

CYGNUS X-2: THE DESCENDANT OF AN INTERMEDIATE-MASS X-RAY BINARY

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ABSTRACT

The X-ray binary Cygnus X-2 (Cyg X-2) has recently been shown to contain a secondary that is much more luminous and hotter than is appropriate for a low-mass subgiant. We present detailed binary-evolution calculations which demonstrate that the present evolutionary state of Cyg X-2 can be understood if the secondary had an initial mass of around $3.5 M_{\odot}$ and started to transfer mass near the end of its main-sequence phase (or, somewhat less likely, just after leaving the main sequence, as recently suggested independently by A. R. King & H. Ritter). Most of the mass of the secondary must have been ejected from the system during an earlier rapid mass transfer phase. In the present phase, the secondary has a mass of around $0.5 M_{\odot}$ with a nondegenerate helium core. It is burning hydrogen in a shell, and mass transfer is driven by the advancement of the burning shell. Cyg X-2 therefore is related to a previously little studied class of intermediate-mass X-ray binaries (IMXBs). We suggest that perhaps a significant fraction of X-ray binaries presently classified as low-mass X-ray binaries may be descendants of IMXBs and discuss some of the implications.

Subject headings: binaries: general — stars: evolution — stars: individual (Cygnus X-2) — X-rays: stars

1. INTRODUCTION

Cygnus X-2 (Cyg X-2) has long been considered a typical low-mass X-ray binary containing a neutron star (e.g., Smale 1998) with a relatively long orbital period ($P = 9.84$ days; Cowley, Crampton, & Hutchings 1979). Recent spectroscopic observations by Casares, Charles, & Kuulkers (1998) and a study of the ellipsoidal light variation by Orosz & Kuulkers (1999) yielded accurate values for the mass ratio ($q = 0.34 \pm 0.04$), the individual masses ($M_x = 1.78 \pm 0.23$ and $M_c = 0.60 \pm 0.13 M_{\odot}$ for the neutron star and the companion, respectively), and the radius of the companion ($R_c = 7.0 \pm 0.5 R_{\odot}$; unpublished). These observations confirm the *present* low mass of the companion.

Rather surprisingly, however, Casares et al. (1998) also showed that the spectral type of the companion is, to within two subtypes, A9 III and that *the spectral type does not vary with orbital phase*. Using the binary parameters above and adopting a temperature of ~ 7400 K for this spectral type (Straižys & Kuriliene 1981), we obtain a luminosity $L_c \sim 130 L_{\odot}$ for the companion star. On the other hand, we can also estimate the expected temperature and luminosity for a low-mass subgiant that is consistent with the binary parameters of Cyg X-2: using the calibrated stellar models by Han (1995), we find an expected temperature of 4500 K and an expected luminosity of $18 L_{\odot}$. This much higher temperature and luminosity of the companion star could in principle be caused by X-ray heating (also see Cowley et al. 1979). However, the fact that the spectral type does not vary with orbital phase despite an inclination $i \sim 62^{\circ}$ (Orosz & Kuulkers 1999) would imply extremely efficient redistribution of the irradiation energy around the star by irradiation-induced circulation currents, much higher than is, for example, observed in the companion of Her X-1 (Kippenhahn & Thomas 1979). The spectra of J. Casares & P. Charles (1998, private communication) also show a helium absorption line whose strength varies with orbital

phase. The very presence of this line on the companion indicates regions of much higher temperature than found on an A9 star. Since the strength of this line is strongest on the illuminated side of the secondary, this suggests that it is caused by external illumination and heating, while the non-varying component of spectral type A9 reflects the true intrinsic spectral type of the companion.

Since a spectral type A9 is not consistent with a low-mass subgiant, this immediately suggests that the original mass of the companion must have been much higher and that most of the mass of the companion must have been lost from the system. Indeed, in § 2 we will show that the present parameters of Cyg X-2 can be understood if, at the beginning of the mass transfer phase, the companion was a somewhat evolved star of mass $\sim 3.5 M_{\odot}$ that lost most of its envelope as a result of highly nonconservative mass transfer. Cyg X-2 may therefore be related to a hitherto little studied class of intermediate-mass X-ray binaries (IMXBs). In § 3 we discuss some of the implications of this conclusion and how it may affect our understanding of X-ray binaries in general.

