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ON THE EVOLUTION OF TIDAL CAPTURE X-RAY BINARIES: 4U 2127+12 (M15) TO 4U 1820−30 (NGC 6624)

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ABSTRACT

We present a new evolutionary scenario for X-ray binaries in globular clusters which begins with a tidal capture of a main-sequence star by a neutron star and ends with a white dwarf–neutron star system. For tidal captures of main-sequence stars into orbits too wide to begin mass transfer immediately, the subsequent evolution of the secondary can lead to a common envelope binary similar to what we suspect the 9 hr X-ray binary 4U 2127+12 in M15 to be. If the common envelope is thick enough, it may cause the neutron star and the white dwarf core of the secondary to spiral in, producing a detached white dwarf–neutron star system. Subsequently, gravitational radiation losses may evolve this into the configuration seen in the 11 minute X-ray binary 4U 1820−30 in NGC 6624. This model appears more likely on statistical grounds than formation by collision of a neutron star and a red giant. In some circumstances, the latter process may result in unstable mass transfer, which would result in coalescence rather than a binary system like 4U 1820−30.

Subject headings: clusters: globular — stars: binaries — stars: neutron — stars: white dwarfs — stars: X-rays

Recently, Stella, Priedhorsky, and White (1987) announced the discovery of a 685 s modulation of 4U 1820−30, the X-ray source in the globular cluster NGC 6624. This periodicity has been confirmed by other groups (Morgan and Remillard 1986; Garcia, Burg, and Grindlay 1986). The remarkable stability of the period over 10 yr, with $\dot{P}/P < 3 \times 10^{-7}$ yr^{-1} (Morgan *et al.* 1986), strongly suggests that this is an orbital period. Since the mass-losing secondary must fit inside its Roche lobe, it is most likely to be a white dwarf. No nondegenerate or semidegenerate hydrogen star would fit into an orbit that small (Stella, Priedhorsky, and White 1987; Nelson, Rappaport, and Joss 1986). Although the minimum period possible for a binary with a helium main-sequence secondary is in fact about 11 minutes (Savonije, de Kool, and van den Heuvel 1986), such an object would not be expected in a globular cluster as a result of single star evolution, since the necessarily massive progenitor would have long since become a white dwarf. It is possible that a helium main-sequence star might be formed by the coalescence of two helium white dwarfs (Hachisu, Eriguchi, and Nomoto 1986), which could evolve in a globular cluster from the tidal capture of a giant by a white dwarf. However, a system with a He main-sequence secondary and an 11 minute orbital period would have a mass-transfer rate of $\approx 10^{-7}$ $M_{\odot}$ yr^{-1} (Savonije, de Kool, and van den Heuvel 1986), considerably greater than that suggested by the X-ray observations. If 4U 1820−30 is a mass-transferring white dwarf–neutron star binary, it is the first such system discovered.

4U 2127+12, the X-ray source in the globular cluster M15, is the first globular cluster source for which an optical counterpart (AC 211) has been suggested (Auriere, Le Fevre, and Terzan 1984). Recently, an 8.5 hr period has been identified for this source both from optical (Naylor *et al.* 1986; Ilovaisky *et al.* 1986) and X-ray (Hertz 1986) data, thus confirming the identification. It has been previously suggested (Grindlay 1986) that this source is very luminous, but is obscured by a substantial corona surrounding the entire system. Given the large optical luminosity of AC 211 ($M_B \approx 0$), which is too luminous for either an accretion disk or an X-ray–heated secondary in a 9 hr orbit, and the large observed optical variations of ≈ 1.5 mag (Ilovaisky *et al.* 1986), we suggest that this source may have a thin common envelope. This is consistent with both the unusual variable low-energy X-ray absorption (Hertz and Grindlay 1983) and the possible mass loss suggested by the ~ -150 km s^{-1} velocities observed in the spectra of AC 211 (Naylor *et al.* 1986; Grindlay and Huchra 1987). We shall show that a common envelope stage is in fact expected as a precursor to a system like 4U 1820−30.

