Massive Stars and their Compact Remnants in High-mass X-ray Binaries

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Abstract. In a high-mass X-ray binary (HMXB) a massive star interacts with a neutron-star or black-hole companion in various ways. The gravitational interaction enables the measurement of fundamental parameters such as the mass of both binary components, providing important constraints on the evolutionary history of the system, the equation of state of matter at supra-nuclear density, and the supernova mechanism. The stellar wind of the massive star is intercepted by the strong gravitational field of the compact companion, giving rise to the production of X-rays. The X-rays increase the degree of ionization in a small to very extended region of the surrounding stellar wind, depending on the X-ray luminosity. This has observable consequences for the structure and dynamics of the accretion flow. In this paper we concentrate on the fundamental parameters of the most massive HMXBs, i.e. those with an OB supergiant companion, including some systems exhibiting relativistic jets (“microquasars”).

1. High-mass X-ray binaries

In a high-mass X-ray binary (HMXB) a massive OB-type star is in close orbit with a compact X-ray source, a neutron star or a black hole. The X-ray source is powered by accretion of material originating from the OB star, transported by the OB-star wind or by Roche-lobe overflow. The majority (≥ 80%) of the HMXBs are Be/X-ray binaries with relatively wide ($P_{\text{orb}}$ weeks to several years) and eccentric orbits. Most Be/X-ray binaries are transients, the X-ray flux being high when the compact star in its eccentric orbit passes through the dense equatorial disk around the Be star (Van den Heuvel & Rappaport 1987, Negueruela, these proceedings). About a dozen HMXBs host a massive OB-supergiant companion (about 10 to over 40 $M_\odot$), in a relatively tight orbit ($P_{\text{orb}}$ several days) with an X-ray pulsar or black-hole companion (e.g. Kaper 2001). Some of these X-ray binaries include a dense accretion disk and produce relativistic jets (e.g. Fender 2005).

HMXBs mark an important though short phase (on the order of 10,000 year) in the evolution of the most massive binaries. The compact companion is the remnant of the initially most massive star in the system that exploded as a supernova (or as a gamma-ray burst). Due to a phase of mass transfer, the secondary became the most massive star in the system before the primary supernova, so that the system remained bound (Van den Heuvel & Heise 1972). A consequence, however, is that HMXBs are runaways due to the kick velocity exerted by the supernova (Blaauw 1961, Kaper et al. 1997, Van den Heuvel et al. 2000). When the secondary starts to become a supergiant, a second phase
of mass transfer is initiated, first through an enhanced stellar wind, later by Roche-lobe overflow, which results in the production of X-rays by the compact companion. With increasing mass transfer rate, the system will enter a phase of common-envelope evolution causing the compact object to spiral into the OB companion. In the relatively wide Be/X-ray binaries the spiral-in likely results in the removal of the envelope of the Be companion, and after the supernova a bound (or disrupted) double neutron star remains, like the Hulse-Taylor binary pulsar PSR 1913+16 (or a neutron star – white dwarf system, if the mass of the Be companion is less than $\sim 8 M_\odot$). In close HMXBs (orbital period less than about a year) the compact object will enter the core of the OB companion which will become a so-called Thorne-Zytkow object (Thorne & Zytkow 1977), a red supergiant with a high mass-loss rate. These objects have been predicted on evolutionary grounds, but have so far not been recognized as such (for an extensive review on binary evolution, see Van den Heuvel 1994).

In case the system hosts an X-ray pulsar, its orbit can be very accurately determined through pulse-timing analysis. When also the radial-velocity curve of the OB supergiant is obtained, the mass of the neutron star and that of the massive star can be derived with precision, given an estimate of the system inclination (cf. Rappaport & Joss 1983). The neutron star mass carries information on the formation mechanism (i.e. the supernova), as well as on the equation of state (EOS) of matter at supra-nuclear density. Evolutionary calculations by Timmes et al. (1996) show that in single hydrogen-rich stars with a mass less than 19 $M_\odot$ the collapsing Fe core has a mass of about 1.3 $M_\odot$, while stars with a higher initial mass produce an Fe core of about 1.7 $M_\odot$. Therefore, one would predict a bimodal mass distribution of the neutron stars in these systems.

The EOS, i.e. the relation between pressure and density in the neutron-star interior, can so far only be studied on the basis of theoretical models. It is not yet possible to produce the required extremely high density (about an order of magnitude higher than an atomic nucleus) in accelerator experiments. Theoretical predictions of the EOS come in two flavors: the so-called “soft” and “hard” equations of state. The hardness of the EOS depends on the fraction of bosons formed in the neutron-star interior, which unlike the fermions (neutrons) do not contribute to the Fermi pressure that helps to sustain gravity. The harder the EOS, the higher the mass a neutron star can have. If a neutron star has a mass higher than the maximum mass allowed by a given EOS, this EOS is ruled out as only one EOS can be the right one. Obviously, this relatively simple measurement has major implications for our understanding of the properties of matter at supra-nuclear density.

