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THE NATURE AND EVOLUTIONARY HISTORY OF GRO J1744−28

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ABSTRACT

GRO J1744−28 is the first known X-ray source to display bursts, periodic pulsations, and quasi-periodic oscillations. This source may thus provide crucial clues that will lead to an understanding of the differences in the nature of the X-ray variability from various accreting neutron stars. The orbital period is 11.8 days, and the measured mass function of $1.31 \times 10^{-4}\ M_\odot$ is one of the smallest among all known binaries. If we assume that the donor star is a low-mass giant transferring matter through the inner Lagrange point, then we can show that its mass is lower than $\sim 0.7\ M_\odot$ and probably closer to 0.25 $M_\odot$. Higher mass, but unevolved, donor stars are shown to be implausible. We also demonstrate that the current He core mass of the donor star lies in the range of 0.20–0.25 $M_\odot$. Thus, this system is most likely in the final stages of losing its hydrogen-rich envelope, with only a small amount of mass remaining in the envelope. If this picture is correct, then GRO J1744−28 may well represent the closest observational link that we have between the low-mass X-ray binaries and recycled binary pulsars in wide orbits.

We have carried out a series of binary evolution calculations and explored, both systematically and via a novel Monte Carlo approach, the range of initial system parameters and input physics that can lead to the binary parameters of the present-day GRO J1744−28 system. The input parameters include both the initial total mass and the core mass of the donor star, the neutron-star mass, the strength of the magnetic braking, the mass-capture fraction, and the specifics of the core mass/radius relation for giants. Through these evolution calculations, we compute probability distributions for the current binary system parameters (i.e., the total mass, core mass, radius, luminosity, and K-band magnitude of the donor star, the neutron star mass, the orbital inclination angle, and the semimajor axis of the binary). Our calculations yield the following values for the GRO J1744−28 system parameters (with 95% confidence limits in parentheses): donor star mass: 0.24 $M_\odot$ (0.2–0.7 $M_\odot$); He core mass of the donor star: 0.22 $M_\odot$ (0.20–0.25 $M_\odot$); neutron-star mass: 1.7 $M_\odot$ (1.39–1.96 $M_\odot$); orbital inclination angle: 18° (7°–22°); semimajor axis: 64 lt-s (60–67 lt-s); radius of the donor star: 6.2 $R_\odot$ (6–9 $R_\odot$); luminosity of donor star: 23 $L_\odot$ (15–49 $L_\odot$); and long-term mass transfer rate at the current epoch: $5 \times 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$ (2×10^{-10} to $5 \times 10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$).

We deduce that the magnetic field of the underlying neutron star lies in the range of $\sim 1.8 \times 10^{11}$ G to $\sim 7 \times 10^{11}$ G, with a most probable value of 2.7×10^{11} G. This is evidently sufficiently strong to funnel the accretion flow onto the magnetic polar caps and suppress the thermonuclear flashes that would otherwise give rise to the type I X-ray bursts observed in most X-ray bursters. We present a simple paradigm for magnetic accreting neutron stars wherein X-ray pulsars, GRO J1744−28, the Rapid Burster, and the type I X-ray bursters may form a continuum of possible behaviors among accreting neutron stars, with the strength of the neutron-star magnetic field serving as the crucial parameter that determines the mode of X-ray variability from a given object.

Subject headings: binaries: close — binaries: general — stars: evolution — stars: individual (GRO J1744−28) — stars: neutron — X-rays: stars

1. INTRODUCTION

The recently discovered hard X-ray transient GRO J1744−28 (Fishman et al. 1995) is the first known X-ray source to display both bursts and periodic pulsations. The ∼0.5 s pulsations, the existence of which demonstrates that the underlying object is an accreting neutron star with a magnetic field sufficiently strong to funnel the accretion flow onto its magnetic polar caps, have been found to be present in both the burst emission (Kouveliotou et al. 1996a) and the persistent emission between bursts (Finger et al. 1996). This source may thus prove to be a Rosetta stone that will link our understanding of the X-ray pulsars, the X-ray bursters, and their possible descendants, binary millisecond pulsars with low-mass companions. The spectra of the bursts and persistent emission are very similar (Briggs et al. 1996; Swank 1996), with a characteristic photon energy of ∼14 keV (Swank 1996), which is comparable to most other X-ray pulsars but higher than other X-ray bursters. The persistent emission also displays quasi-periodic oscillations (QPOs) (Zhang et al. 1996), which may also result from the presence of a magnetic field in the neutron star. The pulse period has been found to be decreasing at a rate of $\sim 6 \times 10^{-5}\ \mathrm{s\ yr^{-1}}$ (Finger, Wilson, & van Paradijs 1996); if the neutron star has a canonical mass of 1.4 $M_\odot$ (Joss & Rappaport 1976) and a radius of 10 km, this spinup rate corresponds to a luminosity of $\sim 4 \times 10^{38}\ \mathrm{ergs\ s^{-1}}$. Combined with the upper limit to the persistent X-ray flux of $\sim 2 \times 10^{-7}\ \mathrm{ergs\ cm^{-2}\ s^{-1}}$ that was observed (Swank 1996; Fishman et al. 1996) at about the same time that the spinup rate was measured, this implies a source distance of ∼6 kpc; the relatively large distance is consistent with the proximity of the source to the direction of the galactic center

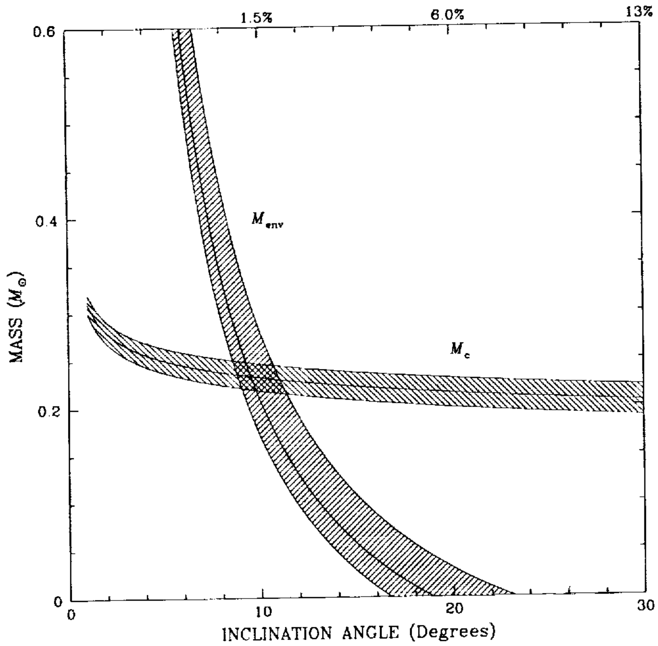

FIG. 1.—Core mass, M_c, and envelope mass, M_{env}, of the giant companion star in the GRO J1744−28 system as functions of the orbital inclination angle, i. The indicated spread in values for both quantities is a result of the uncertainty in the mass, M_{ns}, of the neutron star and in the radius of the giant as a function of its core mass (see text). The curve running through the center of each band indicates the most probable values for M_c and M_{env}, respectively; to generate this curve, we assumed that $M_{ns} = 1.4$ $M_\odot$. The scale at the top of the figure shows the a priori probability that a system chosen at random from an ensemble of systems with isotropically oriented inclination angles would have a value of i equal to or less than the indicated value.

