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COMPACT X-RAY BINARIES IN HIERARCHICAL TRIPLES. I. TIDAL ANGULAR MOMENTUM LOSS AND GX 17+2

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ABSTRACT

A general formalism is developed for the enhanced mass transfer rate expected in a close binary with a (distant) third companion star. Such a hierarchical triple model is applied to the X-ray burster and QPO source GX 17+2, consisting of an inner mass-transferring binary comprising a main-sequence secondary and an accreting neutron star, and a more distant companion. The model is shown to account for the anomalously high mass transfer rate for this burster and other systems with short orbital periods. A G star, which does not appear to be the binary companion of the neutron star but is consistent with the sub–arc second radio error box for GX 17+2, may be the triple companion. A predicted velocity curve for the triple companion is presented.

Subject headings: stars: individual — X-rays: binaries

I. INTRODUCTION

The mass transfer rate in binaries in which one star is undergoing Roche lobe overflow can be increased significantly by the presence of a third body. This occurs through tidal dissipation of orbital angular momentum in the inner binary due to the eccentricity induced in the inner orbit by the presence of the third body, which causes a decrease in the separation of the compact binary. This effect was pointed out by Mazeh and Shaham (1979) and is developed in greater detail here. We also discuss possible modulations of the mass transfer rate on intermediate (close to one orbit of the third body) and longer time scales. Modulations of the mass transfer rate on the time scale of the inner orbital period as well as additional modulation effects on the longer time scales will be discussed in Papers II (Bailyn 1986) and Paper III (Molnar, Bailyn, and Grindlay 1986) of this series.

We apply these considerations to the X-ray burst source GX 17+2, which is one of the brightest X-ray sources in the galactic bulge. It is of interest for its weak X-ray bursts (Kahn and Grindlay 1984; Tawara *et al.* 1984; Sztajno *et al.* 1985) and for being one of the sources found to display quasi-periodic oscillations (QPO) (Stella, Parmer, and White 1985). If the recently reported 5000 s period (Langmeier *et al.* 1986) is confirmed as the orbital period, this would make GX 17+2 the only QPO source with an orbital period so low as to rule out a giant companion. However, the high apparent X-ray luminosity of GX 17+2 ($\sim 10^{38}$ ergs s^{-1} for an assumed distance comparable to the galactic center distance of 7 kpc; see Grindlay 1985) would suggest a giant (or subgiant; "giant" will refer to both possibilities) companion to drive the required high mass transfer rate as discussed by Webbink, Rappaport, and Savonije (1983). The high mass transfer rates inferred for QPO sources are consistent with these systems having their mass transfer driven by the evolution of giant companions (see Lewin and Van Paradjis 1985). In the case of Cygnus X-2, the giant companion is directly observed.

The X-ray flux of GX 17+2 has been reported to be periodic on several different time scales. Ponman (1982) has reported evidence for modulations with a period of ~6.5 days. Interestingly, he was able to distinguish two distinct periodicities of 6.43 and 6.49 days. As mentioned above, Langmeier *et al.* (1986) have suggested a periodicity of 5000 ± 300 s which is (to within the errors) the difference between Ponman's periods (preliminary evidence for a 5000 s period was given by Sztajno *et al.* 1985). Although this 5000 s period must be confirmed, we shall assume in this paper that it is the orbital period since it is comparable with orbital periods for two other low-mass X-ray binaries (4U 1626−67 and 4U 1916−05; see White 1986) and it is too long to be a neutron star rotation period in such a high-luminosity system. Finally, Hertz and Wood (1986) have recently claimed the detection of a 19.4 hr period. We discuss this possible periodicity further in § III.

Einstein HRI observations (Grindlay, Hertz, and Tokarz 1986) yielded a 3".5 error box (90% confidence radius) for the position of GX 17+2. A still more accurate position (0".2) has been derived from VLA observation of the radio source associated with GX 17+2 (Grindlay and Seaquist 1983, 1986). The radio error box is contained within the 0".5 astrometric uncertainty (Grindlay and Seaquist 1986) of a 17th magnitude G star (Tarenghi and Rhema 1972; Margon 1978), which has recently been identified as a possible subgiant (Grindlay 1984). If the binary period is confirmed to be ~5000 s, then such a star would be considerably too large to fit into the mass-transferring binary. The idea that the giant is not itself losing mass to a compact object is further strengthened by the absence of emission lines in its optical spectrum.

