

## INTEGRAL and the Evolution of X-ray Binaries

---

**E.P.J. van den Heuvel\***

*University of Amsterdam,*

*The Netherlands*

*E-mail:* [ed.van.den.heuvel@gmail.com](mailto:ed.van.den.heuvel@gmail.com)

INTEGRAL discovered two new types of High-Mass X-ray Binaries (HMXB): the highly obscured systems and the Supergiant Fast X-ray Transients (SFXT). The causes for the long spin periods of the neutron stars in supergiant HMXBs and of the outbursts of SFXTs are discussed. Furthermore, the formation rate, duration of the X-ray phase and the evolution after the X-ray phase of the HMXBs are discussed. Many systems will later in life merge to form Thorne-Zytkow Objects. The fate of such objects is still unclear, but the relatively high formation rate of supergiant HMXBs in the Galaxy implies that their remnants must be all around us.

*“An INTEGRAL view of the high-energy sky (the first 10 years)”*

*9th INTEGRAL Workshop and celebration of the 10th anniversary of the launch*

*October 15-19, 2012*

*Bibliothèque Nationale de France, Paris, France*

---

\*Speaker.

## 1. Introduction: forty years of X-ray binaries

Forty years ago the discovery of the first-known X-ray binary Centaurus X-3 was published. Etan Schreier of the UHURU team discovered in November 1971 the recurrence of the X-ray low states of this source with a 2,087-day period, indicating that it is an eclipsing binary, and discovered the simultaneous periodic Doppler modulation of its 4,84-second X-ray pulse period (Schreier et al. 1972a). The derived Doppler velocity amplitude of 415,1 km/s sets a lower limit of about  $16 M_{\odot}$  to the mass of its companion, indicating that this neutron star is moving around a massive star. That same year two more pulsating and eclipsing X-ray binaries were discovered by UHURU: Her X-1 (Tananbaum et al. 1972a) and SMC X-1 (Schreier et al. 1972b), as well as the massive eclipsing system 4U1700-37 (Jones et al. 1972). Also in 1972 the suggestion by Webster and Murdin (1971,1972) that Cyg X-1 is associated with the massive blue supergiant binary HD 226868, was confirmed, thanks to the arc-second-precision location of the radio source which in april 1971 appeared in the — then still large — error box of the X-ray source (Braes and Miley 1971). Since this radio source appeared at exactly the same time as a drastic change in the X-ray spectrum of the source (Tananbaum et al. 1972b), and the position of HD 226868 coincided with that of the radio source, it was clear that the radio source, the X-ray source and the massive binary system are the same object. The large radial velocity amplitude of the blue supergiant in its 5,6-day orbit then showed that the compact object in this system has a mass larger than  $5M_{\odot}$ , confirming Webster and Murdin's suggestion that this object is a black hole (Tananbaum et al. 1972b). Thus, by the end of 1972 four High-Mass X-ray Binaries (HMXBs) were known — one of them a black hole - as well as one pulsating Low-Mass X-ray Binary (LMXB), Her X-1. But it would take three more years before also the binary character of non-pulsating LMXBs was discovered, starting with Sco X-1, whose optical counterpart was found to show a brightness modulation with a period of 0,787day (Gottlieb, E.W. et al. 1975).

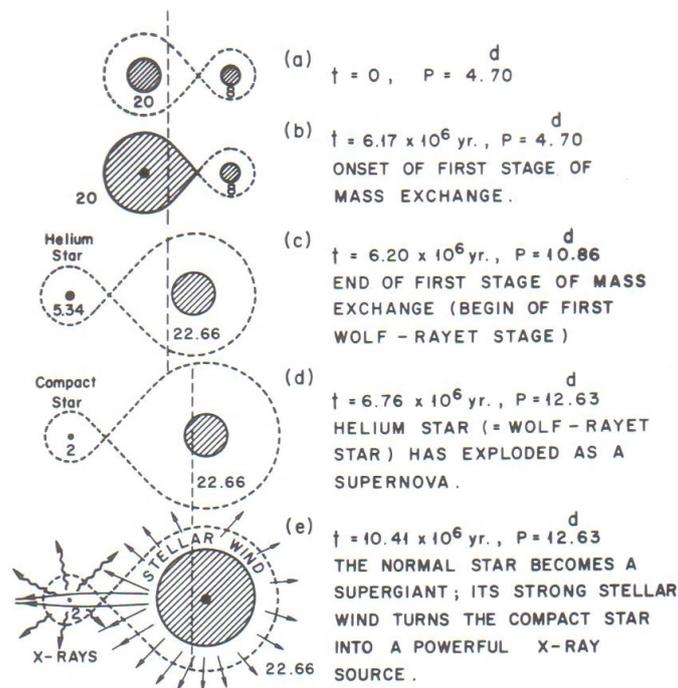
By the mid-1970s also the B-emission X-ray binaries had been recognized as a separate new class of HMXBs (Maraschi, Treves and van den Heuvel 1976). So, by the mid-1970s all important classes of X-ray binaries were thought to be known. However, in 2003 this all changed thanks to INTEGRAL, which discovered two new classes of HMXBs: (1) the highly obscured supergiant HMXBs, of which IGRJ 16318-4848 is the most extreme example (e.g. Filliatre and Chaty 2004), with a column density inside the system is orders of magnitude higher than that of the interstellar extinction, and (2) the Supergiant Fast X-ray Transients (SFXTs, e.g. Sguera et al. 2005), sources which show large short-lasting X-ray flares, and turned out to have blue supergiants as companion stars. In this paper I will restrict myself to the formation and evolution of the HMXBs and to how the two new classes of HMXBs might fit into the over-all evolutionary picture of massive binary systems. I particularly focus also on (i) the origin of the very long pulse periods observed in many of the HMXBs, and (ii) on the final evolution of these systems.

