VI. X-RAY OBSERVATIONS

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X-RAY OBSERVATIONS OF Be STARS

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Be star binaries with neutron star companions are shown to constitute a major class of X-ray sources. Some general observational and interpretive techniques of X-ray astronomy are reviewed. Data for 12 Be/X-ray binary systems are summarized. The Be/X-ray binaries are found to be systematically wider systems, with lower-mass primaries, and with significantly more transient behavior than the "standard" massive X-ray binaries such as Cen X-3 and SMC X-1. The difference between the two types of X-ray binaries is explained in the context of slightly different evolutionary scenarios for the progenitor binaries. The "standard" massive X-ray binaries result from wind-mass-loss dominated evolution of very massive close binaries, while Be/X-ray binaries probably result from mass-transfer dominated evolution of systems with primary masses $\lesssim 20\ M_\odot$. The implications of the X-ray observations of Be/X-ray binaries for Be stars in general are discussed.

A. INTRODUCTION

X-ray and optical observations of binary systems containing an accreting neutron star can provide a powerful astrophysical probe of the system parameters. Through such studies it is possible to determine the mass and radius of the optical star, the mass of the neutron star and an estimate of the stellar wind intensity; mass transfer mechanisms and evolutionary histories may also be investigated. There are presently ~ 75 bright galactic X-ray sources [with $F_x \geq 2 \times 10^{-10}$ ergs/cm^2·s, in the energy range 1-20 keV; see, e.g., Forman et al.(1978)], many of which are believed to be binary systems containing an accreting neutron star. About 20 of these binary X-ray systems are identified with early-type companion stars (see e.g., Bradt, Doxsey and Jernigan 1979). It was noted several years ago that 4 of the sources were identified with Be star companions (Maraschi, Treves and van den Heuvel 1976). Presently, there are at least 12 such X-ray systems identified with Be stars (including three in the Magellanic Clouds).

In this review we describe what can be learned about Be star binary systems through the study of X-ray emission from a compact companion

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star (e.g., a neutron star). In § B we review briefly how observations of X-ray binaries, in general, can yield the system parameters. To date, for reasons that will become apparent, more information has been obtained from observations of X-ray binaries with supergiant companions than for systems containing Be stars. Section B is therefore included to establish the credibility of the observational techniques and the theoretical interpretation in those systems for which more information is available. In § C we summarize the state of X-ray observations of Be star binary systems. In § D we present a simple model to explain the observations and describe a plausible evolutionary scenario for Be star binaries with neutron star companions. Finally, we draw a number of conclusions about Be star/X-ray binaries, some of which may be applied to Be stars in general.

B. DIAGNOSTICS OF X-RAY BINARY SYSTEMS

Most of the bright galactic X-ray sources are luminous X-ray emitters with $L_X \sim 10^{35}$ to 10^{38} ergs/s. These objects are widely interpreted as binary systems powered by accretion from a "normal" optical star into the deep gravitational potential well of a companion neutron star or other collapsed star. The inferred mass accretion rates are in the range $\sim 10^{-11}$ to 10^{-8} $M_{\odot}$/yr. Much of our understanding of X-ray binaries comes from investigations of a relatively small sample of well studied sources. This latter group consists mostly of X-ray pulsars.

There are presently ~ 18 known X-ray pulsars (see, e.g., Rappaport and Joss 1981). The X-ray pulse profiles for 14 of these sources are collected in Figure 1. Note that the pulses have a distinctly larger duty cycle than those of radio pulsars (Manchester and Taylor 1977). The X-ray beam pattern is determined by the external magnetic field of the neutron star, the resultant funneling of the accretion flow, and the complex radiative transfer processes for X-rays propagating from the neutron-star surface through regions of accreting magnetized plasma (see e.g., Lamb, Pethick and Pines 1973). The pulsations result from an X-ray beam pattern that is misaligned with the rotation axis of the neutron star and viewed from different directions as the star rotates.

The pulse periods of a number of the X-ray pulsars have been carefully studied over the past decade. The pulse period histories for 8 X-ray pulsars are shown in Figure 2. Note the trend in most of the X-ray pulsars for a secular decrease in pulse period with time (see, e.g., Schreier 1977). This is in sharp contrast with the radio pulsars which are powered by their store of rotational kinetic energy. This "spin-up" behavior is interpreted as due to torques on the neutron star applied by the accreting matter (Pringle and Rees 1972; Lamb, Pethick and Pines 1973; Rappaport and Joss 1977, 1981; Mason 1977).

The theory of accretion torques on neutron stars (see, e.g., Ghosh and Lamb 1979) predicts that, under many conditions, the fractional rate of change in the pulse period can be expressed as

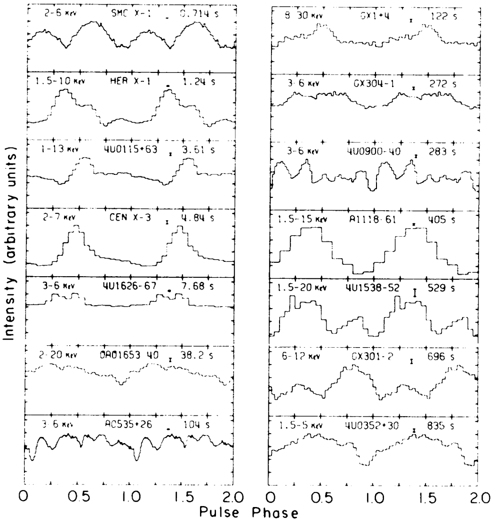

Figure 1: Sample pulse profiles for 14 binary X-ray pulsars (from Rappaport and Joss 1981). In each case, the data are folded modulo the pulse period and plotted against pulse phase for two complete cycles. The approximate pulse periods and energy intervals are indicated for each pulsar. Non-source background counting rates have been subtracted. A typical ± 1 σ error bar, derived from photon counting statistics, is indicated for each pulse profile.