(∼8 kpc). The detection of Doppler variations in the pulse period (Finger et al. 1996) reveals that the neutron star is a member of a binary system, with an orbital period of 11.8 days and with a mass function [$f(M) = 1.31 \times 10^{-4}\ M_\odot$] that is one of the smallest among all known binaries. The very small mass function implies either that we are viewing the system almost exactly pole-on, or that the companion star is of very low mass (∼0.2–0.6 $M_\odot$; for details and references, see § 2). From a variety of arguments, Lewin et al. (1996) and Joss & Rappaport (1996, hereafter JR) have inferred that the bursts are of type II and thus result from an instability in the accretion flow onto the neutron star (see also Kouveliotou et al. 1996b; Daumerie et al. 1996); hence, GRO J1744−28 is only the second system (after the Rapid Burster; see Lewin et al. 1976) known to emit type II bursts on a regular basis.

In this work we investigate the evolutionary paths leading to the present day GRO J1744−28 system (see Joss & Rappaport 1996 for an earlier study). Our calculations lead to further interpretation of the observations (e.g., the constituent masses of the binary, the nature of the donor star, long-term average mass-transfer rate, and the neutron-star magnetic field). Furthermore, our results help to place GRO J1744−28 into an evolutionary context with other low-mass X-ray binaries; both bursters and low-mass binary X-ray pulsars. Finally, our studies indicate where this system is likely to evolve in the future; we find, in particular, that GRO J1744−28 may provide an interesting link with recycled radio pulsars in wide binary systems.

Our calculations comprise systematic and Monte Carlo explorations of the evolutionary paths that lead to the current GRO J1744−28 system. These calculations allow us to derive probability distributions for the initial parameters of the mass-transfer binary, and for the system at the current epoch. Our results, in combination with other arguments, also enable us to speculate on the seemingly unique nature of the accretion process in this source and to propose a simple paradigm for magnetic accreting neutron stars and the singular placement of GRO J1744−28 within this paradigm.

2. CURRENT STATUS OF THE BINARY SYSTEM

The very small mass function of the GRO J1744−28 system implies either that we are viewing the system almost exactly pole-on (Daumerie et al. 1996), a possibility that has a very small a priori probability, or that the companion star has a very low mass (∼0.2 $M_\odot$; Daumerie et al. 1996; Lamb, Miller, & Taam 1996; Sturner & Dermer 1996). In the latter case, a viable model for the binary is one in which the mass transfer is driven by the internal evolution of a giant companion that has already lost most of its hydrogen-rich envelope via the mass-transfer process (Lamb et al. 1996; Daumerie et al. 1996). This type of evolutionary scenario (Taam 1983; Webbink, Rappaport, & Savonije 1983, hereafter WRS) has been adapted (Joss & Rappaport 1983; Paczyński 1983; Savonije 1983; Joss, Rappaport, & Lewis 1987, hereafter JRL; Rappaport et al. 1995) as a model for the prior evolutionary history of wide-binary radio pulsars with nearly circular orbits.

By combining the known orbital period and mass function of the GRO J1744−28 system with (1) Kepler's third law, (2) the relation between the orbital separation and the effective radius of the Roche lobe of the secondary (giant) star, (3) the assumption that the Roche lobe is filled during mass transfer, and (4) the core mass–radius relation for low-mass giants (Refsdal & Weigert 1971; WRS; JRL; Rappaport et al. 1995), we can derive useful constaints on the masses of the core and residual hydrogen-rich envelope as functions of the orbital inclination, i. First, using the measured mass function of GRO J1744−28, we obtain

$$(M_c + M_{env})^3 \sin^3 i/(M_c + M_{env} + M_{ns})^2 \simeq 1.3 \times 10^{-4}\ M_\odot\ , \quad (1)$$

where M_c and M_{env} are the mass of the hydrogen-exhausted core of the giant and the mass of the surrounding envelope (i.e., the remainder of the star), respectively, in units of solar masses, $M_g = (M_c + M_{env})$ being the total mass of the giant, and M_{ns} is the mass of the neutron star, also in solar units. Second, the combination of Kepler's third law with the expression (Kopal 1959) for the effective radius of the Roche lobe of the giant yields

$$(0.46)^3 G(M_c + M_{env})/R_g^3 \simeq (2\pi/P_{orb})^2\ , \quad (2a)$$

or

$$(M_c + M_{env})/R_g^3 \simeq 1.0 \times 10^{-3}\ , \quad (2b)$$

where R_g is the radius of the giant in units of solar radii and P_{orb} is the orbital period. Third, there is a fairly tight relationship between R_g and M_c for low-mass giants; adapting the results of Rappaport et al. (1995) to cases where

$M_c < 0.25\, M_\odot$ (see § 4), we find that this relationship can be well fitted by

$$\log R_g \simeq 0.031 + 1.718 M_c + 8.04 M_c^2 . \quad (3)$$

Here R_g has an uncertainty of a factor of ~ 1.3, owing to the unknown metallicity and initial main-sequence mass of the giant and to the uncertainties inherent in the mixing-length theory of convection. We solve equation (1) by use of the Newton-Raphson method, in order to obtain $M_c + M_{\rm env}$ as a function of i for any chosen value of $M_{\rm ns}$. The result is then substituted into equation (2) to obtain R_g as a function of i. Finally, we substitute into equation (3) to obtain both M_c and $M_{\rm env}$ as functions of i alone. The results of this calculation are shown in Figure 1.

The spread in the values of M_c and $M_{\rm env}$ in Figure 1 reflects the uncertainty in R_g at any given value of M_c and the uncertainty in $M_{\rm ns}$, which, for the purpose of this calculation, we take to lie in the range from 1.2 to 1.9 $M_\odot$. As can be seen from the figure, the largest permissible inclination angle is $\sim 22°$; for an isotopic distribution of orbital inclinations, the a priori probability for a given system to have $i < 20°$ is $\sim 6\%$. It is noteworthy that the largest, and hence most probable, inclination angles correspond to values of $M_{\rm env}$ approaching zero. This suggests the possibility that the GRO J1744−28 system is in the final stages of mass transfer. Once accretion has ceased the magnetic field strength may be marginally sufficient (Ruderman & Sutherland 1975), at the current spin period of the neutron star, to cause the neutron star to turn on as a wide-binary radio pulsar with a nearly circular orbit (Joss & Rappaport 1983; JRL; Rappaport et al. 1995).

