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X-RAY SOURCES IN CLOSE BINARY SYSTEMS

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1. Introduction

The discovery by Giacconi and his colleagues of variable X-ray sources in close binary systems certainly ranks as one of the highlights of astronomical research during the last 3 years. These remarkable objects have already been extensively studied, by optical and radio observations as well as in the X-ray band; and they seem likely to prove as significant and far-reaching in their implications as pulsars.

The 'Third Uhuru Catalogue' (Giacconi *et al.*, 1973a) contains about 160 sources, of which about 100 lie in our Galaxy. Their distribution over the sky (together with other arguments) suggests that these sources have luminosities of the general order 10^{36}–10^{38} erg s^{-1}, and that their typical distances are ~ 10 kpc. These galactic sources generally display rapid variability. Little else is known about most of them, but they are probably of the same general class as systems such as Her X1, Cen X3, Cyg X1 and Cyg X3. These sources have been investigated in detail, and in all cases one infers a system where the X-ray source is orbiting around a relatively ordinary star. Six sources have been optically identified, and there are some others whose binary nature is established by the occurrence of an X-ray eclipse. Orbital periods range from 4.8 h (Cyg X3) up to ~ 10 days.

In this talk I shall review some of the theoretical implications of these systems, summarising the relevant observations where necessary. A fuller account of the data may be found in Giacconi (1973a, b), and in the many recent papers – mainly published in *Astrophys. J.* – referred to in these articles.

The idea of X-ray sources being associated with close binary systems dates back to the earliest days of X-ray astronomy. It was Hayakawa and Matsouko (1964) and Zel'dovich and Guseynov (1965) who first made the suggestion that binary stars might be X-ray sources. After Sco X1, the brightest object in the X-ray sky, had been identified with an object reminiscent of an old nova, many astrophysicists proposed that X-ray sources involved transfer of matter from one star onto a compact companion (see Burbidge, (1972) for an account of these developments). It is still unclear whether this is actually happening in Sco X1, and many other interpretations of this object have been proposed; but there now seems little doubt that it *is* the case for a major class of X-ray sources in the Galaxy.

2. General Theoretical Remarks

What, then, can be said concerning the general nature of these system? The first general point is that the rapid variability suggests, though of course it does not prove,

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that a very small object – probably even smaller than a white dwarf – is involved. The gravitational potential well associated with such an object is very deep indeed, and accretion therefore provides an efficient energy source. If, as seems to be the case in the observed X-ray binaries, the compact object is in a close orbit – almost a grazing orbit – around another star, then a copious supply of material is available from the companion. If the compact object is a neutron star or black hole, then $\sim 10\%$ of the rest mass energy of the accreted material (10^{20} erg gm^{-1}, or ~ 100 MeV per nucleon) can be liberated in the form of radiation (~ 10 times as much as can be obtained from nucleur fusion – in contrast to the 'classical' case of accretion onto ordinary stars, where the gravitational energy is generally insignificant (Bondi, 1952; Mestel, 1954)): for accretion onto a white dwarf the efficiency is 10^{-2}–$10^{-1}\%$ (0.1–1 MeV per nucleon). This means that, for accretion onto a neutron star or collapsed object, the accretion rates need only be in the range 10^{16}–10^{18} gm s^{-1} (10^{10}–10^{-8} $M_{\odot}/\mathrm{yr}^{-1}$) in order to produce the observed luminosities. These are modest compared to the inferred transfer rates in other binary systems, and could be supplied by a stellar wind even if the companion star did not overflow its Roche surface.

A second general point is that most of the gravitational energy is liberated deep in the potential well – at or near the surface of the compact object if it is a neutron star; within a few Schwarzschild radii if it is a black hole. Thus the effective dimensions of the source (assuming that the compact object is in the stellar mass range) are only $\sim 10^{6}$ cm. If 10^{36}–10^{38} erg s^{-1} are radiated thermally from such a small region, a temperature high enough that the energy emerges predominantly in the X-ray band is therefore guaranteed.

The most popular interpretation is one in which the X-ray source is regarded as being associated with either a neutron star or a black hole (Pringle and Rees, 1972). The evidence favouring this model now seems fairly compelling, but the case is certainly not completely watertight; and some quite different interpretations for various aspects of these phenomena still remain tenable. These include models involving pulsating or rapidly rotating white dwarfs (Mock, 1968; Brecher and Morrison, 1972), analogies with pulsars, or particle acceleration at reversing layers of strong magnetic fields in a binary star system which does not contain a compact component at all (for example, Bahcall *et al.*, 1973). My reason for concentrating on this particular model is that it seems more plausible than any specific alternative so far proposed. Also this model has formed the basis for most of the detailed theoretical work carried out so far. Already so much work has been done that it will only be possible for me to sketch most of it; and some interesting aspects of the phenomena will be left out entirely.

The X-ray binaries obviously involve all the problems connected with ordinary close binary systems (see, for example, Paczyński, 1971) – problems which are still ill-understood despite having been with us for many years – together with a whole range of new ones connected with the compact X-ray source itself. I shall first outline the main features of the model, and then comment on some specific consequences as they relate to individual sources. For convenience of exposition, it is appropriate to split the subject into three parts: the mass transfer (relevant length scales $\sim 10^{11}$ cm); the accretion disc (dimensions $\lesssim 10^{10}$ cm); and the compact object itself, which is also the region where the X-rays are presumed to originate (10^6–10^8 cm). Unfortunately these three areas cannot be regarded as entirely disjoint, despite the very different length scales involved. For example, the X-ray intensity and spectrum is probably determined by processes occurring close to the compact object, but it may nevertheless have an important influence on the flow of matter from the companion because of heating and radiation pressure effects. (It has even been proposed that X-ray heating of the companion star's atmosphere may excite a stellar wind which maintains the accretion flow which generates the X-rays which....)

