ACCRETION FLOWS IN BINARY X-RAY SYSTEMS

Richard McCray
Joint Institute for Laboratory Astrophysics, National Bureau of Standards and University of Colorado and Department of Physics and Astrophysics, University of Colorado,
Boulder, CO 80309 USA

1. INTRODUCTION

The subject of accretion flows in binary X-ray systems has been reviewed recently by Lightman et al. (1977), and the subject of accretion disks by Shu (1976). Here I shall emphasize developments that have occurred since those reviews were written, and concentrate on issues concerning the gas flows rather than the radiation mechanisms.

Throughout this paper I shall assume that the X-ray luminosity results from the release of gravitational energy by gas accreting onto a neutron star or a black hole, and that the X-ray luminosity L_x is related to the mass accretion rate $\dot{M}_x$ by

$$L_x = \varepsilon c^2 \dot{M}_x \quad , \tag{1}$$

where the efficiency factor $\varepsilon \approx 0.1$ for a neutron star and $\varepsilon \lesssim 0.3$ for a black hole (Novikov and Thorne 1973). One should bear in mind the possibility that the compact object in some of the binary X-ray systems may be a white dwarf, in which case $\varepsilon \approx 10^{-3}$ (Fabian et al. 1976). Many of the considerations discussed here apply equally well to white dwarf models, although such models are not considered explicitly.

Representative prototypes for the systems we shall discuss are the well-known binary systems Her X-1 and Cyg X-1; models for these systems are shown in figures 1 and 2. The model for Her X-1 shown in figure 1 illustrates the main structures that are expected to exist in the case when the mass transfer is by Roche lobe overflow and the X-ray source is a rotating magnetized neutron star. These structures are: (a) a stream of gas flowing from the primary star HZ Her through the inner Lagrangian point L_1 to (b) an accretion disk whose outer radius is a substantial fraction of the radius of the Roche lobe of the X-ray source, and (c) shown in the inset, a magnetosphere at a radius $\approx 10^8$ cm.

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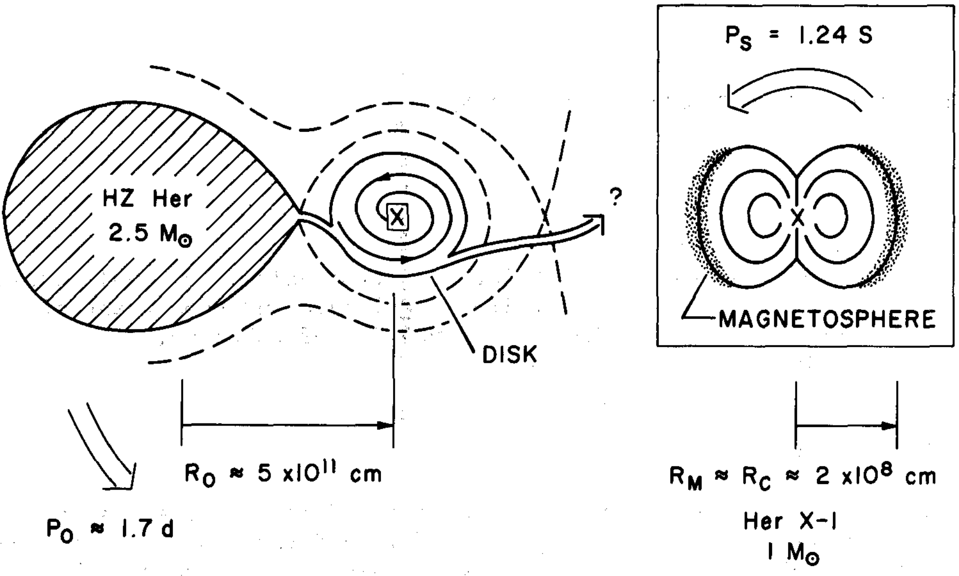

