NON-CANONICAL INSIGHTS INTO THE EVOLUTION OF STARS

1. *An Alternative Model of Massive X-Ray Binaries*

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НЕКАНОНИЧЕСКИЕ ВЗГЛЯДЫ НА ЭВОЛЮЦИЮ ЗВЕЗД

1. *Альтернативная модель массивных рентгеновских двойных*

В работе собраны и критически обсуждены наблюдательные данные о массивных двойных звездах. Предлагается вывод о том, что обмен массой проходит в основном в направлении от рентгеновских вторичных компонентов к оптическим первичным компонентам, а не наоборот, как обычно считают. Рентгеновские компоненты этих систем не нейтронные звезды или черные дыры, а быстро вращающиеся гелиевые звезды, которые сжимаются после окончания случая Б обмена массой.

Observational data on known massive X-ray binaries have been collected and critically examined. It is concluded that the mass transfer in these systems proceeds basically from the X-ray secondaries to the optical primaries, not in the opposite direction as usually believed. The X-ray components of these systems are not neutron stars or black holes, but rotationally unstable compact helium stars contracting after the end of *case B* of mass exchange.

1. Introduction

This communication introduces a new series of rather unusual papers. My intention is to present certain critical thoughts concerning the current understanding of various types of stars, which occurred to me during my own research in the field of early-type stars and in studying the astronomical literature. The reasons for doing so are:

1. To provoke a critical discussion of the validity of some widely accepted, but in my view not safely proven, evolutionary concepts.

2. To inspire new theoretical and observational studies which I am unable to carry out myself.

One large problem of current astronomical research is that many – once apparently successful and accepted – theoretical concepts survive for a long time after the new observational and/or theoretical results have made them untenable. (Just one example: Compelling theoretical and observational reasons indicating that the rapid rotation itself cannot be responsible for the Be phenomenon have been well known for at least ten years. Yet, the rotational hypothesis of the origin of Be stars is still being presented as the only hypothesis in a number of even quite recent general textbooks on astronomy.) Perhaps even more disturbing is that a similar approach exists in a number of current astronomical papers. The magic words „it is generally accepted that ...” have often the taste of a dogma which can never be criticized. This is in a sharp contrast with the fact that our strongest arguments may turn out to be wrong, simply because our knowledge of the processes going in real stars, and our ability to model them adequately, are still very, very limited.

There have only been very few astronomers who provoked a *principal* criticism (or a defense) or more or less generally accepted concepts. Just to mention two recent examples: Who else but Professor Z. Kopal of Manchester (c.f., e.g., Kopal, 1971, 1984) expressed grave doubts about the correctness of the theory of the large-scale mass transfer in close binaries. Who else but Dr. R. N. Thomas of Paris (c.f. Thomas, 1983 and references therein) formulated several times in the recent history a principal critical analysis of the basic assumptions of the theory of stellar atmospheres. I do not claim to be a proponent of the concepts put forward by these two astronomers. However, I believe that the philosophy of their criticism is sound and should be taken very seriously by all of us.

To be more particular: I suspect that too much credence is given even to the two basic theories: the theory of stellar structure and evolution, and the

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Table 1.

Observed properties of massive X-ray binaries.

No.	Optical star	X-ray star X/XRS/4U	X-ray star Other	Spectral type	V $B-V$ $U-B$	$P_{orb}(d)$ $P_{pulse}(s)$ $P_{long}(d)$	Type of light curve Optical	Type of light curve X-ray
1	SMC	0050−727 00503−727	SMC X-3	O9III−Ve	15 −0·3 −1·0			
2	SMC south comp of a close pair	0052−739 00529−739	SMC X-2	B1·5Ve	16 −0·3 −0·5			T
3	27 Cas HR 264 HD 5394	0053+604 00537+604 0054+ 60	MX0053+60	B0·5IVe	1·6−2·8 −0·1 −1·1		P	
4	LSI+65°010	0114+650 01147+650		B0·5IIIe	11·1 1·1 −0·1			
5	V635 Cas	0115+634 01152+634 0115+63		B e	14−16 1·4 0·3	24·309 3·6146	P —	P DP
6	Sk 160	0115−737 01157−737 0115−73	SMC X-1 2A0116−737	BOIe	13·3 −0·1 −1·0	3·892 0·7149	D2(0·12) —	E(0·15) DP−MP
7	V615 Cas LSI+61°303	0236+610 — 0258+60?		B1Ve	10·7 0·8 −0·2	26·52?	P(in radio)	
8	BQ Cam		V0332+53	B e	15·1 2·3	34·25 4·375		D T
9	X Per HR 1209 HD 24534	0352+309 03522+308 0352+30		09·5III−Ve	6·0−6·7 0·1 −0·8	835 581	— —	S: —
10	LMC	0521−720 05213−719 0520−72	LMC X-2 2A0521−720	e	18·5(B)			
11	LMC	0532−664 05390−669	LMC X-4	08V−III	13·8 −0·1 −1·1	1·4083 13·5 30·48	D(0·2) S	E(0·16) P
12	LMC Johnston star Q	0535−668 — —	A0538−66	B2IIi−Ve	13−15 −0·2 −0·9	16·6515 0·06921	P(≦2·0)	P T
13	V725 Tau HDE 245770	0535+262 05357+262 0538+26	A0535+26	09·7IIIe	9·1 0·5 −0·5	110·9 103·8	P(0·04)	P MP T

Table 1. (Cont.)

He II emis.	Orbital elements Optical K	e	ω	He II K	X-ray K	e	ω	Remarks
	K	*e*	*ω*	*K*	*K*	*e*	*ω*	
Yes large RV var.								
No	No convincing RV variations found							Two episodes of long-term cyclic V/R variations (cycle length 3·6—4·0 years) separated by 37 years. Positive correlation of the long-term light and H I emission variations (see the classification by Harmanec, 1983)
Yes								
					−133·7	0·340	48	
Yes	25	0·36	355	−245	−299·5	0·000	—	Variable shape of the rising branch of the X-ray eclipse
								Radio source GT0236+610; Gamma-ray source CG135+1. Continuum 1200—5000 Å fit gives B1Ib. Long-term light variations with amplitude $0{\cdot}5^{m}$.
					32	0·31	313	P Cyg Hα profile with −1400 km/s
Rarely in the past	RV var. cyclic over 560—590^{d} not true per.							Possible light brightenings with a 6-year period documented since 1894. A period of 22^{h} reported but unconfirmed in the X-ray flux and Hα variations.
Yes								Need not be a massive binary.
Yes	55:	0·0		−490	−464	<0·2		H I RV curve has a secondary maximum (bump).
Yes	50:	<0·7	330:					Long-term light and H I emission variations, probably with an inverse correlation. That the 16·6-day period is the orbital period is still open to debate.
	21	0·6	29					Long-term light and H I emission variations, possibly with an inverse correlation. No evidence that the 111-day period is the orbital period.

Table 1 (Cont.)

No.	Optical star	X-ray star X/XRS/4U	X-ray star Other	Spectral type	V / $B-V$ / $U-B$	$P_{orb}(d)$ / $P_{pulse}(s)$ / $P_{long}(d)$	Type of light curve Optical	Type of light curve X-ray
14	LMC	0538−641	LMC X-3	B3III−IV	16·9	1·7049	D(0·2)	
		05389−641	2A0539−642		−0·1			
		0538−64			−0·7			
15	LMC	0540−697	LMC X-1	07e	14·5	4·039		
		05401−697	2A0540−698					
		0540−69						
16			3A0726−260		11·6			
		07283−258			0·3			
		0728−25			−0·6			
17	GP Vel	0900−403	Vela X-1	B0·5Ibe	6·8	8·9644	D1(0·09)	E(0·20)
	HD 77581	09002−403	GX263+3		0·5	282·9		DP−MP
		0900−40			−0·5	93·3	S	
18	He 3−640	1118−616	A1118−61	09·5III−Ve	12·1			
		11189−615			0·9	405		
		—			−0·3			T
19	V779 Cen	1119−603	Cen X-3	07IIIe	13·3	2·0871	D1(0·15)	E(0·22)
		11190−603			1·1	4·8	—	P−DP
		1118−60			0·0			
20	V801 Cen	1145−619	2S1145−619	B1Vne	9·0	187·5?		P
	HD 102567	11455−619			0·2	292		P
	Hen 715	1145−61			−0·9			
21		1145−616	1E1145·1−6141	B1I	12			
					2	297		
22	BP Cru	1223−624	2S1223−624	B1·5Iae	10·8	41·50	P	P
	Wra 977	12238−624	GX301−2(+0)		1·6	699		DP
	Hen 788	1223−62			0·5			
23		1258−613	GX304−1	B2Vne	13·9	132·5		P(0·14)
		12582−613	2S1258−613		0·7	272		S:
		1258−61			0·9			
24		1417−624	2S1417−624	e	16·2			
		14163−622			1·5	17·64		
		1416−62			1·0			T
25	BR Cir	1516−569	Cir X-1	OBe	22·5(B)	16·585	P	P
		15168−569	Nor X-2?			no		
		1515−56	2S1516−569					
26	QV Nor	1538−522	2S1538−522	BOIe	14·3	3·7299	D1(0·08)	E(0·20)
		15386−522	GX327+4·5		2·0	528·9		DP
		1538−52	A1540−53		0·8			

Table 1 (Cont.)