## 2. Evolutionary picture of HMXBs

### 2.1 Overview of the problem

Soon after the discovery of the binary character of Cen X-3 it was understood that the HMXBs owe their existence to the large-scale mass transfer that occurs during the evolution of a close binary

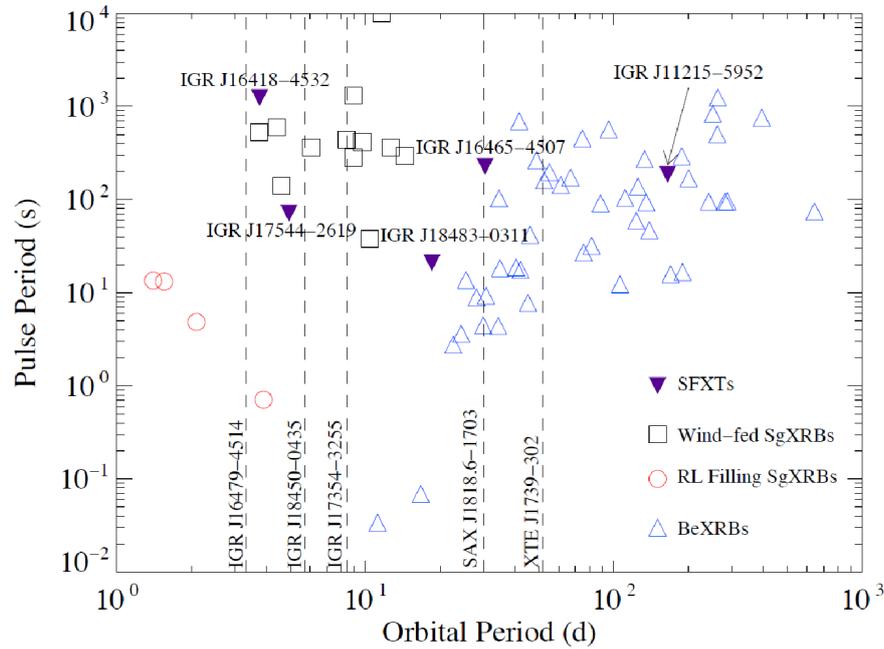
prior to the supernova explosion in which the compact star was formed (van den Heuvel and Heise 1972; Tutukov and Yungelson 1973). Thanks to this mass transfer the more evolved component — which initially was the more massive one — will later in the evolution lose its hydrogen-rich envelope to its companion, such that by the time it explodes as a supernova, it has become the less massive component of the system. Simple celestial mechanics shows that the explosive mass ejection from the less massive component of a binary does not disrupt the system (Blaauw 1961), but imparts it with a runaway velocity. Figure 1 depicts a rough outline of the evolution of a massive binary with initial components of 20 and 8 solar masses up to the X-ray binary phase, taken from van den Heuvel (1976). In this picture “conservative” binary evolution is assumed, that is: conservation of mass and orbital angular momentum during mass transfer phases (this is, of course, a rather crude assumption).



**Figure 1:** Outline of the evolution of a massive close binary into a supergiant High Mass X-ray Binary (van den Heuvel 1976). Numbers near the stars indicate masses in solar masses.

