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Forty Years of X-Ray Binaries

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Abstract. In 2012 it was forty years ago that the discovery of the first X-ray binary Centaurus X-3 became known. That same year it was discovered that apart from the High-Mass X-ray Binaries (HMXBs) there are also Low-Mass X-ray Binaries (LMXBs), and that Cygnus X-1 is most probably a black hole. By 1975 also the new class of Be/X-ray binaries was discovered. After this it took 28 years before ESAs INTEGRAL satellite team discovered two new classes of High-Mass X-ray Binaries: the highly obscured supergiant systems and the Supergiant Fast X-ray Transients (SFXT). In most HMXBs the neutron stars have very long spin periods. The causes of these long periods and of the outbursts of SFXTs are discussed. Furthermore, the formation rate, duration of the X-ray phase and the later 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 (of order $6\times10^{-4} yr^{-1}$) implies that their remnants must be all around us. Finally, the evidence for the existence of three groups of neutron star masses, derived from the study of X-ray binaries and binary radio pulsars, is briefly discussed, as well as the origins of these three types of neutron stars.

Keywords: X-rays, X-ray Binaries, neutron stars, black holes, stellar evolution, transients

1 Introduction

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 [1]. 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 [2] and SMC X-1 [3], as well as the massive eclipsing system 4U1700-37 [4]. Also in 1972 the suggestion by Webster and Murdin (1971,1972) [5, 6] 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 [7]. Since this radio source appeared at exactly the same time as a drastic change in the X-ray spectrum of the source [8], 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 [8]. 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 [9].
By the mid-1970s also the B-emission X-ray binaries had been recognized as a separate new class of HMXBs and the reasons for their transient behaviour understood [10]. Contrary to the "standard" supergiant HMXBs, in which the supergiant is very close to filling its Roche lobe and the X-ray emission is persistent, the Be/X-ray binaries are on as X-ray sources only for a fraction of the time. Their optical stars are rapidly rotating Be stars, which are deep inside their Roche lobes. Such stars from time to time expell an equatorial disk of matter which leads to an accretion outburst of the X-ray source.

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 ESAs gamma-ray satellite INTEGRAL, which discovered two new classes of HMXBs: (1) the highly obscured supergiant HMXBs, of which IGRJ 16318-4848 is the most extreme example [11], with a column density inside the system which is orders of magnitude higher than that of the interstellar extinction, and (2) the Supergiant Fast X-ray Transients (SFXTs), sources which show large short-lasting X-ray flares, and turned out to have blue supergiants as companion stars. These discoveries were due to INTEGRALs high sensitivity not only for gamma rays but also in the hard X-ray part of the spectrum. 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

Immediately 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 [12, 13]. Thanks to this mass transfer the more evolved component 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 show that the explosive mass ejection from the less massive component of a binary does not disrupt the system and accelerates the center of mass of the system, such that it becomes a runaway star. Figure 1 depicts an 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)[14]. 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).

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 [15], which in most 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 [13, 16]. In the scenario of figure 1 it is assumed that the supernova explosion of the WR star (0.56×10^6 yrs after the mass transfer) leaves a $2M_\odot$ neutron star. After this it takes a very long time ($3.65 \times 10^6 years$) before its 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 [17, 18]. They are typically hundreds of seconds and can even range to over an hour, as in $4U2206+54(P_{spin} = 5560sec)$, which has an O9.5V main-sequene companion, and $2S0114 + 65(P_{spin} = 2,73hours)$. 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 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.