Figure 1. Model for the Hercules X-1 Binary System

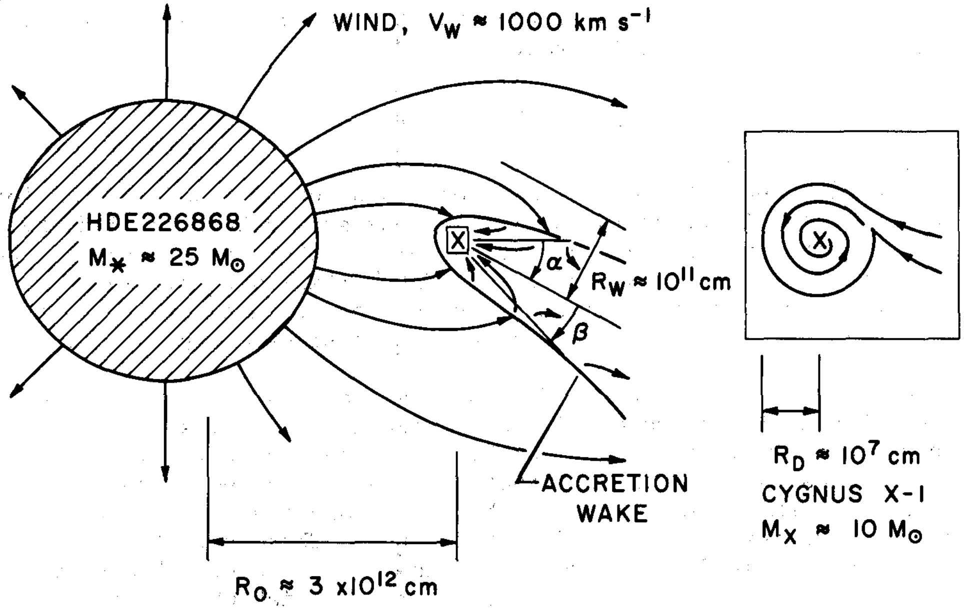

Figure 2. Model for the Cygnus X-1 Binary System

An early-type supergiant star normally has a great stellar wind with mass loss rate $\dot{M}_*$ in the range 10^{-8} to 10^{-5} $M_\odot$ yr^{-1} (Hutchings 1976; Lamers and Morton 1977; Barlow and Cohen 1977). When the optical companion of a binary X-ray source is such a star it is possible (but not certain -- cf. Tananbaum and Hutchings 1975) that the mass transfer occurs by capture of the stellar wind (Davidson and Ostriker 1973). The model for Cyg X-1 shown in figure 2 illustrates the structures that are expected if this is the case, assuming the compact object to be a black hole. The accretion flow is markedly different from that of figure 1. The dominant structures are: (a) an accretion wake; and (b) in the inset, a very small accretion disk around the black hole.

In table 1 we list the physical parameters of the accretion flows and a number of scale lengths, defined by equations (2)-(8), that may be derived from these parameters by dimensional analysis. These scale lengths characterize a nested hierarchy of structures in the flow which may to some degree be isolated and discussed separately. Our plan here is to first discuss the innermost structures, near the compact objects, and work outwards towards the largest structures, whose characteristic

Table 1

Glossary of Parameters and Characteristic Scale Lengths

M_x : X-Ray Source Mass/$M_\odot$
M_* : Companion Star Mass/$M_\odot$
μ_{30} : Neutron Star Magnetic Moment/10^{30} gauss cm^3
L_{37} : X-Ray Source Luminosity/10^{37} erg s^{-1}
P_s : Neutron Star Spin Period (sec)
P_o : Orbital Period (days)
V_{1000} : Stellar Wind Velocity/(1000 km s^{-1})

Innermost Stable Orbit About a Black Hole:

$$R_H \approx 6\, GM_x/c^2 \approx 9 \times 10^5\, M_x \text{ cm} \quad . \tag{2}$$

Neutron Star Radius:

$$R_n \approx 10^6 \text{ cm} \quad . \tag{3}$$

Magnetospheric Radius:

$$R_m \approx 3 \times 10^8\, \mu_{30}^{4/7}\, M_x^{1/7}\, L_{37}^{-2/7} \text{ cm} \quad . \tag{4}$$

Corotation Radius:

$$R_c \approx 1.5 \times 10^8\, M_x^{1/3}\, P_s^{2/3} \text{ cm} \quad . \tag{5}$$

Stellar Wind Accretion Radius:

$$R_w \approx 2GM_x/V_w^2 \approx 1.3 \times 10^{10}\, M_x\, V_{1000}^{-2} \text{ cm} \quad . \tag{6}$$

Binary Orbit Radius:

$$R_o \approx 3 \times 10^{11}\, M_*^{1/3}\, P_o^{2/3} \text{ cm} \quad , \tag{7}$$

(assuming $M_* >> M_x$).

Outer Disk Radius for Accretion from Stellar Wind:

$$R_D \approx 1/4\, R_w^4/R_o^3 \approx 3 \times 10^5\, M_x^4\, V_{1000}^{-8}\, M_*^{-1}\, P_o^{-2} \text{ cm} \tag{8}$$

scale lengths are of the order of the orbital radius. The first two scale lengths listed in table 1 are the neutron star radius R_n and the innermost stable orbital radius R_H of a rapidly rotating black hole. Most of the X-ray luminosity results from release of gravitational energy within a few times these radii, which are comparable and of order 10-100 km. The subject of the emission and transfer of the X-rays there is a complicated one that is beyond the scope of this review. At greater radii the accretion flow acts as a passive medium that can change the spectrum of the emergent radiation but not its luminosity.

