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MASS LOSS AND STELLAR WIND IN MASSIVE X-RAY BINARIES

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1. INTRODUCTION

A number of massive stars of early type is found in X-ray binary systems. The catalog of Bradt et al. (1979) contains 21 sources optically identified with massive stars ranging in spectral type from 06 to B5 out of which 13 are (nearly) unevolved stars and 8 are supergiants. Single stars of this type generally show moderate to strong stellar winds. The X-rays in these binaries originate from accretion onto a compact companion (we restrict the discussion to this type of X-rays).

We consider the compact star as a probe traveling through the stellar wind. This probe enables us to derive useful information about the mass outflow of massive stars.

After presenting the basic data we derive an upper limit to mass loss rates of unevolved early type stars by studying X-ray pulsars. Next we consider theoretical predictions concerning the influence of X-rays on the stellar wind and compare these with the observations. Finally, using new data from IUE, we draw some conclusions about mass loss rates and velocity laws as derived from X-ray binaries.

2. BASIC DATA (based on Bradt et al., 1979)

We divide the massive primaries into Roche lobe filling and non-Roche lobe filling ones. Table 1 lists only systems with known orbital and/or X-ray pulse period.

In the first catagory there is no trace of periodicity in the lightcurves, the orbital periods are very long (> 20 days) and the companion stars are deep inside their Roche lobes. The accreted material can only come from the stellar wind of the primary.

The second catagory shows double wave ellipsoidal lightcurves which are typical for a tidally distorted star (cf. Bahcall, 1979). Therefore these stars are close to filling their Roche lobes. The mass transfer takes place in the form of either Roche lobe overflow or stellar wind, or in a combination of the two.

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TABLE 1

Non-roche lobe filling massive primaries

Source	Opt. star	Sp. type	m_V	log L_x	L_x/L_{opt}	Binary period	Pulse period
0115+63tr	1	BVe	15.6	37.5	2	$24^d.3$	$3^s.6$
0352+30	X Per	09.5(III-V)e	6	34	0.0004	580?	835
0535+26	HDE245770	09.7IIe-BOVe	9.1	37.3	0.08	>20	104
1118-61tr		Be	12.1		2		405
1145-61	Hen715	BIVne	9.0	36.8	0.2		297?
1223-62	WRA977	BIIa	10.8	37.0	0.003	22.6?	699
1258-61	MMV	BO-B5V	14.7	36.3	0.3	>20	272
Roche lobe filling primaries							
SMC X-1	Sk160	BOI	13.3	38.8	1.2	$3^d.9$	$3^s.6$
0900-40	HD77581	BO.5Ib	6.9	36.0	0.003	9.0	283
Cen X-3	Krz's	0.6.5II-III	13.3	37.6	0.05	2.1	4.8
1538-52	12	BOI	14.5	36.6	0.01	3.7	529
1700-37	HD153919	06.5f	6.6	36.5	0.0005	3.4	
Cyg X-1	HDE226868	09.7Iab	8.9	37.3	0.02	5.6	
LMC X-4	Ph-Sk	08III-V	14.0	38.7	1	1.4	

3. SLOW PULSARS, Be STARS AND MASS LOSS

The first group in table 1 is characterized by practically unevolved stars, long binary periods and long X-ray pulse periods. This strong correlation yields an order of magnitude estimate for the mass loss rate of these type of stars (van den Heuvel, 1977).