The properties of the OB star in a HMXB give insight into the evolutionary history of the binary system: its current mass provides a constraint on the initial mass of the primary, its surface may show evidence of nuclearily processed material coming from the primary, and its rotation rate has been altered by the angular momentum content of the gained mass. Also, the space velocity of the system carries information on the amount of mass lost during the supernova explosion (Nelemans et al. 1999, Ankay et al. 2001).

Contrary to the Be/X-ray binaries, a few OB-supergiant systems host a black-hole companion (e.g. Cyg X-1, Gies & Bolton 1982), which suggests that black holes are formed by the most massive stars only. The majority of the
about twenty known black-hole candidates have a low-mass companion (soft X-ray transient or X-ray nova, e.g. McClintock & Remillard 2005), but only the three black-hole candidates known in HMXBs are persistent X-ray sources. Some of the black holes in X-ray novae appear to be linked to hypernovae believed to power gamma-ray bursts, based on the detection of r-processed elements at the surface of the low-mass companions (e.g. Israeli et al. 1999).

2. OB supergiant systems

Table 1 lists the basic properties of the HMXBs with OB supergiant companions in the Milky Way and the Magellanic Clouds. Most sources contain an X-ray pulsar: the pulse period is short and the X-ray luminosity high (near the Eddington limit $L_X \sim 10^{38}$ erg s$^{-1}$) in systems undergoing Roche-lobe overflow due to the higher accretion rate. The latter systems also have circular orbits, while the wind-fed systems have eccentricities up to $e = 0.45$ (GX301-2) and an X-ray luminosity $L_X \sim 10^{35} - 10^{36}$ erg s$^{-1}$.

The X-ray source drastically increases the degree of ionization of the surrounding stellar wind. Hatchett & McCray (1977) predicted that the ionizing power of the X-ray source would cause the orbital modulation of ultraviolet resonance lines formed in the stellar wind. The Hatchett-McCray effect has been detected in several systems (e.g. Van Loon et al. 2001), and recently in the wind-fed system 4U1700-37 for which the original prediction was made (see Ip- ing et al., these proceedings). Van der Meer et al. (2005a) find evidence for the ionization zone in 4U1700-37 through X-ray spectroscopy carried out with XMM-Newton. A secondary effect of the presence of an X-ray ionization zone is the development of a strong shock (called a photo-ionization wake) at its trailing border, where fast wind collides with the stagnant flow inside the ionization zone (Blondin et al. 1990, Kaper et al. 1994). In Roche-lobe overflow systems the high X-ray luminosity makes that only in the X-ray shadow behind the OB supergiant a normal stellar wind can develop, a so-called shadow wind (e.g. Blondin 1994, Kaper et al. 2005).

The mass of the OB supergiant primary and the compact companion in a HMXB can be accurately measured when the system hosts an X-ray pulsar. Knowledge of the orbital inclination is essential; in systems showing an X-ray eclipse the inclination must be larger than $i = 65^\circ$. For Roche-lobe overflow systems a valid assumption is that the OB supergiant is in corotation with the orbit, which provides a strong constraint on the inclination. In eclipsing systems the radius of the OB supergiant can be derived from the duration of the X-ray eclipse. The mass ratio sets the size of the Roche lobe (e.g. Eggleton 1983); it turns out that the measured radii of the OB supergiants are in very good agreement with the estimated size of the Roche lobe (Kaper 2001).

Earlier studies (e.g. Conti 1978, Rappaport & Joss 1983) suggested that the OB supergiants in HMXBs are too luminous for their masses. E.g. the O6.5 giant companion of Cen X-3 has a mass of 20 M$_\odot$, while its luminosity corresponds to that of a star of more than 50 M$_\odot$. Besides this, the radius corresponding to the luminosity and effective temperature is larger than its measured (Roche-lobe) radius (cf. Kaper 2001). Thus, apart from being undermassive, the OB supergiants in HMXBs also seem to be undersized for their luminosity and tempera-
Table 1. High-mass X-ray binaries with OB supergiant companion in the Milky Way and the Magellanic Clouds (ordered according to right ascension). The name corresponds to the X-ray source, the spectral type to the OB supergiant. For the systems hosting an X-ray pulsar the masses of both binary components can be measured (given an estimate of the inclination of the system). The last five systems most likely contain a black-hole candidate; for the galactic sources relativistic jets have been detected. The system parameters were taken from Reig et al. 1996 (2S0114+650); Van der Meer et al. 2005b (SMC X-1, LMC X-4, Cen X-3); Barziv et al. 2001 (Vela X-1); Kaper, Van der Meer & Najarro 2005 (GX301-2); Van Kerkwijk et al. 1995 (4U1538-52); Clark et al. 2002 (4U1700-37); Cox, Kaper & Mokiem 2005 (4U1907+09); Cowley et al. 1983 (LMC X-3); Hutchings et al. 1987 (LMC X-1); McSwain et al. 2004 (LS5039); Hillwig et al. 2004 (SS433); Herrero et al. 1995 (Cyg X-1). The rapid X-ray pulsars are found in Roche-lobe overflow systems. Notes: 

