EVAPORATIVE WINDS IN X-RAY BINARIES

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ABSTRACT

Evaporation of gas from the surface of HZ Her by Her X-1 and its implications regarding the mass transfer process are examined further. The powerful soft X-ray flux results in an evaporation rate greater than previous estimates. The evaporative flow is shown to be subsonic at first, with the result that the capture of evaporated gas by Her X-1 may be efficient, and the self-excited wind mechanism is possible. A criterion for stabilization of mass transfer by stellar wind mass loss is derived. Possible mechanisms for the long-period variability of HZ Her are discussed. Evaporative winds are also estimated for Sco X-1 and Cyg X-2 spectra.

Subject headings: stars: mass loss — X-rays: binaries

I. INTRODUCTION

According to the "self-excited wind" hypothesis for binary X-ray sources, illumination by X-rays evaporates the atmosphere of the companion star and thereby causes enough mass transfer to feed the X-ray source. The possibility that this mechanism is primarily responsible for the X-ray luminosity of the Her X-1 system has been discussed in a number of papers, with significantly different conclusions. For example, Arons (1973) and Basko and Sunyaev (1973) have concluded that the mechanism was effective. On the other hand, Alme and Wilson (1974) derived a lower evaporative mass flux, and McCray and Hatchett (1975) argued that the mass transfer was not sufficient to provide positive feedback to the X-ray source.

A major new development since these papers were written has been the observation of a powerful flux of soft ($\lesssim 0.25$ keV) X-rays in the spectrum of Her X-1 (Shulman *et al.* 1975; Catura and Acton 1975). Another major development is the discovery of a $0^{d}.787$ orbital period of Sco X-1 (Wright, Gottlieb, and Liller 1975; Cowley and Crampton 1975; Basko *et al.* 1976). There are also indications that Cyg X-2 is a binary system, too (Basko *et al.* 1976; Holt *et al.* 1976). Each of these systems contains a late-type star that normally has a low wind, and therefore both systems are also candidates for the self-excited wind mechanism. The only alternative to this mechanism in such systems is mass transfer by Roche lobe overflow, which requires much more specific conditions to be fulfilled and which gives too high mass transfer rates, for which reason it seems to be less attractive. Considering the possible general importance of the self-excited wind mechanisms, we feel it is imperative to examine the problem again, and to resolve the disagreement in our previous works.

The problem of the self-excited wind mechanism divides into two parts. The first is to estimate the rate of evaporation of mass from the companion star by X-ray heating. We believe that we now understand this part of the problem reasonably well and that we can estimate the evaporative mass flux within about a factor of 2, given the parameters of the system. This is done in § II where the evaporative mass loss is shown to depend strongly on the X-ray spectrum and only weakly on the gravitational potential of the illuminated surface. We are less certain about the second part of the problem, which is to estimate the fraction of the evaporated mass flux that is captured by the X-ray star. In §§ III and V we see that the self-excited wind may be a viable mechanism in the Her X-1 system as well as in other systems if the capture fraction is of order unity. (In this case accreting material necessarily forms a disk around the compact star.) We believe that this may happen if the surface of the normal star is close enough (within, say, 100 eV of potential) to the critical Roche surface.

Even if the self-excited wind mechanism does not work, the evaporative wind may indirectly modulate the mass transfer. In § IV we describe this effect and briefly consider various other effects that may be related to the extended low periods in the optical variability of HZ Her that have occurred several times in this century (Wenzel and Gessner 1972; Jones, Forman, and Liller 1973).

II. GAS DYNAMICS OF AN EVAPORATIVE WIND

As discussed by Basko and Sunyaev (1973) and by McCray and Hatchett (1975), gas illuminated by X-rays is subject to thermal instability when its pressure drops below a value $P_{\min}$ which, if the flow is optically thin, is directly proportional to the X-ray flux F. In a stellar atmosphere, whose scale height is small compared to the other dimensions of the system, a point occurs where the atmospheric pressure drops below

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$P_{\min}$. (This point turns out to be very close to the photosphere, and from now on we identify its radius R with the radius of the star itself.) There, radiative cooling of the gas cannot compensate for X-ray heating, and the gas temperature must jump almost discontinuously to a value great enough that the gas begins to flow outward. The X-ray heating rate decreases with increasing gas temperature but is still greater than the radiative cooling rate. The flowing gas may now be cooled primarily by adiabatic expansion. Above the discontinuity, the gas remains at a roughly constant temperature. The resulting mass flux from the stellar surface depends on three parameters—the gravitational potential at the stellar surface Φ, the gas temperature T above the discontinuity, and $P_{\min}$. At the end of this section we discuss the behavior of $P_{\min}$; here we assume that $P_{\min}$ is given and discuss the dependence of the mass flux on Φ and T.

McCray and Hatchett assumed that the transition from subsonic flow to supersonic flow must occur at the temperature discontinuity. This assumption enabled them to obtain a simple estimate of the mass flux in terms of the gas temperature, which they estimated by equating the X-ray heating time scale to the flow time scale. However, the calculations of Basko and Sunyaev showed that the flow above the temperature discontinuity was still subsonic (Mach number $\mathscr{M} \lesssim 1/3$).