After the first phase of mass transfer the system consists of a  $5.34M_{\odot}$  helium star (the helium core of the  $20M_{\odot}$  star) and a  $22.66M_{\odot}$  O-type main-sequence star (the original secondary that received the H-rich envelope of its companion). Massive helium stars are identified with the Wolf-Rayet(WR) stars (Paczynski 1967), which in many cases are members of close binaries in which the companion star is an O-type star. These WR binaries are the direct progenitors of the HMXBs (van den Heuvel 1973; Tutukov and Yungelson 1973). In the scenario of figure 1 it is assumed that the supernova explosion of the WR star ( $0.56 \times 10^6$  yrs after the mass transfer) leaves a  $2M_{\odot}$  neutron star. Due to the sudden explosive mass loss, the center of mass gets accelerated and the system becomes a runaway star. After this it takes a very long time ( $3.65 \times 10^6$  years) before the companion star leaves the main sequence and becomes a blue supergiant with a strong stellar wind

which turns the neutron star into a pulsating X-ray source. The pulse periods of the wind-accreting X-ray pulsars with blue supergiant companions are all very long, as can be seen from the Corbet diagram in figure 2 (after Sidoli 2012). They are typically hundreds of seconds and can even range to over an hour, as in 4U2206+54 ( $P=5560$  sec), which has an O9.5V main-sequence companion, and 2S0114+65 ( $P=2,73$  hours). The spindown to these long periods must have taken place in the long time interval between the supernova explosion and the onset of the strong stellar wind phase, when the companion star becomes a blue supergiant and accretion from its wind turns the neutron star into a strong X-ray source. We now consider in some more detail what happened to the neutron star and its spin during this long time interval.



**Figure 2:** Corbet Diagram of High Mass X-ray Binaries (courtesy L. Sidoli, 2012 and S. Drave, 2012).

## 2.2 Spindown of a neutron star born as a companion of a massive OB-type star

For a spinning and accreting magnetized neutron star one can distinguish the following characteristic radii (e.g. see Ghosh 2007):

1. The light cylinder radius  $l_c = c/\Omega$
2. The Alfvén radius  $r_A$ , which is the radius where the ram pressure  $\rho v^2$  of the freely infalling matter equals the magnetic pressure  $B^2/8\pi$  of the dipole magnetic field of the neutron star. Here  $\rho$  and  $v$  are the density and velocity of the infalling gas. For  $r < r_A$  the infalling matter is forced by the magnetic field to rotate with the neutron star.
3. The co-rotation radius  $r_{co} = (GM/\Omega^2)^{1/3}$ . This is the radius where the Keplerian period of matter orbiting the neutron star equals the spin period  $P = 2\pi/\Omega$  of this star.

The neutron star will be born as a rapidly spinning pulsar, similar to the Crab pulsar, and it is expected to subsequently go through the following spindown phases (Ghosh 2007):

A. Ejector:  $l_c < r_A$ .

Here infalling matter is unable to penetrate into the light cylinder. The neutron star behaves like a normal radio pulsar and produces a highly relativistic electron-positron wind. By the inverse-Compton process the relativistic particles from this wind convert photons of the light of the star into gamma rays, and the system is expected to be a strong gamma-ray source. We know several gamma-ray emitting OB close binaries which are in this phase, e.g.: LSI 61<sup>o</sup>303 (a 27-day orbit gamma- and radio-emitting Be system), LS 5039 (O6V companion, McSwain and Gies 2002) and the Fermi source 1FGL1018.6-5856 (O6V companion).

The duration of the gamma-emitting phase is determined by the strength of the magnetic field of the NS (which determines its spindown rate, cf. Manchester and Taylor 1977; Ghosh 2007), and also by the strength of the wind of its companion star which influences the value of  $r_A$ .

One expects this phase to last up to at most a few times  $10^5$  yrs.

B. Propellor phase

Once the neutron star has spun down such that  $l_c > r_A$ , matter will be able to penetrate into the light cylinder and the relativistic pulsar wind will stop. The further spindown will now depend on whether or not the accreting matter has sufficient angular momentum to form an accretion disk. In the latter case also the co-rotation radius will come into play. There is, however, strong evidence from hydrodynamic computational simulations of wind accretion in HMXBs (e.g. Taam and Fryxell 1988; Blondin et al. 1991) that the net angular momentum accreted by the neutron star from the wind is practically zero (see also the next section).

Assuming the net angular momentum of the inflowing matter accreted from the wind to be zero, the spinning neutron star (NS) with its magnetic field will act as a propellor in this wind, and its spindown can be calculated as follows.

Only wind matter that approaches the NS within a Bondi-Hoyle accretion radius  $r_a = 2GM/v_w^2$  will be gravitationally captured (we assume here  $v_w \gg c_s$  where  $c_s$  is the sound velocity in the wind), and the accretion rate will be

$$\dot{M}_{acc} = \pi r_a^2 \rho_w \cdot v_w = 4\pi(GM)^2 \rho_w / v_w^3 \quad (1)$$

Assuming the accreted matter to fall freely towards the NS, it will be stopped at the Alfvén radius  $r_A$ , given by the condition that the ram pressure of the infalling matter  $\rho(r) \cdot v(r)^2$  equals the magnetic pressure  $B(r)^2/8\pi$  of the dipole magnetic field of the NS at that distance  $r$ .