In our triple star model for GX 17+2, a Roche lobe filling main-sequence star (with an assumed mass of $\sim 0.2\ M_\odot$) and a neutron star orbit each other with the 5000 s period. The center of mass of this "inner" binary is, in turn, orbiting about the G giant with a period of 6.5 days, forming the "outer" binary of a hierarchical triple system. Such a triple system, with a period ratio of ~112, will be stable except under very extreme circumstances (Harrington 1977; Black 1980). Given a modest eccentricity in this "outer" binary, we show that the Mazeh and Shaham (1979) mechanism can yield the required high mass transfer rate, which is otherwise difficult to explain. The hypothesis that GX 17+2 is a triple system also provides a natural explanation for two other curious features of GX 17+2: the various time scales of X-ray variability, and the presence of a late G-type subgiant consistent with the 0".1 radio error box (Grindlay and Seaquist 1986). A three-body model for GX 17+2 has been suggested by Grindlay (1984, 1985, 1986) on evolutionary grounds if GX 17+2 and other bursters in the field were formed in globular clusters.

In § II, we discuss the increased mass transfer rate caused by the presence of a third companion of a compact binary. This could account for the anomolously high persistent luminosity and mass transfer rate in GX 17+2 relative to most X-ray burst sources (Grindlay 1986) as well as be a general mechanism for high mass transfer in low-mass X-ray binaries. In § III we discuss intermediate-term periodicities (close to one outer orbital period) such as those observed by Ponman in GX 17+2. In § IV we briefly discuss how systems such as GX 17+2 might arise and their observational consequences.

II. MASS TRANSFER RATE

Since the evolutionary time scale of a normal main-sequence star of $\sim 0.2\ M_\odot$ (as we assume the secondary of the inner binary of GX 17+2 to be) is greater than 10^{10} yr, mass transfer must be driven by some other mechanism. The problem is analogous to that of cataclysmic variables (CVs), except that in CVs the mass gaining object is a white dwarf, not a neutron star. CVs exhibit a period gap; there are no CVs with periods of between 2 and 3 hr (Patterson 1984). Above this gap, CVs typically have high mass transfer rates ($\dot{M} \approx 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$), while below the gap, $\dot{M} \approx 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$. Below the gap, this mass transfer rate can be satisfactorily explained by orbital angular momentum losses in the form of gravitational radiation (GR), as can the lower limit on the period of ~ 80 minutes if the secondary is a main-sequence star (Rappaport, Joss, and Webbink 1982). The much higher mass transfer rates for CVs above the period gap cannot be explained by GR; other mechanisms, such as magnetic braking (Rappaport, Verbunt, and Joss 1982), must be invoked. All bursters with measured X-ray periodicities lie above the period gap except for GX 17+2 and 4U 1916−05 (White 1985), and thus they could be driven by magnetic braking in accordance with the analogy with CVs.

GX 17+2 not only has a possible X-ray period (1.4 hr) which places it well below the period gap, but also very likely has a mass transfer rate too high to be explained by GR. Thus the mass transfer in GX 17+2 must be explained by some mechanism which can operate below the gap. In this section we explore in detail the consequences of an idea originally put forward by Mazeh and Shaham (1979): a third body, by inducing eccentricity into the inner binary orbit which then attempts to circularize itself, can serve to decrease the orbital angular momentum of the inner binary and drive it together.

a) General Formalism

Mazeh and Shaham (1979) have shown that the semimajor axis a of a close binary with a mean eccentricity $\langle e \rangle$ will decrease according to the equation

$$\frac{1}{\langle a \rangle}\frac{d\langle a \rangle}{dt} = \frac{-1}{\tau_{\mathrm{circ}}} 2\langle e^2 \rangle \ , \tag{1}$$

where τ_{circ} is the circularization time scale of the inner binary. Following the work of Alexander (1973), Press, Wiita, and Smarr (1975, hereafter PWS) give the following expression for τ_{circ}:

$$\tau_{\mathrm{circ}} = \frac{125}{121}(1-e^2)^5\left(\frac{a}{r_2}\right)^8 \frac{m_2^2}{m_1(m_1+m_2)}\frac{n}{\omega_2}\frac{m_2}{r_2\langle \mu \rangle} \ , \tag{2}$$

where r_2, m_2, and ω_2 are the radius, mass, and rotational frequency of a tidally deformed object in a binary system, m_1 is the mass of the other object in the binary, n is the frequency of the binary orbit, a and e refer to the orbital parameters of the binary system, and $\langle \mu \rangle$ is an averaged viscosity defined by

$$\langle \mu \rangle \equiv \frac{a}{r_2^9}\int_0^{r_2} \mu(r) r^8 dr \ . \tag{3}$$

We use the PWS formalism rather than that of Lecar, Wheeler, and McKee (1975) because the latter authors consider only the case of secondaries with thin convective surface layers. The shear-induced eddy viscosity considered by PWS, on the other hand, should be present in any secondary in a binary system with a noncircular orbit, and the eddies will break up any large-scale convective flow.