The rotation rate of an accreting neutron star is thought to be close to its "equilibrium" value (Davidson & Ostriker, 1973). That means that all the torques (exerted on the neutron star by the surrounding matter via the magnetic field lines) more or less cancel. Without going into the physical details (see e.g. Lamb, 1977) the result for the equilibrium spin period of a strong magnetized neutron star embedded in the stellar wind of the companion is (Wickramasinghe & Whelan, 1975; van den Heuvel, 1977):

$$P_{eq} \simeq 31 \left(\frac{\dot{M}_w}{10^{-9}\ M_\odot/yr}\right)^{-3/7} \left(\frac{v_w}{1000\ km/s}\right)^{12/7} \left(\frac{P_{orb}}{20^d}\right)^{4/7} \text{ sec.} \qquad (1)$$

Here we omitted a factor of order unity containing the mass, radius and surface magnetic field of the neutron star, and the mass of the B star for which we used 1 $M_\odot$, 10 km, 10^{12} G and 20 $M_\odot$ respectively. $\dot{M}_w$ denotes the mass loss rate of the B star, v_w the wind velocity and P_{orb} the orbital period.

It is from this expression that we can obtain independent information on the mass loss rates of unevolved massive stars.

Van den Heuvel assumed that the slow X-ray pulsars balance their period not far from the equilibrium value. In fact the equilibrium period will be shorter, as we know that all pulsars are spinning up. In addition he assumed that the wind velocity is roughly three times the escape velocity (Abbott, 1978). Then for reasonable orbital periods we can calculate from (1) that, in order to maintain $P \approx 300$ sec, the mass loss rate must be less than 10^{-9} $M_\odot$/yr.

This is in excellent agreement with recent mass loss determinations of Be and early type main sequence stars which are of order $\dot{M}_w \approx 10^{-9}$ $M_\odot$/yr for 59 Cyg, X Per, γ Cas, τ Sco and μ Col (Snow & Marlborough, 1976; Hammerschlag-Hensberge et al., 1979a; Lamers & Rogerson, 1978; Olson, 1979).

4. THE INFLUENCE OF X-RAYS ON THE STELLAR WIND

Now we turn to the second group of table 1. The existence of winds in early type stars is inferred from the presence of P-Cygni shaped ultraviolet resonance lines of ions like C IV and N V. Radiation pressure in these lines is thought to be the acceleration mechanism of the wind (Lucy & Solomon, 1970; Castor et al., 1975).

More than five years ago McCray (1975) predicted that an X-ray source in a stellar wind may further ionize the relevant ions. This should be observable as a marked orbital phase dependence of the P Cygni lines of these ions. This prediction has been refined and extended by McCray & Hatchett (1975) and Hatchett & McCray (1977).

A secondary effect will be distortion of the velocity profile. Detailed modeling of the interaction of the X-rays with the wind however, is required before any conclusion can be drawn.

A first attempt to observe the ionization effect with *Copernicus* in HD153919/1700-37 was unsuccessful. Recent IUE observations with high resolution of the same source showed strongly saturated P Cygni profiles of the C IV and Si IV resonance doublets (Dupree et al., 1978). Additional spectra with a good phase coverage are shown in figure 1 (Hammerschlag-Hensberge et al., 1979b). Short wavelength edge velocities of 2600 km/s are measured. Again, no phase effect is observed.

On the other hand in the system HDE226868/Cyg X-1 a clear phase dependence in the strength of C IV and Si IV lines was observed. Unfortunately only low resolution spectra are available and no conclusive measurements of the detailed line profiles is possible (Dupree et al., 1978; Treves et al., 1979).

Quite exciting, however, are the IUE observations of the source HD77581/0900-40 taken with high resolution, as reported by Dupree et al. (1979). Figure 2 shows the crucial spectral regions. Near phase 0.0 (X-ray eclipse) we see a nearly undisturbed P Cygni profile, the emission part being somewhat reduced because the wind on the far side of the star (responsible for emission) is ionized by the X-ray source. The Si IV and C IV profiles are similar to those seen by IUE in κ Cas, a supergiant with spectral type similar to HD77581. Near phase 0.5, however, the (blue) terminal absorption velocity is dramatically reduced to 900 km/s compared with 1700 km/s at phase 0.0. Detailed calculations