Using this  $r_A$ , one can calculate the propellor spindown force  $F$  on the magnetosphere of the NS:

$$F = 4\pi r_A^2 \rho(r_A) \cdot (r_A \Omega)^2 \quad (2)$$

which leads to a spindown torque  $N = F \cdot r_A$ :

$$N = 4\pi r_A^5 \rho(r_A) \Omega^2 = dJ/dt \quad (3)$$

where  $J$  is the spin angular momentum of the NS.

We assume a dipole magnetic field

$$B(r) = B_0(R_{ns}/r)^3 \quad (4)$$

where  $B_0$  is the strength of the magnetic field at the NS surface, where  $r = R_{ns}$ .

By combining equations (1)–(4) one then obtains

$$N = dJ/dt = (1/6)B_0^2 R_{ns}^6 \Omega^2 / GM \quad (5)$$

which is completely independent of the properties of the stellar wind (except that the wind should have no angular momentum). This expression differs only slightly from the propeller torque for the case that the wind does have angular momentum, such that a disk forms. For this case Illarionov and Sunyaev (1975) obtained a torque  $N$  that differed only from expression (5) by the fact that the factor  $\Omega^2$  in this expression is replaced by  $\Omega \cdot \Omega_k$ , where  $\Omega_k$  is the Keplerian angular velocity in the disk at  $r = r_A$ .

Since

$$J = k^2 M R_{ns}^2 \Omega \quad (6)$$

where  $k$  is the radius of gyration of the NS, one has

$$dJ/dt = k^2 M R_{ns}^2 (d\Omega/dt) \quad (7)$$

Combination of equations (5) and (7) and integration yields

$$\Omega(t)^{-1} - \Omega_0^{-1} = (1/6)B_0^2 R_{ns}^4 t / (k^2 GM^2) \quad (8)$$

Since in general  $\Omega_0$  is very large,  $\Omega_0^{-1}$  can be neglected, yielding a spindown time  $t_\Omega$  for reaching an angular velocity  $\Omega$  given by:

$$t_\Omega = 6k^2 GM^2 / (B_0^2 R_{ns}^4 \Omega) \quad (9)$$

With the characteristic values  $k^2 = 0, 1$ ,  $M = 3 \cdot 10^{33}$  g,  $R_{ns} = 10^6$  cm for a NS, one obtains for  $B_0 = 10^{12}$  G a timescale  $t_\Omega = 1,8 \times 10^5$  yrs for spinning down to a period  $P = 100$  s =  $2\pi/\Omega$ .

Similarly, for  $B_0 = 10^{13}$  G and  $10^{11}$  G, one obtains timescales of  $1,8 \times 10^3$  and  $1,8 \times 10^7$  yrs, respectively. Since most X-ray pulsars in HMXBs have surface magnetic field strengths typically in the range  $10^{12}$  to  $10^{13}$  G, they will in the winds of their companion stars spin down to very long periods on a timescale of not more than a few times  $10^5$  yrs.

### 3. Angular momentum of accreted wind matter, and Supergiant Fast X-ray Transients (SFXTs)

#### 3.1 Outcome of hydrodynamic simulations of wind accretion from a massive companion star

These simulations show that turbulent eddies form in the wake behind the compact star (Fryxell and Taam 1988, Taam and Fryxell 1988, Blondin et al. 1991, Matsuda et al. 1992, Ruffert

1997), resulting in accretion of matter with alternating directions of the angular momentum. This behaviour of the accretion results in accretion spikes lasting only a few hours (Taam and Fryxell 1988). Due to this “flip-flop” behaviour of the accretion, the net angular momentum accreted in the course of time is zero. This explains why the slow wind-accreting X-ray pulsars in HMXBs do not show a continuous spin up, but keep hanging around the same long pulse period, with irregularly alternating episodes of spin up and spin down. The precise physics of wind accretion of these slow pulsars has been studied in a number of important recent papers by Ikshanov (2007) and Shakura et al. (2012, 2013), Postnov et al., this volume.

### 3.2 Origin of the flaring behaviour of the SFXTs

Although the accretion spikes found in the simulations of Taam and Fryxell (1988) have a similar timescale as the observed flares of the SFXTs, the amplitudes of the accretion variations in the spikes are only about one order of magnitude, while the luminosities of SFXTs vary by several orders of magnitude. Therefore the following other explanations of these flares have been considered (see for example Bozzo et al. 2008):

- (a) *Clumpy stellar winds*. The work of Ducci et al (2009) shows that this model can explain the shapes and magnitudes of the flares of sources like the 164,5-day orbit HMXB IGRJ 11215-5952. Also Ducci et al.’s (2009) simulation of the accretion in the Vela X-1 and 4U1700-37 systems very well represents the observed flaring behaviour of these systems.
- (b) *Effects of a magnetic centrifugal barrier* (Grebenev and Sunyaev 2007). If the NS spins faster than the keplerian angular velocity at the Alfven radius, accretion cannot take place. But when the accretion rate temporarily increases the Alfven radius will decrease, and the keplerian angular velocity at the Alfven surface may become faster than the spin angular velocity, and the “gate” will temporarily open, leading to a flare. Grebenev and Sunyaev showed that also this mechanism provides a plausible way to explain the observed flares.