He II emis.	Orbital elements Optical K	e	ω	He II K	X-ray K	e	ω	Remarks
	235							A very soft X-ray spectrum.
Yes	66			−146				Poor RV coverage around the maximum velocity. A 3·91-day period fits the data with only slightly larger errors. The object is in a bright nebula N159, 6″ away from B5I star R148. A soft X-ray spectrum.
								X-ray flux variable.
Yes	22	0·14	355	−270:	−273	0·10	152	Duration of eclipses varies between 1·6 and 2·0 days. A secondary maximum on the RV curve. Large cycle-to-cycle variations of the X-ray flux, optical flux and radial velocities.
No								
Yes also NIII	25:			−400:	−415·6	0·0008		Better RV data are desirable. High X-ray states occur every 120—165 days.
No above 10%								No evidence that the 187·5-day period is the orbital period. Long-term light variations observed.
No above 10%								
Yes	20:			−223	0·475	311		A strong Hβ emission with a P Cyg profile. Light variations of $0 \cdot 1^m$ do not support the 41·5-day period.
No?								
								Need not be a massive binary.
								Periodic rapid X-ray flux decreases are followed by IR and radio flares, colours do not vary and are compatible with a red star.
Yes	33	0·14	9	−302	−323			Eclipse duration varies between 0·7 and 0·8 days.

Table 1 (Cont.)

27		1553−542	MX1553−54			29·0		
		15539−542	2S1553−542			9·27		
		—						
28	HZ Her	1656+354	Her X-1	A9−B	13·2	1·700	D2(1·6)	E(0·14)
		16560+354	2A1655+353		−0·1	1·238		S−MP
		1656+35			−0·8	35	S:	P
29	V821 Ara	1659−487	GX339−4	e	15−21			
		16589−487	MX1658−48		0·8	no		
		1658−48			−0·2			
30	V884 Sco	1700−377		06·5Ief	6·6	3·41180	D1(0·06)	E(0·27)
	HD 153919	17005−377			0·3	no		
		1700−37			−0·7			
31		1907+097		0Be	16·4	8·380		P
		19078+095			3·2	437·46		
		1907+09				41·6		S?
32	V1343 Aql	1909+048	A1909+04	e	14·2	13·09	D(0·5)	D
	SS 433	19094+047			2·1	no		
		1908+05			0·6	164		
33	V1357 Cyg	1956+350	Cyg X-1	09·7Iabe	8·9	5·5997	D(0·05)	D
	HD 226868	19564+350			0·8	no		
		1956+35			−0·3	294? 39·39?		P
34		—	3A2206+543	Be	9·9			
		22063+544			0·2			
		2206+54			−0·6			

Notation used: *Types of light curves:* D — double-wave curve with the orbital period; suffix 1 denotes that the minimum corresponding to the conjunction when the optical star is behind the X-ray star is deeper, suffix 2 denotes the opposite situation, no suffix indicates that both minima are about equally deep; P — a single-peaked curve with relatively short brightenings; S — a roughly sinusoidal variation; DP, MP — double (or multiple) — peaked curve (usually to characterize the pulse shapes); T — transient X-ray source, details unknown; E — a light curve with a clearly defined eclipse, values in brackets specify the full amplitude of variations (in magnitudes) for the optical, and the duration of eclipse (or of a high state) in fractions of the orbital

theory of stellar atmospheres. Both of them in fact contain gross simplifications. I am aware, however, that in spite of all simplifications, each of these two theories has achieved one remarkable success. It was the explanation of the existence of the main features in the HR diagram for the former, and a remarkably good matching of the observed spectra of several standard stars for the latter.

The success of the former theory tells us that the synthetic nuclear reactions, and the release of the inner and potential energy are indeed, in all probability, the main energy sources of real stars. Moreover, the mere existence of the main sequence in the HR diagram indicates that any other effects like rotation, magnetic fields, mass loss, etc., play only a very limited role in the *evolution* of the majority of real stars during the phases of hydrogen burning. They may, however, substantially affect the *spectral appearance* and *time variability* of such stars in particular cases.

The success of the later theory indicates that at least for some stars the non-stationary phenomena, non-radiative mass and energy transfer and associated phenomena are not decisive for the appearance of the line and continuous spectra observed.

I shall respect these two important findings in my further considerations.

Concluding these introductory remarks, I wish

Table 1 (Cont.)

					−117	0·03	139	No optical identification. Alternatively, periods $28{\cdot}4^d$ ($e = 0{\cdot}05$, $\omega = 177°$) or $30{\cdot}7^d$ ($e = 0{\cdot}036$, $\omega = 64°$) are also possible.
Yes also N III	62			−200	−169	0·000	—	A secondary maximum on the RV curve. Long active and inactive X-ray states with different light curves.
Yes also N III								High and rarely low X-ray states, optical brigtenings, 20^s quasi-oscillations at maximum light. Need not be a massive binary.
Yes also N III	19	0·16	5	+20				A secondary maximum on the RV curve. The He II emission moves with the optical star.
						0·2		An X-ray flare lasting 24 days was recorded.
Yes	60:	0:	—	+195				Maximum of the He II emission velocity occurs $0{\cdot}2^P$ prior to RV maxima of H I, He I emission, and Fe II absorption lines. Relativistic jets; shape of the light curve varies with a period of 164 days.
Yes	76 77	0·02 0·06	279 311	−90: −67				High and low states with a period of 294 days and an anticorrelated radio flux. Line profile variations with $P = 39{\cdot}39$ days.
								X-ray flaring on $1-10^m$ time scales; flux variations by a factor of 10 on longer time scales.

period for the X-ray light curves. The type of the curve is given separately for each indicated period. *X-ray identification:* Numbers from catalogues by Bradt and McClintock 1983 (X), by Amnuel et al. 1979 (XRS), and from the fourth Uhuru catalogue are quoted whenever available. *Orbital elements:* The semi-amplitude of the velocity curve (in km/s), the apparent orbital eccentricity e, and the longitude of the periastron ω (in degrees) are tabulated. *Spectral types:* Suffix *f* is used only in cases when the He II (N III) emission moves with the optical star. It is necessary to stress, however, that all objects with the He II emission visible would probably be qualified by *f* on classification dispersion spectra.

to stress that my approach will be more or less an *observer's view* of the problem, based on simple (for some perhaps too simple) reasoning.

2. The Massive X-Ray Binaries: Why a New Model?

In studying the ample literature on massive X-ray binaries, I have always been surprised by the very quickly established general agreement concerning the basic model of these objects. There is an admirably large number of clever theoretical studies dealing with various aspects of the problem but almost all of them respect the same basic assumptions. All investigators invariably *assume* that the X-rays coming from the secondary components of these binaries are powered by the accretion of matter flowing to these secondaries from their optical counterparts. It is also *assumed* that the secondary components are compact objects – neutron stars, or black holes in a few cases (c.f., e.g., the reviews by Hutchings, 1979, 1982; Bernacca et al., 1979; Bradt and McClintock, 1983; White, 1983; Joss and Rappaport, 1984 and many others).

But what do we really *know* from the observational data? To find an answer to this question, I undertook an extensive search in the astronomical literature and collected important data about 34 massive X-ray binaries – see Tab. 1. (The excellent reviews of Bradt and McClintock, 1983; Joss and Rappaport, 1984; Hutchings, 1979 and 1982 were of great help to me, and references to most of the data in Tab. 1 can be found in them. The data themselves, however, were taken from the original papers in all cases.) For the sake of completeness and for comparison purposes I have included in Tab. 1 also two systems which may not belong to the same group of objects, namely HZ Her/Her X-1 (1656 + 354) and V 1343 Aql (S 433)/1909 + 048. The total mass the HZ Her system is probably lower than 3 $M_\odot$ while in the case of V 1343 Aql also the optical radiation comes from a disk around the X-ray component and no direct observational evidence of the other star is available. Yet, some other observational properties of these two systems are rather similar to the other systems in Tab. 1.

My conclusions, partly illustrated by the data in Tab. 1, are the following:

1. Studies of the continuous X-ray spectra indicate that the energy flux coming from the X-ray binaries is much higher than that corresponding to the thermal radiation of normal stars. Moreover, the hard X-ray spectra are much flatter than that expected for purely thermal radiation. That is why an extra source of the X-ray radiation was sought. When it turned out, through the work of Zel'dovich and Novikov (1964), Shklovsky (1967), Cameron and Mock (1967) and Prendergast and Burbidge (1968), that the accretion onto a compact star produces an X-ray flux of about the same order of magnitude as that deduced for the X-ray binaries, the idea that the X-ray components are compact accreting stars was accepted very quickly and no alternative explanation was looked for. It is necessary to add that no simple description of the observed X-ray spectra in terms of a blackbody, thermal brehmsstrahlung, or power-law shape is usually possible. Broad spectral features, usually interpreted as cyclotron lines, have also been detected in a few cases.

