X-RAY OBSERVATIONS OF B-EMISSION STARS

(Review Paper)

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Abstract

Most evidence on X-ray emission from the vicinity of Be stars concerns the Be/X-ray binaries. Presently some 20 of these systems are known, making them the most numerous class of massive X-ray binaries. Evidence for the binary nature of these systems comes from (i) Doppler modulation of X-ray pulse periods, (ii) periodic X-ray flaring behavior, and (iii) correlated optical and X-ray variability. The correlation between X-ray pulse period and orbital period found by Corbet (1984) can potentially provide important information on the densities and velocities in the circumstellar disks of Be stars.

Evolutionary models indicate that the Be/X-ray binaries represent a later stage in the evolution of normal close binaries with initial primary masses predominantly in the the range 8 to 15 $M_\odot$. These models indicate that also a class of slightly less massive Be star binaries should exist in which the compact companions are white dwarfs. Be-type blue stragglers in galactic clusters may be such systems.

1 INTRODUCTION

In this review we summarize the present state of our knowledge regarding X-ray emission from Be stars. As to soft X-ray emission, which is thought to be characteristic of stellar coronae or colliding stellar winds, little information has been obtained thus far (see also Snow, this volume). The only Be star for which a soft X-ray flux has been detected is ζ Ophiuchi (Cassinelli 1986). Its luminosity of order 10^{30} ergs/s, fits the general relation $L_x/L_{opt} \sim 10^{-6}$ that describes the soft X-ray fluxes from the O-stars (Harnden et al. 1979). This might be the first evidence for the existence of coronae around Be stars.

All other information regarding the X-ray emission from the vicinity of Be stars concerns hard X-rays (typically 1-20 keV), which are characteristic of the pulsating Be/X-ray binaries. The detected hard X-ray luminosities of these systems are all $> 10^{33}$ ergs/s. This review will be confined to these systems. A further restriction is that we shall review only the increase in knowledge since our last review of this subject (Rappaport & van den Heuvel 1982). Attention will especially be given to the new observational evidence for the binary character of these systems (section 4), to information obtained from the Be/X-ray binaries concerning the density and velocity structure in the envelopes around Be stars (section 5), and to refinements in the evolutionary models for the formation of the Be/X-ray binaries and of other evolved binary Be stars (in section 6 and 7). In section 8 the final evolution and fate of Be/X-ray binaries is considered.

2 THE Be/X-RAY BINARIES AS A GROUP

When it was first suggested that there is a class of galactic X-ray binaries associated with Be stars (Maraschi, Treves and van den Heuvel 1976) there were only 4 such objects known. The first three were the strong pulsating transient X-ray sources A0535+26, A1118-61 and 4U1145-61, which all appeared to have a Be star as the brightest object in their X-ray error boxes. The fourth one was the weak persistent X-ray source apparently associated with the very bright and nearby Be star X Per. This source also appeared to be a regular X-ray pulsator, with a period of 835^s. The accurate arc-second Einstein positions subsequently obtained for these sources have left little doubt about a physical association with their Be counterparts (see Bradt & McClintock 1983). In all these cases the sources have hard spectra which, in combination with the regular X-ray pulsations, indicates that we are dealing with strongly magnetized accreting neutron stars. The most obvious explanation for their association with Be stars appears to be that these sources are binaries consisting of a Be star and a neutron star. The transient X-ray outbursts in the first three systems were suggested to be related to the irregular outbursts of mass ejection so characteristic for Be stars; in the X Per system accretion from a weak stellar wind from the Be star (evidence of which is inferred from the presence of blue-shifted ultraviolet resonance lines) was suggested to be the source of the persistent weak X-ray emission (Van den Heuvel 1977). An increasing amount of observational evidence supporting this phenomenological model has since been obtained.

By the time of the previous review (Rappaport & van den Heuvel 1982) the number of X-ray sources associated with Be stars had increased to 12, while the presently known number is 20, making them the most abundant type of massive X-ray binary in the galaxy.
Some important characteristics of the 20 presently recognized systems are listed in Table 1.

3 WHY Be STARS ARE GOOD CANDIDATES FOR COMPANIONS OF X-RAY SOURCES

To make an X-ray source out of a neutron star, the only required ingredient is: a nearby source of matter. This is most easily achieved when the neutron star is in a binary system and its companion is losing mass. The following general types of mass loss from stars are known:
(a) strong stellar winds, as seen in blue and red supergiants; (b) overflow of Roche lobe in a binary system; (c) irregular outbursts of mass outflow from the equatorial regions of rapidly rotating B-stars, causing the "Be-phenomenon".

Thus, if neutron stars can be born as companions to stars of any kind, one would expect to find X-ray binaries with companions of all the above-mentioned types.