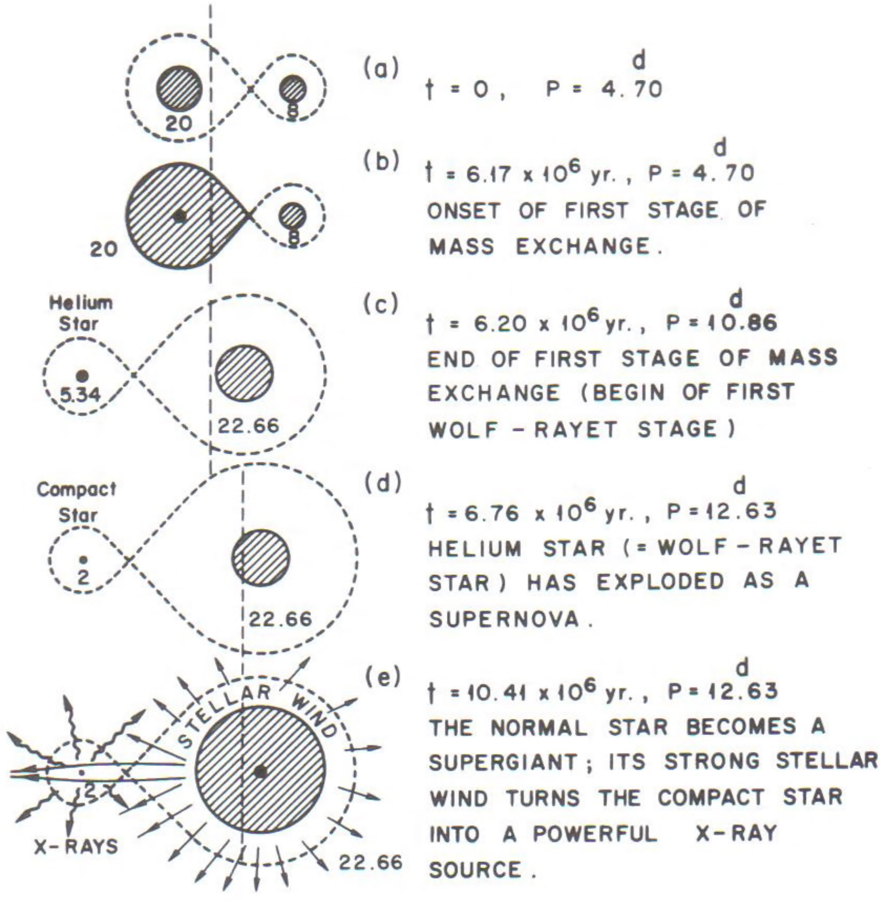

Figure 1: Outline of the evolution of a massive close binary into a High Mass X-ray Binary (van den Heuvel 1976) [14]. Numbers near the stars indicate stellar masses in solar units.

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)[19]:

1. The light cylinder radius $l_c = c/\Omega$, where Ω is the angular velocity of rotation of the star and c is the velocity of light.

2. The Alfven radius r_A , which is the radius where the ram pressure ρv^2 of the freely infalling matter equals the magnetic pressure $B^2/8\pi$ of the dipole magnetic field of the neutron star. Here $\rho(r)$ and $v(r)$ are the density and velocity of the infalling matter. For $r < r_A$ the infalling matter will be 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 of mass M equals the spin period $P = 2\pi/\Omega$ of this star.