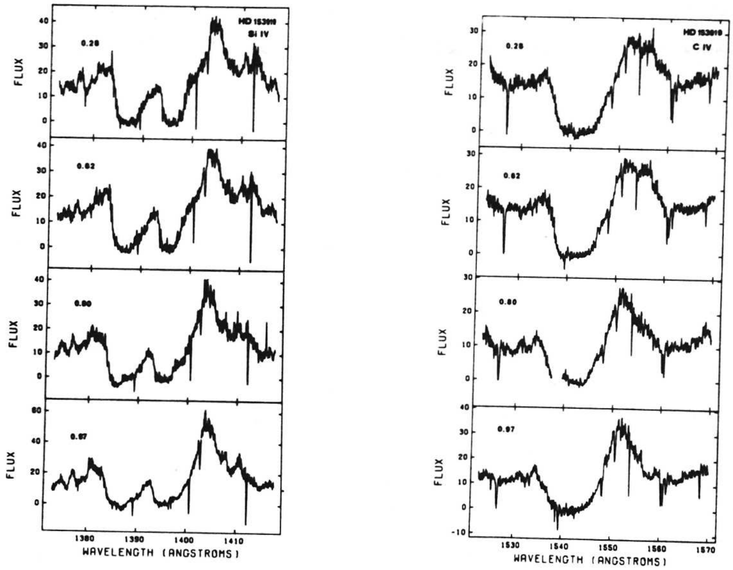

Figure 1. IUE spectra of Si IV and C IV resonance profiles in HD153919 show no obvious changes at different phases of the binary period.

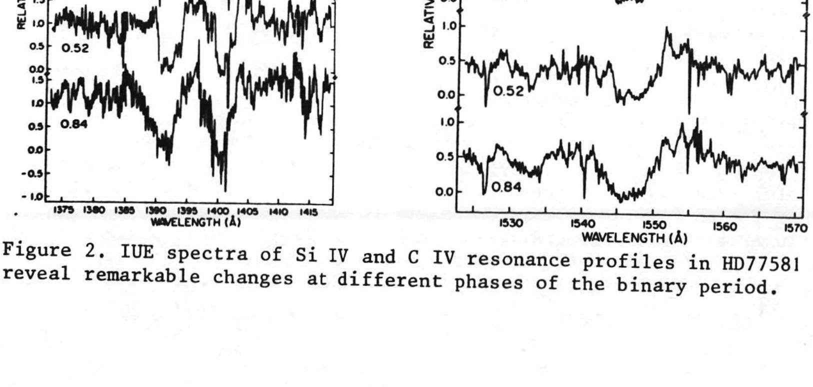

Figure 2. IUE spectra of Si IV and C IV resonance profiles in HD77581 reveal remarkable changes at different phases of the binary period.

presented by Dupree et al. confirm convincingly the prediction by McCray and coworkers.

The reason why this effect is not observed in HD153919/1700-37 might be the following. The much earlier spectral type of this star (O6.5f) and the much higher density in its wind causes C IV and Si IV to be much more abundant than in the wind of HD77581 (B0.5 Ib), as is indicated by the complete saturation of these lines in HD153919. This makes that the removal of some fraction of the C IV and Si IV ions from the wind due to X-ray photon-ionization has a negligible effect in the case of HD153919 and renders the predicted phase dependence unobservable. Transitions from excited levels that are formed over a narrow range in velocity might be more responsive to the effects of the X-ray source.

5. MASS LOSS RATES AND VELOCITY LAW

We return to the question: what can we learn about the stellar wind properties themselves. From studies of Lamers et al. (1976), Petterson (1978) and particularly Conti (1978) it became clear that in the systems SMC X-1 and Cen X-3 the main mass transfer mechanism must be Roche lobe overflow, a result also achieved by Savonije (1978) on different grounds. In the systems 0900-40, 1700-37 and Cyg X-1 the stellar wind might be the main mass transfer mode.