Indeed this appears to be the case (see e.g. Lewin & van den Heuvel 1983):

(i) In persistent massive X-ray binaries like Vela X-1 (4U0900-40), 4U1700-37, and Cygnus X-1, the mass-losing companion is a blue supergiant or Of star with a strong stellar wind, while in the strong pulsating source GX1+4 the companion star is a red giant (of low mass) with a strong wind (Bradt & McClintock 1983), and

TABLE 1. The Be-star X-ray Binaries

	Source	Be-star Counterpart	m_V	P_{pulse}(s)	P_{orb}(d);e	Reference[a]
1.	0050-727 (SMC X-3)	09 IV-Ve	15	---	---	---
2.	0053-739 (SMC X-2)	B1.5Ve	16	---	---	---
3.	0053+604 (γCas)	B0.5IVe	2.5	(6000?)	---	(1) and BM
4.	0114+65 (LSI 65° 010)	B0.5IIIe	11	---	---	---
5.	0115+634	0-Be	15.5	3.6	24.3;0.34^{b,c}	
6.	0236+61 (LSI 61° 303)	B0.5III-Ve	10.7	---	26.52^{d}	(2,3) and BM
7.	V0332+53	Be	15.3	4.4	34.2;031^{b,c,e}	(see text)
8.	0352+309 (X Per)	09.5III-Ve	6.3	835	(560?)	---
9.	0535-668 (≡ A0538-66)	B2IVe (in LMC)	15	0.069	16.65;>0.4^{c,d,e}	---
10.	0535+262	09.7Ve	8.9	104	111; 0.2-0.4^{c,e}	(4)
11.	0544-665 (prob. in LMC)	B1Ve	---	---	---	---
12.	0728-25	B0-1e	11.6	---	---	(11)
13.	1E1048.1-5937	Be	19	6.4407	---	(5)
14.	1118-615	09.5IV-Ve	12.1	404	---	---
15.	1145-619	B0-1Ve	9.0	292	188^{c,e}	---
16.	1258-613 (GX304-1)	B2Ve	14.7	272	132.5^{e}	(4,5) and BM
17.	S1553-542	Be	---	9.3	30.6;<0.09^{b}	(4,7)
18.	1735-28	Be	11.2	---	---	(8)
19.	EXO 2030+375	(Be)	---	41.83	(long)	(9,10)
20.	2206+543	B0-1Ve	9.9	---	---	(11)

a. If no reference is given, data are taken from Bradt & McClintock, (1983, abbreviated BM) & Rappaport and Joss (1983).
The other references cited are either reviews or recent publications, as follows: (1) Dal Fiume & Frontera (1985); (2) Taylor & Gregory (1982); (3) Paredes & Figueras (1986); (4) Habets (1986); (5) Smale et al. (1985); (6) Pietsch et al. (1986); (7) Kelley et al. (1983); (8) Rappaport & Van den Heuvel (1982); (9) Parmar et al. (1985); (10) White et al. (1985); (11) Steiner et al. (1984).

b. Orbit determined from Doppler variations of pulse period;

c. Shows correlated optical and X-ray variability;

d. Orbital period determined from radial velocity variations of Be star;

e. Orbital period determined from recurrent X-ray variability.

in the hard X-ray source 2A1704+2411 the companion is a normal M3II giant, also with a sizeable wind (Garcia et al. 1983).

(ii) In the "disk-fed" persistent massive X-ray binaries Cen X-3 and SMC X-1, as well as in the low-mass X-ray binaries, the companions are overflowing their Roche lobes.

(iii) In the Be/X-ray binaries the companions are Be stars that are deep inside their Roche lobes, but from time to time undergo outbursts of equatorial mass ejection, upon which the neutron star temporarily appears as a strong "transient" X-ray source.

The fact that all types of X-ray binaries that in theory might exist in Nature do indeed exist confirms the law that in the Universe "anything not forbidden is compulsory" (T.H. White, op.cit. Ostriker 1971). This implies that, apparently, neutron stars can be born as companions to stars of any kind.

4 EVIDENCE FOR THE BINARY CHARACTER OF THE X-RAY SOURCES ASSOCIATED WITH Be STARS

4.1 Doppler orbits

In only three cases has the Doppler orbit of the pulsating X-ray source been determined (see Table 1). In all these cases the orbital periods are relatively short, ~ 2 to 5 weeks. The transient nature of the X-ray emission in most of these sources renders the determination of a full Doppler orbit difficult for the longer orbital period systems. On the other hand, measurements of the radial velocity orbits of the Be stars themselves are also very difficult due to the low velocity amplitudes expected for these stars (< 10-15 km/s) in combination with the large rotational broadening of their absorption lines. As a result, thus far in only two cases - those of A0538-66 and LSI+61°303 - have the optical radial velocity orbits been determined (Hutchings et al. 1985; and Hutchings & Crampton 1981). It is no coincidence that these are the two Be/X-ray systems with the shortest known orbital periods.

4.2. Search for correlated optical and X-ray behavior

This is an alternative way to establish the physical relation between the Be star and the X-ray source. In 1981 the only system for which such correlated behavior had been definitely established was A0538-66 in the LMC. When this source is active, it exhibits optical and X-ray outbursts with $16.^{d}6$ intervals. The optical outbursts, which occur near periastron passage in the system's highly eccentric orbit, can amount to up to 2.5 magnitudes. The X-ray outbursts reach a peak luminosity of 10^{39} ergs/s, making this source the intrinsically brightest neutron-star X-ray binary known (Charles et al. 1983).

Since 1981 correlated optical and X-ray behavior has been detected in four more systems, listed in Tables 1 and 2, thus firmly establishing the physical relation between the Be star and the X-ray source.