3. THE EVOLUTIONARY SCENARIO

The primordial binary that was the progenitor of GRO J1744−28 probably consisted of a primary with a mass in the range of $\sim$8–15 $M_\odot$ (the immediate or indirect progenitor of the neutron star), and a secondary with a mass in the range of 0.8–3 $M_\odot$ (the progenitor of the present-day donor star), in a wide orbit. At some point, the internal evolution of the primary caused it to expand sufficiently to begin transferring its envelope to the secondary via Roche lobe overflow. However, the thermal timescale of the secondary would have been too long for the star to incorporate the mass into its envelope. The result, therefore, was probably a common-envelope phase (see, e.g., Sparks & Stecher 1974; Paczyński 1976; Taam, Bodenheimer, & Ostriker 1978; Meyer & Meyer-Hofmeister 1979; Livio & Soker 1988; Webbink 1992; Iben, Tutukov, & Yungelson 1995) wherein the secondary spiraled into the envelope of the primary and ejected it. The resultant supernova progenitor would then have fallen into one of two basic categories: (1) a massive ($>2.3\, M_\odot$) He core which evolved to explode as a supernova (Habets 1985; Bhattacharya & van den Heuvel 1991, and references therein) and left a remnant neutron star; or (2) an ONeMg white dwarf which later grew to the Chandrasekhar limit (see below). In either case, the resultant neutron star could remain bound in orbit with the original secondary star (Verbunt & van den Heuvel 1995).

In the latter scenario, the white dwarf would have to accrete matter from its companion during the second phase of mass transfer until it reaches the Chandrasekhar limit and collapses in an accretion-induced collapse event (AIC; see, e.g., Canal & Schatzman 1976; Nomoto 1981, 1986, 1987a, 1987b; Canal et al. 1986) to form the neutron star that we now observe in GRO J1744−28. In order for the white dwarf to grow in mass, the mass accretion rate must fall within a relatively narrow range near $\sim 5 \times 10^{-7}\, M_\odot$ yr^{-1} (Paczyński 1970a, 1970b; Uus 1970; Iben 1982; Nomoto 1986). A natural way for the system to attain such high transfer rates is via thermal-timescale mass transfer from a donor star that has a mass of $\sim 2\, M_\odot$ (i.e., considerably more massive than the white dwarf; see, e.g., van den Heuvel. 1992; Rappaport, Di Stefano, & Smith 1994). The mass of the white dwarf could grow to the Chandrasekhar limit once it has accreted about $\sim 0.3\, M_\odot$; the orbital period during this accretion phase would shrink to about 1 day. Once AIC has occurred, the evolution continues; the transfer rate onto the neutron star would now exceed the Eddington limit until the mass ratio of the binary is reduced to near unity, at which time the evolution would continue along a path very similar to the one we describe below and utilize in the remainder of this paper. The main reason for considering this scenario (van Paradijs et al. 1996) is that it might lead to an evolutionary path to the present GRO J1744−28 system without the accretion of a substantial amount of matter onto the neutron star. This is a concern in scenarios that invoke the suppression of neutron-star magnetic fields by the accretion of a substantial amount of matter (Bhattacharya & van den Heuvel 1992) since the present magnetic field in GRO J1744−28 is still substantial. However, in the picture outlined above, the neutron star must go on to accrete a significant amount of mass in order for the donor star to be as low in mass as is inferred (see §§ 4 and 5). Therefore, it is not at all clear that an evolutionary pathway involving AIC solves the problem of suppression of the neutron star magnetic field by accretion.

In the first scenario described above, the neutron star forms directly from the continued evolution and explosion of the uncovered He core of the primary (Bhattacharya & van den Heuvel 1991; Verbunt & van den Heuvel 1995; and references in these works). Such a system can remain bound even with the lowest mass secondary that we consider ($\sim 0.8\, M_\odot$), as long as the He star is not too massive (Habets 1985), and as long as there is no large momentum impulse from the supernova explosion (see Verbunt & van den Heuvel 1995, and references therein). The second phase of mass transfer (this time to the newly formed neutron star) will commence once the secondary star has evolved sufficiently and/or the binary orbit has decayed due to angular momentum losses. Once this occurs, there are two cases to consider: either $M_g > M_{\rm ns}$ (case 1) or $M_g < M_{\rm ns}$ (case 2). In the former case, the mass transfer will take place on the thermal timescale of the donor star (Paczyński 1971; Webbink 1979; Savonije 1983b; Pylyser & Savonije 1988, 1989), resulting in a super-Eddington accretion rate. This tends to lead to a shrinking orbit and orbital periods shorter than a day. If the orbit is already wide at the onset of mass transfer in case (1), the mass transfer is likely to be unstable on a dynamical timescale (see, e.g., Paczyński 1967; Kippenhan, Kohl, & Weigert 1967; Webbink 1979, 1992). At some point in the history of any surviving binary, the masses of the two stars will become more nearly equal, and the subsequent evolution will proceed in the same manner as in case 2.

Thus, a good starting point for the binary evolution calculations is a donor star with mass $\sim 1\, M_\odot$ in an orbit with a neutron star with a period of about a day. The evolution will be driven by the nuclear evolutionary expansion of the giant and enhanced by orbital angular momentum losses, such as magnetic braking.

In the following section, we systematically explore a wide range of initial binary parameters and input physics. In particular, we study the effects of the initial mass of the donor star, the initial core mass of the donor star, the strength of the magnetic braking, and the mass-capture fraction on the evolution of the binary system. The range of parameters that we consider is given in Table 1. In § 5, we carry out a Monte Carlo exploration of the paths to the present day GRO J1744−28 system that covers an even wider range of initial conditions and input parameters.

4. SYSTEMATIC BINARY EVOLUTION CALCULATIONS

The binary evolution calculations that we have carried out in the present work utilize the technique developed by WRS, JRL, and Rappaport et al. (1995). In this approach, the properties of the low-mass giant are taken to be nearly unique functions of its core mass only (see also Refsdal & Weigert 1971). In this case, the core mass–radius and the core mass–luminosity relations form a closed set of equations that allow the evolution of the donor star to be followed very efficiently. The core mass–radius relation derived by Rappaport et al. (1995) holds for a wide range of core masses from 0.15 $M_\odot$ to $>1.0\ M_\odot$ and is given by

$$R_g \simeq 4590 M_c^{4.5}/(1 + 4M_c^4) + R_0(M_g) \qquad (4)$$

(see also Eggleton 1997 for an earlier version of this expression), where $R_0(M_g)$ is the radius of a star of mass M_g that is on the main sequence. This relation was obtained by a fit to models that spanned a wide range of chemical compositions and envelope masses for the giant, as well as a range of values for the convective mixing length. Thus, this relation is especially useful if the detailed prior history of the giant is unknown. However, it is not particularly accurate for low core masses ($<0.25\ M_\odot$), simply because it was designed to cover a broad range of core masses. For this reason, we have refit the theoretical results of Rappaport et al. (1995) as well as some supplementary models provided by L. Nelson (1996, private communication) to derive the core mass–radius relation given in equation (3) above for use in the present study, where the core masses involved are always below $\sim 0.25\ M_\odot$. The complementary expression for the core mass–luminosity relation was taken from Eggleton (1997):

$$L_g \simeq 10^{5.3} M_c^6/(1 + 10^{0.4} M_c^4 + 10^{0.5} M_c^5) + L_0(M_g) \quad (5)$$

(see also Eggleton 1966; Paczyński 1970; Refsdal & Weigert 1971), where $L_0(M_g)$ is the luminosity of a star of mass M_g that is on the main sequence.