2.1. The mass transfer ($\sim \lambda 10^{11}$ cm)

Much theoretical work has been based on the hypothesis that the companion star fills its Roche lobe, and that material flows across the Lagrangian point. It is important, however, to remember that these analyses are only strictly valid if the star corotates with the orbital period. This is probably quite a good assumption in these close systems, unless they were perturbed so recently that tidal effects have not yet re-established synchronous rotation. Some calculations – for example, estimated limits on the masses of the X-ray sources – depend rather heavily on this postulate. It is also possible that the star does *not* fill its Roche lobe, but has a strong stellar wind. Gas streams may cause the optical emission lines observed in these systems (and also, incidentally, confuse attempts at radial velocity determinations).

2.2. The accretion disc ($\gtrsim 10^{10}$ cm)

By whatever process material is captured from the companion star, it is likely to have so much angular momentum that it cannot fall directly onto the compact object. The matter will instead dissipate its motions perpendicular to the plane of symmetry and form a differentially rotating disc, the rotational velocity at each point being approximately Keplerian, and then gradually spiral inwards as viscosity transports its angular momentum outwards. If the companion star is overflowing its Roche lobe, it is conventionally assumed that the matter joins the disc at the radius where its angular momentum relative to the compact object equals that of a Keplerian orbit. This argument suggests that the so-called 'hot spot' appears at a radius which is $\sim 20\%$ that of the Roche lobe around the compact star. The structure of the outer part of the disc is not well understood. The disc must extend further out than the hot spot, because *some* of the material transferred from the companion star has to carry away the angular momentum – it cannot all be accreted by the compact object. A further complication is that the gravitational field of the companion star probably cannot be ignored in the outermost part of the disc, so the gas will not circulate in simple Keplerian orbits.

If the accreted matter is captured from a strong stellar wind, it will tend to have less net angular momentum; but the disc would still extend out to a radius $\sim 10^9$ cm in general.

The structure of accretion discs has been discussed by many authors – for example Prendergast and Burbidge (1968), who considered a disc surrounding a white dwarf; Lynden-Bell (1969), Pringle and Rees (1972), Shakura and Sunyaev (1973), and Novikov and Thorne (1973).

An obvious prerequisite for the existence of a disc (whose thickness must, by definition, be only a small fraction of its radius) is that radiative cooling should be efficient enough to remove most of the energy liberated by viscous friction, so that the internal energy is small compared with the gravitational binding energy – i.e.

$$kT\left(1+\frac{p_r}{p_g}\right) \ll \frac{GMm_p}{r}, \tag{1}$$

where p_r/p_g is the ratio of radiation pressure to gas pressure, and m_p is the proton mass. For accretion flows with the parameters appropriate to X-ray sources the densities are high enough, and the timescales long enough, to ensure that (1) is almost certainly fulfilled. Also, the mass in the disc is gravitationally negligible compared to that of the central object.

If a steady state has been set up, the structure of the disc is governed by the following system of equations. First, the same mass flux M must flow across any radius r, so that

$$\dot{M} = 2\pi r \int \varrho(r, z)\, v_r(z)\, \mathrm{d}z \tag{2}$$

for all r, when z is the coordinate perpendicular to the disc measured from the plane of symmetry.

A second, and somewhat less trivial, requirement is that in a steady state the *flux of angular momentum* should be the same at all r. Angular momentum is transported inward by the accreted matter, but transported outward by the viscous stresses. The difference between these quantities represents the rate at which the central compact object is gaining angular momentum. Following Novikov and Thorne (1973) we assume that angular momentum is being accreted at a rate $\beta\dot{M}\,(GMr_1)^{1/2}$, where r_1 is the radius of the inner boundary of the disc. Since the specific angular momentum deposited on the compact object cannot exceed the Keplerian value at r_1, we have $\beta \leqslant 1$. One then finds that the heat dissipated per unit surface area of the disc at a radius $r > r_1$ is

$$p(r) = \frac{3\dot{M}}{4\pi r^2}\frac{GM}{r}\left(1-\beta\left(\frac{r_1}{r}\right)^{1/2}\right). \tag{3}$$

It is important to note that β is a second parameter which is not completely determined by $\dot{M}$ – one cani magine situations with the same $\dot{M}$ but different torques in the disc, and therefore different values of $p(r)$. When $r \gg r_1$, however, one finds, independently of β, that the energy radiated at radii $\geqslant r$ is *3 times larger* than the energy lost by the accreted material while spiralling inward to that radius. The extra contribution arises because the viscous stresses transport *energy* outward as well as momentum, so that the energy liberated by gravitation is actually radiated at a somewhat larger radius.

One might at first sight worry about the energy budget for the disc as a whole. However, when $\beta = 1$ one finds that the total energy radiated, integrating over all $r \geqslant r_1$, is precisely equal to $\dot{M}$ multiplied by the binding energy of Keplerian orbit of radius r_1; when $\beta = 0$, the factor of 3 enhancement applies right in to $r = r_1$, but in this case the extra energy comes from viscous torques which apply a drag to the compact object – i.e. twice as much energy in this case is supplied by the central spinning object as comes from the infalling material itself. (The discussion leading to Equation (3) is strictly Newtonian. When one considers an accretion disc surrounding a black hole, then one finds that the total energy radiated by the disc *equals* the energy lost by infalling matter when the black hole accretes a specific angular momentum appropriate to the circular orbits at the inner edge of the disc (see Novikov and Thorne (1973) for the details of the relativistic case). The appropriate inner boundary condition in this case is that the *viscous stresses* should be zero at $r = r_1$.)

These deductions do not depend on the magnitude of the viscosity – if this is low, then the radial velocity v_r is small, so the equilibrium value of ϱ needed in order to give a given $\dot{M}$ must be high; and conversely. But to analyse the structure of the disc in any further detail one *must* know something about the viscosity, and this is the stumbling-block to further progress. Possible causes of viscosity include turbulence induced by the differential rotation, convective motions, or sheared magnetic fields. Pringle and Rees (1972) and Shakura and Sunyaev (1973) made specific simplifying assumptions about the viscosity, which enabled them to discuss the vertical structure of the disc (i.e. the balance between the pressure gradient perpendicular to the disc and the component of gravity in that direction), and the spectrum of the emergent radiation. However one has little confidence that one knows even the appropriate order of magnitude for the viscosity, and it therefore seems premature to discuss the spectrum of the disc in great detail. The dominant emission mechanism is probably thermal bremsstrahlung, though the spectrum may be appreciably distorted as a result of scatterings by the hot thermal electrons (Felten and Rees, 1972). All that can be said is that the effective temperature must be at least as high as the black body temperature needed to radiate a power $p(r)$. Any line emission would be broadened and distorted by electron scattering, and by the Doppler effect associated with the Keplerian rotation.