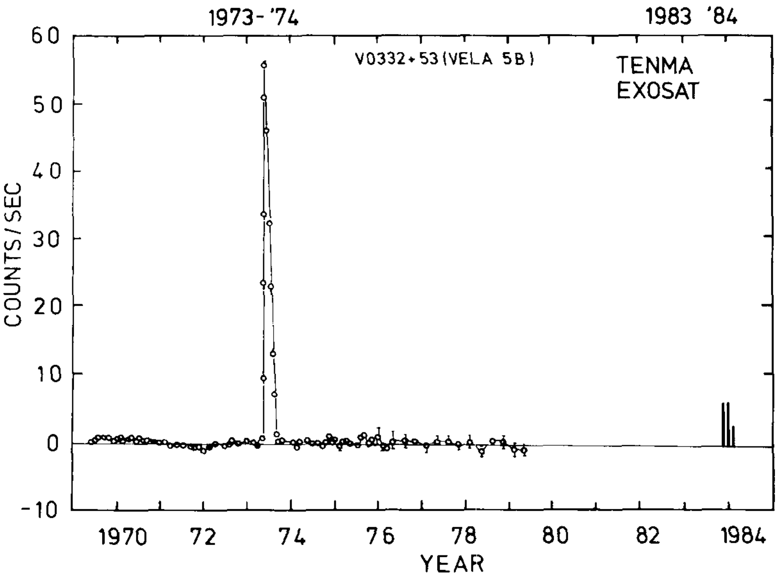
Two types of correlated optical and X-ray behavior are known, i.e.:
(i) When the Be star becomes optically active the X-ray source turns on. Active states occur at completely irregular times, interrupted by long optically inactive episodes, often lasting several years. During the

latter phases the X-ray source goes in an inactive ("off") state as well.

(ii) When the Be star is in an active phase the X-rays show "turn-ons" during periastron passage, i.e.: its outbursts are modulated with the orbital period.

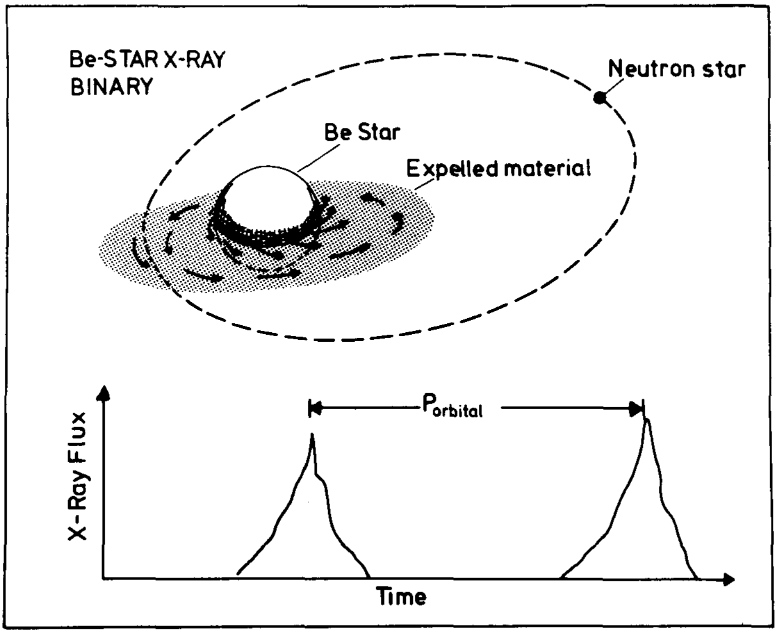
A good illustration of these two types of variability is presented by the system V0332+53, as depicted in Figure 1. This source was discovered on November 14, 1983 by the Japanese satellite TENMA (Tanaka et al. 1983) and was subsequently studied intensively with EXOSAT (Stella et al. 1983, 1985; White et al. 1984; Corbet et al. 1986). Its peak flux reached in November 1983 was 3.0 x 10^{-9} ergs/cm^{2}s in the 1-15 keV band, corresponding to a peak X-ray luminosity in this band of 7 x 10^{35} (d/1.5 kpc)^2 ergs/s, where d is the distance to the source. The source intensity started to decline after November 20, 1983 and became unobservable around December 1. The accurate 10" error box obtained by EXOSAT contains a 15.2 magnitude heavily reddened Be star

Fig. 1: X-ray intensity versus time for the transient Be/X-ray binary V0332+53. The 1973 outburst was discovered in the Vela-satellite database, by Terrell & Priedhorsky (1984) after the discovery of the November 1983 outburst by Tanaka et al. (1983). The outbursts in November and December 1983, and in January 1984 occurred with approximately 34-day intervals. The intensities of the 1983/84 outbursts are drawn to the scale of the 1973 outburst. Further explanation in the text.



(Argyle 1983; Kodaira 1983; Bernacca et al. 1983; Honeycutt & Schlegel 1983). It was noticed by Williams et al. (1983) that on 23 December 1983 the infrared (J-band) brightness of this star had suddenly increased by 0.8 magnitude. The alerted EXOSAT observers discovered the next day that the X-ray source had turned on again at a peak flux level of 2.4×10^{-9} ergs/cm^{2}s. This at once established with certainty that the Be star is physically related with the X-ray source. The source turned off again around January 2, 1984 to reappear once more in the period 19-24 January 1984, now at a much lower flux level ($7 \times {}^{-10}$ ergs/cm^{2}s). Since that time the source has not been seen again. In the meantime, the optical activity of the star has also decreased, as is indicated by the decline of the equivalent width of the H-alpha emission line by over a factor two (Corbet et al. 1986). The EXOSAT observations showed that the source is a X-ray pulsar with a period of 4.4 s. Particularly interesting is that it also exhibits shot-noise variability on timescales down to milliseconds, very similar to that observed in Cygnus X-1. This demonstrates that this type of variability is not a unique characteristic of accreting black holes, as was previously thought.