In almost all investigations on X-ray binaries one proceeds in calculating the X-ray intensity from a guessed or measured mass loss rate and wind velocity. However, Conti (1978) inverted the problem and solved for the wind velocity, using the standard wind accretion theory with X-ray and optical data on orbital elements and luminosity as input parameters in addition to partly observed, partly estimated mass loss rates and, guessed, highly uncertain values for the terminal wind velocity.

Nowadays much more reliable mass loss rates and wind velocities are available (table 2) derived from high resolution UV spectra. Therefore it seems worthwile to repeat Conti's investigations with the newly obtained data. The relevant expression is given by Conti (1978, eq.8):

TABLE 2

	HD153919	(ref)	HD77581	(ref)	HDE226868	(ref)
$\dot{M}_w$ ($M_\odot$/yr)	5×10^{-6}	(1,2)	1×10^{-6}	(1,4)	1.4×10^{-6}	(1)
v_{term} (km/s)	2600	(3)	1700	(4)	2000	(Conti)
L_x max ($L_\odot$)	7.0×10^2	(5)	5.8×10^2	(5)	2.7×10^3	(5)

Ref.: (1) Hutchings, 1976; Hutchings, 1979 revision. (2) Hammerschlag-Hensberge, 1979b. (3) Dupree et al., 1978. (4) Dupree et al., 1979. (5) Bradt et al., 1979.

$$v_w = 8.5 \times 10^5 \left(\frac{M_x}{a}\right)^{\frac{1}{2}} \left(\frac{\zeta \dot{M}_w}{L_x}\right)^{\frac{1}{4}} \text{ km/s} \qquad (2)$$

where M_x denotes the mass of the compact object, a is the orbital separation, L_x the X-ray luminosity (all in solar units) and $\dot{M}_w$ the mass loss rate in solar masses per year.

Figure 3 shows a plot analogue to that of Conti. All input parameter are taken from his paper except the terminal velocity v_{term} and $\dot{M}_w$ for which the new determinations were used; an uncertainty of a factor of two was adopted in the latter. For the X-ray luminosity two values were used: on the one hand a 'mean' value as adopted by Conti, and on the other hand a value obtained by scaling the luminosity as listed by Bradt et al. (1979) to Conti's adopted distances. Bradt's catalog gives maximum luminosities and therefore yields a kind of lower limit to the derived wind velocities.

Velocity curves for different predicted and observationally derived velocity laws are indicated in the figure.

The adopted uncertainties are certainly underestimated since only for L_x and $\dot{M}_w$ the two extreme values were used and the other parameters were assumed to be fixed.

Our chairman will be pleased that the velocity law which he derived (from ζ Pup, Lamers & Morton, 1977) is covered by all three stars. A steep velocity law seems to be favoured. However, the results are probably not accurate enough to discriminate between the different velocity laws. Recent calculations by MacGregor and Vitello (1979) showed that the wind velocity between the star and the X-ray source might increase because of ionization effects. If this result can be applied to this system always a too steep velocity law will be derived. The small ellipse in figure 3 represents the direct observed value by Dupree et al. (1979). The agreement is encouraging and gives us confidence in the applicability of Conti's method.

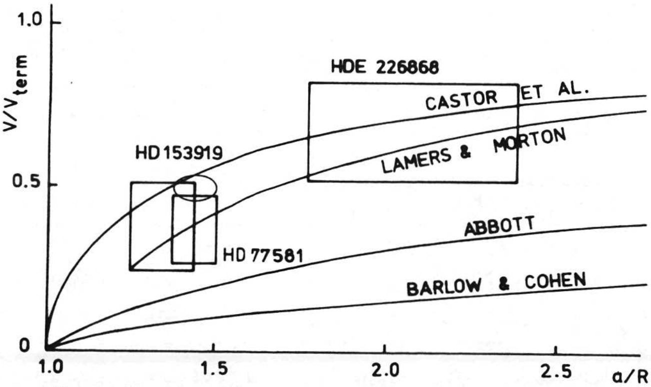

Figure 3. Comparison of different stellar wind profiles with derived values from X-ray emission (see Conti, 1978).

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