Tidal capture of a main-sequence star secondary of mass m_2 by a neutron star primary of mass m_1 will result in one of two kinds of systems: either X-ray luminous or dormant. It has usually been assumed that tidal capture will result in mass transfer from the secondary to the neutron star shortly or immediately after the capture takes place, while the secondary is still on the main sequence. However, if the secondary is captured at a larger distance, Roche lobe overflow will not occur until the secondary has expanded off the main sequence. Fabian, Pringle and Rees (1975), Press and Teukolsky (1977), Lee and Ostriker (1986), and McMillan, McDermott, and Taam (1987) have estimated the maximum distance of closest approach which will result in a tidal capture; all of these authors find values close to 3 times the radius R_2 of the captured star. Since the orbital radius after the system has circularized will be twice the distance of closest approach (when the two stars are on an approximately parabolic orbit) due to angular momentum conservation, a captured secondary will be able to expand to at most 2–3 times its initial radius (depending on the mass ratio of the system) before Roche lobe overflow will occur. It is therefore likely that a substantial fraction of captured main-sequence stars will experience a "dormant" phase following capture and will begin to overflow their Roche lobes as they leave the main-sequence. At this time they will have a very small ($\sim 0.1\ M_\odot$; see Mengel *et al.* 1979) degenerate core of primarily helium. The precise number of such systems as a fraction of the total number of tidal captures by neutron stars depends on such factors as at what point during the secondary's main-sequence lifetime the capture takes place, and on the effects on the structure of the secondary caused by the dissipation of the induced nonradial oscillations which caused the capture (McMillan, McDermott, and Taam 1987).

Since the semimajor axis of such a "dormant" binary formed by tidal capture cannot be greater than $\sim 6\ R_2$, the secondary must overflow its Roche lobe shortly after it leaves the main sequence. On the assumption that the thermal response of the star takes much longer than the dynamical time scale of the mass transfer, a necessary condition for stability of mass transfer is that the Roche lobe of the secondary should increase in size as mass is transferred. If this criterion is not satisfied, the secondary will rapidly become considerably larger than its Roche lobe, and a common envelope phase will result. Eggleton (1983) gives the following expression for the size of the Roche lobe:

$$R_L = a\frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}, \tag{1}$$

where R_L is the effective radius of the Roche lobe, a is the semimajor axis of the binary system, and $q = m_2/m_1$ is the mass ratio of the binary. For conservative mass transfer, we have

$$\frac{\dot{a}}{a} = -\frac{\dot{m}_2}{m_2}2(1 - q), \tag{2}$$

and in this case, the Roche lobe of the secondary will decrease in size (resulting in unstable mass transfer) as mass is transferred if $q \gtrsim 0.8$.

However, equation (2) may not be appropriate for the onset of mass transfer. As van den Heuvel and Bonsema (1984) have pointed out, viscous time scales in the disk are much longer than dynamical time scales in a close binary system, and therefore during the onset of mass transfer, when the disk is still growing, mass transfer will transform orbital angular momentum into Keplerian disk angular momentum. In this case we have (Kieboom and Verbunt 1981)

$$\frac{dJ_{\rm orb}}{dt} = (a - x_{\rm L})^2\omega\frac{dm_2}{dt} - x_L^2\omega\frac{dm_2}{dt}, \tag{3}$$

where $J_{\rm orb}$ is the orbital angular momentum in the binary orbit, ω is the frequency of the binary orbit, and $x_{\rm L}$ is the distance between the center of mass of the secondary and the inner Lagrangian point. Chanan, Middleditch, and Nelson (1976) have shown that $x_{\rm L}$ can be expressed implicitly as

$$q = \frac{(1 - b)^{-2} - (1 - b)}{b^{-2} - b}, \tag{4}$$

where $b = x_{\rm L}/a$. If we use equations (3) and (4) rather than equation (2), we find that mass transfer will be unstable for $q > 0.67$.

Thus for a 1.4 $M_\odot$ neutron star primary, mass transfer will be unstable at its onset if $m_2 > 1.0\ M_\odot$. If the mass of the neutron star is initially 1.2 $M_\odot$, as might be expected if it was originally formed by accretion induced collapse (Taam and van den Heuvel 1986; Grindlay 1987), then *any* main-sequence secondary which has already completed core hydrogen burning (i.e., with $m_2 \gtrsim 0.8\ M_\odot$) would be expected to evolve into a common envelope system. This common envelope phase will end when the small white dwarf core of the secondary and the neutron star have generated sufficient energy by spiraling in to eject the envelope. The spiraling-in time for a neutron star and a white dwarf embedded in an extended envelope may be as short as a few thousand years (cf. Bodenheimer and Taam 1986). However, the change in the mass ratio which occurs as the neutron star accretes matter will quickly reestablish stable mass transfer, as will the change from disk mass transfer to conservative mass transfer if a steady state disk is established. Whether (and on what time scale) the system subsequently evolves toward longer or shorter orbital periods will now depend on the balance between frictional forces, which will tend to drive the binary together, and the effects of mass transfer and angular momentum conservation, which would drive the system apart. The former is difficult to calculate but will depend on how dense a common envelope is established during the epoch of unstable mass transfer. The X-ray source in M15 may be an example of such a system which has started building up a common envelope and whose mass transfer is now driven both by evolution of the secondary and frictional losses.