Fig. 2: Schematic model of a Be-star X-ray binary system such as A0538-66 and V0332+53. The neutron star moves in a moderately eccentric orbit around the Be star, which is much smaller than its own critical equipotential lobe. The rapidly rotating Be star is temporarily surrounded by matter expelled in its equatorial plane. Near its periastron passage the neutron star enters this circumstellar matter and the resultant accretion produces an X-ray outburst lasting several days to weeks.



During the "on" periods of V0332+53 a clear modulation of the pulse period was observed, indicating that the orbit is moderately eccentric (e = 0.31), and that the "on"-phases occur near periastron passage. In the meantime Terrell & Priedhorsky (1984) discovered in the archives of the Vela satellites that at the same location in the sky a strong transient source had turned on in the summer of 1973, at an ~ ten times higher flux level than in November 1983 (see Figure 1). Clearly, we are dealing here with a neutron star orbiting with a 34.2 day period around a Be star which during the past 15 years went through an active mass-ejection phase only twice. Figure 2 gives an "artists impression" of the model of such a system.

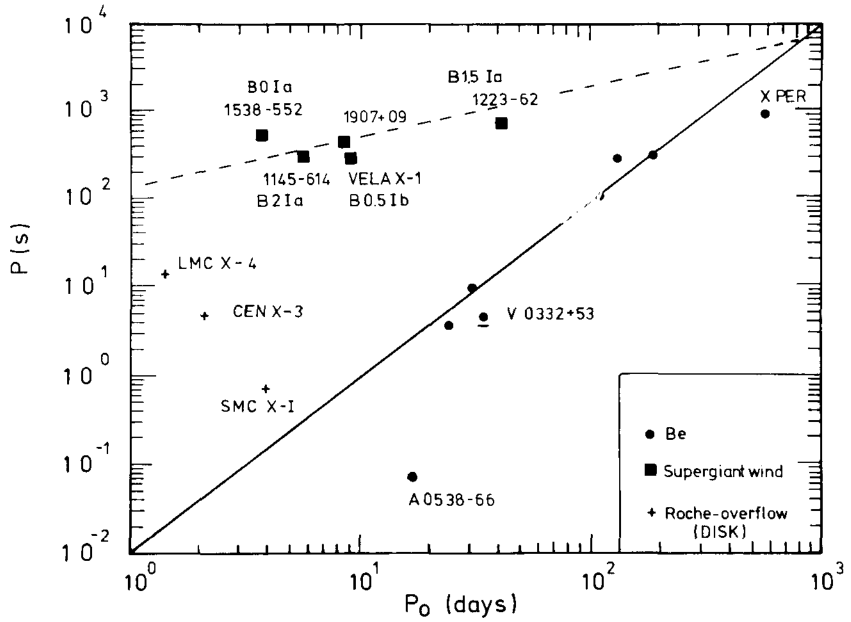
During an "on" phase the large X-ray heating may cause some extra optical emission from the atmosphere of the companion (in addition to the emission produced by the Be-star's own activity). This is clearly observed in the system of A0538-66, where an excess brightening by some 2.5 magnitude occurs during the X-ray outbursts. The X-ray heating itself may enchance the mass loss from the Be star. The interaction between the neutron star and the envelope of its companion is therefore quite complex. First attempts to model the X-ray outbursts from Be systems with eccentric orbits have been, for example, made by Brown & Boyle (1984), Charles et al. (1983), Apparao (1985) and Apparao & Tarafdar (1986).
Table 2 shows that the orbital periods of the Be/X-ray binaries detected thus far tend to be quite long: three systems have periods in the range $100\text{-}200^d$, four systems have periods between 24^d and 34^d and only one system has a period as short as 16.6^d.

5 RELATION BETWEEN ORBITAL PERIOD AND PULSE PERIOD FOR X-RAY BINARIES

5.1 Observations

Figure 3, adapted from Corbet (1986) shows a plot of pulse period vs. orbital period for pulsating binary X-ray sources. Characteristic properties of these systems can be found in Corbet's paper. The Be-systems, the "wind-fed" systems, and "disk-fed" systems (powered by Roche-lobe overflow) are indicated by the dots, squares and crosses, respectively. The figure shows that these three types of systems occupy different parts of the diagram, as was discovered by Corbet (1984, 1986). The positions of the Be-systems appear to be well fitted by a straight line with a slope of ~ 2 in log log coordinates. That the grouping of different types of systems in different parts of the diagram is real is indicated by the fact that it has a predictive as well as diagnostic value: from the position in the diagram one can predict the type of companion of the X-ray source. This is demonstrated by the case of the source V0332+53 (the underlined dot in Figure 3) which was discovered after Corbet constructed the diagram. From its position in Figure 3 one predicts that V0332+53 should have a Be-type companion, which was confirmed by the observations. Another example of the predictive power of this diagram is the case of 1907+09, for which some doubt has recently been cast on the spectral type of its optical counterpart (Iye 1986). According to its large Hα emission and large

Fig. 3: Pulse period versus binary period for pulsating binary X-ray sources (after Corbet 1984, 1986). The Be/X-ray binaries are indicated by dots, systems in which the companion is a blue supergiant with a strong wind are indicated by the squares and Roche-lobe overflowing systems are indicated by the crosses. Some individual systems are indicated. The solid line is the best-fit relation for the Be systems. Dashed line is the theoretical relation for sources accreting from a wind. Further explanation in the text.



reddening ($E_{B-V} = 3.4^m$, $m_V = 16.4^m$) this star must be an OB supergiant at a distance 5-10 kpc (Schwartz et al. 1980). If it were a Be star, as suggested by Iye (1986), its distance would be $\leq$ 1 kpc, and it would be extremely difficult to explain its enormous reddening. Figure 3, in which 1907+09 is indicated, clearly supports the supergiant classification, and indicates that it is very unlikely to be a Be star.