The discussion about which of these mechanisms may be the dominant one is still going on.

## 4. The total number of Supergiant HMXBs in the Galaxy and the duration of the strong X-ray phase of these systems

The discovery of the SFXTs and the highly obscured HMXBs by INTEGRAL have almost quadrupled the known number of supergiant HMXBs (see Sidoli, this volume; and Chaty, this volume). From the fact that 4 such systems are known within 3 kpc from the Sun, we already knew for a long time that the total Galactic number of such systems should be of order  $10^2$  (e.g. van den Heuvel 1976), and these newly discovered systems support such a number. There are some  $2,2 \times 10^4$  O-stars (stars with masses  $> 20 M_{\odot}$ ) in the Galaxy (Helfand and Moran 2001). Of these, some 30% are in close binaries that will produce HMXBs (Sana et al. 2012). Since O-stars live of order  $5 \times 10^6$  years, one expects — assuming that due to supernova kicks half of the systems are disrupted in the supernova explosions — that some 3100 O-stars with compact companions form in  $5 \times 10^6$  yrs, leading to a galactic formation rate of these systems of  $\sim 6 \times 10^{-4} \text{ yr}^{-1}$ . To observe

at any time some  $10^2$  of them as supergiant HMXBs, the duration of the supergiant HMXB phase must be  $\sim 1,5 \times 10^5$  yrs.

Such a long lifetime would not be possible if the supergiants in these systems were already beyond the main sequence (that is: beyond core-hydrogen burning), since beyond the main sequence the envelopes of the supergiants expand very rapidly and would overflow the Roche lobe on a timescale of order  $10^4$  yrs, and then kill the X-ray source by a too high accretion rate. This problem was pointed out already by Ziolkowski (1977), who suggested that the OB companions in HMXBs are undermassive for their luminosities due to enhanced wind mass loss, resulting from their membership of a close binary. Such stripped hydrogen-burning stars may have a bloated radius and may, according to Ziolkowski (1977, and this volume) resemble blue supergiants. Since they are still evolving on a nuclear timescale, their radius may for a long time stay close to the Roche-lobe radius, which could explain their rather long lifetimes as a blue supergiant. Also, in recent years it was realized that with the new opacities the main sequence for the massive stars is wider than thought before, and these massive stars may spend the later part of their core-hydrogen burning phase looking like blue supergiants, even without having lost much mass (see Ziolkowski, this volume). Since during the core-hydrogen burning phase stars expand only on a nuclear timescale, they may spend  $(1-2) \times 10^5$  years as blue supergiants that are very close to filling their Roche lobes. Both these effects may explain the relatively long duration of the supergiant HMXB phase (Ziolkowski, this volume). This reasoning, however, holds only for systems with orbital periods not much longer than 5 days; beyond that, blue supergiants that are close to filling their Roche lobes must be in the hydrogen-shell burning phase, and their envelopes will expand rapidly.

## 5. Final evolution and fate of the HMXBs; possible relation with the heavily obscured HMXBs

### 5.1 Evolution towards a Common-Envelope phase

The mass ratio of HMXBs with an accreting NS is extreme, and once the massive star begins to overflow its Roche lobe, deep spiral-in of the systems is unavoidable (van den Heuvel and DeLoore 1973). Most likely the systems will go into a Common Envelope phase (Taam, Bodenheimer and Ostriker 1978). Much work on the evolution of systems through this CE phase has been done by Taam and his collaborators (e.g. see the review by Taam and Sandquist 2000). The outcome is that, in order to survive as a binary, the initial orbital period must be  $> 1$  year for a  $16M_{\odot}$  donor star and  $> 2$  yrs for a  $24M_{\odot}$  donor (Taam 1996). Only one of the supergiant HMXBs has an orbital period that approaches such a value (IRGJ 11215-5952,  $P=164,5$  d), but quite a number of the Be/X-ray binaries fulfill this condition.