The equation that we utilized to govern the mass-loss rate from the donor star was a standard one (see, e.g., Rappaport, Verbunt, & Joss 1983, hereafter RVJ):

$$-\frac{\dot{M}_g}{M_g} = \left[\frac{1}{2}\left(\frac{\dot{R}}{R}\right)_{\rm ev} - \left(\frac{\dot{J}}{J}\right)\right] \Big/ \left[\left(\frac{5}{6} + \frac{\xi_{\rm ad}}{2}\right) - \frac{(1-\beta)}{3(1+q)} - \frac{(1-\beta)\alpha(1+q)+\beta}{q}\right], \qquad (6)$$

where $(\dot{R}/R)_{\rm ev}$ is the fractional rate of change in the donor radius due to (nuclear) evolutionary changes in the stellar structure, $(\dot{J}/J)$ is the fractional rate of loss of angular momentum from the binary orbit due to effects *other than* mass loss, $q \equiv M_{\rm ns}/M_g$ is the mass ratio, β is the fraction of the mass lost by the donor that is captured by the neutron star, and α is the specific angular momentum, in dimensionless form, of the material lost from the binary system. The quantity $(\dot{R}/R)_{\rm ev}$ was calculated from equations (3) and (5); in this context, equation (5) implicitly gives the rate of growth of the core mass through L_g. Angular momentum losses, $(\dot{J}/J)$, that are independent of mass loss, are taken to be due to the effects of magnetic braking (gravitational radiation losses are unimportant in binary systems with orbital periods greater than 1 day). For angular momentum losses due to magnetic braking, we utilized the Verbunt & Zwaan (1981) prescription as parameterized by RVJ; for the parameter values, we chose $\gamma = 4$ and f spanning the range from 0 to greater than 2. The former parameter is the (uncertain) power of the stellar radius on which the braking strength depends, and the latter is an overall multiplicative coefficient (with $f = 1$ corresponding to the value used by RVJ). For matter ejected from the system, we took α to be the specific angular momentum of the neutron star; in our units we then have $\alpha = 1/(1+q)^2$.

The effects of X-ray heating of the donor star (i.e., changes in the surface boundary conditions and/or the production of a thermally driven stellar wind; see Podsiadlowski 1991; Harpaz & Rappaport 1991, 1994; Eichler & Ko 1988; Ruderman, Shaham, & Tavani 1989) were not considered. Such effects are likely to be the largest near the initial phases of the binary evolution. Later in the evolution, closer to the epoch of interest, the X-ray luminosities will have dropped off substantially (see § 2), the orbital separation will grow to greater than 25 $R_\odot$ (so that the X-ray flux on the companion falls considerably), and the core becomes sufficiently evolved (reaching a mass of $\sim 0.25\ M_\odot$) that the radius attained by the star is less susceptible to X-ray heating than is that of a main-sequence star.

For a given evolution run, the initial masses of the donor star and its core, the mass of the neutron star, the mass capture fraction, and the multiplicative coefficient for magnetic braking were all specified. The first three of these

TABLE 1

MODEL PARAMETERS[a]

Parameter[b]	Lowest Value	Highest Value	Step Size
Initial core mass (M_c)	0.1 $M_\odot$	0.24 $M_\odot$	0.01 $M_\odot$
Initial donor mass (M_g)	0.8 $M_\odot$	1.3 $M_\odot$	0.1 $M_\odot$
Capture fraction (β)	0.0	1.0	0.25
Magnetic braking factor (f)......	0.0	2.0	0, 0.25, 0.5, 1, 2

[a] The initial mass of the neutron star was fixed at 1.4 $M_\odot$.

[b] The nominal values for the parameters were taken to be $M_c = 0.15\ M_\odot$, $M_g = 1.0\ M_\odot$, $\beta = 0.5$, and $f = 1$, respectively; these are the values that were used while another parameter was being varied.

parameters determines the orbital period at which mass transfer commences. The subsequent evolution was followed numerically, in sufficiently small time steps that the fractional change in the core mass was never greater than 10^{-3} and the fractional change in the mass of the donor star was never greater than 3×10^{-3} on any given step. The evolution was followed until the hydrogen-rich envelope of the donor star was exhausted (lost from the binary, transferred to the neutron star, or accreted onto the core after undergoing nuclear burning).

Our approach was to hold all the input parameters fixed at the nominal values given in Table 1, except for one parameter which we varied over the range specified in Table 1. One evolutionary run was made for each variation of this parameter. When this set of runs was completed, we computed another set of runs where a different input parameter was varied, and so forth. The results are shown in Figures 2–5.

In Figure 2 we show the evolution of the mass transfer rate, orbital period, and donor mass, for each of 11 values of the initial core mass of the giant, spanning the range given in Table 1. Among the parameters we varied, this range of variation of the initial core mass produces the strongest effect upon the final state of the binary. Only the models with initial core masses *larger* than 0.13 $M_{\odot}$ reach orbital periods longer than 11.8 days (the current orbital period of GRO J1744−28). Larger initial core masses tend to lead to more massive donor stars at the current epoch and would imply smaller orbital inclination angles in order to yield the observed mass function. Thus, from this plot we find that the preferred initial core masses are in the range of ∼0.13–0.2 $M_{\odot}$. As we mentioned earlier, however, the core mass–radius relation used in these calculations is uncertain by up to a factor of 1.3. We have repeated the calculations shown in Figure 2, but for the cases where the stellar radius is taken to be factors of 1.3 and $(1.3)^{-1}$ times the values given by equation (3). For later use, we define ζ to be the factor by which R_g is multiplied, with $(1.3)^{-1} < \zeta < 1.3$. The result is that the overall acceptable range of initial core masses becomes ∼0.10 to ∼0.23 $M_{\odot}$.

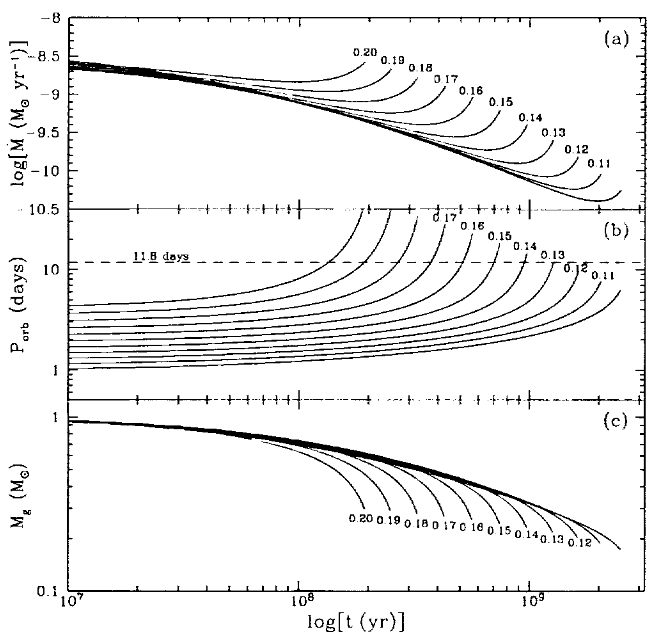

FIG. 2.—Evolutionary tracks that can lead to a binary system comparable to GRO J1744−28, for a range of initial masses of the core of the donor star. At the onset of mass transfer, which corresponds to time $t = 0$, the masses of the giant donor star and the neutron star are taken to be 1.0 and 1.4 $M_{\odot}$, respectively (see Table 1). The effects of both the internal evolution of the giant (WRS; Joss & Rappaport 1983) and magnetic braking (Verbunt & Zwaan 1981; Rappaport, Verbunt, & Joss 1983) have been included in the evolutionary calculations, and a magnetic braking index (Rappaport, Verbunt, & Joss 1983) of $\gamma = 4$ has been assumed (see Table 1). (*a*) The accretion rate, $\dot{M}$, onto the neutron star; (*b*) the binary orbital period, P_{orb}; and (*c*) the mass of the giant donor star, M_g, as functions of log *t*. The numbers labeling the various curves are the initial mass, in solar units, of the degenerate He core of the donor star. For convenience, the orbital period of GRO J1744−28 (11.8 days) is indicated in (*b*).