2.3. THE COMPACT OBJECT AND THE X-RAY EMISSION (10^6–10^8 cm)

When the compact object is a black hole, the emission is concentrated within a few Schwarzschild radii. It is normally assumed that the amount of energy radiated per unit mass accreted equals the binding energy of the innermost stable circular orbit. This implies an efficiency of $\sim 6\%$ if the black hole is described by a Schwarzschild metric, and up to 42% for accretion discs around Kerr black holes, the precise upper limit depending on how much of the emitted radiation is captured by the hole. Once material is closer than the innermost stable orbit, it can be swallowed by the hole without any further loss of angular momentum. However if the viscosity is high enough there would still be emission from this part of the disc, resulting perhaps in even higher efficiencies than those just quoted. (Note that the efficiency would be very much lower if the accreted matter had so little angular momentum that it could fall almost radially inward. This situation, which is relevant to isolated black holes accreting interstellar matter, has been discussed by Schwartzman (1971) and Shapiro (1973a, b). In general, only a small fraction of the mass-energy is radiated away before the infalling matter is swallowed by the hole.)

Attempts to determine the expected radiation spectrum from accretion discs are impeded by our ignorance about the viscosity, which introduces far larger uncertainties than those corresponding to the difference between a Schwarzschild and 'extreme Kerr' black hole. In general, the temperature decreased outwards and, even though the emission is thermal, the integrated spectrum may resemble a power law. Radiation from the outer parts of the disc would not be energetically significant unless, as discussed by Shakura and Sunyaev (1973) the disc were so thick in relation to its radius that X-rays from the inner regions were intercepted by the disc and re-radiated at softer energies. Some further aspects of this model, as it may apply specifically to Cyg X1, are discussed later.

When the central object is a spinning, magnetised neutron star, a far more complex situation ensures, which has been discussed extensively by Pringle and Rees (1972), Davidson and Ostriker (1973), and Lamb *et al.* (1973). If the neutron star were unmagnetised, then the disc would extend inwards until the accreted material grazed the star's surface. If, however, the neutron star has a surface magnetic field of the same strength as is inferred for pulsars ($\sim 10^{12}$ G) then the magnetic stresses will influence the dynamics out far beyond the surface of the star. We define the 'Alfvén radius' to be that distance at which the magnetic stresses are comparable with the viscous stresses in the disc – i.e.

$$\frac{(H(r_A))^2}{4\pi} \simeq \varrho(r_A)\, v_r(r_A)\, v_\theta(r_A).$$

The Alfvén radius depends on $\dot{M}$, but somewhat insensitively because H^2 depends on r at least as steeply as r^{-6}, and for typical parameters is 10–100 times larger than $r*$. r_A, defined as above, is fortunately independent of the viscosity except insofar as this affects the scale height. The disc would not be expected to extend inward to radii much less than r_A, which means that the radiation from the disc itself is relatively unimportant. Once matter penetrates within r_A the high field strengths and conductivity ensure that it is constrained to follow the field lines. If the star has an oblique dipole field, the infalling plasma will impact on the surface in the vicinity of the magnetic polar caps. The situation at $r \simeq r_A$ is analogous to that at the Earth's magnetopause, and is so complicated that one cannot really estimate which of the magnetic field lines can capture matter. These field lines will probably, however, be only a subset of those which would have reached out to radii $\gtrsim r_A$ in the absence of infalling plasma. This guarantees that, when $r_A \gg r*$, the material will be channelled onto only a small fraction of the stellar surface.

The dominant radiation mechanisms would be bremsstrahlung or cyclotron radi-

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ation (including emission at the first few harmonics of the basic cyclotron frequency). Lamb *et al.* (1973), Gnedin and Sunyaev (1973), and Davidson (1973) have discussed the likely beam shape of the emergent radiation. If the dominant opacity were ordinary Thomson scattering, the radiation would tend to leak out of the sides of the accretion column, yielding a fan beam. If the magnetic field is so strong that the cyclotron frequency exceeds the radiation frequency under consideration, then electron scattering is inhibited for radiation propagating along the field direction, and also for radiation travelling across the field which is polarised such that the electric wave vector is at right angles to the magnetic field. Realistic models can yield either pencil beams or fan beams, depending on the strength of the magnetic field and the polarization of the radiation. Modulation of this beam pattern (which is unlikely to possess any especially sharp features) each time the neutron star spins generates the X-ray pulse shape. The spectrum would be broadly thermal; but not exactly a black body, for several reasons – e.g. the temperature may not be the same over all parts of the polar cap where accretion occurs, electron scattering may distort the spectrum, and the surrounding disc may cause absorption below a few keV. The radiation would generally be expected to display a high degree of both linear and circular polarization, especially for the softer X-rays. Detection of such polarization from variable X-ray sources would lend strong support to the accreting neutron star hypothesis.

Some other aspects of this scheme are discussed later in connection with Her X1.

An important role in these models is played by the so-called 'critical luminosity' or 'Eddington limit' at which radiation pressure balances gravity. If Thomson scattering provides the main opacity, and the relevant material is fully ionized, then this luminosity is

$$L_{\text{edd}} = \frac{4\pi G M m_p}{c\sigma_{\text{T}}} \simeq 10^{38}\left(\frac{M}{M_\odot}\right) \text{erg } s^{-1}, \tag{4}$$

σ_{T} being the Thomson cross-section.

One might therefore expect that the accretion rate $\dot{M}$ could approach, but in no circumstances exceed, the value needed to yield this luminosity. Recently, Margon and Ostriker (1973) have in fact analysed the data on X-ray sources, and find that there does indeed seem to be a luminosity cut-off at around the expected value of L_{edd} for $M \simeq M_\odot$, and that there is a class of sources whose luminosities cluster close to this value. But the 'Eddington limit', as given by (4), is relevant only under relatively restrictive circumstances – circumstances which are *not* generally met by the kinds of X-ray source models usually considered.

