1994; Langer 1989; Langer 1994). It has been suggested that as a result of this, the final masses, just before core collapse, of these VMS converge to roughly the same (low) value (Woosley and Weaver 1995; Woosley et al 1993; 1995). For example, the last-mentioned authors, adopting a certain mass-dependent stellar-wind mass loss law calculated that a star with an initial mass of $60 M_{\odot}$ can yield a 4.25 $M_{\odot}$ presupernova configuration which differs not much from that of a helium star which started out with 4.25 $M_{\odot}$ and underwent very little wind mass loss (this is the core of an initial hydrogen-rich star of 16 $M_{\odot}$). The latter star leaves a neutron star remnant and the same is probably the case for the 4.25 $M_{\odot}$ remnant of the 60 $M_{\odot}$ star. On the other hand, if the 60 $M_{\odot}$ star had undergone a factor two less stellar wind mass loss (which is well within the observational uncertainties of stellar wind mass-loss laws - Chiosi and Maeder, 1986)) it would have left a pre-SN remnant of > 30 $M_{\odot}$, with a > 10 $M_{\odot}$ C-O core, which almost certainly, would collapse to a black hole (Woosley and Weaver 1995; Timmes et al. 1996).

Thus, although it is conceivable, from the calculations of Woosley and Weaver (1995) and Woosley et al. (1993, 1995) that above a certain mass (around 40 $M_{\odot}$), stars again leave neutron stars as remnants, this is by no means certain. A serious problem with such an explanation is the existence of stellar black holes in close binaries with masses ranging from 6-13 $M_{\odot}$ (V404 Cygni, LMC X-3,GS2000+25) to 16$\pm$5 $M_{\odot}$ (Cygnus X-1), as listed in Table 1. Since these binaries are close, the pre-collapse stars cannot have had hydrogen-rich envelopes, but must have been helium stars. Because of the strong stellar wind mass loss from helium (Wolf-Rayet) stars, these black holes must have started out as helium stars with masses far above their present values, which certainly in the case of Cygnus X-1 implies a hydrogen-rich progenitor > 40 $M_{\odot}$, and for the other systems probably as well. With the Wolf-Rayet wind mass-loss laws used by Woosley and Weaver (1995) and Woosley et al (1993, 1995) such stars should have left remnants with masses of $\leq$ 4.25 $M_{\odot}$ whereas from the case of Cygnus X-1 we see that this cannot be true, as the collapsing helium star was more massive than 11 $M_{\odot}$. Clearly, the stellar wind mass loss laws used by these authors overestimated the real wind losses which very massive stars experience by a factor two or more, and the pre-collapse masses resulting from stars > 40 $M_{\odot}$ are much larger than estimated by Therefore, this explanation for the existence of a neutron star that originated from a star more massive than 50 $M_{\odot}$ cannot hold.

Case 2. The only alternative that we can envisage for explaining that a large fraction of stars with initial masses $\geq$ 20-25 $M_{\odot}$ leave black holes while, at the same time, some stars ≥ 50 $M_{\odot}$ still leave neutron stars is, therefore, that in the same mass range (20 -50 $M_{\odot}$) not all stars have the same fate. This means that there must be additional parameters, which determine whether the core collapses to a neutron star or a black hole.

Such parameters could be: rotation, magnetic fields, possible asymmetries during core bounce or Rayleigh-Taylor instabilities during core collapse (which might introduce a random component in the outcome of this collapse), etc. As one possible example we discuss here in somewhat more detail the case of rotation and magnetic fields. The possible importance of magnetic energy in obtaining a SN-explosion was suggested more than 25 years ago in a number of authors (Le Blanc and Wilson 1970; Ostriker and Gunn 1971) and numerical calculations of collapsing rotating magnetized cores by Müller and Hillebrandt (1979) and Symbalisti (1984) have shown that a type II SN-explosion might be obtained in this way.