The results of varying the initial mass of the giant are shown in Figure 3. As indicated in Table 1, we have limited this range to 0.8–1.3 $M_{\odot}$; the lower limit is taken to be that of the lowest mass star that can evolve to the giant branch during the lifetime of the Galaxy, while the upper mass limit is taken from the largest mass donor that will lead to stable mass transfer. As can clearly be seen, the properties of the binary near the end of the evolution are not significantly affected by the initial mass of the donor star.

The effects on the binary evolution of different assumed values for the mass capture fraction, ranging from 25% to 100%, are shown in Figure 4. As expected, the evolution of the orbital period, the mass of the donor, and the mass loss rate from the donor star, are hardly affected by the mass capture fraction. This results from the fact that the evolution depends almost entirely on the masss and radius of the donor star, the latter of which in turn depends on its core mass; neither of these is directly affected by the mass capture fraction. The variations in mass transfer rate for different mass capture fractions simply reflect an *unvarying* mass loss rate, coupled with different mass capture fractions.

Finally, we show in Figure 5 how the evolution varies with the assumed strength of the magnetic braking. As discussed above, the magnetic braking is taken to be that given

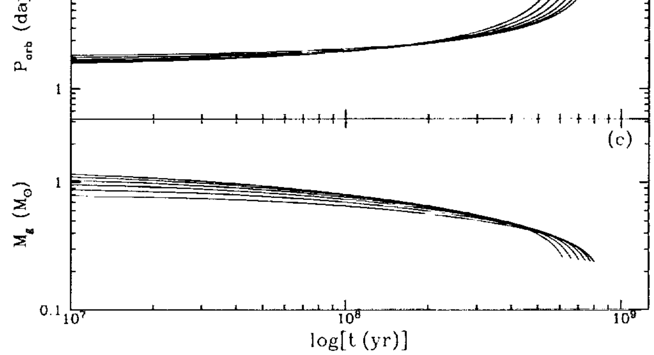

FIG. 3.—Same as for Fig. 2, except that the initial mass of the donor star is varied over the range 0.8 to 1.3 $M_{\odot}$, as indicated in (*a*), while the other parameters are held fixed at the values given in Table 1.

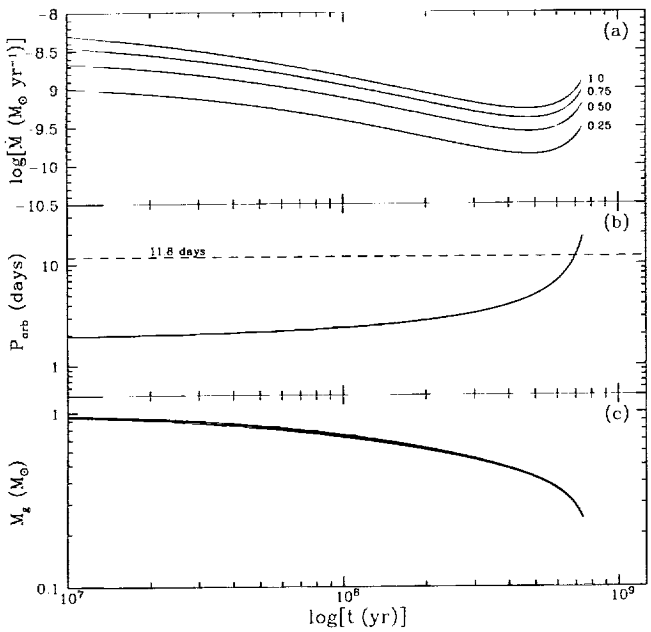

FIG. 4.—Same as for Fig. 2, except that the mass capture fraction, β (i.e., the fraction of mass lost by the donor that is accreted by the neutron star) is varied from 0.25 to unity as indicated in (*a*). The other parameters are held fixed at the values given in Table 1.

by RVJ, but with the value of f taken to be either 0, 0.25, 0.5, 1, or 2. For the first $\sim 10^8$ yr of the evolution, the mass transfer rate is significantly affected by the choice f. However, by $\sim 3 \times 10^8$ yr after the initial model, all models have converged to essentially the same value of mass transfer rate. Still later in their evolution, the models with the *smallest* magnetic braking have somewhat *larger* mass transfer rates. This results from the fact that the models with the smaller f values have larger donor masses at later times. The mass of the giant (donor) enters the expression for $\dot{M}$ (eq. [6]) on the left-hand side in an obvious way, and enters

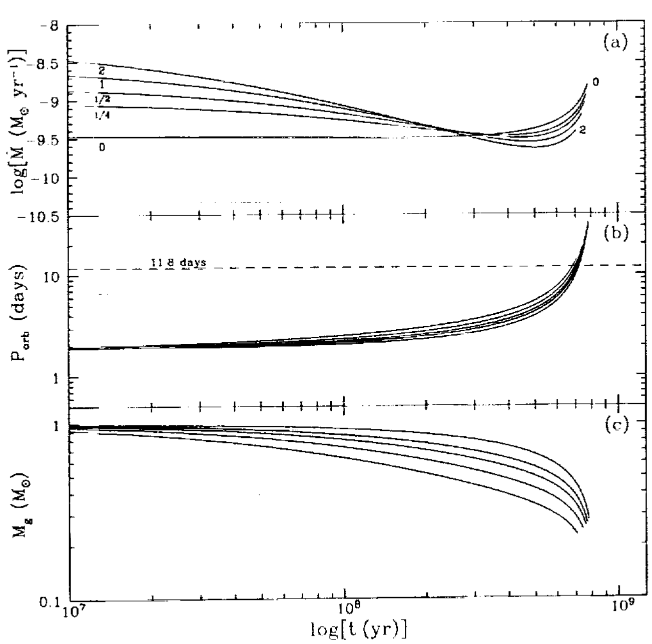

FIG. 5.—Same as for Fig. 2, except that the strength of the magnetic braking constant, f (see text), is varied over the range 0–2, as indicated in (*a*), while the other parameters are held fixed at the values given in Table 1.

on the right-hand side through the mass ratio. It is the former of these that dominates later in the evolution (i.e., larger M_g implies larger $\dot{M}$). In spite of these modest differences in $\dot{M}$, we find that the remainder of the present-day parameters of the system depend relatively little on our assumptions about magnetic braking.