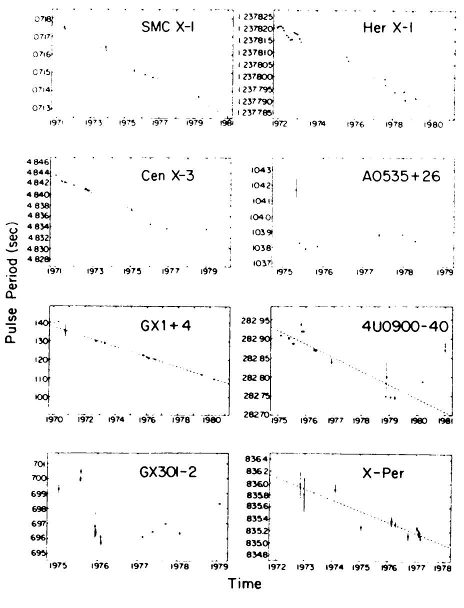

Figure 2: Pulse period histories for 8 binary X-ray pulsars (from Rappaport and Joss 1981;1982). The heavy dots are individual measurements of pulse period; the vertical bars represent the 1 σ uncertainties in the period determination. The data are from the Uhuru, Copernicus, Ariel 5, SAS-3, OSO-8, HEAO-1, Hakucho, and Einstein satellites, the Apollo-Soyuz Test Project, and a balloon and sounding rocket experiment. The dashed lines are minimum chi-squared fits of a straight line to the data points.

$$\dot{P}/P \simeq -3 \times 10^{-5} \; f \; (\frac{P}{1s}) \; (\frac{L_x}{10^{37} \text{ ergs s}^{-1}})^{6/7} , \qquad (1)$$

(Rappaport and Joss 1977) where the dimensionless function f is expected to be of order unity for a neutron star with mass, radius and magnetic moment equal to 1 $M_\odot$, 10 km and 10^{30} G cm^3, respectively. For an accreting white dwarf f will be about two orders of magnitude smaller (Rappaport and Joss 1977). The observed spin-up rates for the X-ray pulsars seem to fit equation (1) quite well given the uncertainties in f and L_x. The data are clearly inconsistent with the expected spin-up rates for accreting white dwarfs.

Observations of X-ray pulsations can also enable one to measure orbital motion. The method of determining orbits from the Doppler delays of X-ray pulse arrival times (see e.g., Gursky and Schreier 1975) is analogous to classical optical Doppler measurements, and is illustrated schematically in Figure 3. For a perfect clock moving with uniform velocity, a plot of pulse arrival time vs. pulse number yields a simple linear relation. If the intrinsic rate of the clock increases with time (as is the case for the spin-up of a neutron star; see above) the same type of plot yields a curved line such as the one shown in Figure 3. If, furthermore, the clock is in a Keplerian orbit there will be superposed periodic systematic Doppler delays due to the time-of-flight of the pulses across the orbit. For the case where the curvature due to orbital motion is much greater than that due to changes in the intrinsic pulse period (or where the measurement interval contains a number of orbital cycles) the orbit can be determined by subtracting a simple polynomial from the arrival-time plot. Complications arise when the reverse of the above condition obtains, and such orbits are difficult to determine. This is the case for slow pulsars (with their concomitantly large values of $|\dot{P}|$) in long-period orbits.

An example of orbital determination from a measurement of Doppler delays of X-ray pulses is shown for the case of 4U0115+63 in Figure 4. These data were obtained with SAS-3 in observations that spanned an interval of 26 days (Cominsky et al. 1978; Rappaport et al. 1978). The Doppler delays in pulse arrival time (Fig. 4) were obtained by subtracting off the expected pulse delays from a constant pulse period. Analyses of these data yielded an orbital period, P_{orb} = 24.3 days, a projected semi-major axis, $a_x \sin i$ = 140 lt-sec = 60 $R_\odot$, and a moderate eccentricity, e = 0.34 (Rappaport et al. 1978). The orbital elements are all determined with a precision of ~ 1 part in 10^3 .

Doppler velocity curves have now been measured for the X-ray star in 7 binary systems (see e.g., Rappaport and Joss 1981). In 5 of these systems it has also been possible to measure the Doppler velocity curve of the optical companion star (see, e.g., Rappaport and Joss 1981 and references therein). As these systems also exhibit X-ray eclipses they can be said to be "double-line spectroscopic eclipsing binaries". With this type of

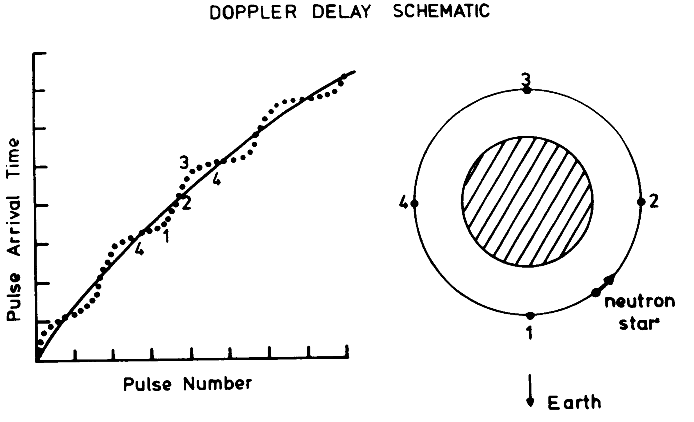

Figure 3: Schematic of the Doppler delays in X-ray pulse arrival times. Such measurements are used to determine the orbital elements in binary X-ray pulsar systems (see text).