5.2 Interpretation of Corbet's diagram

The observed relation for the blue supergiants can qualitatively be understood in terms of stellar wind accretion (see Corbet 1986; Henrichs 1985) assuming that the neutron star rotates with the equilibrium spin period corresponding to its accretion rate. This period is given by

$$P_{eq} = 0.9^s \cdot B_{12}^{6/7} M_x^{-5/7} (\dot{M}_a/\dot{M}_{Edd})^{-3/7} R_6^{15/7} \qquad (1)$$

(see Van den Heuvel 1977; Henrichs 1983), where B_{12} and R_6 are the surface magnetic field strength and radius of the neutron star, in units of 10^{12} G and 10^6 cm, respectively, M_x is the neutron star mass, in solar units, and $\dot{M}_a$ and $\dot{M}_{Edd}$ are the mass accretion rate and the 'Eddington-limit' accretion rate for a neutron star ($\sim 1{,}5 \cdot 10^{-8}\ M_\odot$/yr). In the case of accretion from a wind, $\dot{M}_a$ is given by (see Rappaport & Van den Heuvel 1982):

$$\dot{M}_a \approx 7.10^{-6}\ \dot{M}_c\ M_x^{\,2}\ (v/10^3\ \mathrm{km\ s^{-1}})^{-4}\ (a/5.10^{12}\ \mathrm{cm})^{-2}, \qquad (2)$$

where $\dot{M}_c$ is the wind mass loss rate from the companion, v is the wind velocity relative to the neutron star and a is the orbital radius.

Substitution of equation (2) into equation (1) and use of Kepler's third law yields the relation

$$P_{eq} = (2.1\ \mathrm{sec})\ B_{12}^{\,6/7}\ (\dot{M}_c/10^{-6}\ M_\odot\ \mathrm{yr}^{-1})^{-3/7}\ M_x^{\,-11/7}\ M_c^{\,2/7}\ \cdot$$

$$\cdot (v/10^3 \mathrm{km/s})^{12/7} R_6^{\,18/7} (P_{orb}(d))^{4/7} \qquad (3)$$

where M_c is the mass of the companion (in solar units) and $P_{orb}(d)$ is the orbital period in days.
Assuming that there is the same relative wind velocity v and mass loss rate $\dot{M}_c$ in all the blue supergiant systems, and assuming all neutron

TABLE 2. Orbital periods and pulse periods of the pulsating X-ray sources represented in Figure 3 (after Corbet 1986; some data modified according to references cited in the text).
Be-sources with correlated optical and X-ray variability are designated with the letter c.

	Source	Spec. Type	P_s (seconds)	P_o (days)	e	L_x(peak)
a.	A0538-66^c	B2IVe	0.069	16.65	>0.4	1E39
b.	4U0115+63^c	Be	3.6	24.3	0.34	8E36
c.	V0332+53^c	Be	4.4	34.2	0.31	?
d.	2S1553-542	Be	9.3	30.6	<0.09	?
e.	A0535+26^c	09.7Ve	104	111	.2-.4	2E37
f.	GX304-1	B2Ve	272	133	?	3E36
g.	4U1145-61^c	B1Ve	292	188	?	6E36
h	X Per	09.5III-Ve	835	580?	?	1E34
i.	Vela X-1	B0.51b	283	9.0	0.09	6E36
j.	1E1145.1-614	BII	297	5.6	?	3E36
k.	4U1907+09	OBI	437	8.4	?	4E37
l.	4U1538-52	BOI	529	3.7	?	4E36
m.	4U1223-62	B2Ia	700	41.5	0.447	1E37
n.	SMC X-1	BOI	0.7	3.9	<7x10^{-4}	6E38
o.	Cen X-3	06-8(f)p	4.8	2.1	8x10^{-4}	4E37
p.	LMC X-4	07III-V	13.5	1.4	<0.09	4E38

stars to have the same mass, radius and magnetic field strength, one has:

$$P_{eq} \propto P_{orb}^{4/7} \qquad (4)$$

(since P_{eq} depends only very weakly on M_c).
Equation (3) is represented by the dashed line in Figure 3, where we adopted the values $B_{12} = 10$, $M_x = 1.4$, $R_6 = 1$, $v = 2000$ km/s, $M_c = 20$, $\dot{M}_c = 0.4 \times 10^{-6}\ M_\odot/yr$, as are more or less characteristic for neutron stars and the winds of early supergiants, respectively. As the figure shows, the slope of this relation fits the observed parameters of the systems with blue supergiant companions quite well.
On the other hand, a similar analysis, substituting the low wind mass loss rates ($\dot{M}_c \simeq 10^{-9} M_\odot/yr$) as observed from UV resonance lines in Be stars, would yield a line parallel to that for the supergiant systems, and located higher in Figure 3. Therefore, wind accretion can not explain the location of the Be stars in the diagram. (On the other hand, the locations of the three disk-fed systems can be qualitatively understood from the physics of disk accretion, see Corbet 1986).
In order to understand the position of the Be systems, Corbet (1984, 1986) reversed the question and asked himself: what combination of circumstellar density N and outflow velocity V is required to obtain the observed P_{pulse} vs. P_{orb} relation for the Be systems ? The underlying assumption is, as usual, that the pulse period is the equilibrium spin period. As equation (3) shows, the relation between P_{eq} and P_{orb} depends on the values of the relative velocity v and $\dot{M}_c$, which with the continuity equation can be transformed into outflow velocity V and density N (as the orbital distance and orbital velocity in the system are known). In this way Corbet found the required combinations of outflow velocity and circumstellar density. His results show that the requirements to obtain the observed relation for the Be/X-ray binaries are (if A0538-66 is excluded):

$V = 100$ km/s, $N = 10^7$ cm^{-3} to 10^2 cm^{-3} at distances $a \approx 80$ to $600\ R_\odot$, respectively.

Such densities and velocities agree well with the typical parameters inferred from the optical line emission and infrared continuum emission from the circumstellar disks of Be stars (see Waters, 1986 and this volume, and Waters & Taylor, 1986). (If V is taken a factor 10 larger or smaller, the required densities become 10^3 times larger or smaller, respectively, and would not provide an acceptable fit to the values obtained by other methods). (A0538-66 may not fit the Corbet relation because of the possible presence of an accretion disk around this very rapid pulsar, see Corbet 1986).

The conclusion therefore seems clear: The main source of the accretion in the Be/X-ray binaries is the relatively slowly expanding dense circumstellar disk around the Be-star, and not its weak high-velocity wind (except perhaps in the cases of the low luminosity sources X Per and γ Cas, where wind accretion might suffice). This confirms previous more tentative inferences (see Rappaport & Van den Heuvel 1982). The Corbet diagram of Figure 3 therefore yields potentially important information about the density and velocity structure of the circumstellar disks around Be stars.

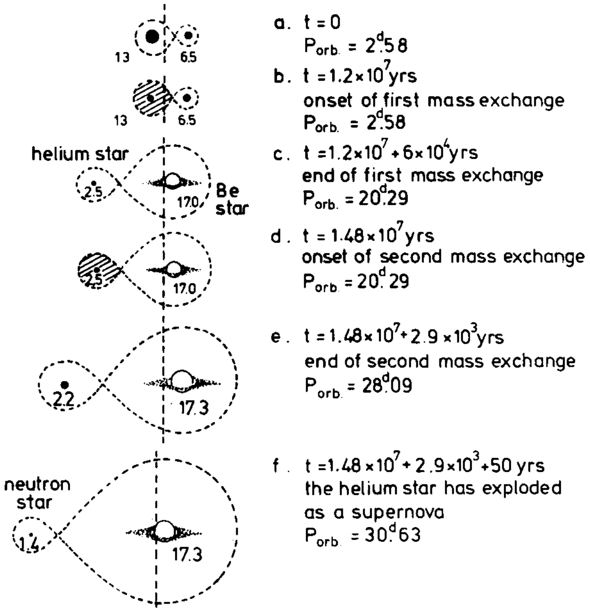
6 THE EVOLUTIONARY HISTORY OF THE Be/X-RAY BINARIES

In the evolutionary models presented earlier (Rappaport & van den Heuvel 1982; De Loore et al. 1982) the Be/X-ray binary is the result of the evolution of a normal B-type close binary of moderate mass, i.e. with component masses of order 10-15$M_\odot$. Conservative mass transfer automatically causes the orbits of such systems to widen considerably before the core collapse of the initially more massive star, such that the orbital periods of the neutron stars in these systems are expected to be at least a few weeks, as is indeed observed.

Some important refinements of this model have recently been made by Habets (1985, 1986) who showed that in these intermediate-mass systems the supernova explosion is practically always preceded by two phases of mass transfer. The second one occurs after the primary has transferred its envelope to its companion and has become a helium star. The reason is that, as noticed by De Greve & De Loore (1977) and Delgado & Thomas (1981), during helium shell-burning, helium stars with masses $< 3.5M_\odot$ evolve into giants. Habets' (1985, 1986, 1987) calculations showed that despite this second phase of mass transfer helium stars more massive than about 2$M_\odot$ in binary systems evolve towards core collapse and are expected to leave neutron star remnants. Since a 2$M_\odot$ helium star is the core of a star initially in the mass range of about 8-10$M_\odot$ (the precise value depends on the binary separation) one expects the Be/X-ray binaries to be products of the evolution of binaries with primary stars more massive than about 8$M_\odot$. Since none of the optical stars in Be/X-ray binaries has a spectral type earlier than B0V, corresponding to a mass of about 15-20$M_\odot$, one expects the Be/X-ray binaries to have originated from systems with initial primary masses in the range ~ 8-15$M_\odot$ (assuming conservative evolution and an average initial mass ratio of secondary and primary of 0.5). This corresponds to an initial spectral-type range B3-4V to B0V. At lower initial primary masses the remnant of the helium star will be a white dwarf (of rather high mass).