2. Periodic variations of the X-ray flux, with periods ranging from fractions of a second to several minutes, usually called pulses, were discovered for 19 such binaries. Light curves of the pulses are most often double-peaked or have a more complicated structure, especially in softer X-ray wavelengths. The pulse periods are not constant. In most cases, a secular decrease of the period is observed but sometimes the time behaviour is more complicated. The X-ray pulse periods were interpreted as *rotational* periods of the X-ray components. This again strengthened the belief that such X-ray secondaries were rotating neutron stars with a strong dipole magnetic field, the axis of which was misaligned with the rotation axis.

There is growing observational evidence, however, that large pulse-to-pulse variations occur – up to a factor of two in intensity in some cases.

In several systems, like Cyg X-1 (1956 + 350), repeated attempts to detect a pulse period have failed. Only very rapid variations of the X-ray flux were observed. Such objects usually have a very soft X-ray spectrum and are considered to be accreting black holes.

3. Several pieces of evidence (accurate positional measurements, correlated optical and X-ray variations, orbital determinations, etc.) led to reliable identifications of the optical primaries of most of the known binary X-ray sources. It turned out that the optical primaries of massive X-ray binaries are Oe or Be stars, spectroscopically usually classified as supergiants or bright giants for shorter-period systems, and dwarfs to giants for longer-period ones.

4. Good or at least acceptable radial-velocity curves have been obtained for the optical primaries of two longer-period and eleven shorter-period systems. Most of them have the *same* shape, which is schematically illustrated by Fig. 1. The bump (a secondary maximum) in the lower part of the curve is variable and missing in some curves. A formal orbital solution of such curves leads to elliptical orbits with the values of the longitude of the periastron passage ω clustering near 0°.

For a number of X-ray pulsars, orbital determinations were also possible from the "Doppler delay" curves of pulse arrival times. They often indicate practically zero eccentricity for shorter-period

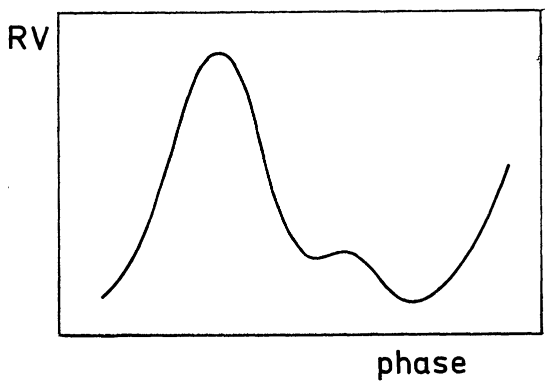

Fig. 1. A typical radial-velocity curve of the optical components of massive X-ray binaries. The secondary maximum (bump) in the lower part of the curve varies from cycle to cycle and is missing in some cases.

systems, and non-zero eccentricity for longer-period ones. The number of reliable determinations of orbital elements for longer-period systems is very limited so far because the accuracy of such determinations suffers from intrinsic variations of the pulse periods, etc.

Typical masses of the shorter-period systems obtained from the combined orbital solutions are $15-25\,M_{\odot}$ for the optical primaries, and $1-2\,M_{\odot}$ for the X-ray secondaries. These values may not be very accurate in particular cases because of non-orbital deformations of the radial-velocity curves but they probably give a correct idea of the mass range involved.

5. From cases where the data are available it appears that the H I emission (or at least the bulk of the emission) is associated with the optical primaries. The optical primaries of all massive X-ray binaries are thus indeed the Be (Oe) stars in the sense of my definition (see Harmanec, 1982 and 1983), no matter which luminosity class was assigned to their spectra. I stress that even for the "supergiant" primaries, the H I emission observed is very strong. Were these objects normal OB supergiants, no such strong Balmer emission should be associated with them.

On the other hand, the He II 4686 (and sometimes the N III 4640) emission, often observed in the optical spectra of massive X-ray binaries, seems to be associated with X-ray secondaries. Its radial-velocity curve is usually about 180° out-of-phase with respect to the radial-velocity curve of the optical primary. It is roughly sinusoidal and its semiamplitude agrees remarkably well with the semiamplitude of the X-ray secondary obtained from the Doppler delay (see Tab. 1). Only in a few cases, the amplitude of the He II emission is somewhat smaller than the amplitude of the X-ray star which may indicate that there is a significant contribution to the whole emission from the space between the two stars. As a small phase shift of the velocity curve is also observed in such cases, this fact is usually interpreted as the evidence of either a hot spot in the accretion disk around the secondary or a gas stream between the components.

6. The optical light variations of massive X-ray binaries, associated with the binary motion, are of two types. For systems with the orbital periods shorter than about 15 days, double-wave curves are observed with one broader and one narrower minimum of roughly comparable depths of $0{\cdot}05-0{\cdot}20^{m}$ ($0{\cdot}5^{m}$ for V 1343 Aql which may not be typical, however). These light curves are not usually perfectly stable — the largest cycle-to-cycle variations occurring near the broader minimum.

When interpreted as arising from combined effects of ellipticity and reflection of the optical primaries, they seem to indicate that the primaries of all short-period massive X-ray binaries are very nearly in contact with their corresponding Roche lobes. More and more researchers realize, however, that the interpretation of these light curves is very model-dependent and therefore somewhat uncertain at present (c.f. Hutchings, 1977).

For longer-period systems, a single-peaked light curve is usually observed. A similar light curve is also observed in the X-ray region. In this case, some cycle-to-cycle variations of the shape of the light curve are observed, as well.

7. Seven out of twelve known short-period systems exhibit X-ray eclipses which nearly coincide with the broader minima of the double-wave optical light curves. The only non-eclipsing systems are LMC X-3 (0538 − 641), LMC X-1 (0540 − 697), 1907 + 097, 1909 + 048, and Cyg X-1 (1956 + 35). Three of these objects LMC X-3, LMC X-1 and Cyg X-1, have very soft X-ray spectra. Moreover, the averaged orbital X-ray light curves of Cyg X-1 and 1909 + 048, for which sufficient data are available, exhibit significant flux decreases around the phases of the expected eclipses. The orbital period of LMC X-1 has only recently been found and some uncertainty as to its exact value still remains. The system 1907 + 097 has an orbital period of 8·4 days and exhibits periodic X-ray flares. Corresponding data for the optical counterpart are lacking so far. The optical identification is thus unconfirmed.

Let us undertake a simple statistical analysis of the probability of the eclipses. First, assuming a random orientation of the orbital planes, the relative number of the binary systems with orbital inclinations between i_0 and 90° is

$$n = 100 \cos i_0 \quad \text{(per cent)}\,. \tag{1}$$

A binary system, consisting of two stars with the relative radii (i.e. radii expressed in units of the distance between the stars) r_1 and r_2, will appear as eclipsing if

$$\cos i < r_1 + r_2\,. \tag{2}$$

Supposing — as an upper limit — that the optical components of the short-period massive X-ray binaries fill their Roche lobes, and neglecting the (much smaller radii) of the X-ray secondaries, one can re-write condition (2) as

$$\cos i < r_1^{\mathrm{Roch}}\,, \tag{3}$$

where r_1^{Roch} depends only on the mass ratio of the components. An inspection of the published mass determinations of the considered X-ray binaries indicates (with only a few exceptions) that the mass ratio M_2/M_1 is between 0·04 and 0·10, with an average value of 0·07. The corresponding radius r_1^{Roch} (0·07) is 0·633. This means that a typical short-period massive X-ray binary will exhibit eclipses for $i > 51°$.

Using a simple relation for the relative duration of the eclipse D (expressed in the units of the orbital period)

(4) $$\cos^2 i = (r_1 + r_2)^2 - \sin^2 \pi D ,$$

and assuming again the above-considered geometry (i.e. $r_1 = r_1^{\text{Roch}}$ (0·07) = 0·633 and $r_2 \doteq 0$), one can estimate the inclinations of the eclipsing systems from the eclipse durations given in Tab. 1.

Taking the data in Tab. 1 at their face value, and using relations (1) and (4), one gets the following observed and expected percentages of the eclipsing binaries with larger than given duration of the eclipses:

	observed	expected
$D \geqq 0·20$	33%	24%
$D \geqq 0·14$	58%	47%

There seems to be a slight overabundance of the eclipsing systems (strengthened by the fact that no systems with $0 < D < 0·14$ are observed while the expectation is 16 per cent) but this result may not be significant considering the low number of the objects used. Note, however, that an upper limit was used in the above considerations. A significant overabundance of the eclipsing systems is obtained already for $r_1 = 0·9 r_1^{\text{Roch}}(0·07)$.

In any case, the same statistics looks quite different, if one omits the "most peculiar" systems from the consideration. One should omit in fact V 1343 Aql (1909 + 048) because it is its X-ray component (or some circumstellar material around it) which dominates the optical spectrum. The nature of the companion is unclear at present. The mass ratios of LMC X-3, LMC X-1, and Cyg X-1 are – in all probability – much higher than 0·1, so the above assumptions are a priori irrelevant with respect to them.