### 5.2 Fate of wide HMXB systems

Here during the CE-phase the H-rich envelope of the massive star is ejected, and only its core, consisting of helium and heavier elements remains, together with the compact star, in a very narrow orbit. An example of such a post-CE system is the 4,8-hour X-ray binary Cygnus X-3 (suggested by van den Heuvel and De Loore, 1973). It consists of a Wolf-Rayet star (helium star) and a compact star (van Kerkwijk et al. 1992). Several more of such helium star plus compact star

close binaries are now known in other galaxies, e.g.: IC10 X-1 and NGC300 X-1 (both with orbital periods  $\sim 35$ h). In the latter systems, with much longer orbital periods than Cyg X-3, the compact star is a quite massive black hole, which may be the reason why they did not spiral in very deeply. When the helium star in such a system explodes as a supernova, and the system is not disrupted, an eccentric close binary will result consisting of two compact stars. The nine double neutron stars that are presently known, and which all have eccentric orbits, clearly are the result of such an evolutionary history (e.g. Flannery and van den Heuvel 1975; van den Heuvel 2007, 2009). Their progenitors will in most cases have been Be/X-ray binaries, since in these systems the compact stars are NSs, and since the Be stars are mostly less massive than  $20 M_{\odot}$ , their final remnants will also be NSs. The remnants of systems like IC10 X-1 and NGC 300 X-1 will most probably be double black hole binaries (e.g. Voss and Tauris 2003, Tauris and van den Heuvel 2006, van den Heuvel 2009). When the compact star is beginning to enter the envelope of its companion, the system will be surrounded by the first ejected matter. It may then resemble the highly obscured IGR source IGR16318-4848, which has a supergiant B[e] spectrum and shows very large circumstellar optical extinction, produced by matter that probably is concentrated in a dense circumbinary disk (Filliatre and Chaty 2004); the only other B[e] X-ray binary, which is very similar to this source is CI Cam (references in Filliatre and Chaty 2004).

### 5.3 Fate of HMXBs with orbital periods $<$ one year: complete spiral in and the formation of Thorne-Zytkow Objects

The drop in orbital binding energy during spiral in in close HMXBs is not sufficient to expell the H-rich envelope of the massive star before the compact object enters the core which consists of He and heavier elements. As a result the compact object spirals in completely and ends up in the center of the massive star. When the compact object is a NS, the resulting star is called a Thorne-Zytkow Object (TZO): a massive star with a NS in its center; the envelope of this star is very extended giving it the outside appearance of a red supergiant (Thorne and Zytkow, 1975, 1977). A major energy source of this star is accretion of matter from the envelope onto the NS. Thorne and Zytkow did not solve the problem of the nuclear energy source in TZOs. This was done independently by Biehle (1991, 1994) and Cannon (1993) who showed that nuclear burning in massive TZOs occurs via the rapid proton (rp) process. Further work on TZOs was carried out by Podsiadlowski, Cannon and Rees (1995), and the results were summarized by Podsiadlowski (1996). The energy source in low-mass TZOs (envelope mass  $< 8M_{\odot}$ ) is accretion onto the NS, while in TZOs with massive envelopes ( $> 14 M_{\odot}$ ) it is nuclear burning via the exotic rp-process. A  $15M_{\odot}$  TZO has  $T_{\text{eff}} = 3200\text{K}$  and a radius of  $\sim 1400R_{\odot}$ . The rp-process produces proton-rich isotopes of which the abundances may be enhanced by several orders of magnitude, e.g.  ${}^7\text{Li}$ , Mo, Br, Rb, Y, Nb. TZOs may be recognized by the overabundances of these elements. Convection in the envelope continuously brings fresh H into the thin burning zone around the NS. Podsiadlowski remarks that at some point a neutrino-runaway becomes unavoidable. This may be due either to (1) the exhaustion of the seed elements for the rp-process (this takes  $\sim 10^6$  yrs), or (2) due to the exhaustion of the envelope mass due to the strong stellar wind mass loss (typically for such stars  $\sim 10^{-5} M_{\odot}/\text{yr}$ ), which happens after  $\sim 10^6$  yrs. In both cases a radiative zone develops between the burning region and the outer envelope, and the supply of fresh H is shut off, causing the burning to stop. This results in accretion heating of the layer just above the neutron core, which boosts

neutrino emission, causing neutrino cooling to become the dominant energy loss mechanism at  $T > 10^{9.4}$  K, and accretion to be no longer Eddington-limited. At this point a neutrino runaway becomes unavoidable, and the calculations by Podsiadlowski et al. (1994) were stopped when the accretion rate exceeded  $10^{-6} M_{\odot}/\text{yr}$ . One is left to speculate about what will happen further. It is likely in the massive TZOs that the NS will be converted into a black hole. Since the envelope had the angular momentum of the original binary, it may then collapse into a disk, such that the final product may be a black hole surrounded by a massive disk. Podsiadlowski (1996) speculates that due to gravitational instability of the disk, out of such a disk low-mass stars could condense, such that possibly later on a black-hole LMXB could form out of such a system. The TZOs with lower-mass envelopes, which are only powered by accretion, might still leave a neutron star, after having lost their envelopes by stellar wind.