Thompson & Duncan (1993) have examined the possibility for dynamo action during various (pre-collapse) phases of convective motion that occur during the evolution of massive stars. From their analysis the magnetic fields of neutron stars at birth may be as high as 3×10^{15} G. If such a neutron star at formation has a rotation period of 10 ms, it generates a magnetic dipole radiation luminosity given by (cf. Manchester and Taylor 1977):

$$L_p = \frac{2R^6B^2}{3c^3}(\frac{2\pi}{P_p})^4 \quad (1)$$

which for B= 3×10^{15}G, P_p=10 ms yields L_p =3.4×10^{46}erg/s (the same L_p results for B=3×10^{13}, P_p=1ms). According to calculations by Ostriker and Gunn (1971) this energy flux is sufficient to expell the remaining matter of the star and accelerate it to high velocities. The e-folding spindown timescale of this neutron star is about 3 hours, in which some 4×10^{50} ergs are released, an amount similar to that of a type II Supernova.

It is important to notice that in this case always a neutron star is produced with a mass close to the Chandrasekhar mass M_{CH}, as this is the mass of the collapsing part of the iron core in all helium stars which started out with masses between $4 M_{\odot}$ and at least 32 $M_{\odot}$ (Timmes et al. 1996; Arnett 1978). As the magnetic dipole radiation of this collapsing core will prevent any subsequent fall-back of matter, one expects all such neutron stars to be formed with masses in a narrow range close to M_{CH}, which is just what is observed for all binary radio pulsars and pulsating binary X-ray sources ($1.35 M_{\odot}\pm0.15 M_{\odot}$; van Paradijs and McClintock 1995). In fact the latter observation would be consistent with a model in which all strongly magnetized rapidly rotating neutron stars(i.e.: pulsars) were produced from magneto-rotationally driven supernovae, also if they originated from stars of lower mass (≤ 20 $M_{\odot}$). (On the other hand, in the mass range ≤ 20 $M_{\odot}$ all collapsing cores are expected to leave neutron stars with masses $\sim$ $9.4 M_{\odot}$ as these stars have only small collapsing iron cores (Timmes et al. 1996).

If indeed rotation and magnetic field would play a role as described above, there could be two kinds of type II (and Ib) Supernovae: those driven primarily by neutrino transport, which produce neutron stars with a variety of spin periods and magnetic fields, as well as black holes, and those primarily driven by magneto-rotation, the latter ones producing only strong-field radio or X-ray pulsars.

We conclude that the masses of the black holes in the systems of Cygnus X-1 ($16 M_{\odot}$), V404 Cygni (6-13 $M_{\odot}$), GS2000+25 (6-14$M_{\odot}$) and LMC X-3 (≥ 7 $M_{\odot}$) in fact exclude possibility (1) and that possibility (2), in which in the mass range ≥ 20 $M_{\odot}$ neutron star formation is causally connected with other stellar parameters (rotation, magnetic field, Rayleigh-Taylor instabilities, etc.) seems the only way to explain both the presence of massive black holes (in the mass range $\geq$ 6 to 16 $M_{\odot}$) in four X-ray binaries and fact that at least one X-ray pulsar (GX301-2) originated from a massive star, $\geq$ 50 $M_{\odot}$.

Our conclusion that neutron star formation - at least in the mass range $\geq 20\ M_{\odot}$ - is connected with other stellar parameters than the initial stellar mass alone, may have implications for the origins of type II (and Ib) SN-explosions. We suggest that the old idea of Ostriker & Gunn (1971) that "pulsars make supernovae" should be given more serious consideration as it is possible that at least part of all type II+Ib supernovae may be produced in this way. We conclude from the above that, apart from giving valuable information on the initial mass range of the progenitors of stellar-mass black holes, the Soft X-ray Transients and other black hole X-ray binaries may provide important information on the mechanisms of neutron star formation and type II + type Ib supernovae.

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