The luminosity of a source powered by accretion cannot even approach L_{edd} if the effective cross section per electron is larger than σ_{T} (see Buff and McCray, 1974). This is quite likely to be the case for a source emitting soft X-rays, because the relevant opacity (unless all the ions are completely stripped) is then primarily due to photoionization, for which $\sigma \gg \sigma_{\text{T}}$. If the value of $\dot{M}$ in binary X-ray sources is controlled by processes occurring near the surface of the companion star or the critical Roche surface, as in the 'self-excited wind' hypothesis (Basko and Sunyaev, 1973; Arons,

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1973) then one might expect the luminosity to stabilise at a value well below L_{edd}. There are, however, several types of situation where luminosities $\gg L_{edd}$ are possible, especially under the extreme conditions prevailing near compact objects. Among these are the following:

(i) The effective opacity may be much *less* than that provided by Thomson scattering. In the context of X-ray source this may, for instance, happen in the accretion column above the magnetic polar caps of neutron stars, where the scattering cross section is $\ll \sigma_T$ for photons below the cyclotron frequency travelling along the magnetic field direction.

(ii) Even if the appropriate cross-section *is* σ_T, the Eddington limit can still be violated in a non-spherically-symmetric configuration. Consider again, for example, the accretion column near a magnetised neutron star. If the magnetic field does *not* modify the opacity and make the scattering highly anisotropic, then radiation will tend to escape from the *sides* of the column. This means that the radiation flux along the column, and therefore the pressure opposing gravity, is then less than it would be in an isotropic situation. (An analogous argument may also apply to accretion discs.)

(iii) As has been pointed out by Lamb *et al.* (1973) there are conceivable circumstances when the luminosity may exceed L_{edd} even when the appropriate cross section is σ_T *and* the acretion is isotropic. This is because $L > L_{edd}$ is merely the condition that infalling matter should be *decelerated.* But unless the total optical depth is sufficiently large, this does not guarantee that radiation pressure can *halt* the accretion. The infalling matter carries momentum across a sphere of radius r at a rate $\dot{M}v(r)$, where $v(r)$ is of the order of the free fall speed. If its kinetic energy is converted into radiation at a radius $\sim r_{min}$ the outward momentum flux, ignoring relativistic corrections, is $\sim (\dot{M}|2c)\,(v(r_{min}))^2$ (and less, of course, if the conversion efficiency is low). This means that the average photon must undergo more than $2c/v(r_{min})$ scatterings if radiation pressure is to stem the accretion flow (unless the main contribution to the opacity comes from radii $r \gg r_{min}$).

(iv) The Eddington limit is of course irrelevant in an *unsteady* or *explosive* situation: it is, for instance, violated by factors $\sim 10^5$ in supernovae.

It is nevertheless interesting that there are no known objects whose X-ray luminosity greatly exceeds L_{edd} (assuming that the sources have masses of stellar order). If the accretion is $\gtrsim 10\%$ efficient, this implies that the inflow rate is $\lesssim 10^{-7}\, M_\odot\, \mathrm{yr}^{-1}$. In Cen X3, the *orbital* period is observed to change on a much shorter timescale than 10^7 yr, probably implying rapid mass loss from the companion star. Most of this mass must presumably escape from the system.

3. X-Ray Properties of Her X1 and Cen X3

X-ray observations of Her X1 reveal that it is occulted by a companion for 0.24 days out of every 1.7 days. The X-rays seem to be completely extinguished during the eclipses (at least in the 2–6 keV energy band recorded by Uhuru), and the transition between the eclipse and the high intensity state occupies less than 12 min. The X-rays also display a 1.24 s periodicity. The 'Doppler effect' over the 1.7 day period allows the size of the orbit to be inferred – its diameter is 13.2 cosec i light seconds – and also establishes that this orbit is nearly circular, having an eccentricity $\lesssim 0.05$. This information also determines the mass function to be

$$\frac{M_{\mathrm{opt}}^3 \sin^3 i}{(M_x + M_{\mathrm{opt}})^2} = 0.85\, M_\odot\,, \tag{5}$$

where M_x is the mass of the X-ray source and M_{opt} the mass of the companion star. The companion star of Her X1 has been optically identified, and its light variations are of great interest. Further information is of course required before M_x itself can be deduced, and I shall return to this question later.

Cen X3 has a regular 4.8 s period, and eclipses for ~ 0.49 days out of every 2.087. Its mass function is

$$\frac{M_{\mathrm{opt}}^3 \sin^3 i}{(M_x + M_{\mathrm{opt}})^2} = 15.4\, M_\odot\,. \tag{6}$$

There is, at the time of writing, no firm optical identification for this source.

Her X1 and Cen X3 are clear candidates for systems when the X-ray source may be a neutron star (and it is gratifying that the mass of Her X1 seems to be within the allowable range 0.3–1.6 $M_\odot$ for neutron stars, and that Cen X3 may also have a low mass). The period of Cen X3 is in fact not uncomfortably short for a white dwarf: however, the similarity to Her X1 suggests that the same model is probably applicable in each case. There are several specific observations which can be tentatively explained on the basis of this model. These systems would then resemble pulsars in that a spinning neutron star provides the 'clock'. However the X-ray power radiated cannot derive from rotational kinetic energy – otherwise the rotation would grind to a halt in $\lesssim 10$ yr – but must come instead from accretion. This, as Schwartzman (1971) has pointed out, suggests at least part of the reason why pulsars are not found in binary systems. An isolated spinning neutron star, surrounded only by diffuse interstellar gas, generates the electromagnetically driven relativistic wind which is believed to be a precondition for the coherent pulsed radio emission. When such an object is embedded in a denser environment, the pressure of the relativistic outflow cannot hold the external matter at bay, and we instead get accretion, manifesting itself in the emission of thermal X-rays. One can estimate that Her X1 would have displayed pulsar-like behaviour only if its period were $\lesssim 0.1$ s. (If a rotating white dwarf, whose moment of inertia might be $\gtrsim 10^4$ times larger than that of a typical neutron star, could have a period as short as 1.24 s, its kinetic energy *would* be able to power Her X1 without there being a larger secular change in spin period than is observed.)