Omitting the above-discussed four systems, we are left with what is usually called "massive systems with neutron-star secondaries" in the canonical picture. All but one of them exhibit X-ray eclipses. The statistics then give

	observed	expected
$D \geqq 0·20$	50%	24%
$D \geqq 0·14$	87·5%	47%

No doubt, with only eight binaries observed, such a statistics inevitably uncertain and any firm conclusions will have to wait for the discoveries of many more such systems.

Nevertheless, as also for several longer-period systems there is some evidence that they are observed more or less equator-on, a distinct possibility should be kept in mind that the X-rays may not be irradiated into the whole volume but rather that they are focused somehow to the orbital plane of the binary. If so, I do not see any apparent reason for such focusing within the framework of the magnetic oblique rotator model of an accreting neutron star, usually considered in connection with the X-ray pulsars.

Two important consequences of the above fact would be: 1. Overestimation of the total X-ray flux observed, and 2. finding that many more massive X-ray binaries than those listed in Tab. 1 are possibly observed which, however, are not recognized as such because of their more pole-on orientation. This would substantially increase the (already existing) slight discrepancy between the expected and observed number of massive X-ray binaries (see van den Heuvel, 1976).

8. For several systems, periodic long-term modulations of the X-ray flux, and of the amplitude and shape of the optical orbital light curve were discovered, with periods 10 to 20 times longer than the corresponding orbital periods. For several other systems such long periodicity has been reported by Cherepaschuk and his collaborators but refuted on the basis of more numerous data and independent analyses by Paradijs et al. (1983, 1984). I wish to stress that a very similar long-term variation of the light curve is also known for the eclipsing Be binary RX Cas (Kalv, 1979: $P_{\text{orb}} = 32·3^{\text{d}}$, $P_{\text{long}} = 516^{\text{d}}$), and is being suspected for several other Be binaries (CX Dra, KX And, ζ Tau, etc.), too. This may again indicate a close similarity of "normal" Be stars to the optical primaries of massive X-ray binaries.

The fact that the ratio of the long to the orbital period is usually between 10 and 20 may bear some important information concerning the nature of the phenomenon, which is most often interpreted as the precession of an accretion disk.

9. Since the radii of the optical primaries in shorter-period systems are limited by the corresponding (generalized) Roche lobes, i.e. by component masses and orbital periods of the binaries in question, it is rather curious that a number of investigators have estimated the basic properties of these optical primaries on assumption that they are "normal Ia or Ib super-

giants"! In particular, the luminosity and distance estimates based on such an assumption must inevitably be very uncertain. The uncertainties are still strengthened by the fact that even for presumably single early-type supergiants the correlation between the observed spectral types and other basic characteristics is poor (c.f., e.g., Underhill, 1983, and references therein).

Also other available distance indicators may fail for Be-type stars ("interstellar" lines may in fact be circumstellar, etc.). It creates a somewhat curious situation that our knowledge of true luminosities may be better for Magellanic Clouds objects than for galactic X-ray binaries.

10. Optical and UV spectra of some X-ray binaries contain signs of an outflow or material with velocities typically several hundreds of km/s. In particular, absorption cores of the Hα line, and absorption lines of the UV resonance lines of Si IV provide such evidence. From a phase plot of such velocities observed for GP Vel (the only system with several high-dispersion UV spectrograms from various orbital phases available) I concluded *that* these lines may in fact originate near the X-ray component! This contradicts the most often quoted interpretation in terms of a stellar wind from the optical primaries. Moreover, any straightforward interpretation of the UV spectra in terms of a stellar wind is very dangerous without a careful study of the problem of heavy line blending as recently demonstrated by Hubený et al. (1985). Consequently, many conclusions along this line of reasoning may possibly need revision.

11. There is (to my best knowledge) *no direct observational evidence* that the mean mass density of any of the known X-ray components is as high as that corresponding to a neutron star. In that sense, the presence of neutron stars in massive X-ray binaries is still only being postulated, not observationally proven beyond doubt.

12. Some simple statistical characteristics of the group of massive X-ray binaries are the following:

With the exception of HZ Her, the spectral types of the optical primaries all range from O 6·5 to B 3, with a pronounced maximum between O 9 and B 1·5 (15 out of the 22 objects with the spectral types available). The lack of later B stars is remarkable.

The orbital periods of most of the shorter-period systems range from 1·4 to 6 days, those of longer-period ones fall mainly between 15 and 45 days. The numbers of shorter-period and longer-period systems are comparable.

The distribution of the objects according to their apparent brightness in the V band has three distinct maxima: between 6th and 7th magnitude, between 9th and 10th magnitude, and a broad one between 13th and 17th magnitude.

My doubts about the correctness of the currently accepted model of massive X-ray binaries arose originally from the simple fact mentioned sub 4, namely the existence of the same type of distortion of the radial-velocity curve (schematically shown in Fig. 1) for all well-observed optical primaries. The fact that the formal orbital solutions of these velocity curves led to eccentric orbits with the longitude of periastron passage near zero was realized soon after the discovery of the first such objects by Hutchings (1974). Milgrom (1978) tried to explain the effect by a phase-dependent absorption in a stellar wind. However, his model is applicable to short-period systems only. Moreover, stellar-wind phenomena are apparently absent in some short-period X-ray binaries, like Sk 160/SMC X-1 (Hutchings et al., 1977), which, however, clearly exhibits the radial-velocity distortion of the type shown in Fig. 1. In my opinion, the most natural explanation of the velocity distortion observed is that we are seeing the same effect as observed for all other types of interacting binaries, namely the classical Barr effect as interpreted by Struve: a gas stream flowing *from the X-ray secondary to the optical primary*! Such a stream – when projected in proper orbital phases against the disk of the optical primary – increases its observed radial velocity to produce a velocity curve with a spurious eccentricity and ω near zero. (Note that the observed effect is only marginal for V 1357 Cyg/Cyg X-1, which is one of the non-eclipsing systems.)

The variable bump in the lower part of the curve may be explained by the density enhancement in the encircling gas stream above the leading hemisphere of the optical (mass-gaining) star. This interpretation has been advanced by Harmanec and Kříž (1976) and by Harmanec et al. (1976) on the basis of hydrodynamical computations of Prendergast and Taam (1974) and the geometry of the effect is illustrated in Fig. 2.

If star 1, the mass-gaining component, is the brighter of the two, we see the projection of the gas stream, having a positive velocity with respect to star 1, against the disk of the star roughly in directions denoted A and C. It is clear that as soon as the mass flux between the stars is variable, the amplitude and position of the secondary velocity maximum (observed along direction C) will be subject to larger variations than the main maximum of the radial-velocity curve seen along A. However, the amplitude and position of the main maximum can also vary with the variations of the mass transfer rate (especially for systems seen exactly equator-on), thus causing the variations in the observed spurious values of e and ω. All these effects are indeed observed in real X-ray binaries and other interacting binaries.

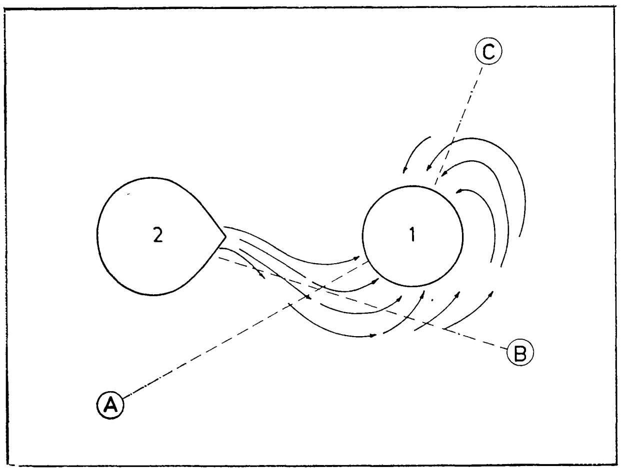

Fig. 2. A schematical illustration of gas streams in an interacting binary.

To substantiate this important point, let us discuss it in detail on the example of U Cep. The behaviour of U Cep (see Batten, 1974, 1981 and references therein) is perhaps the most illustrative among the "classical" interacting binaries, because of its excellent observational coverage over many years. U Cep is an eclipsing binary. A circular orbit is clearly indicated by its light curve. Yet, significantly different (eccentric) orbital solutions were obtained in different epochs, for example $e = 0{\cdot}47$, $\omega = 25°$ or $e = 0{\cdot}20$, $\omega = 40°$. These differences are very probably due to long-term variations in the mass transfer rate – the presence of the latter being an observationally well established fact. Batten has demonstrated that the distortion of the radial-velocity curve by the gas stream can be removed by careful measurements of high-dispersion spectrograms and was able to obtain a sinusoidal radial-velocity curve. Cyclic O – C variations of the observed times of minima (modulated over a secular steady increase of the orbital period), remarkable variations in the distortion of the light curve and cyclic appearance and disappearance of the H I emission in the spectrum of the B 7 mass-gaining component are all considered to be signs of the cyclic variations in the rate of mass transfer.