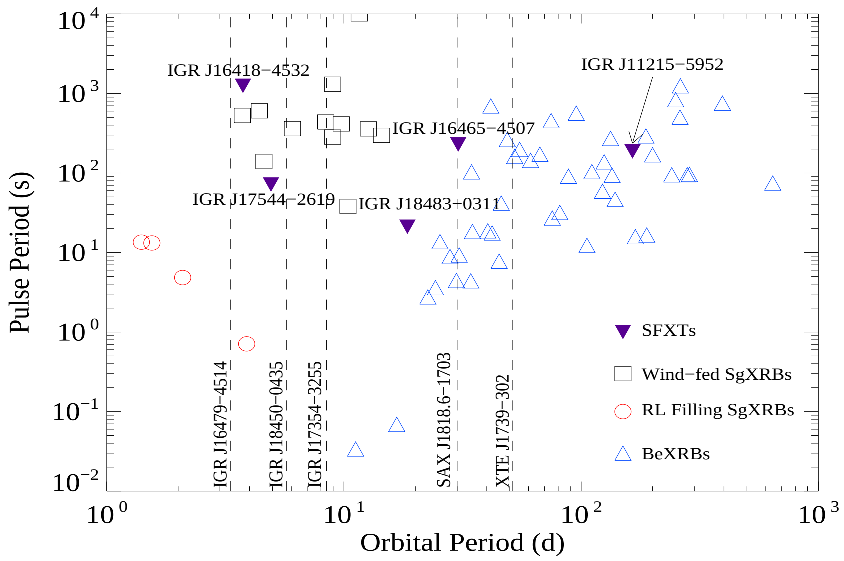

Figure 2: Relation between pulse period and orbital period for the supergiant and Be-type High-Mass X-ray Binaries. Different symbols indicate different types of HMXBs. Dashed vertical lines indicate five systems with unknown pulse periods ($RL = RocheLobe$) (after Drave 2013 and Sidoli 2013a)[20].

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)[19]:

- 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 companion 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.: $LSI61°303$ (a 27-day orbit gamma- and radio-emitting Be system), LS 5039 (O6Vcompanion, McSwain and Gies 2002)[21]and the Fermi source 1FGL1018.6-5856 (O6V companion). Also the wide and very eccentric Be/radio pulsar system PSR 1259-63 is in this phase when it is near periastron passage. 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)[19, 22], 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 [23, 24] 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 $r_a = 2GM/\nu_w^2$ will be gravitationally captured (we assume here $\nu_w \gg c_s$ where c_s is the sound velocity in the wind), and the accretion rate will be

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

Assuming the accreted matter to fall freely towards the NS, it will be stopped at the Alfven radius r_A, given by the condition that the ram pressure of the infalling matter $\rho(r).\nu(r)^2$ 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:

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

which leads to a spindwon torque $N = F.r_A$:

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

where J is the spin angular momentum of het 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 propellor torque for the case that the wind does have angular momentum, such that a disk forms. For this case Illarionov and Sunyaev (1975)[25] obtained a torque N that differed only from expression (5) by the fact that the factor Ω^2 in this expression is replaced by $\Omega.\Omega_k$, where Ω_k is the keplerian angular velocity in the disk at $r = r_A$.

$$\text{Since} \qquad J = k^2 M R_{ns}^2 \Omega \tag{6}$$

where k is the so-called radius of gyration of the NS, one has

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

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

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

Since in general Ω_0 is very large , Ω_0^{-1} can be neglected, yielding a spindown time t_Ω for reaching an angular velocity Ω given by:

$$t_\Omega = 6k^2 G M^2/(B_0^2 R_{ns}^4 \Omega) \tag{9}$$

With the characteristic values $k^2 = 0,1, M = 3.10^{33}g$, $R_{ns} = 10^6 cm$ 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 $P = 100s = 2\pi/\Omega$. Similarly, for $B_0 = 10^{13}G$ and $10^{11}G$, one obtains timescales of 1.8×10^3 and $1.8 \times 10^7 yrs$, respectively. Since X-ray cyclotron lines in the spectra of most X-ray pulsars in HMXBs show that they have surface magnetic field strengths in the range 10^{12} to 10^{13} G [26], 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 [23, 24, 27, 28, 29], 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[23]. 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)[30] and Shakura et al.(2012, 2013)[31, 32].

3.2 Origin of the Flaring Behaviour of the SFXTs

Although the accretion spikes found in the simulations of Taam and Fryxell (1988)[23] 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:

(a) *Clumpy stellar winds.* The work of Ducci et al. (2009)[33] 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)[33] simulation of the accretion in the Vela X-1 system very well represents the observed flaring behaviour of this system, and the same is true for the system of 4U1700-37.

(b) *Effects of a magnetic centrifugal barrier* (Grebenev and Sunyaev 2007)[34]. 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 can provide a plausible way to explain the observed SFXT flares.