3.1. Changes in the pulse period

Since an accreting neutron star is not drawing on its rotational energy as its main power supply, it is not obvious whether its spin rate should slow down or speed up.

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An element of gas accreted by the star carries angular momentum corresponding to corotation at the Alfvén radius. This suggests that the spin rate would speed up on a timescale

$$\left|\frac{P}{\dot{P}}\right| \simeq \frac{M}{\dot{M}}\left(\frac{r_*}{r_A}\right)^2. \tag{7}$$

It has in fact been found that the period of Cen X3 *decreased* by ~ 3 m s during the time January 1971–September 1972, corresponding to a timescale $P/\dot{P}$ of only a few thousand years. Even though $M/\dot{M} \simeq 10^8$ yr, this 'lever-arm' effect certainly allows a speed-up as rapid as that observed in Cen X3. There is, however, a possible opposing effect tending to *brake* the rotation: this is the viscous torque exerted by the accretion disc outside r_A. These two effects can be of the same order of magnitude if

$$\left(\frac{GM}{r_A}\right)^{1/2} \simeq \Omega r_A \tag{8}$$

(and of course if $(2GM/r_A)^{1/2} < \Omega r_A$ it would be energetically possible for material at the inner edge of the disc to be flung out of the system by magnetic forces, leading to a further braking effect). Davidson and Ostriker (1973) suggest that Ω tends asymptotically to a value such that the *net* torque on the neutron star is zero. This value of Ω depends on r_A, which is itself a function of $\dot{M}$. Therefore, if there were fluctuations in the accretion rate, then Ω would tend to increase (decrease) as $\dot{M}$ increases (decreases). In the case of Her X1, the period has, on different occasions, been observed both to decrease *and* to increase. The net effect observed over a 15 month interval was a speed-up of ~ 50 μs. If Her X1 were close to this equilibrium state, and the fluctuations in $\dot{M}$ were small in amplitude, one could perhaps understand why Ω has been observed both to increase and to decrease, and why these changes are slower than in Cen X3.

The effects mentioned above are the dominant ones for causing changes in period. Other effects – for example, the spin-up due to (gradual or sporadic) contraction of the star as it accretes mass – occur on the much slower timescale of $M/\dot{M}$.

3.2. The long-term variability of Her X1

One of the most puzzling properties of Her X1 is that the X-rays are completely extinguished for ~ 24 days out of every 35 (Giacconi *et al.*, 1973b). The source turns on rather abruptly; its mean intensity (when out of eclipse) rises for ~ 4 days; and then the source gradually fades for ~ 7 days. This whole cycle then repeats itself ~ 35 days later. The sharp 'turn-ons' are not strictly periodic. However the data can all be fitted by a model involving an underlying clock with period 34.85 days, plus the additional requirement that the 'turn-ons' always occur around phases 0.2 or 0.7 of the 1.7 day orbital period (which is incommensurable with a 34.85 day cycle). In addition to the eclipses, there is claimed to be a 'dip' which, after the 'turn on' occurs just before the main eclipse, but 'marches' steadily towards earlier orbital phases during the ~ 11 day 'on' period.

There have been many conjectures to explain this peculiar behaviour. In this connection, it is important to bear in mind that optical observations (which will be discussed further in Section 5) impose an important constrain on such suggestions. It appears that the 1.7 day period light variation persist throughouts the 35 day circle with more or less the same amplitude (even though a 35 day periodicity may be discernable in some of the fine details of the light curve (Kurochkin, 1973; Boynton *et al.*, 1973)). Since the thermal inertia of the relevant layers of the companion star is small, this implies that some heating mechanism operates throughout the $\sim$24 days out of $\sim$35 when Uhuru detects no X-rays from Her X1.

3.2.1. *Modulations in Mass Transfer Rate*

One class theory for the 35 day cycle involves supposing that the *mass transfer* is modulated with this period. It seems unlikely that this could be due to some pulsation of the companion star because the expected pulsation periods would be $\ll$35 days. Another possibility (Pringle, 1973a; Henriksen *et al.*, 1973) is that the spin period of the companion differs by $\sim$5% from the orbital period. If the star displayed some departures from axisymmetry – a 'magnetic spot' associated with an especially vigorous wind for instance – then the transfer rate could vary with a synodic period of 35 days.

Conceivably some kind of feedback process may be operating. McCray (1973) has developed an ingenious model which utilises the fact that the X-ray luminosity is a significant fraction (perhaps $\sim$10%) of L_{edd}. When the X-rays are 'on', the X-ray source behaves with respect to the surrounding gas as though it had a somewhat lower mass. The 'effective' Roche lobe around the companion star might then expand so that material no longer overflowed it. Mass transfer would then cease, and no material would be added to the disc. The disc would then drain away, and the X-ray emission would stop. Mass transfer would then begin again, the disc would be replenished, and so on. McCray speculates that some kind of limit cycle is set up. The time-scale of this cycle would be determined by the length of time for a typical element of gas to spiral inward to the central object. A period of the general order of 35 days would certainly not be unreasonable, but one cannot claim to 'predict' it, because of the wide uncertainty about the efficiency of viscosity in the disc.

A fully developed theory along these lines must also take account of a competing process which might cause *positive* feedback. This arises because the X-rays, by heating the surface layers of the companion star, tend to *raise* the mass transfer rate by increasing the scale height in the atmosphere and/or by stimulating an enhanced stellar wind (Arons, 1973; Basko and Sunyaev, 1973; Alme, 1973). It has in fact been proposed (Lin, 1973) that the 35 day cycle could result from this type of positive feedback if the X-rays stimulate a mass transfer rate which 'overshoots' to such an extent that opacity effects around the compact object quench the X-rays.

At the moment we do not even know whether positive or negative feedback is the more important. A proper theory of the 35 day cycle must also await a fuller understanding of how the X-rays interact with the companion star, and of the factors that determine the residence time of material in the accretion disc.