During periods of inactivity, the signs of the circumstellar matter (including the distortion of the velocity curve) may almost disappear.

To demonstrate that the above-discussed distortion of the radial-velocity curves of the optical components of massive X-ray binaries is not only a subtle phenomenon which may or may not be real, but a strong, firmly established observational fact, I shall discuss the radial-velocity observations of HDE 226 868, the optical couterpart of Cyg X-1, for which the effect is exceptionally small, yet clearly detectable.

HDE 226 868 is one of the best observed X-ray binaries. Original orbital solutions clearly indicated an orbit with non-zero eccentricity and $\omega \sim \sim 300-330°$. However, Gies and Bolton (1982), analyzing an excellent series of 78 high-dispersion spectrograms, obtained with the 1·88-m telescope of the David Dunlap Observatory between 1971 and 1981, concluded that the eccentricity of the orbit is statistically insignificant and preferred a circular orbit solution.

Table 2

Various orbital solutions for HDE 226868

Epoch (JD-2 400 000)	No. of RV	e	ω	K	Authority
41 210 – 41 263	11	0·14	299	66	Bolton (1972)
41 534 – 42 155	21	0·06	330	72·2	Bolton (1975)
41 213 – 44 795	78	0·02	279	75·7	Gies and Bolton (1982)
43 090 – 45 064	24	0·06	311	77·3	Aab (1983)
41 213 – 41 558	18	0·01	28	74·0	
41 765 – 42 155	19	0·05	285	78·9	
42 305 – 43 055	14	0·05	261	72·6	Gies and Bolton (1982) data
43 291 – 43 742	10	0·09	255	73·1	recomputed by Harmanec
44 028 – 44 795	17	0·00	–	74·3	
41 213 – 42 985	49	0·02	293	74·9	
43 046 – 44 795	29	0·02	247	75·6	

To check on this point, I obtained independent orbital solutions from their data (mean of all lines) for separate epochs, with their orbital period fixed. These solutions, together with other published orbital solutions, are listed in Table 2.

The data by Aab are based on a completely independent set of high-dispersion spectrograms, obtained with the Soviet 6-m telescope. Were the eccetricity spurious only, how does one explain the fact that all the values of ω, computed for so many various orbital solutions, fall between 250 and 30°? No doubt that the distortion of the velocity curve is only small in this case, resulting in low values of e and large errors in the formal determination of the value of ω, but the *presence* of the effect, the same as for all other well-observed X-ray binaries, is quite clear.

A similar exercise can be repeated for any other well-observed system, with the same – but thanks to larger distortion effects – even more convincing results.

In Fig. 3 the radial-velocity curves of several interacting Algol binaries and Be binaries are shown, together with the velocity curves of several massive X-ray binaries. Their mutual similarity can hardly be coincidental, I think.

It is necessary to stress that for several of the "normal" interacting binaries there is additional evidence that the matter indeed flows from star 2 to star 1 in our notation, namely for the observed secular increase of the orbital period. The instantaneous total mass of the binary in time t is

(5) $$M(t) = M_1(t) + M_2(t),$$

and the orbital angular momentum

(6) $$J(t) = M_1(t) \,.\, A_1(t) \,.\, V_1(t) + M_2(t) \,.\, A_2(t) \,.\, V_2(t),$$

where M_j, A_j, and V_j $(j = 1, 2)$ are the instantaneous masses and radii of the absolute orbits, and orbital velocities, respectively. Denoting $A(t)$ and $P(t)$ the instantaneous distance between the components and their orbital period, respectively, and assuming a circular orbit, we may further write

(7) $$A_j(t) = M_{3-j}(t)\,\frac{A(t)}{M(t)} \quad (j = 1, 2)$$

and

$$V_j(t) = 2\pi\, A_j(t)/P(t).$$

Using the 3rd Kepler law

(8) $$A(t)^3 = G \,.\, M(t) \,.\, P(t)^2$$

and inserting (7) and (8) into (6), we have

(9) $$J(t) = 2\pi\, G^{2/3} \,.\, M(t)^{-1/3} \,.\, P(t)^{1/3} \,.\, M_1(t) \,.\, M_2(t).$$

Assuming that at the period of observations the mass transfer was essentially conservative, and neglecting the (usually much smaller) angular momenta due to rotation, we have

(10) $$M = \text{const.}, \quad J = \text{const.},$$

which leads – after some algebra – to

(11) $$\frac{dP(t)}{dt} = 3\,P(t) \,.\, \frac{M_1(t) - M_2(t)}{M_1(t) \,.\, M_2(t)} \,.\, \frac{dM_1(t)}{dt}.$$

This well-known formula tells us that for M_1 greater than M_2 a secular increase of the orbital period implies that star 1 is the mass gaining component of the binary.

The trouble is that the above outlined simple interpretation of the secular period increase is valid only as long as there is no substantial mass and angular momentum loss from the whole system. I feel, however, that the mass loss from the system (I means the mass loss comparable in order of magnitude to the mass transfer between the components) is a rather rare phenomenon, limited to only very short evolutionary phases. An essentially conservative mass transfer seems to be indicated by the recent exploratory model computations by Sybesma (1985). There is a notable tendency in the recent astronomical literature to stress the role of mass loss from stars. In my opinion, the evidence of a substantial mass loss is strong only for certain particular types of stars (e.g. luminous O stars or cataclysmic binaries) but not for other types of stars. (For a more thorough discussion of this problem, the reader is again referred to Hubený et al., 1985.) Anyhow, it must be kept in mind that the interpretation of the secular changes of the orbital period is not unique at present and must be considered with some caution.

There is another fact supporting my reasoning, however: For some well-studied mass-exchanging binary systems the mass losing star 2 dominates in the optical spectrum. In such a case, the projection of a gas stream against the disk of the observed star is seen along direction B (see again Fig. 2). The gas stream then has *a negative* radial velocity with respect to the star which results in another type of distortion of the velocity curve, leading to spurious eccentricities with the longitude of periastron near

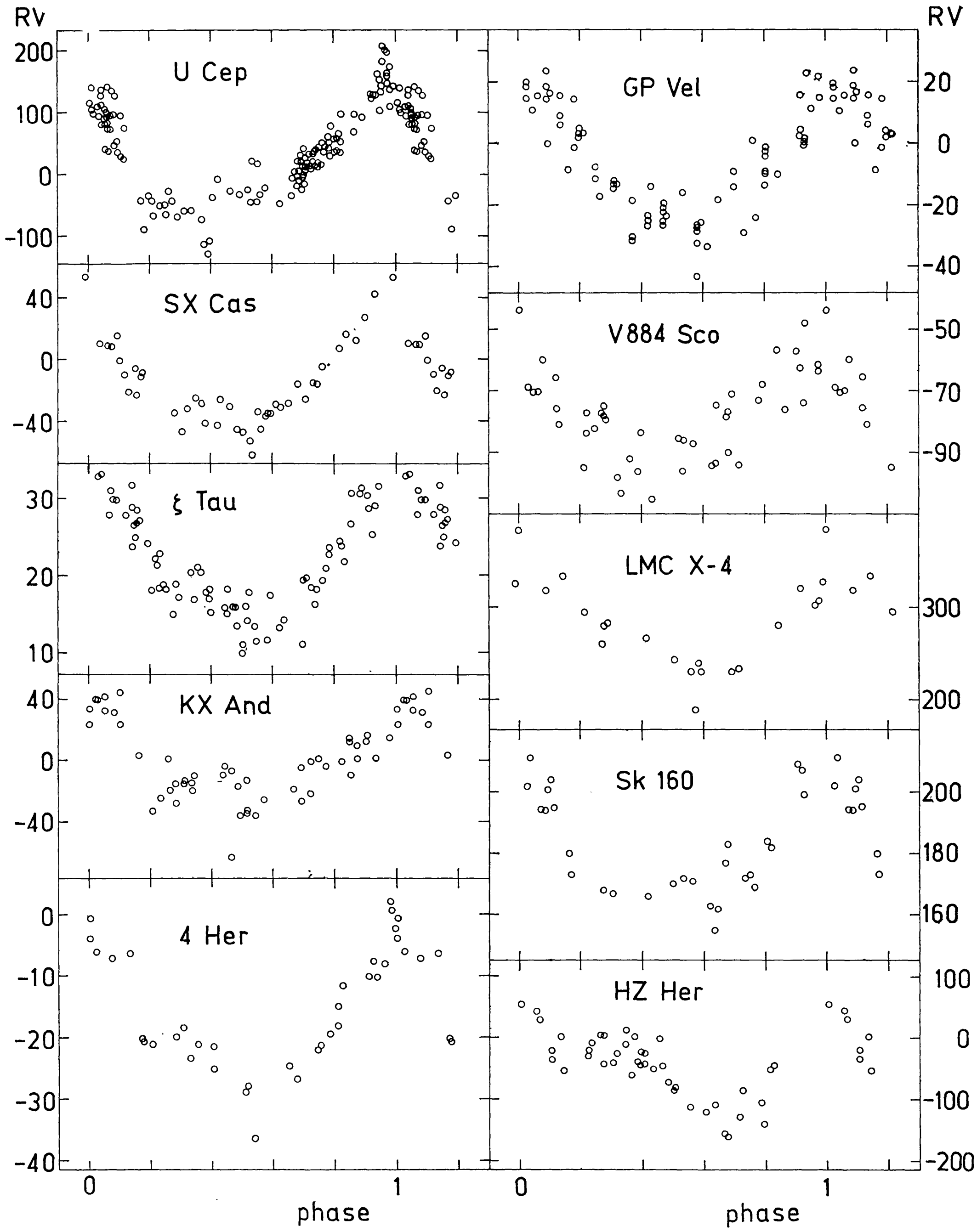

Fig. 3. Examples of the observed radial-velocity curves of the mass-gaining components of several Algol-type interacting binaries and binaries with a Be primary (left panel) and of optical primaries of some well-observed massive X-ray binaries (right panel). The mutual similarity of the curves is apparent at first sight. The following are the basic data on the stars displayed in the left panel:

U Cep (*Batten*, **1974**), $P = 2{\cdot}493^d$: An eclipsing binary with a B7Ve primary and a G8III– IV secondary. The light curve indicates a zero eccentricity and Batten was able to reconstruct indeed a circular radial-velocity curve of the star from a careful analysis of line profiles at high dispersion. The mass transfer from the G8 secondary to the B7 primary is well established. Its rate is variable with time. The orbital period has been increasing since 1880, but the sign of dP/dt varies on a shorter time scale (typically of about 10 years).

SX Cas (*Struve*, **1944***b*), $P = 36{\cdot}567^d$: An eclipsing binary with an A6e primary, and a G6 secondary sending the material towards the primary. As in the previous case, the light curve indicates a zero eccentricity of the orbit. The primary may in fact be a B star enclosed by a circumstellar envelope which — seen roughly equator-on — simulates a later spectral type (Harmanec, 1982; Plavec et al., 1982).

ξ Tau (*Harmanec*, **1984**), $P = 132{\cdot}97^d$: A well-known binary consisting of a B1e primary and probably a contact G8III secondary. The radial-velocity curve shown is from the original data by Hynek and Struve (1942).

Table 3

Basic observational data of selected binary systems in which the radial-velocity curve of the mass-losing star is observed. If not otherwise stated, the data are from Batten et al. (1978).

Star	HD	ω	e	$P(d)$	Spectral types	Remark
17 Lep	41 511	186	0·13	260	M1III+B9Ve	
KQ Pup	60 414/5	203	0·46	9752	M2Iab+Bpe	
W UMi	150 265	222	0·09	1·701	A3+G9IV	1
β Lyr	174 638/9	217	0·02	12·9	B8II+Be	2
CH Cyg	182 917	201	0·29	5750	M7III+Bpe	3
V1507 Cyg	187 399	211	0·39	27·97	B8III+Be	
31 Cyg	192 577/8	201	0·22	3784·3	K4Ib+B4V	
32 Cyg	192 909/10	218	0·30	1147·8	K5Ib+B4IV−V	

Remarks: 1 — a circular orbits is indicated by photometric data; 2 — the effect is marginal for this star and recent papers quote $e = 0$. The elements given here are taken from a previous work (see Batten, 1967, and references therein); 3 — orbital elements from Yamashita and Maehara (1979).

210°. Table 3 lists some such cases. The corresponding radial-velocity curves are shown in Fig. 4. Were the optical primaries of the massive X-ray binaries indeed *the mass-losing* stars, they should also exhibit velocity curves of this type which *is not* the case. This argument is particularly strong for three systems of Tab. 3: V 1507 Cyg, β Lyr and W UMi. All three these systems have orbital periods quite comparable to those of massive X-ray binaries, and their primary components are of spectral type B 8 III, B 8 II, and A 3, respectively, i.e. not too different from those of the optical counterparts of the X-ray binaries.

I stress also that the Balmer emission observed for V 1507 Cyg and β Lyr, and for some other systems in Tab. 2, is associated largely with their *secondary* (mass-gaining) components and partly with the circumsystem material, not with the primaries! This clearly indicates a situation opposite to that seen for the X-ray binaries.

In considering the above – somewhat revolutionary – idea further, I found it very promising also for explaining some other observational facts listed above. Before demonstrating this, I have to explain the evolutionary aspects of my alternative model.

3. Outline of the Alternative Model

Let us consider first the evolution of a massive binary. According to current ideas (for reviews see, e.g., Plavec, 1970; Paczyński, 1971; or Kříž and Harmanec, 1975) most binaries undergo so called *case B* of mass exchange after the depletion of the hydrogen in the core of the more massive component and a subsequent expansion of its envelope. If the mass transfer is essentially conservative, the separation between the components increases in the final stages of the mass exchange process when the mass-losing star is already the less massive of the two (see formula (11) in the previous section). As pointed out by Kříž and Harmanec (1975) and Harmanec and Kříž (1976), this evolutionary phase can be identified with observed binaries containing a Be star as the mass-gaining, and a large, Roche-lobe filling star as the mass-losing component. AX Mon and β Lyr can serve as extreme examples of such systems. If, however, the mass transfer is highly non-conservative during the initial rapid phases, the resulting orbital period need not be a long one and a double-contact system will be formed during the mass-

KX And (*Kříž and Harmanec*, **1975**; *Polidan*, **1976**), $P = 38{\cdot}908^d$: A binary consisting of a Be primary and a G8III secondary. The radial-velocity curve is from data by Struve (1944).

4 *Her* (*Heard et al.*, **1975**), $P = 46{\cdot}194^d$: A single-line spectroscopic binary with a B7e primary. A possible model of gas streaming in this binary has been discussed by Harmanec et al. (1976).

The sources of the radial-velocity data of the optical primaries of the massive X-ray binaries, displayed in the right panel, are the following:

GP Vel (*Paradijs et al.*, **1977**), $P = 8{\cdot}9644^d$: No. 17 in Table 1.

*V***884** *Sco* (*Hammerschlag-Hensberge et al.*, **1978**), $P = 3{\cdot}4118^d$: No. 30.

LMC X-**4** (*Hutchings et al.*, 1978), $P = \mathbf{1{\cdot}4083^d}$: No. 11.

Sk **160** (*Hutchings et al.*, **1977**), $P = \mathbf{3{\cdot}8922^d}$: No. 6.

HZ Her (*Crampton*), **1974**), $P = \mathbf{1{\cdot}7002^d}$: No. 28.

transfer process, i.e. not only the mass-losing but also the mass-accreting star will be filling the corresponding Roche lobe (at least near the orbital plane). This happens because the mass is transferred so rapidly that the other star is unable to accomodate it (c.f. Benson, 1970; Kippenhahn and Meyer-Hofmeister, 1977; Sybesma, 1985) and all the available volume is filled up. Computations showed that the rate of mass transfer is the higher, the more extreme the original mass ratio. It is thus probable that the shorter-period systems of this type originate mainly from the main-sequence binaries with mass ratios very different from one.

Here, an important point must be mentioned. The evolution of the mass-accreting star and, consequently, the evolution of the whole binary system cannot be reliably computed before the problem of hydrodynamic (or perhaps magnetohydrodynamic) treatment of mass and angular momentum transfer is satisfactorily solved. Many serious uncertainties are thus inevitably involved in all present-day evolutionary "scenarios" outlined. I believe, however, that the evolution of the mass-losing star can be modelled quite satisfactorily by means of available interior models. This is so thanks to the high mass concentration of the stars towards the centre (which makes the deviations from the spherical symmetry tolerably small in most cases).

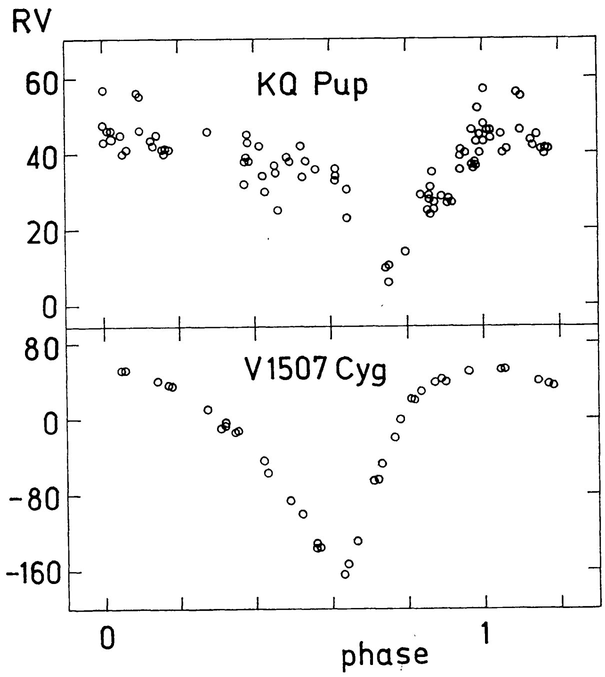

Fig. 4. Two examples of the radial-velocity curves of mass-losing components of interacting binaries:
KQ Pup (*Cowley*, **1965**), $P = 9752^d$: A symbiotic binary with an M 1 Iab primary and a B 2 V secondary.
V **1507** *Cyg* (*Hutchings and Redman*, **1973**), $P = 27{\cdot}9705^d$: An interacting binary consisting of a B 8 III primary and a more massive secondary hidden in an accretion disk similarly as β Lyr.