The discussion about which of these mechanisms may be the dominanent 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 et al 2013b, and figure 2; and Chaty, 2013)[20, 35]. 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 100 (e.g. van den Heuvel 1976)[14], and these newly discovered systems support such a number. There are some 2.2×10^4 O-stars (stars with masses $> 20 M_{\odot}$) in the Galaxy (Helfand and Moran 2001)[36], of which some 30% are in close binaries that can produce HMXBs (Sana et al. 2012)[37]. These O-stars live of order 5×10^6 years, so 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 5×10^6 yrs, leading to a galactic formation rate of these systems of $6 \times 10^{-4} yr^{-1}$. To observe at any time some 10^2 of them as supergiant HMXBs, the duration of the supergiant HMXB phase must be about 1.5×10^5 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)[38], 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 2013)[38, 39] 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 2013)[39]. Since stars expand only on a nuclear timescale during the core-hydrogen burning phase, they may spend of order $(1-2) \times 10^5$ 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 2013)[39]. 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 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)[40]. Most likely the systems will go into a Common Envelope phase[41]. 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)[42]. The outcome is that, in order to survive as a binary, the initial orbital period of the system must be at least one year for a companion star of $16M_{\odot}$, and at least 2 years for a companion of $24M_{\odot}$ [42, 43]. Only one of the supergiant HMXBs has a period apparoaching such a long value (IRGJ 11215-5952, $P = 164.5d$), 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, on the basis of the first spiral-in calculation)[16]. It consists of a Wolf-Rayet star (helium star) and a compact star [44]. 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 $\sim 35h$). In the latter systems, with much longer orbital periods than Cyg X-3, the compact star is a quite massive black hole (masses $\sim 15M_{\odot}$), 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 in 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)[45, 46, 47]. 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 mosly less massive than $20M_{\odot}$, their final remnants will also be NSs. The remants of systems like IC10 X-1 and NGC 300 X-1 will most probably be double black hole binaries (BH+BH; e.g. Tauris and van den Heuvel 2006, van den Heuvel 2009)[47, 48]. (Voss and Tauris (2003) [49] showed that the formation rate of $BH+BH$ systems in galaxies is expeced to be larger than of $NS+NS$ systems.) When the compact star is beginning to enter the envelope of its companion, it 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)[11]; te only other B[e] X-ray binary known, which is very similar to this source, is CI Cam (references in Filliatre and Chaty 2004)[11].

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 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)[50, 51]. 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) [52, 53, 54] 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)[55], and the results were summarized by Podsiadlowski (1996)[56]. The energy source in low-mass TZOs (envelope mass $< 8M_{\odot}$) is accretion onto the NS, while in TZOs with massive envelopes ($> 14M_{\odot}$) it is nuclear burning via the exotic rp-process. A $15M_{\odot}$ TZO has $Teff = 3200K$ and a radius of $\sim 1400R_{\odot}$, and thus looks like a red supergiant. The rp-process produces proton-rich isotopes of which the abundances may be enhanced by several orders of magnitude, e.g. 7Li, 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 $\sim 10^{-5}M_{\odot}/yr$), 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 $10^{-6}M_{\odot}/yr$.

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, this envelope may then collapse into a disk, such that the final product may be a black hole surrounded by a massive disk. Podsiadlowski (1996)[56] speculates that due to gravitational instability of the disk, out of such a disk low-mass stars could condense, such that possibly lateron 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 $6 \times 10^{-4} yr^{-1}$. 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 is clear that their fate is still very unclear. However, the formation rate of their remnants ($6 \times 10^{-4} yr^{-1}$) 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 It is also possible that they may leave slowly spinning CCOs [57]. 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.

6 Two Types of Supernova Kicks, Three Types of Neutron Stars and the Bimodal Distribution of the Pulse Periods of Be/X-Ray Binaries

About a decade ago it was discovered, by studying the Be/X-ray binaries, that there are two groups of NS: one that receives a large velocity kick at birth and another that receives hardly any kick at birth (Pfahl et al. 2002)[58]. Studies of binary pulsars have shown that the NS in the low-kick group typically have masses of $\sim 1.25 M_\odot$, while the high-kick ones have masses in the range 1.3 to $1.5 M_\odot$. For a review and references to earlier work, see Schwab et al. (2010)[59]. The most plausible explanation of this bi-modality of the kicks and NS masses is that the low-kick NS were formed by electron-capture collapse of the degenerate O-Ne-Mg cores of stars in the mass range 8 to about $12(\pm 1) M_\odot$, whereas the high-kick ones were formed in the iron-core collapses in stars that started out with masses larger than $12 M_\odot$ (Podsiadlowski et al. 2004, van den Heuvel 2004)[60, 61]. As to the NS masses, there is a third group, with masses around $2(\pm 0.2) M_\odot$, of which Vela X-1 was the first recognized example (Barziv et al. 2001 , Quaintrell et al. 2003)[62, 63].