3.2.2. *Processes Occurring in the Accretion Disc*

Katz (1973) has suggested that the rim of the accretion disc may not lie in the orbital plane of the system. This might happen if the companion star possessed a component of spin angular momentum which was not aligned with the orbital angular momentum. In this situation, the rim of the disc would precess, and could obscure the X-rays for some fraction of each precession period. To obtain a precession period of 35 days, Katz has to assume that the disc extends outwards to a larger radius than is customarily supposed.

It is also conceivable that the disc might be subject to convective or other instabilities which could cause it to dump material periodically onto the central object. The properties of unsteady accretion discs – in which $\dot{M}$ depends both on r and on t, and (3) no longer holds – have not yet received detailed attention.

3.2.3. *Modulation of Inflow from Alfvén Radius*

Pines *et al.* (1973) have developed a model according to which the neutron star undergoes free precession in such a way that the angle between the magnetic axis and the plane of the accretion disc varies periodically. When this angle is small, accretion along the 'magnetic funnel' can proceed; but when the magnetic axis points too far out of the plane of the disc accretion is suppressed, and material transferred from the companion accumulates in the disc outside the Alfvén radius. It is not clear how large the precession amplitude would have to be in order for such an 'accretion gate' to operate. However Pines *et al.* list some other reasons why the accretion flow near the Alfvén surface could be sensitive to the orientation of the neutron star's rotation axis, so it is conceivable that a wobble through only a few degrees could suffice. On the basis of this model, Pines *et al.* have attempted to explain the other features of the 35 day cycle. The asymmetry between the sharp rise and the gradual fall in X-ray intensity during the 12 day 'on' period is readily explained. Matter accumulating during the 'off' period will be opaque to the X-rays until it has been photoionized. The fact that the switch-off occurs near orbital phases 0.25 or 0.75 is attributed to the higher density of obscuring matter along the line joining the two stars, which makes it more likely that the first X-rays to be seen will escape perpendicular to this line. The hypothetical 'hot spot' where the gas stream merges with the disc may be thick enough to obscure the X-rays at the phase of the orbit when it lies along our line of sight. The outer radius of the disc would decrease during the 'on' period, and the location of the hot spot would change (it is claimed) in such a way that the dip 'marches' in phase in the matter observed. The apparent tendency of the small ($\lesssim 0.2\%$) amplitude 1.24 s *optical* pulsations (which probably come from gas with cooling time $\lesssim 1.24$ s which is being heated by the pulsed X-rays) to occur at particular orbital phases can also be explained.

3.2.4. *Precession of Pencil Beam*

Another idea involving precession of the neutron star (Brecher, 1972; Strittmatter

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et al., 1973) is that the X-rays remain 'on' for the whole 35 day cycle, but that they emerge in a pencil beam which sweeps through our line of sight only for 11 days out of 35. There are some geometrical difficulties associated with this idea. In particular, the broad and relatively smooth observed X-ray pulse profile tells us something about the shape of the beam, and it is hard to reconcile this with the sharp onset of the high state or with the apparent lack of any marked systematic changes in the pulse shape during the 'on' state. A very large wobble amplitude ($\gtrsim 45$ deg) would certainly seem required by this model.

At least in models (a) and (c), the continuous heating of the companion star can only be explained by involving a steady heat source. One possibility (Avni *et al.*, 1973) is that the neutron star emits a steady flux of soft X-rays, powered by the ~ 8 MeV nucleon resulting from nuclear fusion of the accreted matter. This energy is liberated well below the neutron star surface. It is also possible that hear is conducted inwards from the magnetic polar caps, and re-emerges as a steady flux. This emission would not be completely isotropic, because the magnetic field renders the opacity of the crust lower near the magnetic poles. But a serious problem arises with any model in which soft ($\lesssim 0.5$ keV) X-rays play the dominant role in the heating, because these photons (unlike harder X-rays) are absorbed predominantly *above* the photosphere. The associated energy input would then distort the temperature stratification, resulting in the formation of strong emission lines and suppression of the ordinary stellar absorption spectrum (Basko and Sunyaev, 1973; Strittmatter, 1974). It seems more likely that the star HZ Her is heated mainly by *hard* ($\gtrsim 10$ keV) X-rays, though the problem then is the inefficiency resulting from the high albedo (unless one considers photons of $\gtrsim 0.5$ MeV). Heating by fast particles is another possibility. In models (b) and (d), one may suppose that X-rays always hit the companion star even when they cannot propagate along our line of sight (though this requirement places further constraints on the geometry). A more attractive variant of (d) might be to postulate that the star is heated by hard X-rays which are not so strongly beamed as those detected by Uhuru. This is theoretically plausible because the circumstance which might most naturally cause a pencil beam – the reduced scattering cross section for photons travelling along the magnetic field direction – would not be so effective at high photon energies.

35 days is much too short a free precession period for a neutron star with a liquid core. However a neutron star with a *solid* core and the 1.24 s spin period appropriate to Her X1 could plausibly sustain a sufficient deviation from axisymmetry to yield a 35 day precession, and would then automatically be rigid enough to be able to wobble through a large angle. (Mechanisms for exciting this kind of wobble and for sustaining it against damping processes are discussed by Pines (1973).) The question of whether compressed nuclear matter can crystallise at densities $\gtrsim 10^{15}$ gm cm^{-3} is still controversial (see Pandharipande, 1973; Canuto and Cameron, 1973). It will only occur – if at all – in neutron stars with high masses and high central densities, lending added interest to estimates of the mass of Her X1.

In assessing the various models for the 35 day cycle it is of course crucial to know just how regular a phenomenon it really is. It is also relevant that Cen X3 displays extended lows which are apparently *not* strictly periodic. Finally, some explanation is also required for the *very* long ($\gtrsim 10$ yr) time-scale variability inferred from scrutiny of old Harvard plates of Her X1 (Jones *et al.*, 1973) where the 1.7 day optical behaviour changes, implying that whatever agency is responsible for heating the companion star is suppressed. If one were optimistic one might therefore hope that *two* of the possibilities mentioned above might actually be relevant!