For mass-transferring binaries such as GX 17+2, the large tidal torques ensure that the system is very close to synchronous and circularized, so it is reasonable to assume that the factor

$$\frac{125}{121}(1-e^2)^5\frac{n}{\omega_2}$$

is very close to 1. Thus equation (2) can be simplified to the form

$$\tau_{\mathrm{circ}} = \left(\frac{a}{r_2}\right)^8 \frac{m_2^2}{m_2(m_1+m_2)}\frac{m_2}{r_2\langle \mu \rangle} \ . \tag{4}$$

PWS explore the situation in which the dominant source of viscosity is the turbulence generated by the movement of a tidal bulge across a body in a slightly asynchronous (and/or noncircularized) binary orbit. They arrive at the following expression for $\langle \mu \rangle$:

$$\langle \mu \rangle = \frac{2m_1 n\delta}{R_T r_2}\left(\frac{r_2}{a}\right)^3\left[\frac{14}{m_2 r_2^{11}}\int_0^{r_2}\rho(r) r^{13} dr\right] , \tag{5}$$

where all the symbols have the same meanings as in equation (3), R_T is the *effective* Reynold's number of the turbulent fluid estimated to be between 10 and 30 (Tennekes and Lumley 1972, p. 134) and δ is defined as

$$\delta = \max\left[e, 1 - n/\omega_2\right] . \tag{6}$$

For our purposes we take $\delta = e$. PWS take the expression in brackets in equation (5) to be equal to 0.025 for main-sequence stars; it could, in principle, be calculated exactly from an appropriate stellar model. We note that in the unlikely event that the star in question were of constant density, this expression would equal $3/(4\pi)$. It will be seen that even fairly large variations in the value of $\langle \mu \rangle$ will not greatly affect our ultimate result, so we will adopt PWS's value. Thus we can combine equations (4), (5), and (6) to get an expression for $d\langle a \rangle/dt$ in terms of potentially known quantities:

$$\frac{d\langle a \rangle}{dt} = -\langle a \rangle\left[5\times 10^{-3} n\langle e^2 \rangle\langle e \rangle\left(\frac{r_2}{\langle a \rangle}\right)^{11}\frac{m_1^2(m_1+m_2)}{m_2^3}\right] . \tag{7}$$

This decrease in the binary separation can be expected to result in mass transfer. The precise mass transfer rate can only be determined by knowing the response of the dwarf secondary to mass loss. In general, this will depend on the details of the structure of the secondary. For main-sequence stars as small as $0.2\ M_\odot$ (which will be convective throughout) the thermal time scale will be similar to the mass transfer time scales expected for a source such as GX 17+2; under these circumstances mass loss will cause the secondary to expand (Paczyński 1971; Whyte and Eggleton 1980). To keep our argument general, we will assume that mass transfer will occur if the decrease in binary separation due to tidal effects described by equation (7) exactly compensates for the increase in binary separation caused by angular momentum conservation as mass is transferred from the less massive to the more massive member of the system. Note that this corresponds to a slight decrease in the size of the secondary since the change in the mass ratio will result in a smaller ratio of Roche lobe radius to the semimajor axis. The errors introduced by this approximation will be on the order of a factor of 2 since the change of size of the secondary induced by the mass transfer will necessarily occur on the same time scale as the mass transfer itself. As will be seen, factors of 2 will not change our ultimate conclusions.

The tendency of an orbit to expand due to conservation of angular momentum from the less massive to the more massive member can be calculated as follows. The distance between two objects in a circular orbit with a given total angular momentum is proportional to

$$(1+q)^4/q^2\ , \tag{8}$$

where q is the mass ratio. Taking the derivative of expression (8) yields

$$\frac{1}{a}\frac{da}{dq}=\frac{2q-2}{q(1+q)}\ . \tag{9}$$

From the definition of the mass ratio $q=m_2/m_1=m_2/(m_{\rm tot}-m_2)$, we have

$$\frac{dq}{dm_2}=\frac{m_{\rm tot}}{(m_{\rm tot}-m_2)^2}=\frac{m_{\rm tot}}{m_1^2}\ , \tag{10}$$

and thus

$$\frac{1}{a}\frac{da}{dt}=\frac{1}{m_2}\frac{dm_2}{dt}\frac{m_2\,m_{\rm tot}}{m_1^2}\frac{2q-2}{q(1+q)}\ . \tag{11}$$

If we assume that the dwarf secondary of the X-ray binary fills its Roche lobe, we can then use the approximation for the Roche radius obtained by Eggleton (1983) in terms of the binary separation d and mass ratio q:

$$R_{\rm L}=d\,\frac{0.49q^{2/3}}{0.6q^{2/3}+\ln(1+q^{1/3})} \tag{12}$$

to express r_2 in terms of a, m_1, and m_2. Combining equations (7), (11), and (12) and assuming an almost circular orbit for the X-ray binary, we can write the following expression for $\langle e\rangle\langle e^2\rangle$ in terms of m_1, m_2, orbital frequency, and mass transfer rate $\dot m = dm/dt$ of the inner binary:

$$\langle e^2\rangle\langle e\rangle = 2\times 10^2 n^{-1}\,\frac{\dot m}{m_2}\,q^3\,\frac{2q-2}{1+q}\times\left[\frac{0.98q^{2/3}}{0.6q^{2/3}+\ln(1+q^{1/3})}\right]^{-11}\ . \tag{13}$$