How is the Mach number $\mathscr{M}$ of the flow determined, and what is the resulting mass flux? A proper treatment of these questions would involve solution of the hydrodynamical equations together with an energy equation including X-ray heating. Such calculations performed earlier by Basko and Sunyaev (1973) and by Alme and Wilson (1974) show that the flow above the discontinuity may be approximated as an isothermal one. Once the assumption of the isothermal flow is adopted, it is straightforward to show that the flow immediately above the discontinuity is subsonic. We shall treat the temperature T of the flowing gas as a parameter and find that the mass flux as a function of T has a maximum at a value of $T = T^* \approx (\mu m_p/k)\Phi$ such that $\mathscr{M} = 0.3$ to 0.7 immediately above the temperature discontinuity. We shall argue further that the actual value of temperature T in the cases of interest, when the flow can be approximated as an isothermal one, is close to T^*.

To illustrate this, consider first the idealized case of spherically symmetric, isothermal flow in a gravitational potential GM/r with $\Phi = GM/R$. The stellar wind solutions (cf. Parker 1963) are given by

$$\frac{v^2}{a^2} - \ln\left(\frac{v^2}{a^2}\right) = 4\ln\left(\frac{r}{R_s}\right) + 4\frac{R_s}{r} + K, \quad (1)$$

where a is the isothermal sound speed, and

$$R_s = \frac{GM}{2a^2} = \frac{GM\mu m_p}{2kT}.$$

For the cases discussed here $R < R_s$.

The constant K may be determined by the following argument. The single-valued solutions to equation (1) are either supersonic everywhere or subsonic everywhere with the exception of two transonic solutions corresponding to $K = -3$. The condition that the pressure at $r \to \infty$ be zero requires us to pick either the transonic solution whose velocity increases outward or one of the supersonic solutions. We decide among these possibilities by considering the internal structure of the discontinuity in a similar manner to that used by Landau and Lifshitz (1959) for a detonation wave. Our discussion parallels that given by Axford (1961) for a D-type ionization front. We assign the subscript 1 to quantities immediately below the discontinuity and subscript 2 to those immediately above. The situation may then be represented on a (pressure, specific volume) (P, V) graph as in Figure 1. The solid curve is an isotherm $T = T_2$ = constant and represents various possible states of the gas above the discontinuity. The dashed lines are curves of constant mass flux

$$f^2 \equiv (\rho v)^2 = (P_2 - P_1)/(V_1 - V_2), \quad (2)$$

which equation may be derived by combining the mass and momentum conservation equations. The mass flux is a constant throughout the internal structure of the discontinuity, so gas states within the discontinuity are represented by points on such a dashed line. The intersection of the solid curve and the dashed line for the correct value of f determines the gas state above the discontinuity. If $v_2 > v_1$, then $V_2 > V_1$, and hence from equation (2), $P_2 < P_1$, so possible final states lie below point C on the solid curve. A small decrease in the density (increase in V) starts the temperature rising which then causes the gas to expand. We expect therefore that on, say, the dashed curve through A and B, point A will be reached first and must then represent the final state. Hence only points on the solid curve between C and O are physically realizable. From

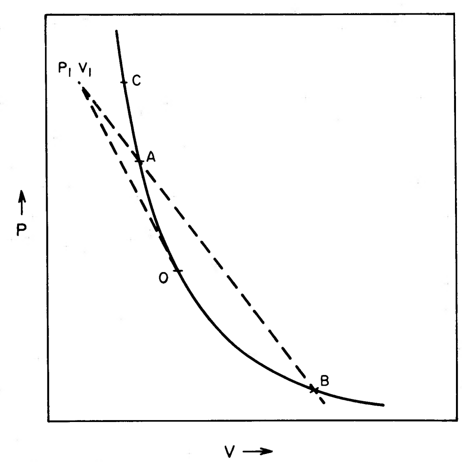

FIG. 1.—Schematic pressure versus specific volume graph showing possible transitions from $P_1 V_1$ to final states across the surface of discontinuity discussed in the text.

equation (2) f is a maximum for final state O, and at O we have $f^2 = -(dP/dV)_2$. Hence,

$$f^2 = (\rho_2 v_2)^2 \leq -\left(\frac{dP}{dV}\right)_2 = \rho_2^2\left(\frac{dP}{d\rho}\right)_2 = \rho_2^2 a_2^2 ,$$

so $v_2^2 \leq a_2^2$: the flow immediately above the discontinuity is *subsonic*. From this we conclude that the correct solution to the wind equation (1) is the transonic solution corresponding to $K = -3$. This will determine the Mach number $\mathscr{M}$ at $r = R$.