4. Cyg X1: A Black Hole?

Cyg X1 is the prime candidate for being an X-ray source involving a black hole. One would expect the accretion disc around a black hole to be subject to various instabilities: thermal instabilities, magnetic instabilities (perhaps analogous to those which Parker has discussed in the context of the interstellar gas in our Galaxy), or perhaps instabilities resulting from irregularities in the mass transfer rate. These could give rise to irregular flickering on all time scales down to the orbital period associated with the most tightly bound stable circular orbits (and perhaps even more rapid fluctuations), but no regular period would be expected. Even if one had no evidence on its mass, one might therefore suspect that the X-rays from Cyg X1 arise from an accretion disc around a black hole. The issue then hinges on the mass of Cyg X1: if this is $\gtrsim 3\ M_\odot$, then it cannot be a stable neutron star or white dwarf, so (assuming that a single compact object is involved) there seems no alternative – at least within the framework of 1973-vintage astrophysical ideas – to the inference that it is a black hole.

The arguments pertaining to the mass have been rehearsed in detail by Giacconi (1973b), and I shall only summarise them here. The first step in this argument depends on the identification of Cyg X1 with the 9th mag., 5.6 day spectroscopic binary HDE 226868. The evidence for this identification is (a) positional agreement to better than 30"; (b) correlations between the X-ray variability and the radio variability (the radio source position agreeing, to better than 1" accuracy, with that of HDE 226868); and (c) recent evidence from the Copernicus satellite for a soft X-ray eclipse near phase zero of the optically-determined 5.6 day period.

The next step concerns the mass of HDE 226868. The mass function determined from optical spectroscopic observations, is

$$\frac{M_x^3 \sin^3 i}{(M_x + M_{\rm opt})^2} = 0.23\ M_\odot \tag{9}$$

(note that, because there is no regular pulse period, one cannot use X-ray observations to determine a mass function with $M_{\rm opt}$ in the numerator, as was done for Her X1 and Cen X3. On the other hand, the fact that the X-rays from Cyg X1 have a less drastic effect on the companion than seems the case in Her X1 allows the radial velocity of Cyg X1's companion to be determined less ambiguously by optical means). If HDE 226868 were a normal B0 Iab supergiant, its mass would be 15–35 $M_\odot$, and the X-ray source would then be $\gtrsim 6\ M_\odot$. For M_x to be below $2\ M_\odot$ (and $1.7\ M_\odot$ is now the best upper limit to a neutron star mass), one would require HDE 226868 to be below $4\ M_\odot$ even if $i = 90°$ (and even lower if $i \lesssim 60°$, as is probably implied by the fact that Uhuru observed no X-ray eclipse). However, as was pointed out by Trimble *et al.* (1973) it is possible for a low mass evolved star (powered by helium burning in a shell) to mimic the spectroscopic appearance of a B0 supergiant. But the star would then have a lower luminosity, and would have to be only ~ 0.5 kpc away. There was, until recently, no very firm evidence on the distance, but Margon *et al.* (1973) have now determined the reddening-vs-distance relation for 50 main sequence stars in the same field. They find a good correlation out to $\gtrsim 2$ kpc. The fact that HDE 226868 displays as much reddening as any of the other stars in the sample thus implies that it is at least ~ 2 kpc away; and this convincingly rules out the possibility of its being an evolved low-mass star.

The natural conclusion seems therefore to be that Cyg X1 involves a black hole of $\gtrsim 6\ M_\odot$. This conclusion could be evaded only if one could devise a plausible model for the source which did not involve a compact object at all. One such possibility (Fabian *et al.*, 1974) involves supposing that the companion of HDE 226868 is itself double: consisting of a neutron star (the source of the X-rays) orbiting a main sequence star of $\gtrsim 6\ M_\odot$. It is the evidence for compactness provided by the rapid X-ray variability which makes Cyg X1 a firmer black hole candidate than the invisible high-mass components of other single-line spectroscopic binaries (ε Aur, for instance). In the latter systems, it is hard to exclude the possibility that, for example, an ordinary star is shrouded by dust.

It is crucially important to determine the shortest timescale on which Cyg X1 varies. (This is an ideal rocket experiment: although a large collecting area is plainly advantageous, 1–2 min of observation should be quite sufficient). Sunyaev (1973) proposed that attempts should be made to search for X-ray pulse trains due to regions of enhanced emissivity orbiting the hole. The typical orbital periods would be $\sim 0.6\ (M/M_\odot)$ *ms* for the innermost stable orbit around a Schwarzschild black hole, but ~ 8 times faster if the black hole had a maximal Kerr metric whose angular momentum was aligned with the disc, but with the same mass. Sunyaev envisaged this test as a method of diagnosing the metric around the black hole. However it seems quite possible that one would get pulse trains emitted from the region of *unstable* orbits in a Schwarzschild geometry. Thus the discovery of pulses of (say) $0.1 \times \times (M/M_\odot)$ ms period would not necessarily prove that the metric was close to 'maximal Kerr'. (Further interesting complications involving precession of the disc can occur if the black hole is obliquely oriented relative to the angular momentum vector of accreted material).

More would be learned if an X-ray spectral feature originating in the disc could be discovered and its profile measured, but this seems unlikely to be feasible before 1980. It is important to remember that black holes are a consequence of almost all 'viable' theories of gravity, and much further work is needed before one can diagnose whether the properties of a given black hole agree better with those expected on the basis of general relativity than with the predictions of a rival theory. Nevertheless, the discovery of black holes – objects where gravity is so overwhelmingly strong that it dominates all other effects – opens the way to testing some of the most crucial and remarkable predictions of Einstein's theory, and will surely have a massive impact on gravitational physics.