The $1.97(\pm 0.04) M_\odot$ NS in the binary pulsar PSRJ 1614-2230 is the most spectacular example (Demorest et al. 2010)[64]. Evolutionary calculations for the origin of the latter system have shown that although the mass of this NS may after its formation have increased somewhat by accretion, this star must have been born with a mass of at least $1.67 M_\odot$ (Tauris et al. 2011, Lin et al. 2011)[65, 66]. In addition, Walter (2013)[67] has pointed out that the NSs in some of the highly obscured HMXBs also have masses of $\sim 2 M_\odot$. Since the amount of mass accreted from the winds in these HMXBs is negligible, these NSs must also have been born with these large masses. The occurrence of these massive NSs was, in fact, predicted by Timmes et al.(1995)[68], who found that stars which started out with masses above $19 M_\odot$ develop much larger mass iron cores than stars that started with masses below this value. It thus appears that there are three categories of NS masses (van den Heuvel, 2004)[61], the lowest mass group due to electron-capture collapses, and the two higher-mass groups due to iron core collapses. A very important recent discovery (Knigge et al. 2011)[69] is that the distribution of the spin periods of the NSs in the Be/X-ray binaries in our galaxy and the SMC is clearly bi-modal (figure 3). So far, I have not seen any plausible explanation for this

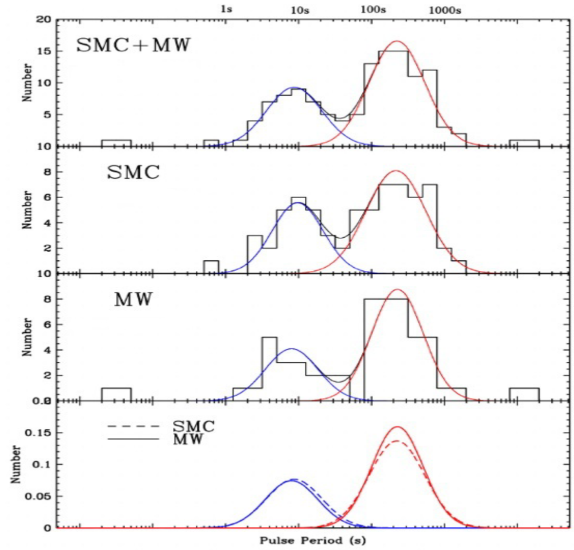

Figure 3: Bimodal distribution of pulse periods of neutron stars in Be/X-ray binaries in the Small Magellanic Cloud and our Milky Way galaxy (after Knigge et al. 2011)[69].

highly surprising discovery. This discovery has, by the way, raised doubts about the, so far, generally adopted relation between spin period and orbital period of the Be/X-ray binaries, as is believed to observed in the Corbet diagram. It must be said that close inspection of this diagram (see figure 2) shows that the spread of the Be/X-ray pulsars in this diagram is very large, and one may indeed wonder whether the alleged spin period vs. orbital period relation for the Be/X-ray binaries really exists.

7 Conclusions

ESA's INTEGRAL satellite 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 [32]. These NSs are important probes of the wind structure of the blue supergiants and may provide information about the clumpiness of these winds [33], and on the existence of a centrifugal barrier [34]. Also, precise hydrodynamical simulations of wind accretion in the partially obscured sources can now even be used to determine the masses of their NSs [67]; (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; (4) finally, X-ray binaries and binary radio pulsars have shown us that there are three classes of neutron-star masses, confirming theoretical predictions about the different ways in which neutron stars can be formed. This information on neutron star masses could not have been obtained in any other way. This demonstrates that with X-ray binaries and binary pulsars nature has provided us with unique tools for testing stellar evolution and the theoretically predicted formation mechanisms of neutron stars and black holes..

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