Having established the correct velocity law for the wind we may now derive the mass flux. Across the discontinuity the momentum conservation jump condition is to an excellent approximation

$$P_{\min} = P_2 + \rho_2 v_2^2 = f v_2\left(1 + \frac{a_2^2}{v_2^2}\right) \qquad (3)$$

so

$$f = \frac{P_{\min}}{v_2}\left(1 + \frac{a_2^2}{v_2^2}\right)^{-1} , \qquad (4)$$

which we may rewrite as

$$f = \frac{P_{\min}}{\sqrt{\Phi}}\, g_A(x) , \qquad (5)$$

where

$$x \equiv \frac{R_s}{R} = \frac{\Phi}{2a_2^2}$$

and

$$g_A(x) = (2x)^{1/2}\frac{\mathscr{M}(x)}{\mathscr{M}^2(x) + 1} . \qquad (6)$$

The function $g_A(x)$, as calculated from equation (1) with $K = -3$, is shown in Figure 2. It has a maximum $g_A^* = 0.773$ at $x^* = 1.37$, which implies $T^* = 0.365\mu m_p\Phi/k$ and $\mathscr{M}^* = 0.67$. McCray and Hatchett estimated the maximum mass flux by assuming $R_s = R$. In this way they obtained equation (5) with $g_A = 0.707$, only 10% less than the actual maximum value.

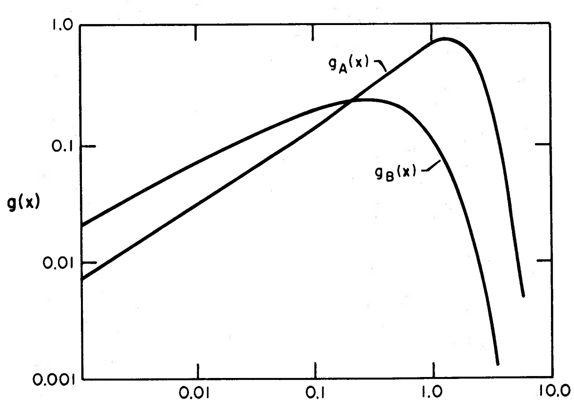

FIG. 2.—Mass flux functions $g_A(x)$ and $g_B(x)$

The weak dependence of the maximum flux f on Φ does not depend strongly on the geometry of the system. For example, one can do the same analysis for plane-parallel flow in the case where the gravitational potential has a maximum at some point R_1 above R, as an approximation to flow through the inner Lagrangian point of a binary system. In this case the flow must become supersonic at R_1, and the mass flux is again given by equation (5) where now Φ is the potential difference between R and R_1, and $x = \Phi/2a_2^2$. The function $g_B(x)$ for plane-parallel flow is also shown in Figure 2. It has a maximum value $g_B^* = 0.244$ at $x^* = 0.28$.

We now wish to argue that the actual temperature of the outflowing gas will be such as to give nearly the maximum mass flux ($x \sim 1$) for cases of interest. First consider radial outflow. The temperature cannot rise above the value corresponding to $x = 1$ since the flow just above the discontinuity is subsonic ($x \geq 1$). Nor can the temperature be very low, because at $x \gg 1$ we shall have a static atmosphere out of thermal balance which is impossible. To find the actual temperature of the wind one should compare the heating and cooling (including adiabatic) rates rather than maximizing $g(x)$. To see how this works qualitatively, let us consider two extreme cases in which the heating and flow time scales differ greatly. In the first case the X-ray flux is so high that the heating rate greatly exceeds the adiabatic cooling rate. If so, the temperature within the discontinuity rises up to $T \sim T_{\rm es}(x \sim 1)$, the outflow begins, and the temperature of the flowing gas gradually increases up to maximum value $T_{\max}$ permitted by X-ray heating, which means that the assumption of constant temperature of the flow breaks down.

In the opposite case, in which the X-ray flux and heating rate are very low, the temperature within the discontinuity jumps up to $T \sim T_{\rm es}$ and then drops gradually in the outflowing gas with characteristic scale height $\sim R$. Thus, the approximation of constant-temperature flow (inferring $x \approx x^*$ above the discontinuity) is justified insofar as the heating and cooling time scales of the outflowing gas are of the same order of magnitude. The numerical calculations mentioned above as well as simple estimates show that this is the case for X-ray binaries discussed below. The exception to this rule occurs when the gravitational potential is so deep, $\mu m_p\Phi > 1$ to 10 keV, that the temperature at which $x \sim 1$ is comparable to $T_{\max}$.

For the case of plane-parallel flow as a rough approximation for flow through the inner Lagrangian point (L_1), we can estimate x by comparing the thermal and flow time scales. We define a flow time as the time for a gas element to flow from the discontinuity to the potential maximum (L_1). The velocity is determined from an equation similar to equation (1). We find that the flow time t_f is given by

$$t_f = \frac{Z}{a_2}\tau(x) , \qquad (7)$$

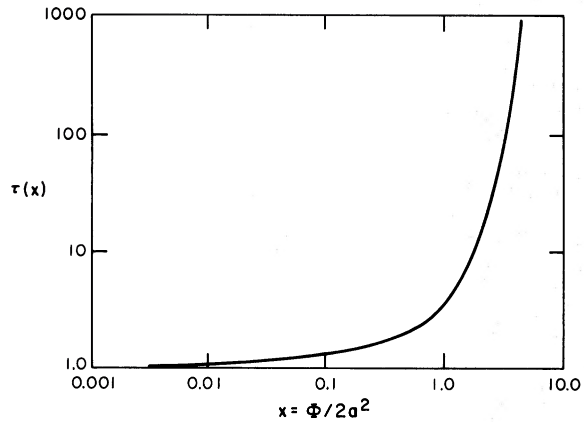

FIG. 3.—Dimensionless flow time $\tau(x)$

where Z is the distance from the discontinuity to L_1, and $\tau(x)$ is shown in Figure 3. We estimate x (hence the temperature above the discontinuity) by equating t_f to the appropriate heating time scale. When applied to the Her X-1 system (see below), this technique gives $x \approx x^*$ only if Φ is not too small ($\Phi \gtrsim$ few $\times$ 10 eV/μm_p) or too large ($\Phi < kT_{max}/\mu m_p$).