Adopting parameters for the inner (X-ray) binary of GX 17+2 of $m_2=0.2$, $m_1=1.6$, $dm/dt=10^{-8}\,M_\odot$, and $n=13\times10^{-3}\ {\rm s}^{-1}$, we obtain the result

$$\langle e\rangle\langle e^2\rangle = 6.7\times10^{-9}\ . \tag{14}$$

The derivation of equation (14) contains many potential sources of error in addition to the problems associated with the response of the seondary discussed above. The exact mass transfer rate, for example, is taken from an assumed efficiency (≈ 0.1) and absolute X-ray luminosity, which in turn varies with the square of the distance. However, the distance to GX 17+2 is not well known, except from the assumption of a precisely Eddington luminosity for its X-ray bursts (Ebisuzuki Hanawa, and Sugimoto 1984; Matsuoka 1985). Also, the mass ratio assumed for the X-ray binary is very uncertain, since the mass of the compact object is undetermined. However, for a plausible neutron star mass in excess of 1.4 $M_\odot$, the secondary must be of low mass (0.2 $M_\odot$) to fill its Roche lobe and yet to fit within the binary orbit for the assumed 1.4 hr period. If $m_{\rm com}/m_{\rm sec}$ is greater than our assumed value of 8, this will lead to a larger value of the term involving the masses directly in equation (7) but will result in a smaller value for the term $(r_1/a)^{11}$. Thus this uncertainty is not as drastic as it might appear to be. Finally, the theory of turbulent viscosity on which equation (5) and the value of 20 adopted for R_T are based is not yet fully understood. Fortunately, the high power to which the eccentricity is raised also means that relatively large changes in the value of the numerical constant in equation (14) must be made to change the overall result. Thus the value derived from equation (13) for the value of $\langle e\rangle$ itself is surprisingly robust to our assumptions and is probably accurate to within a factor of 2.

In general, however, there will be variations in $\langle e\rangle$ on a time scale of

$$P_{\rm long}=CP_{\rm outer}^2/P_{\rm inner}\ , \tag{15}$$

where C is a constant of order unity (Mazeh and Shaham 1979). For simulations starting with initially circular conditions, such as those reported below, Mazeh and Shaham found that the mean eccentricity can undergo substantial oscillations over a period of order $P_{\rm long}$, with the minimum occurring at the start of the simulation. This would not only drastically affect the values for $\langle e\rangle$ and $\langle e^2\rangle$ to be used in equation (14) but would cause luminosity variation on a time scale of $P_{\rm long}$. When the inner eccentricity is at its largest, we would expect especially large mass transfer events, and hence high luminosities. This long-term luminosity modulation would be superposed on the intermediate-term effects discussed in § III.

b) *Numerical Simulations*

We have performed a series of numerical calculations to determine under what circumstances equation (14) would be satisfied. A fourth-order Runge-Kutta program was used to integrate the equations of motion for three point masses with step size small enough to conserve energy to one part in 1000 over the duration of the simulation; increased accuracy was found to have no effect on the results reported here. The three bodies were given initial conditions as follows. The inner X-ray binary, with masses $m_1=1.6\,M_\odot$ and $m_2=0.2\,M_\odot$, was given a circular orbit. The third star (given a mass of 0.8 $M_\odot$) was then placed in orbit around the center of mass of the inner binary, with orbital parameters corresponding to a given period and eccentricity. We note from equations (4) and (5) that the circularization time scale for the inner binary of a system with these parameters (given that the secondary fills its Roche lobe) will be on the order of 10^6 times its period. Therefore the changes in the motion of the stars in the compact binary introduced by tidal effects will operate only in the long term and should not affect the eccentricities created by the presence of the third body, which are introduced on a time scale of a few inner binary orbits. The errors introduced by considering the three bodies as point sources are of the same order as the numerical errors, and we have therefore ignored this effect.

Changing the relative orbital inclinations was found to vary the results only marginally (except for relative inclinations close to 90°); therefore the orbits were taken to be coplanar and prograde. The eccentricity of the orbit of the two inner bodies (after the motion of the center of mass of that system had been subtracted) was computed using the usual formulae involving the separation and relative motion of the two bodies every 0.3 of an inner orbital period until one full orbit of the outer body had been completed. The resulting values for $\langle e_{\rm inner}\rangle$ and $\langle e_{\rm inner}\rangle \times \langle e_{\rm inner}^2\rangle$ were recorded, and the process was repeated for the next outer orbit. This process was repeated until more than a half-cycle of the Mazeh-Shaham (1979) effect (i.e., variations on a time scale of $P_{\rm long}$) had elapsed; i.e., until the mean inner binary eccentricity (averaged over one outer binary period) had reached a maximum and begun to decline. We then took one-half the value of the maximum $\langle e\rangle \times \langle e^2\rangle$ obtained to be the long-term mean induced value of this quantity. These values for several different period ratios are reported in Table 1, and for a period ratio of 112 and various $e_{\rm outer}$ in Table 2.