#### 5.4 Formation rate and galactic number of TZOs and their remnants

The formation rate of TZOs is equal to the formation rate of HMXBs with orbital periods  $<$  one year, which — as mentioned above — is of order  $6 \times 10^{-4} \text{ yr}^{-1}$ . With a TZO lifetime of  $\sim 10^5$  to  $10^6$  yrs, their galactic number is expected to be between 60 and 600. From the above it appears that their fate is still very unclear. However, the formation rate of their remnants ( $6 \times 10^{-4} \text{ yr}^{-1}$ ) is of order 20 per cent of the Type Ia supernova rate in the Galaxy, which implies that their remnants must be all around us. The big questions are: *what are they*, and *where are they*? The remnants of the lower-mass TZOs could be very hot NSs. Could some of their remnants be the X-ray emitting Dim Isolated NSs (DINS), whose origin is still very puzzling? As suggested by Podsiadlowski (1996) possibly some of the BH-LMXBs might be remnants of the more massive TZOs. If so, massive close binaries would have *two lives* as X-ray binaries: first as HMXBs, and later as BH-LMXBs.

#### 5.5 Conclusions

INTEGRAL has greatly contributed to a better understanding of the evolution of the High Mass X-ray Binaries. The discovery of the SFXTs and the highly obscured systems has given boost of new interest in a variety of long-standing problems concerning the physics and evolution of HMXBs, in particular: (1) the spindown of magnetized neutron stars to very long spin periods, in the winds of their massive companion stars; (2) the precise process of the wind accretion onto these slowly rotating magnetized neutron stars (Shakura et al. 2012, 2013). These NSs are important probes of the wind structure of the blue supergiants and may provide information about the clumpiness of these winds (Ducci et al. 2009), and on the existence of a centrifugal barrier (Grebenev and Sunyaev 2007); also, precise hydrodynamical simulations of wind accretion in the partially obscured sources can even be used to determine the masses of their NSs (Walter, this volume); (3) The final evolution of HMXBs, leading for wide systems to the formation of close binaries consisting of two compact objects, and for close systems to the formation of Thorne-Zytkow Objects, whose evolutionary products must be all around us in the Galaxy, but so far have not been identified.

## References

- [1] Biehle, G.T. 1991, ApJ 380, 167.
- [2] Biehle, G.T. 1994, ApJ 420, 364.
- [3] Blondin, J.M., Stevens, J.R., Kallman, T.R. 1991, ApJ 371, 684.
- [4] Bozzo, E., Falanga, M., Stella, L. 2008, ApJ 683, 1031.
- [5] Braes, L. and Miley, G.K. 1971, Nature 232, 246.
- [6] Cannon, R.C. 1993, MNRAS 263, 817.
- [7] Drave, S. 2012 (private communication).
- [8] Ducci, L., Sidoli, L., Mereghetti, S., Paizis, A., Romano, P. 2009, MNRAS 398, 2152.
- [9] Filliatre, P. and Chaty, S. 2004, ApJ 616, 469.
- [10] Flannery, B.P. and van den Heuvel, E.P.J. 1975, Astron. Ap. 39, 61.
- [11] Fryxell, B.A. and Taam, R.E. 1988, ApJ 335, 862.
- [12] Ghosh, P. 2007, "Rotation and Accretion Powered Pulsars", World Scientific Series in Astronomy and Astrophysics, Vol. 10, Singapore (772 pp).
- [13] Gottlieb, E.W., Wright and Liller, 1975, ApJ 195, L33.
- [14] Grebenev, S.A. and Sunyaev, R.A. 2007, Astronomy Letters 33, 149.
- [15] Helfand, D.J. and Moran, E.C. 2001, ApJ 554, 27.
- [16] Ikhsanov, N.R. 2007, MNRAS 375, 698.
- [17] Illarionov, A.F. and Sunyaev, R.A. 1975, Astron. Ap. 39, 185.
- [18] Jones, C., Forman, W., Liller, W., Schreier, E., Tananbaum, H., Kellogg, E., Gusky, H., Giacconi, R. 1972, BAAS 4, 329.
- [19] Manchester, R.N. and Taylor, J.H. 1977, "Pulsars", Freeman, San Francisco (281pp).
- [20] Maraschi, L., Treves, A., and van den Heuvel, E.P.J. 1976 Nature 259, 292.
- [21] Matsuda, T., Ishi, T., Sekino, N., Sawada, K., Shima, E., Livio, M., Anzer, U. 1992, MNRAS 255, 183.
- [22] McSwain, M.V. and Gies, D.R. 2002, ApJ 568, L27.
- [23] Paczynski, B. 1975, Acta Astron. 17, 355.
- [24] Podsiadlowski, Ph. 1996, in "Compact Stars in Binaries" (IAU Symp. 165; editors J. van Paradijs et al.), Kluwer Acad. Publishers, Dordrecht, p.29.
- [25] Podsiadlowski, Ph., Cannon, R.C. and Rees, M.J. 1995, MNRAS 274, 485.
- [26] Ruffert, M. 1997, Astron. Ap. 317, 793.
- [27] Sana, H., de Mink, S.E., de Koter, A., Langer, N., Evans, C.J., Gieles, M., Gosset, E., Izzard, R.G., Le Bouquin, J.-B., Schneider, F.R.N. 2012, Science 337, 444.
- [28] Schreier, E., Levinson, H., Gursky, H., Kellogg, E., Tananbaum, H. and Giacconi, R. 1972a, ApJ 172, L79.