5. MONTE CARLO EXPLORATION OF EVOLUTIONARY PATHS

As we have seen in the preceding section, the parameters that dominate the binary evolution are the initial core mass of the donor star and the uncertainty (by a factor ζ) in the core mass–radius relation for giants. However, by studying the effects of varying only one parameter at a time, we were not able to explore the full range of possible results in the multidimensional parameter space of the GRO J1744−28 system. Even more importantly, we were not able to determine the relative probability of any particular path to the parameters of the current system. Accordingly, we have devised a novel Monte Carlo scheme for evaluating the relative probabilities for various evolution paths leading to the observable parameters of GRO J1744−28.

In this approach, we choose from a wide range of initial binary conditions and parameters that affect the subsequent evolution. The evolution is followed until either the orbital period reaches 11.8 days or the giant envelope is exhausted, whichever comes first. If P_{orb} reaches a value of 11.8 days first, the system parameters at that epoch are saved; if not, the evolution run is discarded. For "successful" systems that reach $P_{orb} = 11.8$ days, the orbital inclination angle that would yield the observed mass function is then computed. The parameters for these systems are entered into probability distributions, by weighting them with a factor of $\sin^2 i/\cos i$ to take into account the a priori probability of observing a binary system that yields the correct mass function to within a specified accuracy. Approximately 3×10^5 such evolution runs were computed in order to form probability distributions with sufficient statistical accuracy.

Table 2 lists the various initial system or physical parameters and their distributions which we utilize in the Monte Carlo calculations. The range of values considered encompasses those given in Table 1 for our systematic study, but is somewhat broader.

From these numerous binary evolution calculations, we produce probability distributions of the following quantities: the initial and current-epoch mass of the donor star, He core mass of the donor star, and mass of the neutron star; the current-epoch luminosity, radius, and K-band magnitude of the donor; the current-epoch semimajor axis and inclination angle of the binary; and the long-term mass transfer rate at the current epoch. (Note that for any particular input parameter, the corresponding output distribution is not necessarily the same as the input distribution because some systems are discarded and the remainder are weighted by the probability associated with the inclination angle.) The distributions for eight parameters associated with the present GRO J1744−28 system are shown in Figure 6. Table 3 lists the most probable value, as well as the 95% confidence upper and lower limits, for all but one of the parameters listed above, as derived from the probability distributions.

We thus find that the donor star in GRO J1744−28 has a most probable mass of only $\sim 0.23\ M_\odot$, but its mass could be as high as $\sim 0.7\ M_\odot$ (95% confidence upper limit). The

TABLE 2

MODEL PARAMETERS FOR MONTE CARLO STUDY

Parameter	Assumed Distribution
Initial core mass (M_c)	Uniform: 0.05–0.30 $M_\odot$
Initial donor mass (M_g)	Uniform: 0.8–1.3 $M_\odot$
Initial neutron-star mass (M_{ns})	Uniform: 1.2–1.4 $M_\odot$
Mass capture fraction (β)	Linearly increasing: for $\beta < 1$
Magnetic braking factor (f)	75%, uniform for $f < 2$; 25%, exponential decay with $f_0 = 3$
ζ[a]	Linearly increasing[b] for $(1.3)^{-1} < \zeta < 1$; linearly decreasing[b] for $1 < \zeta < 1.3$

[a] Uncertainty factor in the core mass-radius relation for giants.

[b] Distribution goes to zero at $\zeta = 1.3$ and at $\zeta = (1.3)^{-1}$.

He core mass of the donor star lies in the narrow range of 0.20–0.25 $M_\odot$; therefore, the envelope mass could be very low (a few hundredths of a solar mass) or it could range up to $\sim 0.5\ M_\odot$. The neutron star in this system is a candidate for having a large mass (significantly greater than 1.4 $M_\odot$); if a relatively high value for the neutron-star mass is confirmed in future work, this result would place significant new constraints on the equation of state of matter at and above nuclear matter densities. On the other hand, a conventional neutron-star mass of 1.4 $M_\odot$ is still acceptable at the $\sim 10\%$ level. The orbital inclination angle is small, 6° to 21°, but the a priori probabilities of finding angles this small are 0.5% and 6%, respectively. Roughly one hundred X-ray binary systems have heretofore been studied in some detail;