After this work had essentially been completed, we became aware that a similar suggestion concerning the evolutionary status of Cyg X-2 has been made independently by King & Ritter (1999). They suggest that Cyg X-2 is at the end of a massive, early case B mass transfer phase and discuss the relationship of systems of this type and millisecond pulsars. In § 2, we present detailed binary calculations, which also include the King & Ritter case. As we show, our best model (case AB) differs substantially from their suggested model (early case B), in both its details and its predictions.

2. BINARY CALCULATIONS

In order to explore the possibility that Cyg X-2 is the descendant of an IMXB, we performed a series of detailed binary calculations using an up-to-date, standard, Henyey-

type stellar evolution code (Kippenhahn, Weigert, & Hofmeister 1967), which uses OPAL opacities (Rogers & Iglesias 1992), complemented with those from Alexander & Ferguson (1994). Our calculations use solar metallicity ($Z = 0.02$), an initial hydrogen abundance of $X = 0.70$, and a mixing length parameter $\alpha = 2$ and assume 0.2 pressure scale heights of convective overshooting from the core (cf. Schröder, Pols, & Eggleton 1997). To calculate the mass transfer rate \dot{M} explicitly, we use a prescription very similar to the one proposed by Ritter (1988). For each binary-evolution sequence, one needs to specify what fraction, β , of the mass lost by the donor is accreted by the neutron star and the specific angular momentum of any matter that is lost from the system. We somewhat arbitrarily choose β to be $\frac{1}{2}$ and limit the maximum accretion rate to the Eddington accretion rate, taken to be $\dot{M} = 2 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ and kept constant throughout each run. We further assume that the mass lost from the system carries away the specific angular momentum of the accreting neutron star which has an initial mass of $1.4 M_{\odot}$. We include angular momentum loss due to gravitational radiation (although it is of no real importance here), but do *not* consider magnetic braking, since during all slow evolutionary phases, the envelopes of our donor stars tend to be fully radiative (for a general background review see, e.g., Ritter 1996). We have also performed some calculations that include magnetic braking and found that this would not significantly change any of the main conclusions in this paper.

The evolution of a binary is very sensitive to the evolutionary state of the donor star at the beginning of the mass transfer phase. For example, if the donor is initially relatively unevolved (early case A; Kippenhahn & Weigert 1967), it will subsequently mimic a single star of the same

actual mass rather than its initial mass (e.g., Hellings 1983), provided that it is not too far out of thermal equilibrium. Since the companion of Cyg X-2 does not presently resemble a single star of the same mass, this type of evolution cannot be applicable. To illustrate this evolution, we show in Figure 1 the evolutionary track in the Hertzsprung-Russell (H-R) diagram of a $3.5 M_{\odot}$ donor star that is somewhat evolved (marked “case A”). At the beginning of the mass transfer phase, it has used up only half of its initial hydrogen supply in the center. After a short, rapid mass transfer phase (*dashed portion*), the star spends most of the remaining main-sequence phase in the low-mass region of the main sequence (*dot-dashed portion*) and then evolves like a low-mass star up the Hayashi line (*solid portion*). It never resembles a star like the companion of Cyg X-2 (the parameters for Cyg X-2 are shown as a boxed region in Fig. 1).

In order to explain the presently overluminous companion, it must have been relatively evolved at the beginning of the mass transfer phase. This constraint allows two possibilities: either the secondary was near the end of the main sequence and had already developed a core structure typical of a post-main-sequence intermediate-mass star (case AB), or it had already left the main sequence and filled its Roche lobe while evolving through the Hertzsprung gap (case B).