- [29] Schreier, E., Giacconi, R., Gursky, H., Kellogg, E. and Tanabaum, H. 1972b, ApJ 178, L71.
- [30] Sguera, V., Barlow, E.J., Bird, A., Clark, D.J., Dean, A.J., Hill, A.B., Moran, L., Shaw, S.E., Willis, D.R., Bazzano, A., Ubertini, P., Malizia, A. 2005, A&A 444,221.
- [31] Shakura, N., Postnov, K., Kochetkova, A., Hjalmarsdotter, L., 2012, MNRAS 420, 216.
- [32] Shakura, N., Postnov, K., Hjalmarsdotter, L. 2013, MNRAS 428, 670.
- [33] Sidoli, L. 2012 (private communication).
- [34] Taam, R.E. 1996, in “Compact Stars in Binaries” (IAU Symp. Nr. 165, editors J.A. van Paradijs et al., Kluwer Acad. Publishers, Dordrecht), p.3.
- [35] Taam, R.E., Bodenheimer, P. and Ostriker, J.P. 1978, ApJ 222, 269.
- [36] Taam, R.E. and Fryxell, B.A. 1988, ApJ 327, L73.
- [37] Taam, R.E. and Sandquist, E.L. 2000, Annual Rev. Astron.Ap. 38, 113.
- [38] Tananbaum, H., Gursky, H., Kellogg, E.M., Levinson, R., Schreier, E., Giacconi, R. 1972a, ApJ 174,L143.
- [39] Tananbaum, H., Gursky, H., Kellogg, E., Giacconi, R., Jones, C. 1972b, ApJ 177, L5.
- [40] Thorne, K.S. and Zytzkow, A.N. 1975, ApJ 199,L19.
- [41] Thorne, K.S. and Zytzkow, A.N. 1977, ApJ 212, 832.
- [42] Tauris, T.M. and van den Heuvel, E.P.J., 2006, in “X-ray Binaries” (editors W.H.G.Lewin and M. van der Klis), Cambridge Univ. Press, p. 623.
- [43] Tutukov, A.V. and Yungelson, L.R. 1973, Nautsnie Informatisie 27, 58.
- [44] Van den Heuvel, E.P.J. 1973, Nature Phys. Sci. 242, 71.
- [45] Van den Heuvel, E.P.J. 1976, in: “Structure and Evolution of Close Binary Systems” (editors: P.Eggleton, S. Mitton and J. Whelan), Reidel, Dordrecht, p.35.
- [46] Van den Heuvel, E.P.J. 2007, in “The Multicolored Landscape of Compact Objects and Their Explosive Origins” (editors T. DiSalvo et al.) AIP Conf. Proc. Vol. 924, 598.
- [47] Van den Heuvel, E.P.J. 2009, in “Physics of Relativistic Objects in Compact Binaries: From Birth to Coalescence”, Astrophysics and Space Science Library, Springer, Heidelberg, Vol. 359,p.125.
- [48] Van den Heuvel, E.P.J. and Heise, J., 1972, Nature Phys. Sci. 239, 67.
- [49] Van den Heuvel, E.P.J. and De Loore, C., 1973, Astron.Ap.25, 387.
- [50] Van Kerkwijk, M.H., Charles, P.A., Geballe, T.R., King, D.L., Miley, G.K., Molnar, L.A. and van den Heuvel, E.P.J. 1992, Nature 355, 703.
- [51] Voss, R. and Tauris, T. 2003, MNRAS 342, 1169.
- [52] Webster, B.L. and Murdin, P., 1971, Nature 233, 110.
- [53] Webster, B.L. and Murdin, P. 1972, Nature 235, 37.
- [54] Ziolkowski, J, 1977, Proc. 8th Texas Symp. on Relativistic Astrophysics (ed. M.D.Pappagiannis), Ann. NY Acad. Sci. 302, 47.