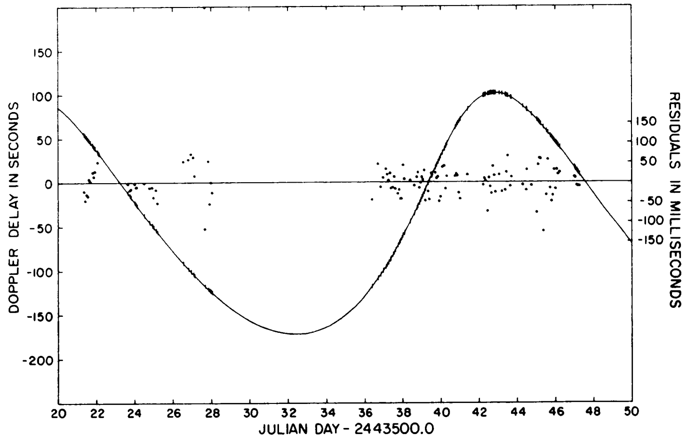

Figure 4: Doppler delay data for 4U0115+63 (from Rappaport et al. 1978). The vertical bars are the measured delays in pulse arrival time (left-hand scale); the length of each bar is considerably greater than the uncertainty in the measurement. The solid curve represents the expected delays for a Keplerian orbit with the best-fit orbital parameters (see text). Small circles (right-hand scale) indicate the residual differences between the measured delays and the best-fit curve.

information, many of the binary system parameters for these 5 sources can be determined; in particular, the masses of the neutron stars have been obtained. The most probable masses of the individual neutron stars and the corresponding uncertainties are summarized in Figure 5. Most of the neutron stars are seen to have a mass consistent with $\sim 1.5\ M_\odot$ (Joss and Rappaport 1976; Bahcall 1978; Rappaport and Joss 1981).

C. X-RAY OBSERVATIONS OF Be STARS

Hard X-rays ($E \gtrsim 3$ keV) have been observed from the vicinity of at least 12 Be stars. The observational results are summarized in Table I. In general, the identification of the X-ray source with the Be star (or Be star binary system) is based on a positional coincidence (the X-ray positions have typical uncertainties of ~ 30"). The identifications of most of these Be stars are discussed extensively by Bradt, Doxsey and Jernigan (1979).

A priori, we must consider the possibilities that the X-ray emission could come from either the Be star or from an unseen companion (e.g., a neutron star). Binarity can be established in one of three ways. First, a direct measurement of orbital motion may be possible. Though there have been a number of searches, the only orbital motion detected from X-ray observations has been for the case of 4U0115+63 (discussed in § B). Secondly, the existence of rapid X-ray pulsations ($P \lesssim 1000$ s) directly implies the presence of a compact companion star. Because X-ray pulsations are observed from the first 6 sources listed in Table I we can conclude that these are Be star binaries with a compact companion. Finally, we note that X-ray luminosities in excess of $\sim 10^{34}$ ergs/s are apparently too large to come from the stellar corona of an isolated Be star. Recent results from the Einstein observatory (Pallavicini et al. 1981) indicate that the coronal X-ray emission (at least for $E \leq 4$ keV) from early type stars is $\sim (1.4 \pm 0.3) \times 10^{-7}$ times the bolometric luminosity. This high optical luminosity criterion applies to all of the non-X-ray pulsars in Table I except possibly for γ Cas (Jernigan 1976). We note, however, that if anything the X-ray fluxes from Be stars may be slightly lower than predicted by the above relation (Rosner 1981). Thus, we conclude that at least 11 and possibly all of the Be stars listed in Table I are binaries with a compact companion star.

Also of interest is the nature of the compact companion star in these Be-binary systems. For the 6 X-ray pulsars listed in Table I only white dwarfs or neutron stars are serious candidates for the compact objects. The spin-up rates for X Per (White, Mason and Sanford 1977) and 4U0115+63 (Rappaport et al. 1978) are too large to be associated with a white dwarf companion (see § B). The X-ray luminosities of A0535+26 and A1118-61 (at peak brightness; Rosenberg et al. 1975; Ives, Sanford and Bell-Burnell 1974) are too large to be produced by accretion onto a white dwarf (Katz 1977; Kylafis and Lamb 1979). From the fact that the X-ray properties (e.g., pulse profiles and energy spectra) of GX304-1 (McClintock et al. 1977) and 4U1145-61 (White et al. 1980) are very

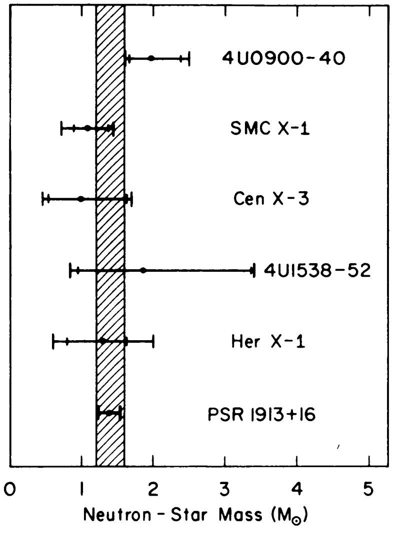

Figure 5: Empirical knowledge of neutron star masses (from Rappaport and Joss 1981). Five of the neutron-star masses are derived from observations of binary X-ray pulsars. PSR1913+16 is a binary radio pulsar (Taylor et al. 1979) and is added for completeness. The most probable value for the mass of each neutron star is indicated by the filled circle. For the X-ray binary systems, an inner set of error limits is also shown, corresponding to less conservative assumptions. The hatched region represents the range of neutron-star masses (1.2-1.6 $M_\odot$) that might be expected on the basis of current theoretical scenarios for neutron-star formation.