Note that small deviations from $e_{\rm outer}$ give rise to large increases in the induced $e_{\rm inner}$. This is because the Mazeh-Shaham effect is strongly dependent on $e_{\rm outer}$ and indeed disappears entirely when the outer orbital eccentricity is precisely zero (Mazeh and Shaham 1979; Paper II). Paper II also shows that if the eccentricity changes considerably over the course of one orbital period, then it is not in general the appropriate measure of the difference between the maximum and minimum separation of the two bodies. In this case, since we are averaging over many measurements of e, this should not provide a significant source of error.

Thus we conclude that a small, but nonzero, outer orbital eccentricity is required to drive the observed mass transfer rate in GX 17+2. This outer binary eccentricity must be close to 0.02 (for the mass ratios chosen). For more circular orbits the induced inner binary eccentricity is too small by an order of magnitude. For an initial outer eccentricity of zero, for example, the period ratio would have to be as low as 20 to produce the necessary induced eccentricity. For $e_{\rm outer} \gtrsim 0.03$ the induced eccentricity is considerably too high, as can be seen from Table 1. The results reported in Table 1 also include the value of the constant C in equation (15) found for the set of parameters chosen. For the case of $e_{\rm outer} = 0.02$, this constant is equal to 2.3. We suggest that there may therefore be a long-term periodicity on the order of 1700 days in GX 17+2.

TABLE 1

COMPUTED PARAMETERS FOR GENERAL MODEL[a]

Period Ratio	$\langle e_{\rm inner}\rangle$	$\langle e_{\rm inner}^2\rangle$	$\langle e_{\rm inner}\rangle \times \langle e_{\rm inner}^2\rangle$
14	7.5×10^{-3}	6.7×10^{-5}	5.1×10^{-7}
20	3.6×10^{-3}	1.5×10^{-5}	5.4×10^{-8}
30	1.6×10^{-3}	3.0×10^{-6}	4.8×10^{-9}
40	9.0×10^{-4}	9.9×10^{-7}	8.9×10^{-10}
50	5.9×10^{-4}	4.2×10^{-7}	2.5×10^{-10}
60	4.2×10^{-4}	2.2×10^{-7}	9.2×10^{-11}
70	3.1×10^{-4}	1.2×10^{-7}	3.7×10^{-11}
80	2.4×10^{-4}	7.1×10^{-8}	1.7×10^{-11}
90	2.3×10^{-4}	6.0×10^{-8}	1.4×10^{-11}
100	1.8×10^{-4}	3.9×10^{-8}	7.0×10^{-12}
110	1.6×10^{-4}	2.9×10^{-8}	4.6×10^{-12}
120	1.1×10^{-4}	1.4×10^{-8}	1.5×10^{-12}

[a] Parameter values shown are for systems with $m_1 = 1.6$, $m_2 = 0.2$, $m_3 = 0.8$, and $\langle e_{\rm outer}\rangle = 0$.

TABLE 2

COMPUTED PARAMETERS FOR GX 17+2 MODEL[a]

$\langle e_{\rm outer}\rangle$	$\langle e_{\rm inner}\rangle\langle e_{\rm inner}^2\rangle$	C
0.0	3.1×10^{-12}	NA
0.005	5.1×10^{-11}	1.0
0.01	1.4×10^{-10}	1.2
0.02	5.5×10^{-9}	2.2
0.03	2.6×10^{-8}	3.9
0.04	3.1×10^{-8}	4.5

[a] Values for $\langle e_{\rm inner}\rangle\langle e_{\rm inner}^2\rangle$ and C (defined by eq. [15]) for a system similar to that described in Table 1, but with a period ratio of 112 and various values for $\langle e_{\rm outer}\rangle$.

The 199 day period in 4U 1916−05 (Priedhorsky and Terrell 1984*a*) and the 176 day period in 4U 1820−30 (Priedhorsky and Terrell 1984*b*) may also be examples of such long-term periodicities in a triple system. Note also that the source 4U 1820−30 (in the globular cluster NGC 6624, where a hierarchical triple might be expected; see Grindlay 1986) is both a burster and a QPO source, and thus similar to GX 17+2. Given the values of C recorded in Table 1, we can infer outer orbital periods $\lesssim 1$ day for 4U 1916−05, given its 50 minute orbital period, and a few days for 4U 1820−30 for an assumed inner binary period (still unknown for this system) of 4 hr. We note that the constant C, like the induced inner binary eccentricity, is strongly dependent on the value of the outer eccentricity. Because of this it is difficult to infer exact outer binary periods for these objects.