Thus we have the following simple formula for the maximum evaporative mass flux

$$f = g^* P_{min} \Phi^{-1/2} , \quad (8)$$

where the numerical factor g^* is of the order of unity but still remains uncertain to about a factor of 3 ($g_A^* = 0.773$ for spherically symmetric flow and $g_B^* = 0.244$ for plane-parallel flow through the inner Lagrangian point).

McCray and Hatchett have discussed the calculation of $P(\rho)$ and hence P_{min} for an atmosphere heated by X-rays. An incident spectrum and flux of X-rays is assumed, and the state of the gas and X-ray radiative transfer through it is calculated in a manner similar to that discussed by Hatchett, Buff, and McCray (1976). Results can be presented, as done by McCray and Hatchett, in the form of $P/F(\rho/F)$ graphs since in the optically thin case the parameter ρ/F (for a particular spectral distribution) is sufficient to determine the state of the gas. The results may then be scaled for various F values. We have computed $P/F(\rho/F)$ graphs for assumed Her X-1 spectra including the newly discovered soft X-ray flux at its observed level compared to the hard X-ray component, at one-tenth that level, and absent. For the hard component we have assumed either a 6.2×10^7 K blackbody spectrum or a 22 keV (25.5×10^7 K) exponential spectrum. The soft component was assumed to have a 5.5×10^5 K blackbody spectrum. The various combinations and corresponding values of P_{min}/F are shown in Table 1. Perhaps the most striking effect evident in Table 1 is the precipitous drop in P_{min} (down by a factor of $\sim 10^3$) for the models with a blackbody hard X-ray component when the soft X-rays are absent, which is due to the deficiency of the Planckian curve in soft quanta, $h\nu \lesssim 1$ keV, as compared to the exponential spectrum. This effect is discussed further in § IV in relation to the long-term behavior of the HZ Her/Her X-1 system.

We can now apply these results to the HZ Her/Her X-1 system to calculate the mass loss rate from HZ Her. The X-ray flux F in the atmosphere of the primary is given by

$$F = \frac{L_x}{4\pi D^2}(1 + \mathscr{R}) , \quad (9)$$

where L_x is the luminosity of the X-ray source, D is the distance from the primary photosphere to the X-ray source, and $\mathscr{R}$ is the X-ray albedo taken to be 0.4. The incident angle of X-rays does not enter equation (9) since the flowing gas and thin transition region are transparent to illuminating X-ray flux. Integrating over the exposed surface of the primary, we obtain

$$-\frac{1}{L_x}\frac{dM_{opt}}{dt} = \frac{f}{F}(1 + \mathscr{R})\frac{\Delta\Omega_*}{4\pi} h\left(\frac{R}{A}\right) , \quad (10)$$

where $\Delta\Omega_*$ is the solid angle subtended by the primary at the X-ray source, R is the radius of the normal star, A is the separation of binary components, and f/F is calculated from equation (5) and the results in Table 1. The function $h(\xi)$ depends only weakly on ξ: $h(0) = 2$, $h(0.5) = 2.05$, $h(0.9) = 2.35$.

For application to HZ Her/Her X-1 we need certain parameters of that system. We assume masses of 2 $M_\odot$ and 1 $M_\odot$ for HZ Her and Her X-1, respectively, and an orbital separation of 8 $R_\odot$. These are the parameters assumed by Alme and Wilson (1974) and are consistent with observation. By assuming Roche geometry we can derive the minimum distance Z from the

TABLE 1

VALUES OF P_{min}/F FOR VARIOUS ASSUMED X-RAY SPECTRA

X-ray Source	Hard X-ray Component Spectrum	Ratio of Soft Component Flux to Hard Component Flux	P_{min}/F [cm^{-1} s]
Her X-1........	22 keV exponential	1.15	4.3×10^{-12}
	22 keV exponential	0.12	3.1×10^{-12}
	22 keV exponential	0.00	1.5×10^{-12}
	6.2×10^7 K blackbody	1.15	3.2×10^{-12}
	6.2×10^7 K blackbody	0.12	1.2×10^{-12}
	6.2×10^7 K blackbody	0.00	4.0×10^{-15}
Sco X-1 } Cyg X-2 }......	4 keV exponential	...	2.2×10^{-12}