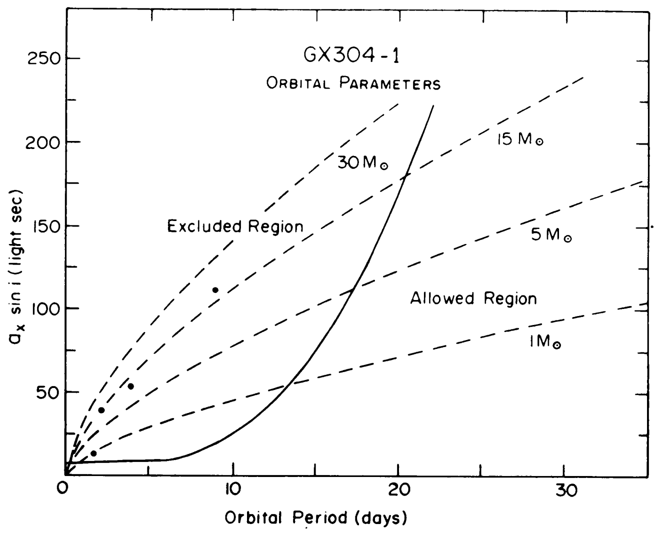

Figure 6: Allowed circular orbits for GX304-1 that are consistent with the SAS-3 timing data (Mc Clintock et al. 1977). *Heavy curve*, upper limits (95% confidence) on $a_x$sin i as a function of orbital period. *Dashed curves*, contours of constant mass function f(M). *Four dots*, the orbits of Her X-1 (P_{orb} = 1.7 days), Cen X-3 (P_{orb} = 2.08 days), SMC X-1 (P_{orb} = 3.89 days) and 4U0900-40 (P_{orb} = 8.96 days).

Table I
Properties of Be-star X-ray Binaries[a]

Source	Be-star counterpart	V	Spectral Type	Distance (kpc)	L_x[b] (10^{36} ergs/s)	Pulse Period (s)	$-\dot{P}/P$ (yr^{-1})	P_{orb} (days)	K_{opt} (km/s)	X-ray temporal variability
4U0352+30	X Per	6.3	09.5(III-V)e	0.35	0.005	835	2×10^{-4}	580?	$\lesssim 50$	steady
GX304-1 4U1258-61	MMV star	14.7	B2Vne	2.4	0.3	272	-	$\gtrsim 13$	-	highly variable
A0535+26	HD245770	9.2	BOVe	1.5	5	104	-	$\gtrsim 18$	$\lesssim 30$	transient
A1118-61	Hen 3-640	12.1	09.5(III-V)e	5	5	405	-	-	-	transient
4U0115+63	Johns star	15.5	Be	3	2	3.6	3×10^{-5}	24.3	-	transient, varies by $\gtrsim 10^4$
4U1145-61	HD102567 Hen 715	9.0	B1Vne	1.5	0.03-0.3	292	$<10^{-4}$	$\gtrsim 35$ 187?	-	highly variable
A0538-66	Johnston star Q	15	Be	55 (LMC)	800	-	-	16.65?	-	transient flares periodically every 16.65d, varies by $>10^4$
2S0053+60	γ-Cas[c]	2.4	B0.5(II-V)e	0.30	0.003	-	-	-	$\lesssim 10$	highly variable
2S0114+650	LSI+65°010	11.0	BOVe	1.4	0.01	-	-	-	-	variable
SMC X-2	Murdin star	16	BIVe	65 (SMC)	100	-	-	-	-	transient
SMC X-3	Clark star 4	15	09(III-V)e	65 (SMC)	70	-	-	-	-	transient
4U1735-28	Hen 3-1450?	11.2	Be	$\gtrsim 1$	$\gtrsim 1$	-	-	-	-	transient

a. Much of the data from this table are taken from Bradt, Doxsey and Jernigan (1979); most of the original references may be found therein. Additional references are cited in the text.
b. Average X-ray luminosity (2-10keV) when the source is bright.
c. Not yet established as a binary (see text).

similar to those of the other X-ray pulsars, already well established as neutron stars, we conclude that the compact objects in these systems are also neutron stars. Of the remaining 6 sources in Table I three have peak luminosities greatly in excess of that which can plausibly be produced by accretion onto a white dwarf (Katz 1977; Kylafis and Lamb 1979); therefore the compact objects in these systems could be either a neutron star or perhaps a black hole, though there is no evidence for the latter case.

Despite the fact that at least 11 of the 12 Be-star X-ray sources listed in Table I are binaries, direct evidence for orbital motion is found in only two of them. As discussed in § B the orbit of 4U0115+63 has been directly measured (P_{orb} = 24 days). The source A0538-66 exhibits X-ray flares at highly regular intervals of 16.65 days (Johnston, Griffiths and Ward 1980; White and Carpenter 1978; Skinner et al. 1980). Such regular outbursts of the X-ray source will probably ultimately be associated with motion of the compact star in an eccentric binary orbit with P_{orb} = 16.65 days or, if the orbit is not coplanar with the equatorial plane of the Be star, P_{orb} = 33.30 days, but to date this has not been demonstrated conclusively. Similarly, seemingly regular X-ray outbursts have been observed from 4U1145-61 with a recurrence time of ~ 187 days (Watson, Warwick and Ricketts 1981), though the evidence for a strictly periodic behavior is not as convincing as for A0538-66.

X-ray observations for 4 of the sources in Table 1 (GX304-1, A0535+26, X Per and 4U1145-61) have allowed constraints to be set on the orbital parameters of the binary system. Typically, the pulse arrival times from a given source are closely monitored for an interval ranging from a few days to a month. No compelling evidence for orbital motion was detected in any of the above 4 sources. A limit to the size of the semi-major axis of the orbit can then be set for any assumed orbital period.