5. Optical Properties

The interpretation of the optical properties of X-ray binaries raises a whole range of problems. (See Bahcall and Bahcall (1973) for a survey of the observational data.) X-ray heating causes the side of the star facing the compact object to be hotter and brighter than the eclipsed side. A quantitative understanding of this effect involves detailed computations (along the lines of those already done by Arons (1973) and Basko and Sunyaev (1973) of the structure of a stellar atmosphere irradiated by X-rays). A second quite different effect which leads to optical variations with *half* the orbital period arises from the distortion of the companion star by the compact object's gravitational field. Interpretation of actual light curves is complicated by further effects (emission by gas streams, radiation and absorption by the accretion disc itself, etc.) and one suspects that detailed model-building may prove somewhat fruitless unless some very clear-cut correlations between X-ray and optical variability are found.

Her X1 is the system where the X-ray luminosity is highest relative to the intrinsic luminosity of the companion star (which is a late A or early F type main sequence star). It is thus a system where X-ray heating (or heating by some other radiation flux emanating from the compact object) is a dominant effect, being sufficient to make the 'hot side' of the star ~ 10 times more luminous than the unheated side; and the effects of gravitational distortion are relatively minor. The actual light curve, however, is not 'flat-bottomed', implying that the X-ray source is having some observable effect during some of the time when it is eclipsed. This may mean that some of the X-rays are absorbed above the photosphere and reradiated, or else that there is significant emission from an extended disc around the X-ray source. As already mentioned in Section 3, the persistence of the 1.7 day optical variations throughout the 35 day cycle suggests that a 'steady heat source' is operative in addition to the X-rays seen by Uhuru. This conclusion is also supported by simple energetic arguments, which suggest that the excess light emitted from the hot side of the companion star involves more energy than the fraction of 2–6 keV X-rays intercepted by the star.

Because of the drastic perturbing effects of the X-rays a given spectral line is not emitted uniformly over the star's surface, so it is difficult to interpret the radial velocity measurements of the companion star of Her X1. This means that one cannot readily obtain the second equation which, in conjunction with (5), would allow the mass of the X-ray source to be determined. The best estimates, however, suggest $M_x \simeq \simeq 1\ M_\odot$ and $M_{\mathrm{opt}} \simeq 2\ M_\odot$. Other methods of determining the mass M_x – which are very uncertain, but yield consistent results – involve using the spectral classification of the companion star, or assuming that the Roche lobe is filled.

In Cyg X1, where the companion star is much more luminous relative to the X-ray source than is the case for Her X1, the heating augments the stellar luminosity by only $\sim 2\%$, and the effects of gravitational distortion are more important. Attempts have been made to derive an independent mass estimate from the theory of this effect, but these are somewhat unreliable. The other known X-ray binaries – for instance, 3U 1700 – 37, Vela XR1 and SMC X1 – seem to resemble Cyg X1 rather than Her X1, in that the companion star is a highly luminous supergiant, and X-ray heating effects are *not* important.

The only other case where X-ray heating may be important is the peculiar source Cyg X3 (which first attracted attention because of the spectacularly strong radio outburst which it underwent in September 1972). This object has a 4.8 h period, which should probably be interpreted as an orbital period during which the X-ray intensity changes by a factor ~ 2. No optical counterpart has been found, presumably because it is in a strongly obscured region, but synchronous 2.2 variations of $\sim 15\%$ amplitude have been reported (Becklin *et al.*, 1973). The gradual and incomplete character of the X-ray eclipses suggests that in this system the eclipse is caused not by the surface of the companion star, but by scattering and absorption in a strong wind. The observed infrared variations imply that the relevant layer of the heated side of the companion star has a temperature $\gtrsim 10^6$ K. This, however, is quite possible if one is seeing emission from the wind, which is heated to this temperature (Pringle, 1973b).

Although Cyg X3 has a shorter period than the other X-ray binaries, the period is longer than that of systems such as DQ Her. It may differ from such systems merely in having a neutron star (or black hole) as the compact component, instead of this being a white dwarf.

The occurrence of X-ray heating sets a rough *lower limit* to the apparent brightness of the optical counterpart for any eclipsing X-ray source. If there were no interstellar absorption, any X-ray source with an intensity of C Uhuru counts (Her X1 is ~ 100 in these units) which is observed to eclipse for a fraction f of every period should have an optical apparent magnitude

$$m \simeq 15 - 2.5\left\{\log\left(\frac{C}{10}\right) + 2\log(4f)\right\}. \tag{10}$$

Thus any eclipsing source in the Uhuru Catalogue would be optically identifiable were it not for the often severe effects of interstellar extinction.

6. Concluding Remarks

Many interesting and important aspects of binary X-ray sources have not even – for reasons of time – been touched on in the foregoing remarks. In particular, I have said almost nothing about the radio observations, which are certainly not yet adequately explained. However the fact that – even in the extreme case of Cyg X3 at the peak of its radio flare – the radio luminosity is a tiny fraction of the X-ray output, suggests that to concern ourselves with the details of the radio variability may be as premature as it would be to worry about solar flares before understanding the basic elements of stellar structure. Moreover, some binary systems containing two relatively normal stars have similar radio properties and this suggests that the radio behaviour, fascinating and puzzling though it may be, is unlikely to be intimately connected to the compact object itself.

The existence of these close binary systems with compact components raises many astrophysical questions. How do they fit into the general scheme of binary star evolution? How do they evolve to their present state and what role did mass transfer play during their earlier history? How did they avoid disrupting during the catastrophe which formed the collapsed component? Why, nevertheless are there only $\lesssim 100$ such systems in the Galaxy? What will be their eventual fate? – for example, what happens if a neutron star accretes so much material that it comes to exceed the limiting mass; or what happens when, later in its evolution, the companion star swells up and engulfs the compact object? What are their relations to pulsars, and do we really understand why there are no ordinary pulsars observed in binary systems? How does the famous source Sco X1 fit into this pattern?

This is such a new topic that the theorists have a rather better excuse than usual for raising questions instead of providing answers. Let us hope, however, that some of the speculative ideas already proposed are transmuted into 'solid' theoretical models before the theorists are distracted by something even more exciting. We can certainly expect much new data from the next generation of X-ray satellites and from more refined optical observations. It should be feasible to detect X-rays from this type of source in nearby galaxies, thereby acquiring a larger sample for statistical analysis, which will allow us to check the theory of black holes and neutron stars against observations in many key respects.

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