And it is indeed the evolutionary structural change of this – originally more massive – star which *basically controls* the evolution of the whole binary and the mass-transfer process. The experience with the models of mass-losing stars (c.f., e.g., the detailed discussion by Harmanec 1970) clearly shows that there is no apparent physical cause which could prevent the hydrogen-depleted core, and the hydrogen-burning shell enclosing this core, to send further and further material over the corresponding limiting surface (the Roche lobe in the classical case) until the helium burning is ignited in the core. Model computations clearly show that the properties and evolution of such stellar cores are *almost unaffected* by the mass loss – even if more than some 80 per cent of the original mass has been lost.

This fact sets at least some limits to our following speculations concerning the further evolution of the mass-exchanging binaries: At the end of the process, the originally more massive star will have no more than some 20 per cent of its original mass but the orbital period of the system may be either long or short depending on how much mass and angular momentum was lost from the whole system. This means that at the end of the mass exchange, the mass-losing star will have a mass of 0·5 to 1 $M_\odot$ if it was originally a B star, and some 2 to 10 $M_\odot$ if it was an O star at the beginning. It will consist of a hot helium core and an extended envelope which shrinks rapidly (typically on a time scale of $10^5 - 10^6$ years) as soon as the helium in the core is ignited. The final outcome is a hot and a rather compact helium star with a thin hydrogen envelope – the typical radii being of the order of a few tenths of the solar radius. Horn (1970) and Horn and Harmanec (1983) have already pointed out that such a relatively rapid contraction must inevitably speed the contracting star up the limit of its rotational instability. However, as the star must shrink even after reaching this limit due to the changes in its internal structure, the probable outcome of this situation will be a hot compact object enclosed by a highly flattened disk which may – near the equatorial plane of the binary – even lose further mass towards the other star. This process may thus lead to a new phase of a "post case B" (let us call is "*case PB*") of mass exchange. The existence of such a phase of mass exchange was first considered by Kříž (1978, 1982). A stellar wind from the compact contracting star may also occur which would further increase the mass loss from the star.

It is quite natural to assume that the rate of this mass transfer will also be much higher in shorter-period systems. As a result, the limiting volumes around the mass-gaining components of such systems may be completely filled up by extended envelopes formed from the infalling matter, at least in regions near the orbital plane.

In systems with longer orbital periods there is space enough for the formation of much more extended envelopes around the mass-gaining stars. The expected result is then a classical Be star, in full agreement with the binary hypothesis of the Be phenomenon (Kříž and Harmanec, 1975; Harmanec and Kříž, 1976) as re-formulated by Kříž (1978) and Harmanec (1982). The idea that many observed Be stars may be binaries with secondaries in the phase of contraction after the end of a *case B* mass transfer was first proposed by Kříž (1978). He estimated that mass-transfer rates of only about 10^{-9} $M_{\odot}$/year from the disk around the contracting secondaries would be sufficient to produce (or to maintain the existing) Be envelope.

A natural question is: Do we have some observational evidence of systems in this evolutionary stage? I now have good reasons to believe that the well-known spectroscopic binary φ Per (HR 496) with a B 1e primary is such a system. Poeckert (1981) discovered that the secondary component of φ Per is a hot helium star, enclosed by a disk producing the He II 4686 emission, i.e. an object not quite dissimilar in spectral appearance to a WR star. The radial-velocity curve of the hydrogen lines of the Be primary, shown in Fig. 5, bears very clear signs of the distortion discussed above and illustrated by Fig. 1. Poeckert himself proposed, however, that there is no mass transfer between the components and that the distortion of the velocity curve is due to the fact that the Be envelope around the primary has the form of the stable orbits of the restricted problem of three bodies as first suggested by Suzuki (1976, 1980).

There are some objections to such an interpretation, however. Presently, I am preparing a detailed analysis of more than 800 radial velocities of φ Per obtained by various astronomers and rather uniformly distributed in time since 1898. A preliminary inspection of these data clearly indicates large cycle-to-cycle variations in the width of the main maximum as well as of the secondary maximum on the velocity curve, exceeding the observational errors. Such variations

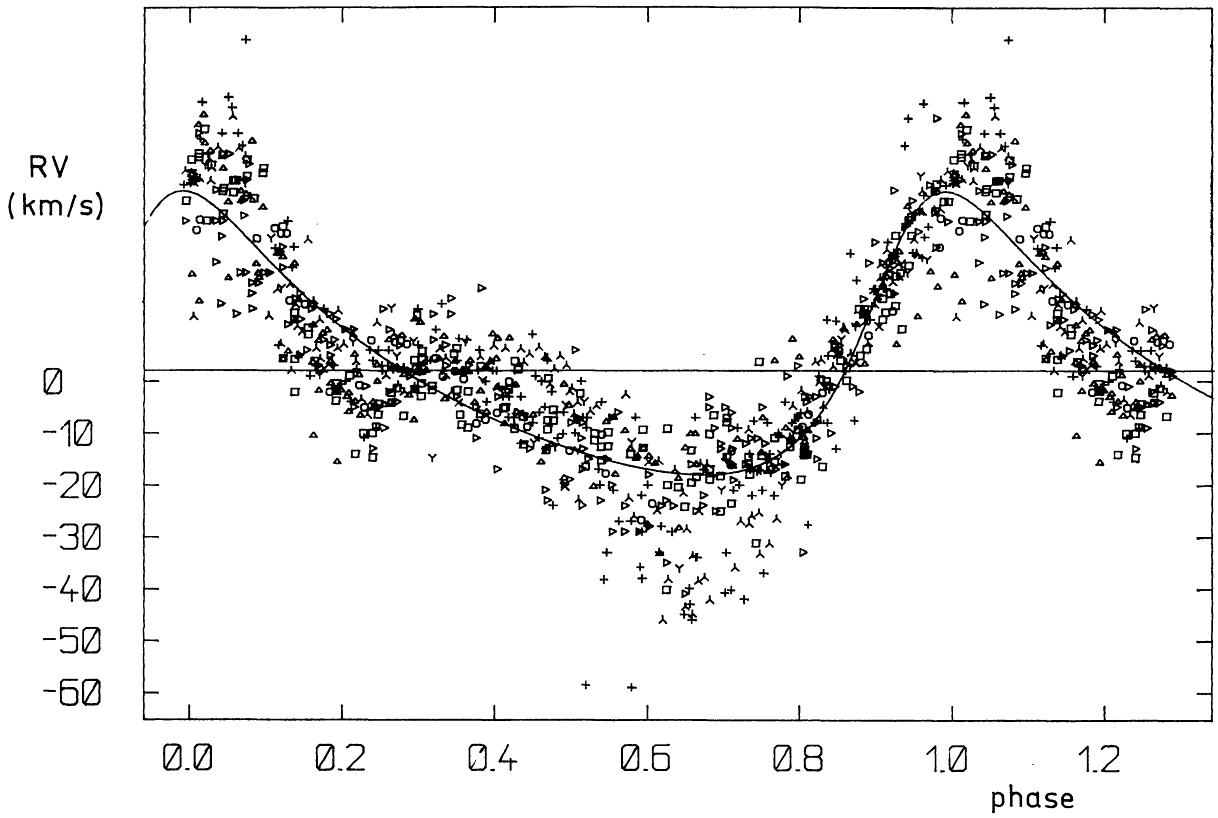

Fig. 5. The radial-velocity curve of φ Per based on my compilation of 861 radial velocities found in the astronomical literature. The value of the orbital period, $P = 126{\cdot}699 \pm 0{\cdot}003$ days, obtained from the orbital solution, is used.

are not expected in the absence of a strong interaction between the stars. Moreover, the preliminary orbital solutions for subsequent subsets of the data seem to indicate a steady increase of the orbital period, suggesting thus the possibility of a mass transfer from the compact helium to the Be component. The component masses, obtained by Poeckert, are $21{\cdot}1\ M_\odot$ for the B 1e star, and $3{\cdot}4\ M_\odot$ for the secondary. φ Per may thus well be a system undergoing a case PB of mass exchange.

Considering the above discussion, I therefore propose to identify the massive X-ray binaries with later phases of case PB of mass exchange (earlier ones possibly corresponding to WR binaries). In the following section I shall show how the observed properties of the X-ray binaries can be reconciled within the framework of this alternative model.

4. How Does the New Model Agree With the Observed Properties of Massive X-Ray Binaries?

Let us now consider the probable observational appearance of the suggested alternative model:

1. The massive X-ray binary is a system undergoing a case PB of mass exchange. The optical primary is gaining mass from its counterpart and its observational appearance is that of a Be (or Oe) star. The apparent luminosity class of the primary depends on the instantaneous orbital period, on the phase of the mass transfer and on the rate of the mass transfer (thus probably on the initial mass ratio and initial separation of the stars).