A sample of such orbital constraints for the source GX304-1 (McClintock et al. 1977) is shown in Figure 6. Limits on $a_x \sin i$ vs. P_{orb}, as well as contours of constant mass function in the $a_x \sin i/P_{orb}$ plane are shown. The (X-ray determined) mass function in a Be star binary is

$$f(M) = \frac{4\pi^2 (a_x \sin i)^3}{G \ P_{orb}^2} = \frac{M_c \ \sin^3 i}{(1+q)^2} , \qquad (2)$$

where M_c is the mass of the Be star and $q \equiv M_x/M_c$. To a good approximation $f(M) \approx M_c \sin^3 i$ because q is likely to be a small number (in § B we showed that $M_x \approx 1.5 M_\odot$ for several systems). Because the masses of B0-2 IV, Ve stars lie in the range 10-20 $M_\odot$ we expect $f(M) \simeq (8-17) \sin^3 i$. Therefore, if we adopt $f_o(M) = 1 M_\odot$ as a reasonable lower limit for a Be star X-ray binary, we can see from Figure 6 that P_{orb} for the

GX304-1 binary system should be greater than ~ 13 days. In a similar manner it has been determined that P_{orb} in the A0535+26 (Li et al. 1979) and 4U1145-61 (White et al. 1978) systems should be greater than 18 days and 35 days, respectively. For X Per, a limit on $a_x \sin i$ of ~ 15 lt-sec for orbital periods in the range 0.7 to 3 days has been obtained (Jernigan, Nugent and Rappaport 1981). This is only barely consistent with a neutron star in a short-period orbit of a few days around a Be star of radius $\lesssim 5\ R_\odot$, viewed with an inclination angle of $i \lesssim 60°$. Marginal evidence has been found for the 584-day orbital period (Hutchings et al. 1974) in X-ray data obtained over a 4-year interval (White, Mason and Sanford 1977).

We also note that no X-ray eclipses are seen from any of the sources in Table I, which provides additional evidence that these binary systems are not close (i.e.contact systems). In general, all of these systems are consistent with having binary periods greater than ~ 15 days.

As a final point concerning the X-ray characteristics of the Be/X-ray systems, we note that all of them with the exception of X Per are highly variable or transient sources (see, e.g., Forman et al. 1978; Bradt, Doxsey and Jernigan 1979). Many of the sources are known to vary by a factor of 10 or 100; recent observations with the Einstein observatory indicate that at least at soft X-ray energies (0.1-3 keV) two of the sources 4U0115+63 (Kriss et al. 1980) and A0538-66 (Long, Helfand and Grabelsky 1981) have varied by more than a factor of 10^4.

D. MODEL AND EVOLUTIONARY HISTORY

D.1 *Mass transfer mechanisms in Be X-ray binaries*

As argued above, at least 11 Be/X-ray systems are binaries. In the following important respects these binaries differ from the standard massive X-ray binaries such as Cen X-3 and SMC X-1 (see Figure 7). (1) The orbital periods of the Be/X-ray binaries are in excess of 15 days and probably range up to several years (see section C), while the standard massive X-ray binaries (with the sole exception of 4U 1223-62) have periods between 1.4 and 9 days. (2) The optical components of Be systems are generally unevolved stars of spectral types 09 Ve to B2 Ve. Such stars have relatively small radii, i.e. $\lesssim 5 - 10\ R_\odot$, absolute luminosities $\lesssim 3 \times 10^4\ L_\odot$ and masses between ~ 10 and 20 $M_\odot$. On the other hand, in the standard massive X-ray binaries the optical stars tend to be evolved (giant, Of or supergiant stars) with radii 10-30 $R_\odot$, $L_{opt} \gtrsim 10^5\ L_\odot$ and initial masses (derived from their luminosities) in excess of ~ 20 $M_\odot$). (3) Characteristics 1 and 2, together with the absence of X-ray eclipses and of periodic (ellipsoidal) light variations indicate that the Be stars in X-ray binaries reside deep inside their Roche lobes. This rules out Roche-lobe overflow as a possible source for the mass accretion. The standard massive systems, on the other hand, often eclipse and always show periodic ellipsoidal light variations, indicating that their optical components practically fill their Roche

lobes. The mass transfer in these systems is thought to be due to beginning Roche-lobe overflow or to enhanced winds that are expected from stars that nearly fill their Roche lobes (cf. Savonije 1979,1980).
(4) The X-ray luminosities of the Be systems generally exhibit much larger variability than those of the standard systems. In fact, with the possible exception of the two nearby weak (~ 10^{33} ergs/s) sources X Per and γ Cas, all known Be/X-ray sources are transients. This shows that the mass transfer rate in the Be systems must be highly variable.

Since Roche-lobe overflow is ruled out, the mass transfer must be due to the intrinsic mass-losing properties of the Be-component. Be stars show two types of intrinsic mass loss: (i) by a stellar wind and (ii) by mass ejection in their equatorial regions. This latter type of mass loss produces the characteristic emission lines in their spectra. Since Be stars are the most rapidly rotating B stars the equatorial ejection of matter is presumably rotationally driven, though the physical processes involved are not yet well understood (Marlborough 1976; Slettebak 1979).

The stellar wind parameters of the Be stars X Per, γ Cas and HD 102567 (4U1145-61) (as well as of other early Be stars) derived from UV observations indicate typical wind mass loss rates $\dot{M}_c \simeq 10^{-9}$ to 10^{-7} $M_\odot$/yr, and outflow velocities v ~ 10^3 km/s (Hammerschlag-Hensberge et al. 1980). Using the standard stellar wind accretion theory (Davidson & Ostriker 1973) one finds for the accretion rate onto a compact companion with mass M_x:

$$\dot{M}_x \approx 7\text{x}10^{-6}\ \dot{M}_c\ (M_x/M_\odot)^2\ \ (v/10^3\ \text{km s}^{-1})^{-4}\ \ (r_{orb}/5\text{x}10^{12}\text{cm})^{-2}\ , \tag{3}$$

where r_{orb} is the orbital separation of the Be star and compact companion. Equation (3) indicates that the wind capture accretion rates in Be systems are typically expected to be 10^{-14} to 10^{-12} $M_\odot$/yr, corresponding to X-ray luminosites of ~ 10^{32} to 10^{34} ergs/s. It is very well possible, therefore, that all Be/neutron star systems with P_{orb} $\lesssim$ 1 year have steady X-ray luminosities of the order of 10^{33} ergs/s during their low states.