2. NEUTRON STAR MAGNETOSPHERES

When two characteristic scale lengths become comparable, the resulting flows may display fascinating phenomena having to do with the interplay of different physical forces. This appears to be the case with the magnetospheric radius R_m [eq. (4)] and the corotation radius R_c [eq. (5)]. Equation (4) is derived by equating the ram pressure $P_r = \rho v^2$ of spherically symmetric freely falling accretion flow (such that $\dot{M}_x = 4\pi r^2 \rho v$) to the magnetic pressure $P_m \approx (1/8\pi)(\mu^2/R^6)$ of a dipole field. Within R_m the accreting gas must be entrained in the rotating magnetic field of the neutron star. The corotation radius R_c is that radius where the Kepler period equals the rotation period of the neutron star. Here we classify the magnetospheric flows according to the relative magnitudes of R_m and R_c, following Elsner and Lamb (1976).

2.1 Slow Rotators: $R_m << R_c$.

Examples are the pulsating X-ray sources with periods greater than a few seconds, such as 3U0900-40, A0535+26, etc. In this case centrifugal forces are unimportant at R_m, where the magnetic influence of the neutron star is first felt by the gas. It is possible in this case to consider a model for spherically symmetric flow onto such a magnetosphere that is susceptible to detailed analysis and that may bear some semblance to physical reality. Such studies have been performed by Arons and Lea (1976a,b), Elsner and Lamb (1977) and Michel (1977a,b). The essential results are as follows. The above authors have calculated the shape of the resulting magnetospheric boundary for a dipole field and their results agree in detail. In contrast to a free field all lines of force are contained within a radius $\sim R_m$ and the enclosed field has cusps above the magnetic poles. The inflowing gas encounters a shock at the magnetopause, and the shocked gas is unstable and will fall into the magnetosphere.

Arons and Lea, and Elsner and Lamb have calculated the growth rate of the interchange instability, in which parcels of gas become entrained in the magnetosphere, even at the equator, without diffusing onto the lines of force. The subsequent development of this instability is unclear. Perhaps the entrained flow is channeled toward the magnetic poles, or perhaps it continues to tumble through the lines of force and is not effectively channeled until the higher multipole components of the field become important. Elsner and Lamb (1976) have suggested this to explain the complex pulse shapes of the slowly pulsating X-ray sources.

Michel (1977a,b) has analyzed a somewhat different instability in which gas enters the magnetosphere at the polar cusps. Perhaps both types of instability are important. What is common to all these studies is that some radiative cooling of the shocked gas is necessary to start the instabilities, and that once started the instabilities can develop at the free-fall timescale. This raises the interesting possibility that the flow into the magnetosphere is regulated by radiative processes in the shocked gas, and that thermal instabilities in this gas may be responsible for burst-like behavior in X-ray sources (Lamb et al. 1977 -- see also the discussion by Lamb in these proceedings).

2.2 Intermediate Rotators: $R_m \approx R_c$.

Examples are Her X-1 and Cen X-3. In this case the possibility arises that gas locked on to the rotating magnetic field at R_m may be supported by centrifugal force. Detailed analyses of the gas flow have not been attempted. However, McCray and Lamb (1976) and Basko and Sunyaev (1976,1977) have suggested that the powerful component of soft X-rays observed in the spectrum of Her X-1 comes from an opaque shell of gas partially surrounding the neutron star at R_m. They point out that a simple estimate based on the Stephan-Boltzmann law indicates that the surface area emitting the soft X-rays is of order πR_m^2, and that the gas accumulated at the magnetopause will be opaque if the storage time there is of order ten times the free-fall time. The opaque shell acts as a collimator that absorbs the hard X-rays and re-emits the soft X-rays. Detailed studies of the pulse shape as a function of X-ray energy may therefore provide an observational handle on the structure of the flow at and within R_m.

2.3 Fast Rotators: $R_m >> R_c$.

Basko and Sunyaev (1977) have suggested that this might be the case with some non-pulsating X-ray sources such as Sco X-1 and Cyg X-2. If so, and if corotation were enforced at R_m, the centrifugal force would be greater than gravitation and accretion could not occur. So gas must continue to pile up at R_m until the weight of the shell exceeds the force due to the ram pressure of the infalling gas. This weight will force the radius of the magnetopause to a value much smaller than that given by equation (4), until the new R_m is of order R_c, at which point accretion may occur. The resulting shell is very thick and is likely to completely obscure the pulsing hard X-ray source from the neutron star. The Stephan-Boltzmann law suggests that the temperature of the X-rays radiated by the shell should be less than that of the slowly rotating pulsars ($kT_x \approx 40$ keV) but greater than that of the soft X-ray component of Her X-1 ($kT_x \approx 0.5$ keV). As in case (2.2) the neutron star should continue to spin up as long as accretion continues. Case (2.3) is only speculation at present, but it might be confirmed by, say, finding a regular pulsation of short period and small amplitude caused by a lack of spherical symmetry at the magnetopause.