In principle, a higher luminosity class is to be expected for shorter instantaneous orbital periods

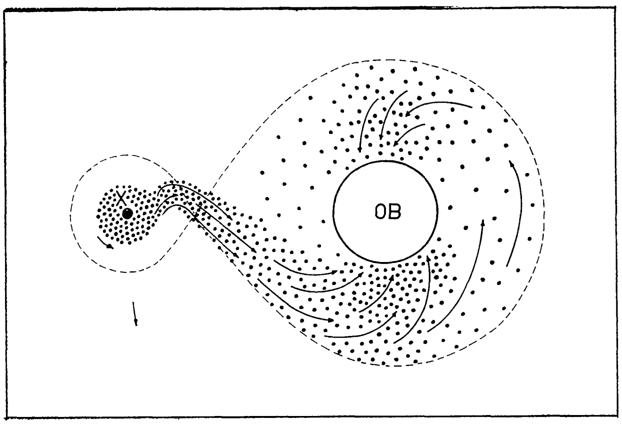

Fig. 6. A diagram illustrating a possible distribution of circumstellar matter in massive X-ray binaries according to the alternative model proposed here.

and for higher rates of mass transfer. This is due to the fact that the mass accretion leads to an overluminosity of the star with respect to its instantaneous mass (see, e.g., the model computations by Kippenhahn and Meyer-Hofmeister, 1977, or by Sybesma, 1985).

The secondary is a rapidly rotating compact helium star (contracting after the ignition of helium in its core), which is losing mass towards the primary. This star very probably possesses a highly flattened equatorial envelope which may demonstrate its presence – for instance – by the He II emission and also by some photometric effects. Any initial global magnetic field of this star must have been strengthened enormously in the contraction phase during which the star decreased its radius roughly by a factor of 100.

2. One important thing, indicated as a possibility by particle trajectories (but to be verified by appropriate hydrodynamic treatment) is illustrated by Fig. 6: The gas flow emanating from the rotationally unstable disk around the contracting helium star may first deflect in a direction opposite to that expected from the action of the Coriolis force and only then return to its "usual" path. This may qualitatively well explain the presence of "accretion wakes", "hot spots" and similar phenomena often suggested to be present on the trailing side of the X-ray star. In other words: what has until now been considered as two separate streams, a main one from the optical to the X-ray star, and a secondary one, from the disk around the X-ray star (c.f., e.g., Wickramashinghe and Bessell, 1974), may in fact be two aspect of one stream flowing from the X-ray secondary to the optical primary.

3. A potential problem of the canonical model is to explain the evolutionary stage of the "supergiant" primaries which fill or almost fill the corresponding Roche lobes and yet do not lose mass too rapidly. On the other hand, primaries filling the limiting surface in the orbital plane are to be expected in shorter-period systems from the point of view of my model (as follows from Kippenhahn's and Meyer-Hofmeister's 1977 computations).

4. A crucial problem of the new model is to find an alternative source of the X-rays observed. I do not pretend I have solved this problem. Rather, I appeal to theorists to consider such an alternative. The following are my comments relevant to the question:

a) The rapid contraction of the now compact star may have led to a huge strengthening of surface magnetic fields, extreme gravitational darkening, formation of a corona, and other rather unusual phenomena. What if the observed X-ray radiation (with rather complicated spectral characteristics) is a superposition of thermal contributions of very different temperatures? And what if the pulsed part of the radiation somehow comes along the spiral-like (or spoke-like) structures in the flattened equatorial disks of the contracting secondaries? I cannot prove the relevance of the following facts to this problem but I wish to stress that the existence of such structures is either known or suspected in some other stars. Solar streamers (c.f., e.g., Fig. 3 in Zirker, 1982) may serve as the best example. A model of rotating spokes (spaced at about 45°, like the solar streamers) in the equatorial disk around the Oe star ζ Oph, developed by Vogt and Penrod (1983), proved to be very successful in modelling the observed profile variations of that star (although refuted by the authors). The natural question then is: Was it not a logical error of the current reasoning to identify the observed pulse periods with the rotational periods of the underlying stars? Apart from the preconception that these pulses are connected with the magnetic dipole fields of rotating neutron stars, there are no compelling reasons for such an identification. In fact, Staubert et al. (1980) found significant pulse-to-pulse variations of Vela X-1 up to a factor of two in intensity. Such "pulses" can, therefore, arise from rotation of a more complicated, but roughly repeatable (spoke-like), structure in the disk around the compact star. The true rotational period can then be *an integer multiple* of the observed pulse period of the source.

Let us consider the case of Vela X-1 for illustration The critical radius of the star rotating with the critical velocity at the equator can be estimated from the formula

$$R_{crit}/R_{\odot} = (74{\cdot}43 \, . \, P_r^2 \, . \, M/M_{\odot})^{1/3} , \qquad (12)$$

where P_r is the rotational period in days, and M is the mass of the star. The observed pulse period of Vela X-1 is $282{\cdot}9^s$. Taking the mass of the X-ray star to be $1{\cdot}9 \, M_{\odot}$, one obtains $0{\cdot}115 \, R_{\odot}$, $0{\cdot}289 \, R_{\odot}$, and $0{\cdot}533 \, R_{\odot}$ for the radius of the X-ray star, assuming the rotational period to be equal to, or four and ten times longer than the observed pulse period, respectively. The two latter values are not incompactible with the computed radii of the contracting helium stars after the end of *case B* mass exchange.

b) An association of the origin of the X-ray flux with the structures in the equatorial disk of the star could also be indirectly supported by the finding (if confirmed) that the X-ray radiation may not be omnidirectional but irradiated mainly in the orbital plane (c.f. point 7 of Section 2). The same fact could perhaps also be responsible for the difference in the type of light curves between shorter- and longer-period systems. The data about longer-period systems are still too scarce to allow any firm conclusions about the role of real eccentricity of orbits which is usually considered in explaining the recurrent X-ray and optical brightenings by a transient mass flow during the periastron passage. It is notable, however, that the radial-velocity curve of AO 538 − 66 obtained recently by Corbet et al. (1985) has also the characteristic shape, illustrated by Fig. 1. It may indicate that the high orbital eccentricity, assumed invariably in various models of this system, may be an artefact of the mass transfer from the X-ray to the optical star.

5. The new model makes definite prediction concerning the orbital and "pulse" period changes. A secular increase of the orbital period, and a secular decrease of the rotation period of the X-ray star is clearly to be expected in most cases but alternate period decreases and increases can occur on shorter time scales, similarly as in other types of interacting binaries, due to the exchange of the orbital and rotational angular momenta or due to other mechanisms (see, e.g., Matese and Whitmire, 1983).

Long series of observations are clearly needed but new accurate observations of period variations of, e.g., GP Vel/Vela X-1 (see, for instance, Nagase et al., 1984; Klis and Bonnet-Bidaud, 1984) present more and more problems for a model of an accreting neutron star.

6. Variable duration of the X-ray eclipses, observed for many eclipsing sources, can easily be understood within the framework of the new model: The eclipsing body is no longer a supergiant star but a star enclosed by an opaque disk, the dimensions of which may vary with time.

7. Circular orbits of the short-periodic X-ray binaries also seem quite natural now. There was no supernova explosion in these systems till now. There are also no neutron stars or black holes there. The difference between the "neutron-star" and "black-hole" secondaries may be connected either with different aspects under which we observe the particular systems, or with a different phase of the case PB mass transfer, or with a different mass range involved. In particular, the failure of the attempts to find any apsidal motion in the "Doppler-delay" orbital elements of Vela X-1 (the only short-periodic system with an apparently non-circular "Doppler delay" orbit) seen quite natural now: the orbit is in fact circular and the eccentricity is spurious. I am unable to suggest a detailed mechanism which could produce

such a false eccentricity in the pulse timing data, but it is certainly interesting to note that the observed value of the longitude of periastron, 155°, deviates for −25° from 180° while for normal mass-losing components these values are 200−220°, thus deviating for +20 to +40°. It is temping to speculate that this is somehow connected with the fact that also the outflowing gas stream is, in the case of the X-ray secondaries, inclined in a direction opposite to the line joining the two stars than in normal binaries (compare Figs 2 and 6).

5. Conclusions

Certain observational facts seem to support the idea that the massive X-ray binaries are less evolved objects than usually believed. They may be objects in the evolutionary phase after the end of *case B* mass exchange. The mass transfer proceeds essentially from the X-ray to the optical star. The model seems to be well applicable to the most of the massive X-ray binaries observed. It is not clear whether it is also applicable to the systems containing very short-periodic pulsars (with pulse periods of the order of 1 second or less).

The crucial problem of the new model is to find and alternative explanation of the X-ray flux observed.

In a separate paper, detailed data on some well-observed X-ray binaries will be analysed and confronted with the predictions of the new model.

A final remark: No doubt, a new insight into the problem of massive X-ray binaries could be achieved by comparing their properties with those of their low-mass counterparts. I have deliberately left this problem aside for the moment, for purely practical reasons: the compilation of the data in this rapidly developing branch is a very time-consuming procedure, and the extent of this already long paper would be even larger.

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