If the common envelope is thick enough, frictional forces will dominate, and the binary will quickly spiral in. This stage will end when the envelope has become unbound (through energy generated by the spiraling-in of the two compact objects), and the system will enter a second "dormant" phase as a detached white dwarf–neutron star binary. Such a binary will continue to spiral in due to gravitational radiation until the white dwarf fills its Roche lobe and the system once again becomes X-ray–active. How long this second dormancy period lasts depends on the size of the orbit after the common envelope has been ejected.

If we assume that the compact objects have masses m_1 and m_2 with $m_1 \gg m_2$, and initial separation of r_i, and that the envelope has mass M and is initially in a shell at distance r_i from the primary, then, in simple energetic terms, the separation distance r_f at which the envelope becomes unbound from the binary will be

$$r_f \approx r_i\frac{m_2}{M + m_2}. \tag{5}$$

Consider, for example, a 0.8 $M_\odot$ secondary with radius

$R_2 \lesssim R_\odot$ captured by a 1.2 $M_\odot$ primary with a postcircularization separation of 2×10^{11} cm $= 3R_\odot$ ($P = 9$ hr). This period is similar to what is observed for AC 211 and would result in the secondary overflowing its Roche lobe only when it leaves the main sequence. From equation (5), the white dwarf core of 0.1 $M_\odot$ should spiral in to $r_f = 2.5 \times 10^{10}$ cm (where the orbital period is 31 minutes) by the time the common envelope is blown off.

The angular momentum loss through gravitational radiation, which will determine the time scale for the second dormancy period, is

$$\frac{1}{J}\frac{dJ}{dt} = -\frac{32}{5}\left(\frac{2\pi}{P_{\rm orb}}\right)^{8/3}\frac{G^{5/3}}{c^5}\frac{m_1 m_2}{(m_1+m_2)^{1/3}}. \quad (6)$$

In the case described in the preceding paragraph, integrating equation (6) to zero separation yields a time scale of $\approx 10^7$ yr. Such a system will therefore spiral in and become X-ray–active once again in a small fraction of the age of the cluster. Thus we are justified in considering secondaries which originally had $m_2 \approx 0.8$ $M_\odot$ as precursors to 4U 1820−30.

After the white dwarf spirals in far enough to fill its Roche lobe, the question of the stability of the mass transfer must again be considered. Bonsema and van den Heuvel (1984) have shown that disk mass transfer, which is expected when the white dwarf first overflows its Roche lobe, is unstable for $m_2 > 0.4$ $M_\odot$ for a 1.4 $M_\odot$ primary. Thus Verbunt's (1987) hypothesis that 4U 1820−30 might result from the collision between a giant and a neutron star is untenable if the degenerate core of the giant is more massive than 0.4 $M_\odot$; in this case, the two compact objects may rapidly coalesce (van den Heuvel and Bonsema 1984; Hachisu, Eriguchi, and Nomoto 1986). While the formal solution curves for R_2/R_L allow for the reestablishment of a stable solution when m_2 has been reduced to 0.1 $M_\odot$ (van den Heuvel and Bonsema 1984), the catastrophic events likely to be associated with the disruption of most of the white dwarf and the transfer of $\gtrsim 0.3$ $M_\odot$ into the Roche lobe of the neutron star in a matter of seconds suggest that these solutions may not be physically relevant. Thus 4U 1820−30 is unlikely to have formed from a collision of a neutron star with a horizontal-branch star, or a star significantly evolved up the giant branch.