3. STRUCTURE OF ACCRETION DISKS

This discussion can be brief, since up-to-date and comprehensive reviews have been written by Lightman et al. (1977) and by Shu (1976). It is worthwhile to distinguish between the inner disk ($r \lesssim 10\ R_H$) that is thought to be responsible for X-ray emission in the vicinity of a black hole and a much larger, outer disk that may be responsible for X-ray eclipses and light variations in the case of Roche lobe overflow. As is suggested by the models of figures 1 and 2, it is possible that some sources (e.g. Cyg X-1) have an inner disk but no outer disk, and that others (e.g. Her X-1) have an outer disk but no inner disk. Both, or neither, are also conceivable.

Most discussions of the theory of disk structure start from the elegant "standard model" of Pringle and Rees (1972) and Shakura and Sunyaev (1973) for an axisymmetric thin disk with a stationary accretion flow caused by internal viscosity. Intrinsic to the model are several bold assumptions, each of which can be sensibly challenged. The most important of these is stationary flow. From the point of view of the observations there is no particular reason to make such an assumption, since the X-ray luminosity of Cyg X-1 (the best candidate for an accretion disk around a black hole) fluctuates wildly on every timescale. Therefore, it would be fair to say that this assumption is motivated primarily by practical exigencies, and by the hope that a stationary flow model represents in some sense the time-averaged behavior of an unsteady flow. In fact, no self-consistent stationary model for an accretion disk exists. Studies by Shakura and Sunyaev (1976), Pringle (1977), and by Shibazaki and Hoshi (1975) all show that the optically thin inner part of the accretion disk is thermally unstable because the gas radiates less efficiently when it becomes hotter, and conversely.

The standard model fails to explain the high X-ray temperature ($kT_x \approx 50$ keV) observed in Cyg X-1. Shapiro et al. (1976) have constructed models in which the ion temperature in the inner part of the disk exceeds the electron temperature ($kT_i \approx 10^9$ K, $kT_e \approx 10^8$ K). In this model the inner disk is thick compared to its radius. The resulting X-ray spectrum fits the observations better, but the model still suffers the thermal instability.

Another big assumption of the standard model is the character of the viscosity law. It is assumed there that the viscous stress tensor can be written $\sigma_{ij} = \alpha p$ where α is a constant parameter and p is the gas pressure. This is an unusual viscosity law in that the shear stress is independent of the velocity gradient. There is great uncertainty in the assumption of constant α. This parameter can be expressed as $\alpha = \nu_k / c_s h$, where ν_k is the true kinematic viscosity and $c_s h$ is the viscosity due to fully developed turbulence in a disk of thickness h and local sound speed c_s. If one could claim such fully developed turbulence, one might justify $\alpha \approx 1$ on dimensional grounds. But the claim would be questionable on the grounds that the accretion disk is a classic example of stably stratified shear flow (Landau and Lifshitz 1959). Of course, the absence of shear instability does not prove stability. Other instabilities, for example, to convection normal to the disk (Livio and Shaviv 1977), might contribute to turbulent viscosity.

However, one can argue against the assumption $\alpha \approx 1$ from observations of dwarf novae. It is established that some of these objects are systems in which there is an accretion disk around a white dwarf. The outer structure of an accretion disk should be insensitive to the nature of the compact object, so we can use these better observed objects to test disk models. One important test is based on the mass of the disk. According to the standard model most of the mass is located near the outer radius R_D, and the characteristic radial flow timescale $t_D \approx R_D/v_{radial}$ can be written (Novikov and Thorne 1973)

$$t_o \approx 0.3[R_o/10^{11}\,\mathrm{cm}]^{5/4}\,(M_x/M_\odot)^{-1/4}(\dot{M}_x/10^{-9}\,M_\odot\,\mathrm{yr}^{-1})^{-3/10}\alpha^{-4/5}\,\mathrm{yr} \quad . \qquad (9)$$

Therefore, the mass of the disk in the standard model can be estimated by $M_D \approx \dot{M}_x t_D$, where $\dot{M}_x \approx 10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$ is the accretion rate inferred from the X-ray luminosity and equation (1). From equation (9) and assuming $R_D \approx 10^{11}$ cm one finds $M_D \approx 10^{-9}\ \alpha^{-4/5}\ M_\odot$. Interpretation of observations of dwarf novae (Warner 1974; Smak 1972) suggests $M_D \approx 10^{-5}$ $M_\odot$, which implies $\alpha \approx 10^{-5}$. One is more inclined to doubt the assumption of constant α if its value is so far from the value unity suggested by a dimensional argument.