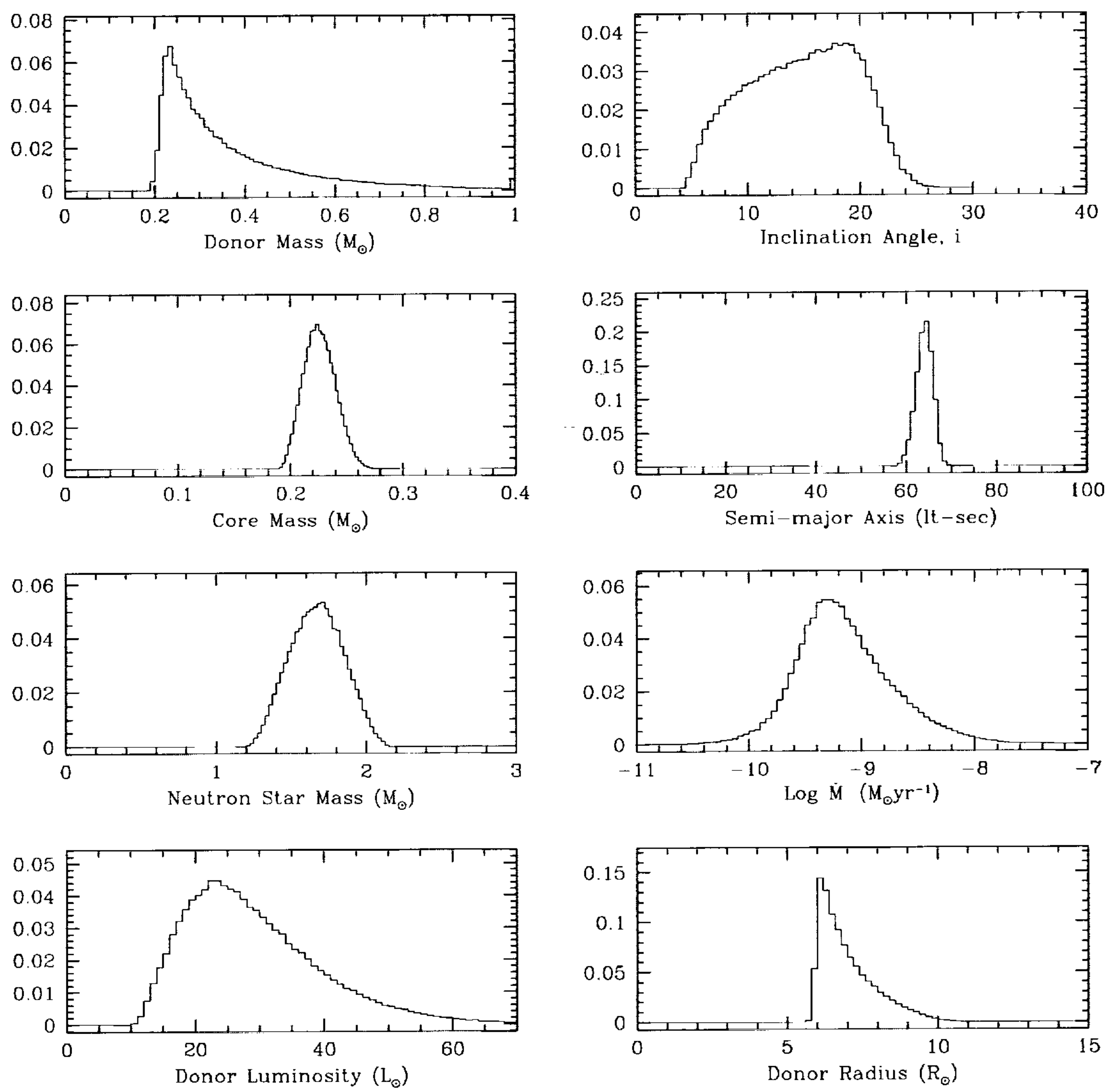

FIG. 6.—Computed probability distributions for eight parameters associated with the binary GRO J1744−28 at the current epoch. These distributions were computed from 3×10^5 binary evolution calculations whose starting and input parameters were chosen via Monte Carlo techniques from the distributions described in Table 2. Each binary that contributed to the distributions shown in this figure was required to (1) grow to an orbital period of at least 11.8 days, and (2) have parameters that would yield the observed mass function for GRO J1744−28 for some orbital inclination angle in the range of 0° to 90°. If so, the parameters of that system were added to the distribution with a weighting function of $\sin^2 i/\cos i$. The most probable values and 95% confidence limits derived from these distributions are listed in Table 3.

TABLE 3
INFERRED PARAMETERS FOR GRO J1744−28

Parameter	Range[a]	Most Probable
Initial donor mass	0.8–1.3 $M_\odot$	1.1 $M_\odot$
Initial core mass	0.10–0.23 $M_\odot$	0.15 $M_\odot$
Inclination angle	7°–22°	18°
Semimajor axis	60–67 lt-s	64 lt-s
Luminosity of donor	15–49 $L_\odot$	23 $L_\odot$
Radius of donor	6–9 $R_\odot$	6.2 $R_\odot$
Log ($\langle \dot{M} \rangle / M_\odot$ yr^{-1})[b]	−9.7 to −8.3	−9.3
K-band magnitude[c]	13.5–14.5	14.1
Current donor mass	0.21–0.7 $M_\odot$	0.24 $M_\odot$
Current core mass	0.20–0.25 $M_\odot$	0.22 $M_\odot$
Current neutron star mass	1.39–1.96 $M_\odot$	1.69 $M_\odot$

[a] 95% single-parameter confidence limits.
[b] Accretion rate onto the neutron star.
[c] For an assumed distance of 8 kpc, with no interstellar extinction.

it is, therefore, not unreasonable that at least a few systems with small inclination angles, in the range we have inferred for GRO J1744−28, should have been found, especially if selection effects mitigate against the detection of edge-on systems (see, e.g., Milgrom 1976).

6. MAGNETIC FIELDS AND MODES OF ACCRETION

Our estimates of the long-term accretion rates in GRO J1744−28 (see § 5), coupled with its measured pulse period, can yield information on the surface magnetic field strength, B, of the neutron star. Here we assume that the 2.1 Hz rotation frequency of the pulsar represents the equilibrium spin period of the neutron star that has been established over the past several million years of evolution, and hence that the recent outburst of GRO J1744−28 does *not* represent the long-term accretion behavior of this source. The magnetospheric radius of the neutron star is given by

$$r_m \simeq \mu^{4/7}(2GM_{\rm ns})^{-1/7}(\dot{M})^{-2/7}$$
$$\simeq 1.5 \times 10^8 \mu_{30}^{4/7}(M_{\rm ns}/1.4\ M_\odot)^{-1/7}(\dot{M}_{-8})^{-2/7}\ {\rm cm} \quad (7)$$

(Rappaport & Joss 1977; Ghosh & Lamb 1979), where μ_{30} is the magnetic dipole moment of the neutron star in units of 10^{30} G cm^3 and $\dot{M}_{-8}$ is the accretion rate in units of 10^{-8} $M_\odot$ yr^{-1}. The Keplerian frequency for matter orbiting at this radius is

$$\nu_{\rm K} \simeq 1.18(M_{\rm ns}/1.4\ M_\odot)^{-1/7}(R_6)^{-18/7} \times (B_{12})^{-6/7}(\dot{M}_{-8})^{3/7}\ {\rm Hz}\ , \quad (8)$$

where R_6 and B_{12} are the radius of the neutron star in units of 10 km and the surface magnetic field of the neutron star in units of 10^{12} G, respectively. If we take the equilibrium spin frequency (2.1 Hz) to be that of matter orbiting at the magnetosphere, we find that the surface magnetic field in the GRO J1744−28 system is given by

$$B_{12} \simeq 1.15(\dot{M}_{-8})^{1/2}\ . \quad (9)$$

(In this derivation, we have neglected uncertain factors of order unity in relating the magnetospheric radius to that of the inner edge of the accretion disk; see, e.g., Ghosh & Lamb 1979). We can now utilize the probability distribution for the current long-term mass transfer rates in this system (see Fig. 6), in conjunction with equation (9), to yield a most probable value for B of 2.7×10^{11} G, with 90% confidence limits of 1.8×10^{11}–7×10^{11} G. Of course, this range of values for B reflects only the uncertainty in $\dot{M}$, and not the uncertainty in equation (9) itself. Magnetic fields in this range are more than an order of magnitude smaller than those usually cited for X-ray pulsars (see, e.g., Joss & Rappaport 1984). On the other hand, they are considerably stronger than the magnetic fields associated with most low-mass X-ray binaries and most of the so-called "recycled" radio pulsars (see, e.g., Bhattacharya & van den Heuvel 1991). It is, therefore, quite possible that a number of the properties of GRO J1744−28, e.g., notably the nearly sinusoidal X-ray pulse profile (Swank 1996; Strickman et al. 1996) and the bursting behavior (Fishman et al. 1995; Giles & Strohmayer 1996), are related to the fact that the magnetic field is of intermediate strength.

In this regard, it is interesting to speculate that the X-ray pulsars, GRO J1744−28, the Rapid Burster, and the type I X-ray burster may form a continuum of possible behaviors of an accreting neutron star, with the neutron-star magnetic moment, μ, serving as the crucial parameter that determines the mode of behavior in any given source (see Lewin & Joss 1981; Joss & Rappaport 1984; Lewin, van Paradijs, & Taam 1993; Lewin et al. 1996; and Joss & Rappaport 1996 for reviews and discussions of our observational and theoretical knowledge of the behavior of these sources). In the case of X-ray pulsars, μ would be sufficiently large that the accretion flow is funneled onto the magnetic polar caps of the neutron star, producing periodic X-ray pulsations but suppressing the thermonuclear flashes that would give rise to type I X-ray bursts, even if the accretion rate is relatively low. In GRO J1744−28, μ would still be sufficiently large to funnel the accretion flow but small enough to permit an instability in the flow that gives rise to type II X-ray bursts. In the Rapid Burster, which is the only known source to display both type I and type II bursts (at least on a regular basis), μ would be too small to funnel the accretion flow, so that the accretion onto the neutron-star surface is roughly isotropic and type I bursts can occur but still sufficiently large to produce the accretion instability that results in type II bursts. Finally, if μ is even smaller than in the Rapid Burster, the magnetic field should have relatively little effect upon the accretion flow; as long as the accretion rate is not too high, the source will be a type I X-ray burster. If this picture is correct, an important challenge for both observers and theorists will be to determine the critical values of μ that distinguish the various modes of behavior of an accreting neutron star.