These luminosities are very similar to those of the two nearby weak Be/X-ray sources, X Per and γ Cas (see Table I). However, accretion from a spherically symmetric wind falls short by 4 to 6 orders of magnitude to explain the X-ray luminosities of the transient Be sources at X-ray maximum. It seems most natural to ascribe these high luminosities to the rotationally-induced mass ejection from the equatorial regions of the Be stars since this type of mass ejection: (a) is actually observed, and (b) is highly variable. The strength of the emission lines of rapidly rotating Be stars is known to vary irregularly from complete absence to large intensities, on timescales of months to years (Slettebak 1979). Indeed, in at least one Be system (A0538-66) a clear correlation has been established between X-ray high states and the presence of emission lines in the spectrum (Pakull and Parmar 1981).

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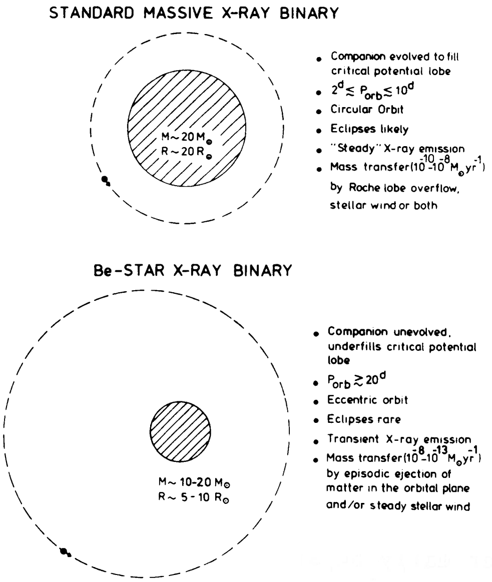

Figure 7: Schematic of a "standard" massive X-ray binary vs. a Be/X-ray binary system.

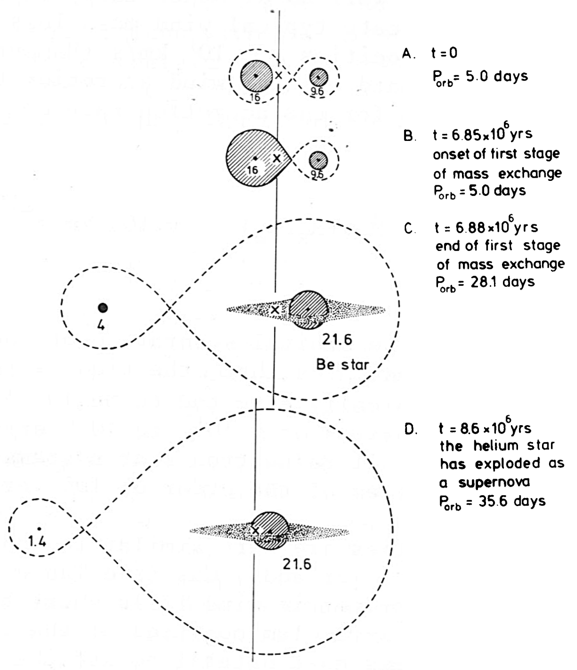

Figure 8: Evolution of a Be/neutron star binary from a close pair of early B stars. Conservative mass transfer is assumed. The mass of each component, in solar units, is indicated. At each epoch, the dashed curve represents the Roche surface. After the end of the first stage of mass exchange the Be star may have a circumstellar "disk or shell" of matter associated with its rapid rotation.

Although the precise causes and mechanism of the irregular mass outbursts from Be stars are not known, the observed properties of the X-ray outbursts can be used to derive constraints on the gas density $\underline{n}$ in the stellar envelope during an outburst, as follows. Equation ($\overline{3}$) can be rewritten as

$$\dot{M}_x \approx 6x10^{-9} \; (M_x/M_\odot)^2 \; (v_{rel}/10^3 \text{ km s}^{-1})^{-3} \; (n/10^{12} \text{cm}^{-3}) \quad M_\odot/\text{yr}, \qquad (4)$$

where v_{rel} is the relative velocity between the outflowing matter and the neutron star. Since during an outburst $\dot{M}_x$ can rise to $\sim 10^{-8}$ $M_\odot$/yr, one finds that temporarily: $(v_{rel}/10^3 \text{ km s}^{-1})^{-3}$ $(n/10^{12} \text{ cm}^{-3}) \approx 1.$ Hence, if the ejection velocity is of the same order as the stellar wind velocity ($\sim 10^3$ km/s), n must be $\sim 10^{12}$ cm^{-3}. On the other hand, if the ejected cloud moves out with a somewhat lower velocity (e.g., $\sim$200 km/s), densities as low as n$\sim 10^{10}$ cm^{-3} are sufficient to yield the observed X-ray luminosities. These densities are in good agreement with the values of $\sim 10^{10}$-10^{12} cm^{-3} inferred from the strengths of the Balmer emission lines (see, e.g., Peters 1976; Slettebak 1979). For still smaller outflow velocities (i.e., less than or comparable to the orbital velocity of the neutron star, as are often observed in Be shells; see Underhill 1966), the accretion rate given by equation (4) may no longer be appropriate. Instead, the matter may form an accretion disk about the neutron star. This could lead to even larger values of $\dot{M}_x$ than those given by equation (4).