For $0.005 < m_2 < 0.4$, Bonsema and van den Heuvel conclude that mass transfer will be stable for the case of conservative or disk mass transfer. However, we show that a degenerate helium white dwarf secondary with $m_2 \gtrsim 0.1$ $M_\odot$ cannot transfer mass conservatively to a neutron star primary due to the Eddington accretion limit. If the white dwarf secondary just fills its Roche lobe, the mass-radius relation (Chandresekhar 1939) leads to the following relation between the orbital period of the system and the mass of the secondary (Rappaport, Joss, and Webbink 1982, hereafter RJW):

$$P_{\rm orb} = 0.77(1+X)^{5/2}(m_2/M_\odot)^{-1}\ \text{minutes}, \quad (7)$$

where X is the fractional hydrogen abundance and m_2 is the mass of the secondary. We will assume that the secondary is a He white dwarf as might be expected to be produced as the core of a nascent red giant (although relaxing this assumption will not change the general argument). In this case, equation (7) yields a value of 0.07 $M_\odot$ for the white dwarf secondary in 4U 1820−30, suggesting that it may already have transferred a substantial fraction (~ 30%) of its mass onto the neutron star. Use of a more realistic mass-radius relation for low-mass white dwarfs leads to an even lower mass for a pure helium white dwarf secondary of 0.055 $M_\odot$ (Stella, Priedhorsky, and White 1987).

We can then use a version of equation (29) of RJW to determine the mass transfer rate of the system:

$$\frac{\dot m_2}{m_2} = \left[(\dot J/J)_{\rm GR}\right]\left\{\frac{2}{3} - \frac{q(1-\beta)}{3(1+q)} - [\beta q + \alpha(1-\beta)(1+q)]\right\}^{-1}, \quad (8)$$

where β is the ratio of mass accreted on the neutron star to mass lost from the secondary, and α is the specific angular momentum of material lost to the system in units of $2\pi a^2/P_{\rm orb}$ and $(\dot J/J)_{\rm GR}$ is determined from equation (6). Figure 1 shows $\dot m_2$ as a function of m_2 for the conservative ($\beta = 1$) case with a helium white dwarf secondary and a 1.4 $M_\odot$ primary. (We now assume a 1.4 $M_\odot$ primary, though this is not critical, since the neutron star will have accreted some mass from the secondary.) We also see from Figure 1 that for $m_2 > 0.1$ $M_\odot$ the mass transfer rate is above the Eddington limit of 6×10^{-8} $M_\odot$ yr^{-1} for helium accreting onto a neutron star of 1.4 $M_\odot$. The mass transfer rate for a 0.07 $M_\odot$ secondary ($\approx 10^{-8}$ $M_\odot$ yr^{-1}) is encouragingly close to what is expected from the typical X-ray luminosity (e.g., Stella, Priedhorsky, and White 1987). Given this rate of mass transfer, the current X-ray luminous phase of 4U 1820−30 has persisted for less than 10^7 yr, or $\lesssim 10$% of the time since the initial (main-sequence secondary) phase of X-ray emission. This is a very short time scale compared to the lifetime of the cluster (although the rate of mass transfer will decrease dramatically in the future as the components of the binary spiral apart). If the X-ray lifetimes of some (i.e., initially dormant) tidal capture binaries are generally this short, their frequent occurrence might necessitate a larger population of neutron stars in globular clusters than has generally been assumed (e.g., Grindlay 1987).

If mass is being lost by the secondary faster than it can be accreted by the primary, then some matter may accumulate inside the Roche lobe of the primary in a thick accretion disk. Eventually matter must be lost by the system, i.e., β will become smaller than unity. If the decrease in β led to a *larger* mass transfer rate onto the neutron star, then the mass transfer will be unstable, since the Eddington limit will be further exceeded, forcing β to become still lower and $\dot m$ still larger. Thus a necessary condition for stable mass transfer if $\dot m > \dot m_{\rm Edd}$ is that the amount of mass accreted by the neutron star ($\beta \dot m$) be smaller than the amount of mass which would have been transferred in the conservative case [$\dot m(\beta = 1)$]. From equation (8) we see that this stability criterion can be expressed as

$$\left(\frac{2}{3} - q\right)\beta < \frac{2}{3} - \frac{q(1-\beta)}{3(1+q)} - \beta q - \alpha(1-\beta)(1+q). \quad (9)$$