TABLE 2

EFFECTIVENESS OF EVAPORATION

X-ray Source	$\Phi\mu m_p$ [eV]	Z [cm]	$g_B(x)$	$-(1/L_x)dM_{opt}/dt$ [g erg^{-1}]	$[-(1/L_x)dM_{opt}/dt]_B{}^*$ [g erg^{-1}]	$[-(1/L_x)dM_{opt}/dt]_A{}^*$ [g erg^{-1}]
Her X-1......	10	6.2×10^{10}	0.069	1.0×10^{-20}	3.6×10^{-20}	1.4×10^{-19}
	100	9.8×10^{10}	0.175	8.4×10^{-21}	1.2×10^{-20}	3.6×10^{-20}
Sco X-1 }	10	...	...	...	2.0×10^{-20}	6.4×10^{-20}
Cyg X-2 }	100	...	...	...	6.4×10^{-21}	2.0×10^{-20}

photosphere of HZ Her to L_1 as a function of Φ. Finally, from the eclipse duration and orbital period we estimate $\Delta\Omega_*/4\pi \approx 0.05$. Using the plane-parallel mass flux function $g_B(x)$, we then estimate an upper and a rough lower limit for $-(1/L_x)dM_{opt}/dt$ by using either the maximum $g_B{}^* = 0.244$ or the value of $g_B(x)$ derived by considering the heating and flow time scales as discussed above. For spherically symmetric geometry the maximum of $-(1/L_x)dM_{opt}/dt$ exceeds that for the plane-parallel one ($g_A{}^* > g_B{}^*$); the true value for the binary system geometry should lie somewhere between these two extreme values. The results for the Her X-1 spectrum giving the largest mass flux (22 keV exponential plus observed soft component, cf. Table 1) are given in Table 2 for two values of Φ.

III. CAPTURE OF THE EVAPORATED GAS BY THE X-RAY STAR

The mass accretion rate dM_x/dt necessary to account for a given X-ray luminosity is given by

$$\frac{dM_x}{dt} = (GM_x/R_x)^{-1}L_x \approx 1.8 \times 10^{-8}(L_x/10^{38}\ \text{ergs s}^{-1})\ M_\odot\ \text{yr}^{-1}\,, \quad (11)$$

assuming a gravitational potential at the neutron star surface of $GM_x/R_x = 0.1c^2$. According to § II, the evaporative mass flux $-dM_{opt}/dt$ is less than dM_x/dt by a factor of $\gtrsim 10^3$ for a Planck spectrum, but $-dM_{opt}/dt \approx (1\text{–}4)dM_x/dt$ (for $\Phi\mu m_p \lesssim 100$ eV) if the soft source is present. We believe that the uncertainties in the parameters of the system and in our calculation allow the possibility that $-dM_{opt}/dt$ could be even greater by up to a factor of 3. If so, we see that positive feedback is possible if the capture fraction $f_c \approx 1$ and the soft source is present.

McCray and Hatchett (1975) argued that $f_c \lesssim 1/30$, and therefore concluded that the mechanism did not work, in conflict with the conclusion of Basko and Sunyaev (1973) who assumed $f_c \approx 1$. The conclusion of McCray and Hatchett depended on the assumptions that the gas flow above the discontinuity was supersonic and that the flow was at all times illuminated and heated by the X-ray source. However, the evaporative flow is subsonic above the discontinuity, and there certainly must be some sort of accretion disk that creates a zone of X-ray shadow around Her X-1 (Basko and Sunyaev 1973; Petterson 1975; Gerend and Boynton 1976; Jones and Forman 1976). Therefore, f_c may be much greater than the value estimated by McCray and Hatchett. This fact and the observed soft source make the self-excited wind a viable possibility.

What determines the capture fraction f_c, and how does f_c depend on the parameters of the system? A proper answer to this question would require a three-dimensional hydrodynamical calculation including rotation and X-ray heating, far beyond the scope of this paper. We shall only attempt here to discuss qualitatively the character of the flow and to consider a very simple model that indicates how f_c can be a very sensitive function of the potential difference Φ between the temperature discontinuity and the inner Lagrangian (L_1) point.

The subsonic flow above the discontinuity should be directed by pressure gradients toward the L_1 point. The flow velocity $v(L_1)$ there is equal to the sound speed (Lubow and Shu 1975); we have argued in § II that $v(L_1) \sim (2\Phi)^{1/2}$. Beyond L_1 the flow should go into free fall; and if $\Phi\mu m_p \lesssim 100$ eV, $v(L_1)$ is less than the orbital velocity of the L_1 point relative to the X-ray star. Therefore, the flow should form a large accretion disk, as indicated by observations. The outer radius of the disk and the fraction of the gas flowing through the L_1 point captured by the disk should be sensitive to $v(L_1)$ and decrease rapidly as $v(L_1)$, or Φ, increases (Illarionov and Sunyaev 1975). A large accretion disk can cast an X-ray shadow which permits a cool accretion stream to flow past the L_1 point toward the disk. Then, according to the calculations of Lin and Pringle (1976), the fraction of the cool stream that is ultimately captured by the X-ray source may approach unity.

With increasing Φ, an increasing fraction of the gas may escape from the system. This can happen in three ways. First, as the gas temperature increases beyond 10^6 K, the pressure scale height becomes comparable to the dimensions of the system. This has the consequence that the hot corona has a significant density at the "escape surface," defined as the Roche equipotential where the sound speed of the gas equals the escape velocity from the binary system. This surface is roughly where the corona goes into supersonic free expansion and leaves the binary system. Second, as the velocity of the gas past the L_1 point increases, both the cross section for capture by the compact star and the specific angular momentum of the captured material decrease, and the outer radius of the disk shrinks, reducing the size of the X-ray shadow. If this occurs, a smaller fraction of the matter that passes through the L_1 point can enter the disk without being illuminated and heated by the X-ray source. According to McCray and Hatchett (1975), such illumination may strongly suppress the accretion. Third, as the gas temperature increases, the cross sectional area of the flow through the L_1 throat increases, and this effect also tends to reduce the importance of shadowing. We estimate that the combination of these effects causes the capture fraction to drop rapidly as $\Phi\mu m_p$ increases beyond about 100 eV.