2.1. The Case AB Scenario

The curves marked “case AB” in Figure 1 and Figure 2 illustrate the evolution of a $3.5 M_{\odot}$ star that fills its Roche lobe for the first time near the end of the main sequence, when its central hydrogen abundance has been reduced to $X_c \simeq 0.10$. The exact value of X_c is not crucial, but should probably be less than ~ 0.2 . The panels in Figure 2 show the radius and Roche lobe radius (panel *a*), the orbital period

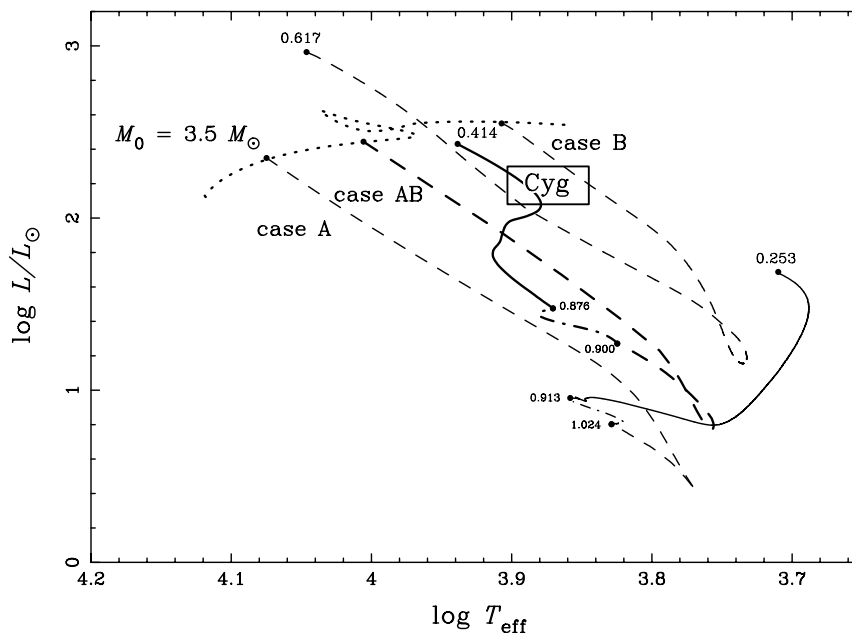


FIG. 1.—Evolutionary tracks of the secondaries in three binary calculations in the Hertzsprung-Russell diagram. The secondary has an initial mass of $3.5 M_{\odot}$ and the primary, assumed to be a neutron star, an initial mass of $1.4 M_{\odot}$ in all calculations. The dotted curve shows the track of a $3.5 M_{\odot}$ star without mass loss. The mass-loss tracks, labeled case A, AB, and B, start at different evolutionary phases of the secondary (“case A”: the middle of the main sequence; “case AB”: the end of the main sequence; “case B”: just after the main sequence). The dashed portions in each track indicate the rapid initial mass transfer phase, the dot-dashed and solid portions the slow phases where mass transfer is driven by hydrogen core burning and hydrogen shell burning, respectively (only in case A and case AB). The beginning and end points of the various phases are marked by solid dots; the small figures next to them give the mass of the secondary at these points. The boxed region labeled “Cyg” indicates the observationally determined parameter region for the secondary in Cyg X-2. The tracks after mass transfer has ceased are not shown.