Figure 4 depicts the evolution of a characteristic progenitor system with component masses 13+6.5$M_\odot$ and an initial orbital period of 2.58 days, as calculated by Habets (1986). The total mass and orbital angular momentum are assumed to be conserved during phases of mass transfer (but not during the final supernova explosion, between stages e and f). The evolutionary stages are described below and in the figure and its caption. The 17$M_\odot$ star resulting from the first phase of mass transfer (stage c) is expected to be a very rapid rotator due to the accretion, through a disk, of 10.5 solar masses of matter with high angular momentum (derived from the orbital motion). Due to its rapid rotation this star is expected to be a Be star. This remains the case after an additional 0.3$M_\odot$ of helium has been transferred to it (between stages d and e). (This helium will rapidly mix into the stellar interior). Shortly after the second mass-transfer stage the helium star explodes as a supernova. As the ejected amount of matter is small (0.7$M_\odot$) and the orbit is wide, the effects of the impact of the supernova ejecta on the companion are negligible. The sudden mass loss causes the orbital period to increase from $28^{d}.09$ to $30^{d}.63$, induces an orbital eccentricity of only 0.043 and imparts a runaway velocity to the center of mass of the system of about 7 km/s. The supernova mass ejection was assumed to take place in a spherically symmetric way. With the exception of the small orbital eccentricity, the orbital and other characteristics of the final system closely resemble those of the Be-X-ray binaries such as V0332+53, 4U0114+63, LSI+61°303 and 2S1553-542. The only significant difference is in the much larger observed orbital eccentricities of the Be/X-ray binaries (with the exception of 2S1553-542). The fact that the mean observed orbital eccentricity of Be/X-ray binaries is around 0.2–0.3 cannot be explained by this model, in which

Fig. 4: Conservative case BB evolutionary scenario for the formation of a Be/X-ray binary from 13.0 + 6.5 $M_\odot$ binary system (after Habets 1985, 1986). The initial more massive primary first transfers mass to the secondary due to hydrogen-shell burning (at t = 1.2 10^7 yr) and later on (but now being the less massive, helium-star component) due to helium-shell burning in the carbon-core phase (at t = 1.48 10^7 yr). The original secondary becomes a rapidly rotating Be star as a result of the first mass exchange, by which mas and angular momentum is accreted through a disk. Finally the original primary star undergoes core collapse and forms a neutron star. As a result of the mass-exchanges the binary orbit becomes wide. A symmetric SN explosion makes the orbit slightly wider and gives it a small eccentricity. Further explanation in the text.



the underlying assumption was: spherically symmetric supernova mass ejection. The only way to obtain the higher observed eccentricities seems to be: to assume that the supernova mass ejection was not spherically symmetric i.e., that the neutron star received a kick velocity of about 100 km/s at its birth. The fact that most radio pulsars tend to be runaway objects is an indication that neutron stars indeed receive a kick velocity of ~ 100 - 200 km/s when they are born (Dewey & Cordes 1986). The high observed orbital eccentricities of Be/X-ray binaries provide additional support for this conjecture.

An alternative explanation for the relatively high orbital eccentricities might be that the systems originated from quite massive close binaries which underwent highly non-conservative evolution (see Habets, this volume).

7 Be STARS WITH WHITE DWARF COMPANIONS AND Be BLUE STRAGGLERS

For the same reasons as in the Be/X-ray binaries one expects that in post-mass exchange binaries in which the remnant of the primary star is a white dwarf, the companion star will be a rapidly rotating Be star. Thus, in view of the shape of the initial mass function, we expect that there exists a sizeable group of Be stars that are accompanied by fairly massive (~ 1 $M_\odot$) white dwarfs, consisting of C+O or O+Ne+Mg, in relatively wide orbits (P > 15 days).

In galactic clusters, Be stars that have a white dwarf or helium star companion may be more massive than the single stars near the cluster turn-off point in the HR diagram. This is because, with conservative mass transfer, the accretion of a large fraction of the mass - up to 80 to 90 percent - of the initially more massive component can have increased their masses to a value of up to 1.7 times the mass of single stars near the cluster turn off (assuming initial binary mass ratios up to ~ 0.9). Furthermore, since these stars were rejuvenated (see Van den Heuvel 1968, 1969) one would expect them to be close to the ZAMS, i.e. bluer than single stars near the cluster turn off (although this effect may be partly compensated by the slight reddening due to the rapid rotation). Consequently, Be stars with white dwarf or helium star companions in galactic clusters are expected to be - on average - bluer and, depending on the initial mass ratio of the system, sometimes also brighter than single stars near the cluster turn off. In other words, one would expect them to be "blue stragglers". This is just what is observed in many galactic clusters (see Abt, this volume). We therefore suggest that the tendency for Be stars in galactic clusters to be blue stragglers is due to the fact that they are post mass-transfer binaries. Since the Be X-ray binaries received a kick due to the supernova mass ejection, one does not expect to find them in galactic clusters any more, which is in agreement with the observations (see Van den Heuvel 1985).