IV. MODULATION OF THE MASS TRANSFER RATE

The studies of light variations of HZ Her by Jones, Forman, and Liller (1973) show inactive periods lasting from months to years during which HZ Her does not show the photometric variations of order 1.5 mag that indicate illumination by Her X-1. Instead, the star shows only very small ($\Delta m \approx 0.2$ mag) variations due to tidal deformation. The simplest explanation for these extended lows is that the mass transfer has ceased, and the X-ray source is off. If so, we are challenged to find a mechanism that modulates the mass transfer with such a characteristic time scale. A nonlinear modulation mechanism is indicated by the absence of photometric variability intermediate between the X-ray illuminated level with $\Delta m \approx 1.5$ mag and the tidal level with $\Delta m \approx 0.2$ mag.

We cannot be sure at this point whether the mass transfer is a result of the self-excited wind mechanism or Roche lobe overflow. In the former case specific nonlinear effects may be pointed out which may cause the necessary modulation. As was found by Basko and Sunyaev (1973), for a fixed value of Φ the evaporative mass loss rate $-dM_{\text{opt}}/dt$ is an essentially nonlinear function of the X-ray luminosity L_x. Now we can say that this nonlinear behavior may be even more pronounced due to the sensitivity of $-dM_{\text{opt}}/dt$ to the X-ray spectrum. We have seen that positive feedback is possible if the X-ray spectrum has a powerful soft component, but not otherwise. McCray and Lamb (1976), Basko and Sunyaev (1976), and Sunyaev (1976) have argued that the soft source results from absorption and reradiation of harder X-rays from the neutron star surface by an opaque shell of gas in the vicinity of the magnetopause, at a radius of order 10^8 cm. If so, the presence of a strong soft component in the X-ray spectrum may require a high rate of mass transfer in order that enough gas is stored at the magnetopause to absorb the hard X-rays. Therefore, with a given Φ there may be two possible states, one with a low rate of mass transfer, no soft source, and no amplification; and the second with a high rate of mass transfer resulting in a soft source and positive feedback in the mass transfer rate.

The other nonlinear effect is a strong dependence of the mass transfer rate $-f_c dM_{\text{opt}}/dt$ on Φ. First, it arises from the strong dependence of f_c on Φ (see § III). Second, a small change in Φ may significantly affect the spectrum of X-rays, thus resulting in a crucial change in $-dM_{\text{opt}}/dt$ (for a fixed spectrum $-dM_{\text{opt}}/dt$ depends only weakly on Φ; see § II). The reason for this is that an opaque magnetopause shell (which we assume to be a source of soft X-rays in Her X-1) can exist only if accreting material forms a disk (Basko 1977). So, a rapid decrease of the outer disk radius with increasing Φ may result in an abrupt cutoff of the soft X-ray flux and a sudden termination of mass transfer.

Thus, we can envisage a model in which the surface of HZ Her is separated from the L_1 point by a substantial potential difference, say $\Phi\mu m_p \approx 100$ eV, such that the capture fraction f_c is less than unity and the mass transfer is marginally sufficient for positive feedback, i.e., $-f_c dM_{\text{opt}}/dt \approx dM_x/dt$. With positive feedback the X-ray luminosity will stabilize at a high equilibrium level at which saturation, due to the absorption of the soft part of the X-ray spectrum in the outflowing gas (Basko and Sunyaev 1973) or due to the radiation and/or gas pressure (Hatchett, Buff, and McCray 1976; Ostriker *et al.* 1976), limits the accretion flow. This saturated luminosity can be significantly less than the Eddington limit. But with a slightly greater value of Φ, such that $-f_c dM_{\text{opt}}/dt < dM_x/dt$, the positive feedback does not occur; and in that case, the mass transfer rate and X-ray luminosity should be negligible.

If this model is correct, Φ should fluctuate about the value at which positive feedback is marginally possible. This situation could be the result of an equilibrium between the stellar evolution of HZ Her, which causes the star to expand and tends to decrease Φ, and the evaporative wind, which strips matter off the stellar atmosphere and tends to increase Φ. In that case the mass loss rate averaged over a long time should be given by $\langle -dM_{\text{opt}}/dt \rangle \approx M_{\text{opt}}/t_{\text{ev}}$, where the stellar evolution time scale t_{ev} is likely to be somewhere between the nuclear evolution time scale and the thermal (Kelvin-Helmholtz) time scale, $10^9 \text{ yr} \gtrsim t_{\text{ev}} \gtrsim 10^7$ yr. This gives a probable range $10^{-9} M_\odot \text{ yr}^{-1} \lesssim \langle -dM_{\text{opt}}/dt \rangle \lesssim 10^{-7} M_\odot \text{ yr}^{-1}$. The mass accretion rate inferred from the average X-ray luminosity (eq. [11]), $\langle dM_x/dt \rangle \approx 3 \times 10^{-9} M_\odot \text{ yr}^{-1}$, is in this range.