- A spin period of 2.7 h is proposed by Corbet et al. (1999).

| Name          | Sp. Type | $M_{OB}$ (M$_\odot$) | $M_X$ (M$_\odot$) | $P_{orb}$ (d) | $P_{pulse}$ (s) |
|---------------|----------|----------------------|-------------------|---------------|-----------------|
| 2S0114+650    | B1 Ia    | 16                   | 1.7               | 11.6          | 860$^a$         |
| SMC X-1       | B0 Ib    | 15.5                 | 1.1               | 3.89          | 0.71            |
| LMC X-4       | O7 III-IV| 15.6                 | 1.3               | 1.40          | 13.5            |
| Vela X-1      | B0.5 Ib  | 23.9                 | 1.9               | 8.96          | 283             |
| Cen X-3       | O6.5 II-III| 19.7                | 1.2               | 2.09          | 4.84            |
| GX301-2       | B1.5 Ia$^+$| >40                 | >1.3              | 41.5          | 696             |
| 4U1538-52     | B0 Iab   | 16.4                 | 1.1               | 3.73          | 529             |
| 4U1700-37     | O6.5 Iaf+| 58                   | 2.4               | 3.41          |                 |
| 4U1907+09     | early B I| 27                   | 1.4               | 8.38          | 438             |
| LMC X-3       | B3 Ve    | ~6                   | 6-9               | 1.70          |                 |
| LMC X-1       | O7-9 III | ~20                  | 4-10              | 4.22          |                 |
| LS5039        | O6.5 V((f))| 20–35               | 1.4               | 4.43          |                 |
| SS433         | A3-7 I   | 10.9                 | 2.9               | 13.08         |                 |
| Cyg X-1       | O9.7 Iab | 17.8                 | 10                | 5.60          |                 |

3. Neutron stars and black holes

In Figure 1 the mass distribution is shown of neutron stars and black holes, based on measurements collected from literature (Stairs 2004, McClintock & Remillard 2005). The neutron stars occupy a relatively narrow mass range near 1.4 M$_\odot$. The most accurate neutron-star masses have been derived for the binary radio pulsars, with an average mass of 1.35±0.04 M$_\odot$ (Thorsett & Chakrabarty 1999). The X-ray pulsars show a somewhat larger mass range, extending both below and above 1.35 M$_\odot$. The neutron star in Vela X-1 is significantly more
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Figure 1. Neutron star and black hole masses obtained from literature (Stairs 2004, McClintock & Remillard 2005, and references therein). The neutron stars, especially the binary radio pulsars (at the bottom), occupy a relatively narrow mass range near 1.35 M\(_\odot\). The X-ray pulsars (to the middle) show a wider spread, including two systems with a neutron-star mass near 2 M\(_\odot\). Such a high neutron star mass would rule out a soft equation of state. The black-hole candidates (at the top) are significantly more massive, indicative of a different formation mechanism.
massive: 1.86±0.16 M\(_\odot\) (Barziv et al. 2001, Quaintrell et al. 2003). Such a high neutron-star mass would rule out the soft equations of state. Also for 4U 1700-37 a high neutron-star mass is claimed (2.4±0.3 M\(_\odot\), Clark et al. 2002), although the X-ray source is, contrary to Vela X-1, not an X-ray pulsar (and perhaps a low-mass black hole). Van der Meer et al. (these proceedings) are currently analyzing the radial-velocity curves of other OB-supergiant systems with an (eclipsing) X-ray pulsar to find out whether Vela X-1 is an exception or that the neutron stars in these systems systematically deviate from the “canonical” mass of 1.35 M\(_\odot\). This would provide an important constraint on the neutron-star formation mechanism (i.e. the supernova).