From equations (2) and (5) we see that a 0.8 $M_\odot$ giant with $R = 3\ R_\odot = 2 \times 10^{11}$ cm in a 6.5 day orbit with $e = 0.02$ around an object with mass 1.8 $M_\odot$ (the inner binary) will have a tidal circularization time scale of $\sim 3 \times 10^{10}$ yr. Given the current X-ray luminosity, and hence mass transfer rate of GX 17+2, this is much longer than the lifetime of the system. However, the factor a/r_2 enters to the 11th power, and therefore if the triple companion is further up the giant branch than we assume, the system would circularize rapidly. Also, the Mazeh-Shaham effect itself may be an efficient mechanism for circularization of the outer binary (see Paper III). Thus the nearly circular outer orbit of GX 17+2 is not inconsistent with its current long circularization time scale.

III. INTERMEDIATE PERIODICITIES

In addition to the Mazeh-Shaham effect discussed above, the separation of the inner binary will be modulated on much shorter time scales. These modulations provide a residual induced inner binary eccentricity for the case where $e_{\rm outer} = 0$ when the Mazeh-Shaham effect does not operate (Paper II). They are discussed in detail in Papers II and III. In the case of GX 17+2, the Mazeh-Shaham effect must dominate if the period ratio is 112 and the induced inner binary eccentricity is to account for the observed mass transfer rate. Nevertheless, the shorter term modulations will still be present.

Consider the variation of $r_{\rm min}$ with time, where $r_{\rm min}$ is defined as the distance of closest approach of the two inner bodies during the course of one inner binary orbit. If the inner binary has a significant eccentricity induced by the Mazeh-Shaham effect, $r_{\min}$ will depend on e_{inner}, which will vary over a period of P_{long}. It can be shown, however (Paper II), that there are variations over one outer orbital period superposed on this. In particular, there will be one minimum each outer orbit for which $r_{\min}$ is itself at a minimum. At this "super minimum" the closest approach of the two inner bodies will be closer than at any other time during that outer orbital period. This super minimum will occur at the same outer orbital phase during each outer orbit if long-term precession effects (Paper III) are ignored.

When the two inner stars are particularly close together, one might expect an enhanced mass transfer rate, and hence a luminosity flare. Particularly large flares might then be associated with "super minima" as described above. This might give rise to power in the Fourier transform of the X-ray light curve at one outer orbital period. After the super minima, each successive closest approach of the inner bodies will be more distant, and hence one might expect the mass transfer rate and the luminosity to decrease (depending on the response of the secondary). If there are a nonintegral number of inner orbits in one outer orbit, as is to be generally expected, then the time elapsed between such super minima of the inner binary separation will be either nP_{inner} or $(n+1)P_{\text{inner}}$, where $P_{\text{outer}} = (n+r)P_{\text{inner}}$, where n is an integer and r is the fractional number of orbits and is between 0 and 1. In this case we might expect to see two periodicities, one of nP_{inner} and one of $(n+1)P_{\text{inner}}$ surrounding the outer orbital period and differing by one inner orbital period.

The fact that a $\sim$6.5 day periodicity (Ponman 1982) may be present in the GX 17+2 X-ray intensity data on a time scale of $\sim$112 times that of the 5000 s (inner orbital) period generally supports our triple star model for the high mass transfer rate. Ponman's finding of two periodicities, apparently separated by one inner orbital period, is highly suggestive, and, if confirmed, would provide strong support for our model. However, these periodicities do not appear in the same data set; one manifests itself when the entire data set is analyzed, the other when data taken during large flares are removed. Ponman interprets this as indicating that the flares have introduced a false periodicity. Our suggestion, based on the fact that the two periodicities are separated (to within the errors) by one inner binary orbit, is that this behavior may indicate the presence of a third body and be due to the variations in inner binary separation discussed above (and in Papers II and III). The flaring behavior might be the result of mass transfer events triggered by "super" minima in the inner binary separation.

Our interpretation is clouded, however, by the difficulties involved in associating a change in the separation of the inner binary with a change in luminosity. To do this would involve calculating the exact response of the outer regions of the secondary to the changing potential, and also understanding the details of the X-ray production mechanism, both of which are beyond the scope of this paper. It is also not clear why Ponman's data show a power spectrum with peaks at nP_{inner} and $(n+1)P_{\text{inner}}$, but none at the intermediate value of P_{outer}, which we expect to be the long-term mean periodicity. However, the relative heights of these peaks would in general depend on the shape of the light curve over one inner binary orbit, and details of the temporal coverage.