Shu (1976) has pointed out a number of other issues that merit further consideration. For example, it appears that in the case of Her X-1 the outer disk radius R_D is nearly as large as the Roche lobe radius. If so, the flow in the outer disk cannot be described accurately by an axisymmetric model -- one must consider motion in the presence of two force centers. A related issue is that of tidal friction in the disk. It may be the case that the transfer of angular momentum through the disk depends critically on the tidal distortion due to the companion star, and that the spin angular momentum of the disk is converted to orbital angular momentum just as tidal friction spins down the earth and causes the moon to recede.

Other issues related to disk structure and appearance are the nature of the flow through the inner Lagrangian point, the formation of the disk, and the "hot spot" where the stream first impacts the disk. These issues have been examined recently by Lubow and Shu (1975,1976) and by Lin and Pringle (1976).

The best observational evidence for a large disk around an X-ray source comes from studies of the photometric variations of HZ Her by

Boynton and his collaborators (Deeter et al. 1976; Gerend and Boynton 1976). In my view these studies demonstrate conclusively that the 35^d modulation of the X-ray brightness of Her X-1 is the result of eclipsing by a tilted accretion disk that precesses around Her X-1 counter to the orbital motion. The compelling evidence for this conclusion is the prominence, second only to the 1.7^d orbital period, of a $1.62^d = [(1.7^d)^{-1} + (35^d)^{-1}]^{-1}$ periodicity in the photometric variations. Petterson (1975) has made a significant advance by developing a disk model which combines the free precession of particle orbits in the disk due to tidal forces (Katz 1973) with forced precession of the entire disk which is slaved to an assumed 35^d precession of HZ Her (Roberts 1974). Petterson argues that the former mechanism causes the disk to be twisted, and that the latter mechanism provides the basic 35^d clock mechanism, and he has developed a very clever set of equations that enable one to calculate the shape of the disk. However, the detailed shape of the disk may not be as calculated by Petterson, because additional forces on the outer part of the twisted disk, such as radiation pressure due to X-rays from Her X-1, are likely to dominate the tidal and viscous forces included in his equations. Interesting questions remain regarding how one should interpret observations of Her X-1 in the light of the precessing disk model. For example, the observations of X-rays during the middle of the "off" part of the 35^d cycle (Fabian et al. 1973; Cook and Page 1975) may result from X-rays shining through the most twisted part of the disk (Gerend and Boynton 1976) or -- perhaps more likely -- from the X-ray source peeking beneath a tilted, precessing inner disk (Jones and Forman 1976).

4. ACCRETION FROM STELLAR WINDS

When the companion of the X-ray source is a late-type star, as with Sco X-1, Cyg X-2, and Her X-1, it is likely that the mass transfer is due to Roche lobe overflow which occurs as a result of stellar evolution (but cf. §5). However, when the companion is an early-type supergiant, as with Cyg X-1, 3U1700-37, Cen X-3, SMC X1, etc., another mode of mass transfer, first suggested by Davidson and Ostriker (1973) is possible. That mode is the gravitational capture by the compact object of the strong stellar wind that such stars normally have. The gas flow in the hypersonic stellar wind follows free particle orbits until these orbits converge downstream. A shock, or accretion wake, must develop, as illustrated in figure 2. For this case the relevant length scale is the Bondi-Hoyle radius R_w [eq. (6)], which is roughly the impact parameter at which a test particle moving past the compact object with velocity V_w will be deflected by 90°.

The capture cross section is roughly πR_w^2 and the resulting mass accretion rate is given by

$$\dot{M}_x \approx \pi R_w^2 \rho_w V_w \approx \frac{G^2 M_x^2}{R_o^2 V_w^4} \dot{M}_* \quad , \tag{10}$$

assuming that the stellar wind is spherically symmetric, so $\dot{M}_* = 4\pi r^2 \rho_w(r)V_w(r)$. The mass loss rates of OB supergiants are typically in the range $\dot{M}_* \approx 10^{-5}$ to 10^{-8} $M_\odot$ yr^{-1} (Hutchings 1976; Barlow and Cohen 1977) and the terminal velocities of the winds are in the range $V_T \approx 1000$ to 3000 km s^{-1} (Snow and Morton 1977).

Lamers et al. (1976) have pointed out that a straightforward application of equation (10) with $V_w \approx V_T$ yields a value of $\dot{M}_x$ sufficient to account for the luminosity of Cyg X-1, for which $M_x \approx 10$ $M_\odot$, but not sufficient to account for the luminosities of SMC X-1 and Cen X-3, for which $M_x \approx M_\odot$. Of the various resolutions they suggest for this problem, it seems that the most likely explanation is that the velocity of the stellar wind at R_O is considerably less than the terminal velocity inferred from UV resonance lines. (The wind velocities inferred from the width of optical lines are systematically less than those from the UV lines, because the optical lines are formed in the dense part of the wind that is still accelerating.)