Presumably in this model the evaporation wins over the stellar evolution while the X-ray source is on, so that f_c and $-dM_{\text{opt}}/dt$ slowly decrease as Φ increases, until the amplification is lost and the X-ray source goes off. But once this happens, there is nothing built into this model that might restart the X-ray source after a characteristic interval of a few months or years. Because of the nonlinearity of the mechanism a large amplitude fluctuation in mass transfer is required to restart the self-excited wind. Although for this just a small decrease in Φ may be sufficient, stellar evolution does not seem to do the job—the relevant time scale still greatly exceeds 1 year. Perhaps the observed time interval is characteristic of some completely different physical mechanism, such as a large stellar flare on HZ Her.

Since the self-excited wind mechanism is only a marginal possibility, we should consider the alternative model of Roche lobe overflow, in which $\Phi\mu m_p \lesssim 10$ eV. We shall see that in this model the evaporative wind may still play an important role in modulating the mass transfer, even without positive feedback.

One might make the following naive argument against Roche lobe overflow as a mass transfer mechanism. If mass is transferred from a heavier primary star to a lighter star in a binary system in such a way that corotation and orbital angular momentum are conserved, the orbital separation shrinks and so does the volume of the primary Roche lobe. In fact, the volume of the primary Roche lobe decreases more than the volume of the primary star as a result of the mass transfer; this leads to an instability in the mass transfer rate (Plaveč 1968; Paczyński 1971) with a growth time like the thermal time scale. The resulting mass transfer rate should be of order $10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$—more than can be accepted by the X-ray source. Such a high rate of mass transfer should cause the X-ray source to be enveloped by absorbing material; but there is no evidence for such behavior in the Hercules system.

However, various subtle effects can remove the instability. One such effect, pointed out by Pratt and Strittmatter (1976), is departure from corotation by the primary star as a result of the mass transfer. Another stabilizing effect that we wish to point out here is that of mass loss from the system in a stellar wind. If mass lost from the primary star escapes the binary system with low specific angular momentum instead of being captured by the secondary, the effect is to increase the orbital separation and the volume of the primary Roche lobe. Thus, the fraction of the evaporative wind from the primary star that is not captured by the secondary has a stabilizing effect on the Roche lobe overflow.

As an example, we have considered the stability of a simple model for an X-ray binary system in which corotation of the primary is conserved, and a fraction $-f_c dM_{\mathrm{opt}}/dt$ is transferred to the X-ray source while a fraction $-(1-f_c)dM_{\mathrm{opt}}/dt$ is lost from the system in a wind with given specific angular momentum. Let $\alpha = \Delta \log R/\Delta \log M_{\mathrm{opt}}$ express the variation of the primary radius on some time scale in response to mass loss, and let $\alpha_L = \Delta \log R_L/\Delta \log M_{\mathrm{opt}}$ express the corresponding variation of the effective radius R_L of the Roche lobe of the primary star. The system is stable against mass transfer if $\alpha_L < \alpha$. We define a parameter β which represents the fraction of the orbital angular momentum of the system that is lost by the escaping wind: $dJ_{\mathrm{orbit}} \approx \beta(1-f_c)dM_{\mathrm{opt}}\Omega y^2$, where y is the distance between the barycenter of M_{opt} and that of the binary system. If A is the distance between the barycenters of M_{opt} and M_{x} and $q = M_{\mathrm{x}}/M_{\mathrm{opt}}$, we find from Plaveč (1968) the approximate formula $R_L/A \propto q^{-0.194}$. From this and Kepler's laws we may derive

$$\alpha_L = 0.194(1+f_c/q) + \frac{(1+2\beta q)(1-f_c)}{1+q} - 2(1-f_c/q). \quad (12)$$

Consider as an example the stability of the mass transfer in the Her X-1 system, for which $q \approx 0.5$. Assuming that the internal structure of HZ Her is like that of a homogeneous main-sequence star with $M_{\mathrm{opt}} \approx 2\ M_\odot$, we find from Cox and Giuli (1968) that $\alpha \approx 0.52$. The parameter β is difficult to estimate because the wind is not symmetric, but we may reasonably expect that $0 \leq \beta \lesssim 1$ for this system, and fortunately the stability criterion is rather insensitive to the adopted value of β. We find that mass transfer in the Her X-1 system is stabilized by the evaporative wind if $f_c \lesssim 0.33$ to 0.45, where the former value has been derived with $\beta = 1$, and the latter with $\beta = 0$.

The same stabilization effect would result from the mass loss due to the normal stellar wind of a massive OB primary star in binary X-ray systems such as Cyg X-1 and SMC X-1. For such stars the stability criterion that follows from equation (12) is approximately $f_c \lesssim q$, assuming $\beta \lesssim 1$. This criterion appears to be satisfied in general for such systems, because the mass loss rate due to the stellar winds is $(-dM_{\mathrm{opt}}/dt)w \gtrsim 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$, and the mass transfer rate inferred from the X-ray luminosity is $M_{\mathrm{x}} \lesssim 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$, so that $f_c \lesssim 10^{-2}$.