Hertz and Wood (1986) have recently claimed yet another X-ray periodicity ($\approx$19.4 hr) for GX 17+2. This period appears in one of two sets of *HEAO 1* observations, each of which contains data taken over the course of 1 week. A striking feature of both sets of observations is the presence of flares of up to twice the continuum level spaced between 6 and 7 days apart (Hertz, private communication). These data thus provide further evidence for Ponman's 6.5 day period. If one assumes that the 19 hr period is in fact the orbital period of a third body, which would be $\sim$14 times the inner binary period, the 6.5 day period might be a manifestation of Mazeh and Shaham's long-term periodicity (with $C \approx 0.5$ in eq. [15]). However, as can be seen in Table 1, a period ratio of 14 would result in a high induced inner binary eccentricity which would produce an extremely large mass transfer rate. This difficulty can be overcome by relaxing the requirement that the third body be identified with the observed G star (see discussion) which would allow a smaller third body mass. In particular, for an initially circular outer orbit, $m_3 = 0.1\ M_\odot$, $P_{\text{out}}/P_{\text{in}} = 14$ and with the masses of the two inner bodies equal to 1.6 $M_\odot$ and 0.2 $M_\odot$ as before, we find that $\langle e_{\text{in}}\rangle\langle e_{\text{in}}^2\rangle = 2.5 \times 10^{-9}$.

IV. DISCUSSION

a) *Formation Scenario*

It has been suggested (Grindlay 1984, 1985, 1986; Grindlay and Hertz 1985) that the galactic bulge burst sources were created in globular clusters, which were subsequently disrupted, possibly by giant molecular clouds in the Galaxy. The major motivation behind this suggestion (besides the similarity of the galactic bulge bursters and globular cluster sources) is the attractiveness of the tidal capture mechanism in forming the close binary systems required to form X-ray burst sources. The bursters almost certainly contain a low-mass main-sequence star as the neutron star companion since both the binary periods and luminosities observed preclude giant companions. (It is possible, though, that systems such as 4U 1916−05 contain post–giant evolution stars, such as helium stars, as their companions.) In the globular cluster binary formation scenario (see Grindlay 1986), the neutron star evolves separately from the main-sequence companion it later captures. Because of mass segregation, such neutron stars are to be found preferentially in the dense central regions of the globular cluster, where the density of stars is so high that enough tidal captures will take place to account for the number of burst sources observed in clusters (Fabian, Pringle, and Rees 1975; Lightman and Grindlay 1982). Such capture binaries will have semimajor axes of $\sim 3R$ or less, where R is the radius of the main-sequence star, and are thus good candidates for eventual mass transfer.

Under such circumstances, it seems likely that some percentage of tidally formed binaries will tidally capture a third companion, or, in cluster cores undergoing collapse with a high concentration of binaries, that binary-binary interactions will produce bound triple systems (Grindlay 1986; Mikkola 1985, and references therein). Since this would take place preferentially near the center of the cluster, the average mass of the stars available for capture would be higher than the average stellar mass in the cluster. Therefore the chances of such a third body either being or becoming a giant are higher than the cluster mean.

The problem of the disruption of globular clusters by close encounters with giant molecular clouds (Grindlay 1986) or otherwise (e.g., by cluster expansion after core collapse, and general tidal disruption; see Lee and Ostriker 1986) has been insufficiently studied to predict accurately the number of such disruptions and their remnants. Recent calculations of Chernoff, Kochanek, and Shapiro (1986) offer the most detailed treatment thus far and suggest that cluster disruption may be confined to the inner 4 kpc of the Galaxy. This, combined with the lack of suitable formation mechanisms for the galactic bulge X-ray burst sources, which would only be exacerbated by the additional requirement for the origin of a triple system such as we propose for GX 17+2, may make the globular cluster origin hypothesis more attractive. Furthermore, whereas it is likely that a significant number of tidal capture binaries are ejected from globular clusters (see Statler, Ostriker, and Cohn 1986) during core collapse, it is very implausible that hierarchical triples formed in globulars could be ejected in this way. Although perhaps one-third of all field stars are members of triple systems (Abt and Levy 1976), the extremely short periods suggested for GX 17+2 are unlike any known for "normal" triple systems, suggesting a different origin.

b) *Identification with the G Star?*

Identifying the observed G star with the third star in the GX 17+2 system is an attractive possibility. However, there are some difficulties with this. If the star is luminosity class III, its absolute visual magnitude would be about $m_V \approx +1$. At the distance of 7 kpc obtained by assuming the bursts to be of approximately Eddington luminosity, the expected absorption (Neckel and Klara 1980) of $A_V \gtrsim 3$ would suggest that the star be fainter than $\gtrsim 18$th magnitude, close to the observed value of $M_V \approx 17.5$. However, Catura (1983) finds that 21% of the X-ray luminosity of GX 17+2 may be in a scattering halo. Applying the results of Mauche and Gorenstein (1986), this would indicate considerable optical absorption of $A_V \gtrsim 10$, so that the observed G star could not be associated with GX 17+2, despite the low probability of such a chance superposition.