D.2 *Galactic Number and Evolution*

The discovery of Be/neutron star systems is hampered by several observational selection effects. During low states their expected steady hard X-ray fluxes are typically of the order of 10^{33} ergs/s, which implies that beyond $\sim$0.5 kpc such systems are not readily detectable. Beyond $\sim$0.5 kpc the only systems that will have been discovered are those that have exhibited large outbursts at times when X-ray satellites were monitoring the appropriate parts of the celestial sphere. Since the sky coverage has been far from complete, and since in most Be stars emission or shell phases tend to occur not more than once per decade, one expects that the actual number of Be/neutron star systems is perhaps an order of magnitude larger than the detected number of bright Be X-ray transients. With $\sim$5 bright Be transients detected within a 2.5 kpc distance in 10 years one thus expects the actual number of Be/neutron star binaries within this distance to be at least $\gtrsim$50. (Such a number is consistent with an expected number of $\sim$100 within 2.5 kpc, derived by extrapolation from the fact that two permanent weak sources - X Per and γ Cas - are found within 0.35 kpc distance.)

With $\gtrsim$50 Be/X-ray systems within 2.5 kpc distance, against only 3 "standard" systems (4U0900-40, 4U1700-37 and Cyg X-1) the Be/X-ray systems are by far the most abundant type of massive X-ray binary in the galaxy.

If we adopt a radius of the galactic disk of 14 kpc and a uniform distribution of early type stars throughout this disk, we conclude that the total number of Be/X-ray binaries must be $\geq 1.5 \times 10^3$, against a total number of "standard" massive X-ray binaries of ~ 50 (van den Heuvel 1978).

An important difference between the Be/X-ray systems and the "standard" massive X-ray binaries is in their expected lifetimes. The Be-systems have relatively unevolved (i.e., hydrogen-burning) optical components with an expected lifetime of order 5×10^6 yrs (i.e., they must correspond to the "quiet" stage in the standard evolutionary scenario for massive X-ray binaries; cf. van den Heuvel 1976, 1978). On the other hand, in the "standard" systems the optical component is an evolved star which is just beginning to overflow its Roche lobe (or is close to doing so); the lifetime in this stage is not expected to be longer than ~ 10^5 yrs (Savonije 1979, 1980). Since the Be/X-ray systems are expected to live some 50 times longer than the "standard" systems, and are some $\gtrsim$ 30 times more abundant in the galaxy, the galactic formation rates of both types of objects should be roughly similar.

The combination of systematically longer binary periods and lower optical companion masses for Be/X-ray systems as compared to the "standard" massive X-ray systems may find a qualitative explanation in an evolutionary scenario for the progenitor binary systems as follows. The most massive stars ($M \gtrsim 20$-$30\ M_\odot$) suffer large mass loss by stellar winds during their evolution. [This mass loss is presumably generated by radiation pressure driven instabilities in the interior, connected with the increase in mean molecular weight, μ, during the evolution (see van den Heuvel 1979; Maeder 1980).]In a binary system, such a star may lose most of its hydrogen rich envelope by wind mass loss before it reaches its Roche lobe. Therefore, mass transfer by Roche-lobe overflow may play a relatively minor role in these systems (see also Vanbeveren and Conti 1980). Since in this case not much angular momentum transfer takes place between the components, the binary period need not change drastically during the evolution. This is evidenced by the fact that the Wolf-Rayet (WR) binaries, which are the products of this evolution, have about the same distribution of binary periods as their progenitors, the O-type spectroscopic binaries, although their mass ratios are very different (Massey 1981). Since the WR binaries tend to have short binary periods (mostly $\lesssim$ 10 days) the same is expected for their descendants, the massive "standard" X-ray binaries (van den Heuvel 1973).

On the other hand, in stars with $M \lesssim 20\ M_\odot$ stellar wind mass loss hardly affects the evolution (see Lamers 1981) and the primary star evolves to overflow its Roche lobe, which results in an extensive exchange of mass and (orbital) angular momentum with the companion. If this transfer takes place more or less conservatively (i.e., total mass and orbital angular momentum are approximately conserved), the orbital period will, in general, increase by a considerable factor. This is due to the fact that unevolved close binaries tend to have mass ratios, q, fairly close to unity (i.e., in the range $q \simeq 0.5$ to 1.0, see Abt and Levy 1978; Lucy 1981), while after the transfer the mass ratio will be far from unity, since the primary star will have lost over 70% of its initial mass. Figure 8 shows as an example the conservative evolution of a short-period system of 16 + 9.6 $M_\odot$ that produces a much wider Be/X-ray binary. In this example, with an initial mass ratio of q = 0.6 and a final mass ratio of q = 5, the binary period will increase by a factor of about 5 (see Paczynski 1971). Hence the difference between the mean binary periods of the "standard" massive X-ray binaries and the Be/X-ray binaries would be the result of *wind-mass-loss dominated evolution* in the very massive close binaries vs. *mass transfer dominated evolution* among close binaries with primary mass $\lesssim$ 20 $M_\odot$.

If a number of the Be/X-ray binaries turn out to have orbital periods greater than ~ 100 days, a complementary reason for the systematically lower masses of the widest neutron-star binaries might be that the lower mass limit for evolving to core collapse is lower for primaries in these wide binaries than in short-period ones. This results from the fact that in a long-period binary the core of the primary star still has time to grow significantly during hydrogen shell burning, before the star overflows its Roche lobe and loses its envelope. Therefore, in binaries that evolve according to Kippenhahn and Weigert's (1967) case C (i.e., the primary does not overflow its Roche lobe before core-helium ignition) the core mass that remains after Roche lobe overflow can be over 40% larger than in the short-period systems that evolve according to the cases A and B. Thus, for primaries in case C systems, the lower mass limit for evolving to core collapse may be as low as 10 to 12.5 $M_\odot$, whereas in case B and A systems it probably ranges from 15 to 20 $M_\odot$ (see van den Heuvel 1981). As a consequence, very wide neutron-star binaries (products of case C) are expected to have, on the average, lower masses than closer binaries (products of the cases A and B).