This simple model makes a definite prediction about the orbital period variation of the system, namely,

$$\frac{1}{P}\frac{dP}{dt} = \left(\frac{2+3q}{f_c} - 2 - \frac{3}{q}\right)\frac{1}{M_{\mathrm{x}} + M_{\mathrm{opt}}}\frac{dM_{\mathrm{x}}}{dt}, \quad (13)$$

where dM_{x}/dt may be inferred from the X-ray luminosity. For the Hercules system stabilized by a wind this gives $P^{-1}dP/dt \gtrsim 10^{-8}\ \mathrm{yr}^{-1}$.

The point of the above exercise is to illustrate that the evaporative wind can stabilize the Roche lobe overflow and allow the mass transfer to proceed on a nuclear time scale rather than a thermal time scale. This appears to be a realistic possibility with the Her X-1 system if we compare equation (11) to the results in Table 2. Assuming that dM_{x}/dt is entirely a result of Roche lobe overflow and that all the mass evaporated from HZ Her escapes the system, we have

$$f_c = \frac{dM_{\mathrm{x}}/dt}{dM_{\mathrm{x}}/dt + (-dM_{\mathrm{opt}}/dt)_w} \approx 0.4\text{–}0.7\ . \quad (14)$$

Another nonlinear mechanism that may be important in X-ray binaries when the normal star nearly fills its critical Roche lobe is the effect of X-ray heating on the structure of the stellar atmosphere. This effect has been investigated in some detail by Anderson (1975). Anderson's calculations for X-ray illuminated photospheric models indicate that X-ray heating effects should substantially increase the temperature of the outer envelope of the primary to a depth of about 60 g cm^{-2} if the X-ray flux at L_1 exceeds the primary's own radiation flux there. He estimates that this depth corresponds to about 10 density scale heights in the case of HZ Her. Hence, X-ray heating can greatly increase the density at a given geometric point in the primary atmosphere, thereby decreasing Φ and increasing the wind as well as any overflow mass transfer. Anderson has shown how the heating effect may cause a sudden onset and termination of overflow mass transfer (if the stability problems discussed above may be disregarded). It may likewise have a similar though less pronounced effect on the self-excited wind mechanism via the induced variations in Φ.

V. EVAPORATIVE WINDS IN OTHER X-RAY SOURCES

All the above discussion has dealt with the HZ Her/Her X-1 system, for which we have much more information than for the other X-ray binaries. Recently the binary nature of Sco X-1 has been established (Wright, Gottlieb, and Liller 1975; Cowley and Crampton 1975; Basko *et al.* 1976). The X-ray spectrum of this source is rather soft; we represent its spectrum by an exponential with $kT_x \approx 4$ keV. (A blackbody spectrum would be unreasonably deficient in photons of energy below 100 eV.) The results of calculations for this spectrum are also given in Tables 1 and 2. Besides the X-ray spectrum, the only combination of parameters of the binary system which enters the equation (10) for the effectiveness $-(1/L_x)dM_{\text{opt}}/dt$ of the self-excited wind is the solid angle $\Delta\Omega_*$ subtended by the normal star at the X-ray source. If the size of the normal component is close to that of the Roche lobe (a necessary condition for mass transfer to occur), $\Delta\Omega_*$ is only a weak function of the mass ratio of the binary components and, most likely, differs from the value adopted for the HZ Her/Her X-1 system by not more than a factor of 2. So, for Sco X-1 (as well as for Cyg X-2), we also assume $\Delta\Omega_*/4\pi = 0.05$. From Table 2 one can see that the self-excited wind is a possible mass transfer mechanism in Sco X-1.

One more X-ray source in which this mechanism may be operative is Cyg X-2. If this X-ray star has a normal companion (we believe that it has, see Basko *et al.* 1976), then the latter should be of late spectral type. The X-ray spectrum of Cyg X-2 is even softer than that of Sco X-1 and can also be approximated by an exponential with $kT_x \approx 4$ keV. The evaluation of $P_{\min}$ for this spectrum (see Tables 1 and 2) also favors the self-excited wind hypothesis.

We wish to mention one more possible type of X-ray binary—red supergiants with relativistic companions—in which mass transfer may occur through an evaporative wind because of the low surface gravitational potentials (tens of eV) and low effective temperatures of red supergiants. Binary periods of such systems may be as large as months and years.

Our conclusions are that there certainly must be a substantial evaporative wind in the Her X-1 and other systems, but our estimate of the mass transfer rate due to this wind has a range such that the self-excited wind mechanism is a possibility but not a certainty. Perhaps further observations will resolve the issue, and several opportunities come to mind. The first is to observe the soft X-ray absorption by the wind as a function of orbital phase and to infer from that the density structure in the wind (cf. Buff and McCray 1974). The second is to observe the evaporative wind by UV spectroscopy (cf. Hatchett and McCray 1977); such an observation will require a more powerful UV space telescope than is currently available. A third possibility would arise if Her X-1 should enter another extended low—an event that may be overdue. If so, precise observations of the ellipsoidal photometric variations of HZ Her should determine whether the star nearly fills its Roche lobe. If not, the self-excited wind mechanism is the probable means for mass transfer.

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