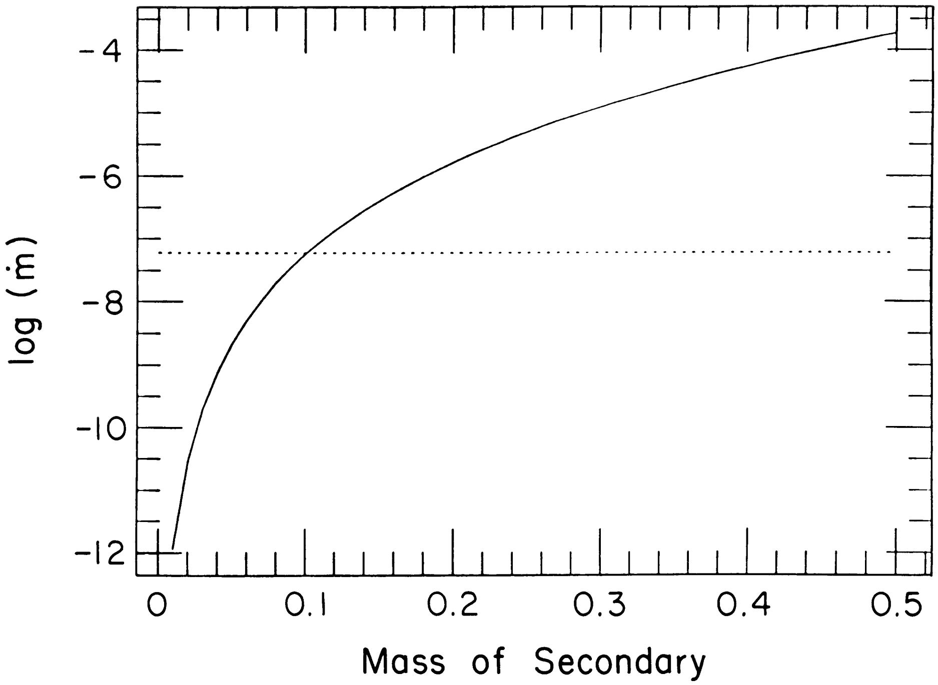

FIG. 1.—Value of $\dot{m}$ from eq. (8) for a Roche lobe–filling white dwarf orbiting a 1.4 $m_{\odot}$ neutron star for various masses of the secondary. We assume conservative mass transfer and a $\frac{1}{3}$ power-law mass-radius relation for the white dwarf (which will not be accurate for very low masses). Note that for masses of the white dwarf greater than 0.1 $m_{\odot}$, the mass accretion rate will be considerably greater than the Eddington limit (*dotted line*).

or equivalently as a requirement on α,

$$\alpha_{\text{crit}} < \frac{2 + q}{3(1 + q)^2}, \quad (10)$$

for any $\beta < 1$. This is the same as RJW's stability criterion for the $\beta = 0$ case, but due to its dependence on $\dot{m}$, β drops out of our formulation. Physically, this result says that if the mass leaving the system takes a sufficient amount of angular momentum along with it, the binary will not be able to expand fast enough to accommodate the growing secondary, and mass transfer will be unstable.

The specific angular momentum carried off by the material lost from the system (i.e., α) depends on from where it is lost. If the excess matter is expelled directly from the Roche lobe of the primary, for example, by a jet, then the specific angular momentum will be low, and the mass transfer is likely to be stable. On the other hand, if a common envelope is again formed, either from a wind from the disk or because the secondary overflows its Roche lobe at points other than the L_1 point, mass may be lost from the outer Lagrangian surface, in which case it will carry off much higher angular momentum, and the mass transfer is likely to be unstable. We note, for example, that the center of mass of the secondary has a specific angular momentum which will be greater than α_{crit} for $q < 1$. If mass is lost from the system with $\alpha > \alpha_{\text{crit}}$, then white dwarf secondaries with $m_2 \gtrsim 0.09\ M_{\odot}$ will not be able to evolve into systems like 4U 1820−30, and the giant collision hypothesis becomes extremely implausible.

In comparing our scenario for the formation of 4U 1820−30 with that the collision of a red giant with a neutron star suggested by Verbunt (1987), we note that the initial capture of the $\gtrsim 0.8\ M_{\odot}$ main-sequence star we require can occur *at any time* during the history of the cluster. If the circularized binary orbit is large enough that the secondary does not overflow its Roche lobe before core hydrogen burning is complete and the neutron star was previously formed by accretion induced collapse and therefore has $m \approx 1.2\ M_{\odot}$, the eventual mass transfer will be unstable, and the system will necessarily go through a terminal phase similar to 4U 1820−30. Collision with a giant, on the other hand, must occur in the brief time interval when the mass of the core is between 0.07 and 0.4 $M_{\odot}$ (or perhaps only 0.07–0.1 $M_{\odot}$, as discussed above). Given the short expected lifetimes of 4U 1820−30 and similar systems, the giant must also have had an initial mass of 0.8 $M_{\odot}$. The relative probabilities of these events can be expressed as an appropriate capture cross section integrated over the main-sequence lifetime of a 0.8 $M_{\odot}$ star divided by a collision cross section integrated over the lifetime of a giant with $m_{\text{core}} < 0.4\ M_{\odot}$.