Perhaps the most reliable technique for measuring the mass loss rates and velocity profiles of stellar winds is the observation of infrared and microwave continuum radiation from the stars. Using this method, Barlow and Cohen (1977) have shown that stellar winds accelerate much more gradually than the law $V_w(r) = V_T(1 - R_*/r)^{1/2}$ that was suggested by Castor et al. (1975) on the basis of their theory for radiation pressure driven stellar winds. For example, the results of Barlow and Cohen suggest that $V_w(2R_*) \approx 0.15\ V_T$, in contrast to the result $V_w(2R_*) \approx 0.71\ V_T$ from the above theoretical law.

The behavior of $V_w(r)$ within a few stellar radii of the OB star bears strongly on the interpretation of binary X-ray sources, because of the strong dependence of $\dot{M}_x$ on $V_w(r)$ in equation (10) and because the X-ray sources have very tight orbits (Tananbaum and Hutchings 1975). For example, consider the eccentric binary hypothesis for the transient X-ray sources in which the mass transfer due to the stellar wind is greatest near periastron. This model has gained support from the observations of outbursts from the transient source 3U1630-47, which repeat with a period of order 600^d (Jones et al. 1976). Avni et al. (1976) have derived high values for the minimum orbital eccentricity required to explain the luminosity variations of such systems by assuming a stellar wind of constant velocity. However, that assumption is too restrictive, and if a more realistic velocity law is assumed much lower values of orbital eccentricity would be required.

A potentially powerful method for learning more about accretion from stellar winds is to observe X-ray absorption by the accretion wake. The orbital phase and duration of the absorption are characterized by the angles α and β shown in figure 2 (as well as by the inclination angle of the orbit). The angle α is related to the relative orbital and wind velocities, $\tan \alpha = V_{orb}/V_w$ for a non-rotating star. The apex angle β of the shock cone depends on the details of the hydrodynamical flow. Features have been observed in the light curves of eclipsing binary X-ray sources that have been interpreted as due to absorption by accretion wakes -- for example by Jackson (1975) for the case of Cen X-3 and by Eadie et al. (1975) for the case of 3U0900-40.

The basic idea of these papers may be correct, but the detailed inferences are probably premature. For one thing, it is doubtful whether the data are adequate to distinguish between true absorption features and random fluctuations of the source luminosity and spectrum. For another, the hydrodynamical theory of the wake structure is underdeveloped. The crucial theoretical issue is the dependence of β on the equation of state of the gas. Numerical calculations of the wake structure have been done for flows with polytropic index $\gamma = 5/3$ (Hunt 1971) and $\gamma = 4/3$ (Eadie et al. 1975). In each case the wake has a large apex angle, $\beta \approx 30°$, that is independent of V_w, ρ_w, and L_x. These results are in accord with the estimate by Illarionov and Sunyaev (1975) of $\sin\beta \approx 2\rho_w/\rho_1 \approx 2(\gamma-1)/(\gamma+1)$, where ρ_1 is the post shock density.

However, the gas pressure is not likely to obey a polytropic law in the vicinity of the X-ray source (cf. §5). The timescales for radiative processes to determine the gas temperature may be short compared to flow timescales. For example, I estimate that at R_A, $t_c/t_f \approx (M/M_\odot)V_{1000}^{-1} L_{37}^{-1}$, where t_c is the timescale for Compton scattering to drive the gas temperature toward the X-ray temperature and t_f is the timescale for free fall to the X-ray source. (This result contradicts a remark by Illarionov and Sunyaev, who considered only bremsstrahlung cooling.) Therefore, the gas within a distance R_A of the X-ray source might obey an isothermal law, so that $\rho_w/\rho_1 \approx (C_s/V_w)^2$, where C_s is the isothermal sound speed in the shocked gas. Suppose for example that $V_w = 2000$ km s^{-1} and $C_s = 300$ km s^{-1}. Then the wake would have a narrow apex angle, $\beta \approx 3°$. It is likely that beyond R_A the shocked gas would have a yet lower temperature, $T \lesssim 3 \times 10^5$ K, as a result of atomic cooling processes, so that the wake might be narrower yet. Hydrodynamical calculations of wake structure using a realistic equation of state for the gas illuminated by the X-ray source would be very desirable.

As figure 2 indicates, the accretion disk may be very small when the mass transfer occurs by gravitational capture of a stellar wind. The outer disk radius R_D, given by equation (8) in table 1, is found by equating the mean specific angular momentum of the captured gas to that of a Kepler orbit at R_D. The more detailed calculation by Shapiro and Lightman (1976) results in a value of R_D four times greater than the earlier estimate by Illarionov and Sunyaev (1975). One sees that for typical values of V_w, M_x, and R_o, R_D is likely to be less than R_M and perhaps less than R_H. Therefore, it appears unlikely for a neutron star in a stellar wind to have any accretion disk, and marginal for a black hole. (Actually, the outer disk radius may be somewhat greater than R_D because internal viscosity may cause the disk to spread.)