Evolutionary calculations by Timmes et al. (1996) predict that massive stars in close binaries which explode as Type Ib supernova give rise to initial neutron star masses in a narrow mass range around 1.3 M\(_\odot\). This value does not include subsequent mass accretion from a reverse shock or from a massive component in a binary system, and Timmes et al. expect that the final masses could be somewhat higher. Interestingly, for single stars, which explode as Type II supernovae, they find a bimodal neutron-star mass distribution, with narrow peaks near 1.27 and 1.76 M\(_\odot\). As mentioned, they did not find a bimodal distribution for stars in close binaries, but at present it is not clear whether this result will hold. If stars in close binaries turn out to be more similar to single stars after all, one could assign most neutron stars to the first peak, and Vela X-1 (and 4U1700-37) to the second.

The estimated masses of black-hole candidates are substantially larger (8.4±2.0 M\(_\odot\)) than those measured for neutron stars. This suggests that neutron stars and black holes are formed in different ways. If, for example, black holes are the result of “failed” supernovae in which the stellar mantle is not blown away, but accreting on the compact remnant, one would expect a significant difference in mass between neutron stars and black holes. However, if the mass of the (proto) neutron star is increased by the fall back of material which was located outside the collapsing degenerate Fe core, one would predict that neutron stars would occupy a range in mass, up to the maximum neutron star mass allowed by the equation of state. Certainly in the binary radio pulsars such a mass distribution is not observed. With the recent evidence that a black hole may be formed during the collapse of a massive star during a gamma-ray burst (GRB980425, Galama et al. 1998, Iwamoto et al. 1998), the hypothesis would be that neutron stars are formed in “ordinary” supernovae, while black holes originate from gamma-ray bursts.

4. Microquasars

Some X-ray binaries, most notably those hosting a black hole, produce relativistic jets (e.g. Fender 2005). A famous example is SS433 which shows collimated, precessing jets with velocities of \(v = 0.26c\) (Margon 1982). In some systems, e.g. GRS1915+105, superluminal motions have been measured, proving that the material in the jet is moving at relativistic velocities as is observed in quasars. In our sample (Tab. 1) three “microquasars” are included, i.e. LS5039, SS433, and Cyg X-1. LMC X-1 and LMC X-3 are also candidate members of this group, but for these systems only upper limits are obtained in observations searching
for the radio synchrotron emission produced by the jets. This jet phenomenon is not unique to black-hole systems; also some X-ray binaries hosting a neutron star are known to produce jets (e.g. Sco X-1, Cir X-1). Besides the jets, these systems also include a (large) accretion disk. Apparently, a relatively large mass and angular momentum accretion rate results in the formation of a dense accretion disk and jets.

Cyg X-1 is one of the most famous stellar-mass black-hole candidates and one of the most intensively studied X-ray sources in the sky, at all wavelengths. Cyg X-1 probably represents a situation between pure, spherical wind accretion and Roche-lobe overflow. Every few years Cyg X-1 makes a transition from a low/hard state to a high/soft state in which the soft X-ray flux increases dramatically and the spectrum softens for a period of weeks to months. The radio flux also varies during state changes and is associated with jets (Stirling et al. 2001). The precise physical cause for the state transitions remains unclear, but may be triggered by episodes of decreased mass-loss rate in the supergiant donor star (Gies et al. 2003).

Hillwig et al. (2004) present spectroscopy of SS433 obtained near primary eclipse and disk precessional phase Φ = 0.0, when the accretion disk is expected to be most “face-on”. These conditions are the most favourable to have a change to detect the mass donor. The spectra show clear evidence of absorption features consistent with a classification of an A3-A7 supergiant. The observed radial velocity variations are in antiphase to the disk spectrum; the latter includes strong emission lines similar to those observed in Wolf-Rayet stars (see also Fuchs et al., these proceedings). Hillwig et al. derive masses of $10.9 \pm 3.1 \, M_\odot$ and $2.9 \pm 0.7 \, M_\odot$ for the mass donor and compact object plus disk, respectively.

LS5039 is an O6.5 V((f)) star (Clark et al. 2001) with a compact companion, most likely a neutron star. It has radio-emitting relativistic jets and is probably a high-energy gamma-ray source as well (Paredes et al. 2000). It is a 4.4-day binary with a high eccentricity ($e = 0.41$), which probably results from the huge mass loss that occured with the supernova producing the compact star. McSwain et al. (2004) present new optical and ultraviolet spectra of the O star and find evidence for nitrogen enhancement and carbon depletion in its atmosphere, indicative of the accretion of nuclearily processed material originating from the compact star’s massive progenitor. The observed eccentricity and runaway velocity can be reconciled only if the neutron star received a modest kick velocity due to a slight asymmetry in the supernova explosion (during which more than 5 $M_\odot$ was ejected).

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