8 THE FATE OF THE Be X-RAY BINARIES

One may speculate about the fate of these systems after the Be star itself had evolved away from the main sequence to become a red giant star. At that stage the system may resemble a source like 2A1704+241 in which the companion is an M3II giant with a mass between 3 and 30 $M_\odot$ (see Garcia et al. 1983). Due to the extreme mass ratio of the neutron star and its companion (~ 0.1), one expects the neutron star to be subsequently engulfed by the expanding envelope of the companion. Orbiting inside this envelope it will experience a very large frictional drag causing it to spiral rapidly inwards. The large frictional energy release causes the envelope to be finally ejected, leaving a very close system consisting of the dense core of the giant (consisting of helium and/or heavier elements) together with the neutron star (Taam et al. 1978; Bodenheimer & Taam 1984). If the evolved core is sufficiently massive it will also finally explode as a supernova. Since the cores of Be-stars are generally less massive than 4 $M_\odot$, the supernova mass ejection will - if it is symmetric and if both neutron stars have a mass of about 1.4 $M_\odot$ - not disrupt the system, although it will make the orbit quite eccentric. Thus a close neutron star binary with a close eccentric orbit will remain. (If supernova mass ejection is asymmetric, the system may also be disrupted). It thus seems that the two double neutron star binaries with eccentric orbits, PSR 1913+16 and PSR 2303+46, are both the final products of the evolution of Be X-ray binaries (see Van den Heuvel & Taam 1984; Van den Heuvel 1984, 1986). The same basic scenario holds for the system PSR 0655+64 which has a close circular orbit, in which the companion is a massive white dwarf (Van den Heuvel 1984, 1986; Van den Heuvel & Habets 1985).

9 THE NUMBER OF GALACTIC Be/X-RAY BINARIES

This point was covered quite extensively in our previous review (Rappaport & Van den Heuvel 1982). The Be/X-ray binaries are, clearly, the most abundant group of massive X-ray binaries in the galaxy, with a total inferred number of between 10^3 and 10^4. The ones which do occasionally flare up as transient Be/X-ray systems are only the "tip" of this vast "iceberg" of systems.

In order for the undiscovered Be X-ray binaries not to contribute significantly to the observed galactic ridge of X-ray emission (Warwick et al. 1985; Worrall & Marshall 1983) and not to be detectable in the Einstein galactic plane survey of Hertz & Grindlay (1984), they would have to have quiescent X-ray luminosities of less than about 10^{32} to 10^{33} ergs/s. This is consistent with the quiescent X-ray luminosities of the known X-ray binaries.

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We are indebted to Mr. J. van Oyen for providing us with up to date literature regarding the optical counterparts of the Be/X-ray binaries.

NOTE

After submission of this paper we became aware of an important new paper discussing the accretion processes in Be/X-ray binaries, by Stella, L., White, N. E., and Rosner, R. (1986, Ap. J., 308, 669). In this paper the variability of the X-ray emission from Be/X-ray binaries is discussed in terms of intermittent stellar wind accretion, and a thorough discussion is given of many aspects of the physics of the accretion processes in these systems.

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DISCUSSION FOLLOWING VAN DEN HEUVEL

Giovannelli:

My comment is about the optical precursors of x-ray outbursts in Be/x-ray systems. What you have presented about V0332+53 is not the first example of an optical precursor of an x-ray outburst. The first one detected was in 1981: looking at the late November 1981 optical spectra of HDE245770, my group discovered an unusual Be activity of the star (IAU Circ: 1981, No. 3655) especially in the Hα line, and suggested to the Hakucho team to observe in x-ray range A0935+26. They did and detected an x-ray flare of the source on December 13, 1981. De Loore et al. (this colloquium) will present an attempt to model this event. My suggestion is to encourage a better study of these optical precursors, in general, on all Be/x-ray transient systems.

van den Heuvel:

I fully agree. I only presented the case of V0332+53 because it is an interesting and characteristic example of the type of correlated optical and x-ray variability observed in these systems, not because it was the first case.

Thomas:

You overlooked two important data: (1) $L_x(\tau\mathrm{Sco}) \sim 6L_x(\zeta\mathrm{Oph})$. (2) Kuhi and Walter (1981) showed Lx inversely correlated with Hα strength in about 25 T Tauri stars. The T Tauri atmospheres are essentially the same as the Be. Therefore three phases of x-rays can arise; (a) in a corona; (b) in the region where the very large velocity outflow from the post-corona collides with the quasi-static Hα envelope; (c) the binary mass interchange you discuss. Data (1) and (2) imply x-ray absorption from regions (a) and (b) in the extended Hα cool envelope surrounding the coronal and post-coronal regions. Even though these data are not numerous, they are all consistent and must be considered.

Harmanec:

Horn and I have computed evolution of the mass-losing star after the end of case B mass exchange (i.e. after helium ignition in the core) taking rotation into account (in a simplified way, of course). The rapid decrease in the radius of the star seems to lead to a rotational instability of the star. This may change the evolutionary picture you have shown and lead to another phase of mass transfer, in fact.

van den Heuvel:

This is an important point. We did not take this into account. Would you think that mass-ejection from the helium star could induce emission phases of the companion? As a matter of fact, as you and Kriz have pointed out, many Be-systems must still have these helium-star companions. It is a pity that so far nobody has been able to detect these stars, as their energy fluxes must peak very far in the ultraviolet.

Conti:

I noticed that both the SMC and LMC have two systems of the Be/x-ray type, yet the LMC is considerably larger. Is the lack of a substantial difference an identification problem, or small number statistics, or something potentially more significant?

van den Heuvel:

I think that it is small number statistics, although also identification problems in the LMC may play a role. There are many more x-ray sources detected in the LMC than in the SMC in the *Einstein* surveys.