One might even suppose that if $R_D \lesssim R_H$ the accretion flow would become nearly spherical with a very low resulting X-ray luminosity (Shapiro 1973). However, as Mészáros (1975) has emphasized, accretion flows onto a black hole are not likely to be so perfectly uniform, and just a little turbulence would be sufficient to cause a high X-ray luminosity in a spherical accretion model. Furthermore, there is no basis for believing that stellar winds are very uniform in time or space, particularly when influenced by a variable X-ray source; and Shapiro and Lightman (1976) have made the very reasonable conjecture that in a slightly non-uniform stellar wind the accretion disk may have reversals in direction with resulting changes in X-ray source spectrum.

5. X-RAYS AND GAS FLOWS

Up to this point we have barely touched on the relationship between the X-rays and the gas dynamics of the accretion flows. In fact, there is an intimate one. On the one hand, the X-rays can profoundly affect the gas flow, either by directly imparting momentum through radiation pressure or by heating the gas and creating thermal pressure gradients. On the other hand, propagation through the gas can greatly modify the emergent spectrum, and a relatively featureless source spectrum generated near R_n or R_H may emerge encumbered with all sorts of absorption and emission features that are potential diagnostics of the gas flows. In order to investigate such phenomena, it is necessary to consider the detailed atomic processes of emission and absorption of radiation by the gas as well as the radiative transfer and gas dynamics. Such work has barely begun, and detailed calculations exist only for highly idealized models such as spherically symmetric and plane-parallel geometries. Even so, these rudimentary studies have revealed a number of important physical effects that will probably apply in modified form to more realistic models.

The pioneering work on transfer of X-rays through gases was done by Tarter et al. (1969) and by Tarter and Salpeter (1969), who calculated models for the ionization and temperature of a gas cloud of atomic density n surrounding a point source of X-rays with luminosity L_x. They assumed a local balance between ionization and recombination and between heating and cooling due to absorption and emission of radiation, and showed that, for a given source spectrum in the optically thin approximation, the gas temperature and ionization distribution of each element are functions of a single variable $\xi \equiv L_x/nr^2$, where r is the distance from the X-ray source. These calculations have been developed further by Buff and McCray (1974a) and by Hatchett et al. (1976), who included several important atomic processes that were ignored in the earlier studies. Hatchett et al. also showed the emergent spectra for a variety of optically thick models and found a simple scaling law that allows one to characterize optically thick systems by a single additional parameter. (It is important to watch for breakdown of the local balance assumption used in these calculations when applying the results to particular models.) The most important qualitative results of these studies are: (a) the emergent spectrum is rich in optical, UV, and X-ray emission lines; (b) with changing ξ there can be abrupt changes in gas temperature that may lead to thermal instabilities in the flow;

(c) the radiation force on the gas can substantially exceed that due to electron scattering.

Effects (b) and (c) bear on the limiting luminosity of X-ray sources powered by accretion. For example, the well-known Eddington limit

$$L_E = 1.2 \times 10^{38} (M_x/M_\odot) \text{ erg s}^{-1} \tag{11}$$

is derived by equating the outward radiation force due to electron scattering of X-rays to the gravitational attraction of the atoms to the source. However, Tarter and McKee (1973), Buff and McCray (1974), and Hatchett et al. (1976) have shown that the net radiation force on the gas may exceed the electron scattering force by a factor β that may be as large as 10^3. This effect could in principle reduce the limiting luminosity to a value $L_E' = L_E/\beta$.

A different physical mechanism that has a similar effect results from the heating of accreting gas by the emergent X-rays. If the gas temperature is so great that the thermal atomic velocities exceed the escape velocity, the gas has no propensity to accrete. The critical scale length controlling this phenomenon is the "Bondi radius," which may be found by substituting the isothermal sound speed $C_s = (kT/\mu m_H)^{1/2}$ for V_w in equation (6). Ostriker et al. (1976) have developed this idea and have derived a new luminosity limit for steady spherical accretion onto a compact X-ray source that may be less than the Eddington limit by a factor $\sim 10^{-3}$ if the efficiency factor $\epsilon \gtrsim 10^{-3}$. Both the radiation pressure effect and the heating effect are sensitive to the X-ray source spectrum, and are most important when a significant component of soft ($\lesssim 2$ keV) X-rays is present.