Natural direct progenitors of the Be/X-ray systems are binaries such as AX Mon (B1e + K2II, P = 232 days), Φ Per (B0e, P = 126 days), HR2142 (B1Ve, P = 81 days) (Peters 1976), and also the ζ Aurigae systems, which consist of a late-type supergiant and an early Be star, and have binary periods of over a year (Wilson 1960). The B-components in these systems are always surrounded by a rapidly rotating ring or disk of accreted matter. The accretion of mass with high specific angular momentum through a disk will spin up the B-star and will cause it most probably to rotate near break-up at the end of the accretion stage when the core of the K-supergiant finally collapses. Hence, after the supernova, one expects the remaining binary system to consist of a rapidly rotating Be star and neutron star, in a relatively wide orbit.

E. CONCLUSIONS

(1) Be stars in binary systems with a neutron star companion are not uncommon.

(2) The Be star characteristics of the Be/X-ray systems are apparently indistinguishable from those of other Be stars. Whatever their past history, the presence of the neutron star does not seem to have any

influence on its companion. The neutron star acts solely as a probe with which the intrinsic mass loss characteristics of the Be star can be monitored. (A possible exception is A0538-66.)

(3) The Be characteristics need not arise from matter accreting onto the Be star, as suggested by some authors.

(4) The rapid rotation of the Be stars in Be/X-ray binaries is most probably due to their spin-up during a preceding mass transfer phase. It may well be that many other Be stars derived their rapid rotation from a similar evolutionary history with mass transfer (cf. Kriz and Harmanec 1975).

(5) The transient X-ray behavior of most of the Be/X-ray systems indicates a high degree of variability in the flux of matter expelled in the equatorial regions of the Be star. (A spherically symmetric stellar wind is highly inadequate to power the flaring X-ray source.) During periods of X-ray outburst, densities and outflow velocities of the ejected matter of 10^9 - 10^{12} cm^{-3} and 10^2 - 10^3 km/s, respectively, are indicated.

(6) From evolutionary and statistical considerations thousands of Be/neutron star systems are expected to exist in the galaxy. Therefore many classically studied Be stars may well have neutron star companions. In most cases, with $P \gtrsim 15$ days and $M_x \lesssim 1.5\ M_\odot$ the radial velocity variations in the optical companion will be $\lesssim 20$ km/s and will be very hard to detect. Nonetheless, careful, precise studies of a few selected objects (e.g., γ Cas and X Per) may prove very fruitful in this regard.

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DISCUSSION

Harmanec: Is there some evidence from RV that the H emission is really connected with the optical components of x-ray/Be sources?

Rappaport: No optical Doppler velocity curves have yet been reliably determined for any of the x-ray/Be binaries.

Stalio: I am impressed by the very large range of variability you mentioned: for one source (4U0115+63) the x-ray luminosity varies by a factor of at least 3×10^4 and large variations are also observed for a number of others (SMCX-2, SMCX-3, A0538-66 etc.). Since these variations have been detected by different instruments, are you sure that this is not an instrumental problem?

Rappaport: The observed x-ray variability is certainly real.

Persi: What do you think about the transient x-ray phenomenon of A0595+262? Could it be due to sudden variations of the stellar wind of the Be star? Our IR observations taken during a quiescent x-ray phase very close to a flar-up show no significant variations of the characteristics of the envelope. X Per shows a long-term x-ray variability. Could this be correlated with an observed long-term IR variability?

Rappaport: The transient behaviour of A0535+26 can be explained by episodic mass ejection in the equatorial plane of the companion star HD245770. It is not obvious that a disc of matter, with density and flow velocity in the vicinity of the orbiting neutron star sufficient to power the x-ray emission, would necessarily be detectable in the IR. The source 4U0352+30, on the other hand, has a relatively more steady x-ray luminosity, which is sufficiently low that it may, perhaps, be accounted for in terms of the stellar wind on X Per. Studies of the long term IR and x-ray variability might prove to be a very useful diagnostic probe of this system.

Giovannelli: 1. Would you like to explain better the arguments you use to support your opinion that the orbital period of A0535+26 is $\sim$40 days, since we have found a weak evidence of $\sim$30, 40, 63 and 77 days orbital periods using our photometric measurements?
2. Do you believe it is possible that the short time variations are due to the orbital motion or to changes in the intrinsic rotation rate of the neutron star?

Rappaport: 1. Recent pulse timing data on A0535+26 obtained with the Hakucho's satellite by M. Oda and coworkers can be interpreted completely in terms of a spin-up of the neutron star. Even if the observed pulse arrivel times represent orbital motion of the neutron star, it is obvious from an inspection of the raw data that the orbital period must be at least twice the duration of the observation i.e., $\gg$ 40 days.

2. It is difficult at this time to say, whether the observed short-term variations in pulse period are due to orbital motion or intrinsic changes; however, I tend to favor the latter hypothesis.

Snow: You have not mentioned soft x-rays at all. Can you clarify whether Be stars are known to be soft x-ray emitters at a level comparable to the coronal x-ray emission from O stars? This could be very important in assessing the relationship of Be phenomena to coronal activity, and their relationship (if any) to O stars.

Rappaport: Such results will hopefully be available shortly from the Einstein x-ray survey of Be stars.

Pakull: So far the optical identifications with Be stars have been made on positional coincidence alone I would like to comment that recently correlations between x-ray intensity and envelope characteristics have been established for 1145-61 and A0538-66 in the sense that the x-ray were turned off when the counterpart apparently lost part of its envelope being a more or less normal B V-IV star.

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