The absence of X-ray heating effects on the G star may also indicate that it is not in fact associated with GX 17+2. Such effects might be expected to include weak emission lines varying on the 6.5 day period, since the G star would be subjected to a similar X-ray flux as the F giant companion in the Cygnus X-2 system, which has a 9.8 day period. However, a giant triple companion to GX 17+2 might be more shielded (and thus less heated) by the secondary of the compact binary and/or the accretion disk. Finally, as mentioned above, the 19 hr period (if confirmed) would rule out the G star as the triple companion since a lower mass (and fainter) star is then required.

Nevertheless, if the G star is associated with GX 17+2, our model applied to Ponman's (1982) results provides one obvious observational prediction: it should exhibit orbital motion with a period of between 6.43 and 6.49 days. Figure 1 shows velocity curves (uncorrected for sin *i*) of an object of $m = 0.8\ M_\odot$ in a circular (since the required $e = 0.02$ is nearly circular) 6.45 day orbit about an object of 1.8 $M_\odot$ (the inner

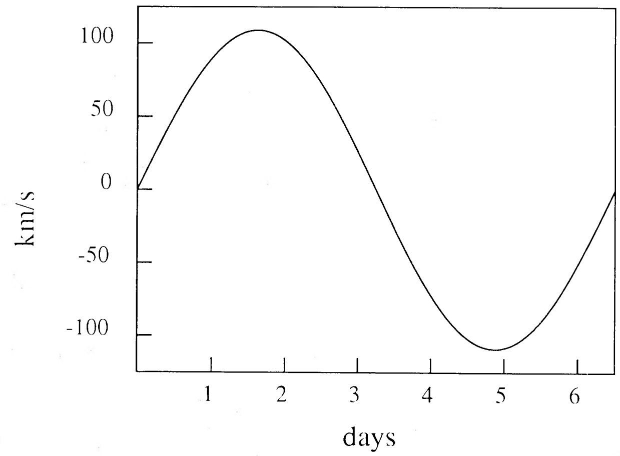

FIG. 1.—Velocity variations which would be exhibited by a 0.8 $M_\odot$ object (e.g., the giant in the proposed model for GX 17+2) in a circular orbit with a 1.8 $M_\odot$ object (e.g., the inner binary) with a period of 6.5 days. The curve is uncorrected for sin *i*.

compact binary). We have recently obtained (on two consecutive nights) velocities of the G star and found no significant variations to within an error of ± 43 km s^{-1} (both velocities are consistent with 0 with respect to the LSR). This suggests that the G star is not the proposed triple companion. However, such a lack of velocity variation could occur with $\sim 40\%$ chance probability, and so further monitoring is needed.

c) *Other Effects*

There are other more subtle effects which a third body should have on an X-ray binary. There may be observable effects on a synodic period slightly longer or shorter than the inner orbital period, depending on whether the third body is in a prograde or retrograde orbit respectively (Papers II and III). The difference between the radio and X-ray periods of Cygnus X-3 (Molnar, Reid, and Grindlay 1984) may be an example of such an effect (Paper III; Molnar 1985, 1986). For GX 17+2 the exact value of the inner binary period is still far too uncertain for these effects to be predicted. Her X-1 (Mazeh and Shaham 1977) and SS 433 (Fabian *et al.* 1986) are other systems for which three-body interpretations have been offered. For SS 433 it has been suggested that the long-term period (164 days) is the result of precession of a compact binary with a period of 1 day orbiting a third body with the observed 13 day period. As mentioned above, our model predicts that similar long-term variations on a time scale of several years may exist in GX 17+2, and may have been observed in 4U 1916−05 and NGC 6624.

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Note added in proof.—Recently W. Priedhorsky, L. Stella, and N. E. White (*IAU Circ.*, No. 4247 [1986]) have discovered an orbital period for 4U 1820−30 of $\sim$685 s, which has been confirmed by other groups (E. H. Morgan and R. A. Remillard, *IAU Circ.*, No. 4254 [1986]; J. P. Norris, P. Hertz, and K. S. Wood, *IAU Circ.*, No. 4257; M. Garcia, R. Burg, and J. Grindlay, *IAU Circ.*, No. 4259 [1986]). They suggest that this source consists of a white dwarf of $\sim 0.07\ M_\odot$ losing matter to a neutron star. If the 176 day periodicity is to be explained as a Mazeh-Shaham period, we find from numerical simulations that such a system will have an outer orbital period of order 1 day, depending on the mass of the third body and the relative angle of inclination of the orbital planes. This possibility will be discussed further in Paper III.

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