As emphasized by Lightman et al. (1977), there are several caveats to the Eddington limit, the most obvious of which is the assumption of spherical symmetry. In principle it would be easy to violate the Eddington limit by having the gas accrete along one path and the X-rays emerge in other directions. This effect is likely to cause a self-focusing of accretion flows far from the X-ray source, because dense opaque streams that shield themselves from radiation pressure and heating by X-rays become natural self-sustaining funnels. However, it is more difficult to violate the Eddington limit near the compact object where the X-rays are generated because the X-ray emission mechanisms tend to be isotropic. In the case of accretion onto a neutron star, the strong channeling of the accretion flow by magnetic forces may allow violation by a factor ~10, as is indicated by observations of SMC X-1; and Basko and Sunyaev (1976) have given examples of such accretion flows. But nobody has succeeded in constructing a model for accretion onto a black hole in which the X-ray luminosity exceeds the Eddington limit.

The fact that many of the observed X-ray sources have luminosities within a factor of 10, more or less, of L_E for a compact object with $M_X \approx M_\odot$ (Margon and Ostriker 1973), and the above considerations, suggest that these sources may have their luminosity regulated by radiation pressure or heating. A more quantitative statement will require a better knowledge of the detailed geometry of accretion flows than we now have.

One can also define a "critical accretion rate" $\dot{M}_C$ related to the Eddington limit by $\dot{M}_C \equiv L_E/\varepsilon c^2$. One must be careful not to confuse the two concepts. For example, in the case of disk accretion onto a black hole it is possible for the inward spiraling gas flow to drag the emitted radiation along into the hole before it is able to escape (Maraschi et al. 1976; Maraschi and Treves 1977). In this case the radiative efficiency factor ε decreases with increasing $\dot{M}_X$ in such a way that L_X asymptotically approaches L_E but $\dot{M}_X$ may substantially exceed $\dot{M}_C$ estimated with $\varepsilon \approx 0.1$.

Another way in which thermal instability of a gas illuminated by an X-ray source manifests itself is by causing an evaporative wind to be driven from the atmosphere of the companion star. Davidson and Ostriker (1973) suggested that this effect may result in a "self-excited wind" with a positive feedback in the sense that the $\dot{M}_X$ of the captured evaporative wind results in sufficient L_X to drive the wind. This idea has had a see-saw history. Arons (1973), Basko and Sunyaev (1973), and Alme and Wilson (1974) all concluded that the mechanism would work in the Her X-1 system, although they differed substantially in their quantitative estimates. McCray and Hatchett (1975) calculated a much lower evaporation rate than Basko and Sunyaev; they argued that only a small fraction of the evaporated wind would be captured by the compact object and concluded that the mechanism did not work. Now Basko et al. (1977) have reconsidered the problem. Their best estimate of the evaporative mass flux, $\dot{M}_X \approx 10^{-9}\ M_\odot\ yr^{-1}$, is slightly greater than that calculated by McCray and Hatchett, and they believe that the captured fraction of the evaporative wind may approach unity. The net result is inconclusive: the self-excited wind appears to be a marginal possibility for Her X-1 and also for other binary X-ray systems with late-type stellar companions, such as Sco X-1 and Cyg X-2. More detailed calculations or, better yet, observations with more sensitive spacecraft are required to settle the issue.

Regardless of whether the positive feedback is sufficient to drive a self-excited wind, there is no doubt that X-ray heating must drive a significant evaporative mass flux from the atmosphere of a late-type companion star, that may affect the rate of mass transfer and may be observable through optical, UV, or X-ray emission lines. Also, the rocket effect due to X-ray induced evaporation from the surface of gas streams or the accretion disk may be dynamically important.

Although there is much to be learned by further theoretical modeling of the gas dynamics of accretion flows, I believe that the approach that offers the most promise is to observe these flows directly via high resolution UV and X-ray spectroscopy. By observing UV absorption lines and soft X-ray absorption edges we may measure column densities of highly ionized trace elements near an X-ray source, and with X-ray emission lines we may observe emission measures and velocities of the accretion flow structures. It already appears that we have seen the variable soft X-ray absorption in the spectrum of Cyg X-1 (Sanford et al. 1974; Holt et al. 1976) predicted by Buff and McCray (1974b). Hatchett and McCray (1977) have developed methods for calculating the radiative transfer of X-rays through stellar winds in binary systems that may be used to interpret observations of Cen X-3 (Schreier et al. 1976) and other such systems. The advent of high resolution of X-ray spectroscopy (cf. McCray 1977) that is imminent with the launching of HEAO-B and other advanced spacecraft holds the promise of a new level of understanding of the binary X-ray systems.

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DISCUSSION

P. Mészâros - I think it is far too pessimistic to assume that in the absence of a disk there should be no radiation. This is because random magnetic fields should be present in spherical flows as well as in disks, and the magnitude of the shear is similar, therefore magnetic fields build up to equipartition, and in the process of reconnecting produce heating. Using the same kind of physical assumptions and processes as in disk models, one can make spherical accretion models of Cyg X-1 or other X-ray sources, accreting from a stellar wind, which reproduce X-ray observations satisfactorily (e.g. Nature, 258, 583-584, 1975).