7. SUMMARY AND DISCUSSION

We have introduced a novel method for computing probability distributions for the binary parameters in a system where only the mass function and orbital period are known. This approach was specifically applied to GRO J1744−28, but should also work well for other systems in which the mass transfer is driven largely by the evolution of a low-mass giant donor star. In this method, a wide range of initial parameters for the binary, as well as a range of input parameters to represent the uncertain physics in the binary evolution (e.g., the strength of magnetic braking), are sampled via a Monte Carlo technique. Each binary system is evolved until the entire envelope of the donor star has been transferred to the accreting star and/or lost from the system. Only those systems where orbital periods grow to the known period of the binary under investigation, and which have masses that can reproduce the known mass function for some inclination angle, are kept as part of the

Monte Carlo sample. The parameters of the "successful" systems are weighted by a function of the inclination angle to take into account the a priori probability of viewing the system at that angle.

Our studies of GRO J1744−28 using this type of Monte Carlo exploration of parameter space have yielded the following system parameters (with 95% confidence limits in parentheses): donor stars mass: 0.24 $M_\odot$ (0.21–0.7 $M_\odot$); He cores mass of the donor star: 0.22 $M_\odot$ (0.20–0.25 $M_\odot$); neutron-star mass: 1.7 $M_\odot$ (1.39–1.96 $M_\odot$); orbital inclination angle: 18° (7°–22°); semimajor axis: 64 lt-s (60–67 lt-s); radius of the donor star: 6.2 $R_\odot$ (6–9 $R_\odot$); luminosity of the donor star: 23 $L_\odot$ (15–49 $L_\odot$); and long-term mass transfer rate at the current epoch: 5×10^{-10} $M_\odot$ yr^{-1} (2×10^{-10}–5×10^{-9} $M_\odot$ yr^{-1}).

The donor star may have only a very tenuous residual envelope of less than 0.1 $M_\odot$, but its envelope might just as well contain a few tenths of a solar mass. The core mass is in just the right range to be consistent with the unseen companion stars in a half dozen binary radio pulsars (see, e.g., Rappaport et al. 1995), so that GRO J1744−28 may well be a progenitor for this type of system. The neutron star is probably more massive than the values close to 1.4 $M_\odot$ that are measured for a number of binary radio pulsars with neutron-star companions (van Kerkwijk, van Paradijs, & Zuiderwijk 1995); however, there is a 40% probability that its mass does not exceed 1.6 $M_\odot$, which could still be marginally compatible with some of the softer equations of state currently under theoretical consideration (see, e.g., Brown & Bethe 1995). Finally, we note that the orbital inclination angle is small, with only a few percent a priori probability of finding such a value in any particular system. However, after taking into account the number of X-ray binaries that have been studied in detail, the probability of finding a few systems with an inclination angle this small is actually quite high.

There is little doubt that the donor star in GRO J1744−28 will evolve to lose its entire envelope, and, if the magnetic field of the neutron star is sufficiently strong, the system will then become a binary radio pulsar consisting of a neutron star in a wide, nearly circular orbit with a low-mass degenerate He star. There are more than 20 systems of this general type known, with probably very similar evolutionary histories (see, e.g., Rappaport et al. 1995, and references therein). The present core mass of GRO J1744−28 is consistent with the crudely determined masses of the unseen companions in about a half dozen binary radio pulsars with wide, nearly circular orbits. In particular, the orbital period and system parameters of GRO J1744−28 match those of the binary radio pulsar 1855+09 (Kaspi, Taylor, & Ryba 1994) quite well. Note that the pulse period of GRO J1744−28 is considerably longer than that for most of the supposed descendant systems; however, it is not unprecedented for recycled pulsars to have pulse periods and B fields as large as those inferred for GRO J1744−28 (e.g., 0820+02; Taylor & Dewey 1988; Taylor, Manchester, & Lyne 1994).

We point out three possibilities as mechanisms for producing the current transient outburst of the GRO J1744−28 system. The first, and perhaps least interesting, possibility is that the outburst is the result of an instability in the accretion flow near the neutron star (e.g., an accretion-disk instability; see Cheng & Lin 1992; Cannizzo 1993; and references in these works); in this regard, it is worth noting that the Rapid Burster is also a transient source, with outbursts occurring at typical intervals of ∼6 months (see, e.g., Lewin et al. 1993). The remaining two possibilities are both related to the evolutionary status of the binary system. If, as suggested above, the GRO J1744−28 system is in the terminal stages of mass transfer, then the current outburst may be the result of a final hydrogen-burning flash that occurred as the residual hydrogen-rich envelope collapsed onto the core of the giant (Härm & Schwarzschild 1975). Alternatively, if the envelope has not yet collapsed but its mass has dropped below $\sim 10^{-3}$ $M_\odot$, an estimate based on the mixing-length theory of convection (Böhm-Vitense 1958; Cox & Giuli 1968) indicates that convective heat transport will have become inefficient through a large portion of the envelope. Under these conditions, the velocities of the turbulent convective eddies will become transonic, and there will be relative density fluctuations of the order of unity on effective equipotential surfaces (Cox & Giuli 1968), including the surface of the Roche lobe. It is then possible that the current transient outburst is a result of the penetration of the Roche lobe by a particularly large density excursion. In this scenario, the duration of the outburst corresponds to the amount of time required for all of the excess matter excreted through the Roche lobe to make its way to the surface of the neutron star, and future outbursts of varying intensity may be expected from this system. In regard to the latter two scenarios, it is worth noting that the largest orbital inclination angles, which have the highest a priori probabilities, correspond to the smallest residual envelope masses (see Figs. 1 and 6).

Finally, we note the recent attempts by two groups to detect the optical/near-infrared counterpart of GRO J1744−28 (Augusteijn et al. 1996; Cole et al. 1996). A possible faint counterpart in the K band may have been detected on a couple of (but not all) attempts, and there is some controversy over the reality of the detection. Nonetheless, these observations can be used to set a limit of $K > 16.5$ on the K-band magnitude of the giant companion in quiescence (i.e., in the absence of any light due to reprocessed X-radiation). The authors of the above studies cite a probable extinction to a source in this direction of the Galaxy, at a nominal distance of 8 kpc, of $A_K \sim 3.1$. Thus, the limit on the quiescent K-band magnitude at this distance, in the absence of extinction, is $K_0 > 13.4$ (Augusteijn et al. 1996; Cole et al. 1996). Our range of computed K-band magnitudes for the giant companion in GRO J1744−28 at this same assumed distance (see Table 3) is $13.3 < K_0 < 14.4$, which marginally excludes the sensitivity limits of the observations to date. It seems likely, therefore, that the detection of any optical or near-infrared emission from this source could have been from reprocessing of X-radiation (van Paradijs & McClintock 1994; Kouveliotou 1996; Augusteijn et al. 1996; Cole et al. 1996). In the future, however, direct detections of the companion are still quite possible.

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