Since gravitational focusing will be important in globular clusters (Fabian, Pringle, and Rees 1975), the cross sections will scale with the distance of closest approach. While any tidal capture of a giant will result in subsequent mass transfer, which, as we have described, could lead to a common envelope stage and a neutron star–white dwarf binary, the resulting detached white dwarf–neutron star binary will be too far apart to spiral into contact in a Hubble time. Therefore we will follow Verbunt (1987) and consider only collisions of the neutron star with red giants, for which the cross section will be proportional to the radius of the giant. Appropriate tidal captures for the scenario described in this

Letter will be those with closest approaches between the maximum distance which will result in a bound system (estimated by McMillan, McDermott, and Taam 1987 to be 3.3 R_2), and the distance below which the secondary will overflow its Roche lobe while still on the main-sequence. Since the orbital size will double during circularization, and $R_L/a(q = 0.67) = 0.34$, this minimum distance of closest approach will be $\approx 3\ R_{\rm TAMS}/2$, where $R_{\rm TAMS}$ is the stellar radius at the terminal-age main-sequence. Thus we can write

$$\frac{P_{\rm MS}}{P_{\rm RG}} = \frac{\int_{t_{\rm MS}} R(t) f(t)\, dt}{\int_{t_{\rm giant}} R(t)\, dt}, \tag{11}$$

where $P_{\rm MS}$ and $P_{\rm RG}$ are the probabilities that 4U 1820−30 could have arisen through interaction with a main-sequence star and a red giant respectively, $t_{\rm MS}$ is the time a 0.8 $M_\odot$ star spends on the main-sequence (which will be close to the age of the cluster), $t_{\rm giant}$ is the time such a star stays on the giant branch prior to its core becoming larger than 0.4 $M_\odot$, $R(t)$ is the radius of the captured giant or main-sequence star, and

$$f(t) = \max\left\{0, \left[3.3 - \frac{3}{2}\frac{R_{\rm TAMS}}{R(t)}\right]\right\}. \tag{12}$$

Interpolating between the 0.7 $M_\odot$ and 0.9 $M_\odot$ models of Sweigart and Gross (1978) for giants and Mengel *et al.* (1979) for main-sequence stars (using $Z = 0.001$ in both cases) with weights such that the interpolated model has a main-sequence lifetime of 1.4×10^{10} yr, we find that

$$P_{\rm MS}/P_{\rm RG} \approx 6. \tag{13}$$

The analysis leading to equation (13) ignores many complicating effects, including the changes in stellar structure resulting from capture (McMillan, McDermott, and Taam 1987) and the changing density of the cluster. Nevertheless, the long time a 0.8 $M_\odot$ star spends on the main-sequence relative to its giant lifetime makes it more likely that 4U 1820−30 originated as a main-sequence neutron star binary which evolved through a common envelope stage, possibly similar to AC 211 in M15 today. In this case, the neutron star may be as old as 10^{10} yr, which would impose constraints on magnetic field decay in neutron stars if the magnetospheric models for the quasi-periodic oscillations (observed from 4U 1820−30) are correct (see van der Klis 1986).

Since the secondary of 4U 1820−30 is a white dwarf, its luminosity will be dominated by the accretion luminosity. This can be no greater than the Eddington limit for the neutron star and appears from X-ray observations (Priedhorsky and Terrell 1984) to be only $\approx 6 \times 10^{37}$ ergs s^{-1}. The accretion luminosity must emerge from inside the Roche lobe of the neutron star. The maximum optical luminosity (emitted between 300 and 1000 nm) will occur if the X-ray luminosity were completely reprocessed, emerging as blackbody radiation from the entire Roche lobe. This maximum optical luminosity will be $\sim 1\ L_\odot$. At the distance of NGC 6624, this would result in an apparent magnitude of $m_V \gtrsim 20$. In the dense core of NGC 6624, such an object would be essentially impossible to observe from the ground (Bailyn *et al.* 1987). We also note that if 4U 2127+12 has undergone the first dormant phase suggested by our scenario, and therefore has an age comparable to the main-sequence lifetime of the secondary, then it is extremely unlikely that it is now being ejected from M15 at ~ 150 km s^{-1} as suggested by Naylor *et al.* (1986). Rather, this apparent velocity would *require* outflowing gas, which would be a natural consequence of our common envelope model.

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