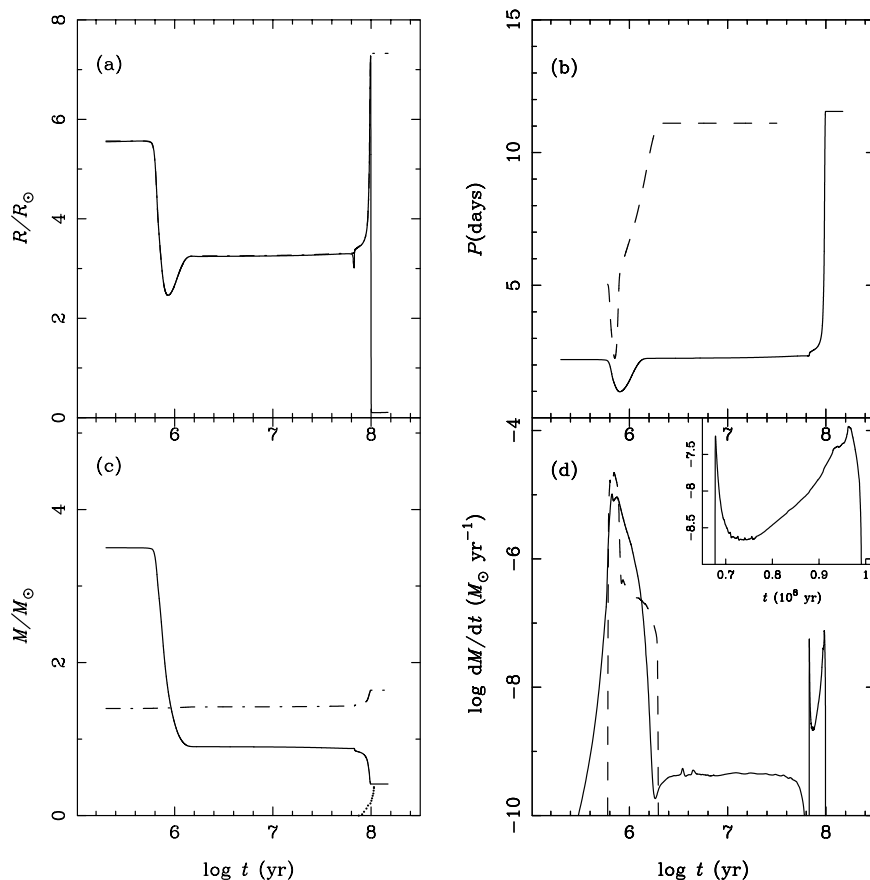


FIG. 2.—Primary binary parameters for the case AB binary calculation as a function of time (with arbitrary offset). (a) Radius (solid curve) and Roche lobe radius (dot-dashed curve) of the secondary (almost coincident most of the time); (b) the orbital period (solid curve); (c) the mass of the secondary (solid curve), of its hydrogen-exhausted core (dotted curve), and of the primary (dot-dashed curve); (d) the mass-loss rate from the secondary (solid curve); the inset shows a blowup of the second slow mass transfer phase (hydrogen shell burning). The dashed curves in (b) and (d) show the orbital period and mass transfer rate for the case B calculation for comparison.

(panel *b*), the masses of the two components and the secondary's core mass (panel *c*), and the mass-loss rate from the donor (panel *d*) since the beginning of the mass transfer phase. As is most evident from the last panel, one can clearly distinguish three separate phases, one very rapid phase and two slower phases.

The rapid initial phase.—Because of the large initial mass ratio, the initial mass transfer rate is of order $10^{-5} M_{\odot} \text{ yr}^{-1}$, and most of the mass lost from the companion has to be ejected from the system. The high \dot{M} implies a mass-loss timescale that is short compared to the thermal timescale of the donor, and the donor star is therefore driven significantly out of thermal equilibrium (i.e., it is undersized and underluminous for its mass). The mass transfer rate only starts to decrease significantly after the mass ratio has been reversed and the system, and hence the Roche lobe, begins to expand. At this stage, mass transfer is driven entirely by the thermal expansion of the companion. The rapid phase ends once the companion has reestablished thermal equilibrium (after $\sim 2 \times 10^6$ yr, of order the thermal timescale of the star). By this time, the secondary's mass has decreased to $0.900 M_{\odot}$. Since the material that is now exposed at the surface has undergone partial CNO burning, its composition shows the signature of CNO processing (enhanced nitrogen, decreased carbon and oxygen) and the surface hydrogen mass fraction is reduced to 0.55 (from 0.7).

The hydrogen core-burning phase.—Once the star has returned to thermal equilibrium, the further evolution is driven by the nuclear evolution of the core (hydrogen core burning). During this phase, which in this example lasts 6×10^7 yr, the mass transfer rate is of order $4 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$ and the mass decreases to $0.876 M_{\odot}$. The phase ends when hydrogen has been exhausted in the core and the system becomes temporarily detached, accompanied by a small hook in the H-R diagram (Fig. 1).

The hydrogen shell-burning phase.—After the exhaustion of central hydrogen, the star expands again and soon starts to fill its Roche lobe for a second time. Initially the evolution of the secondary resembles that of a low-mass star evolving off the main sequence. However, its behavior changes qualitatively once it has lost all of the material that was outside the convective core at the beginning of the mass transfer phase (which had a mass of $0.5 M_{\odot}$). At this point, the surface hydrogen abundance drops to 0.1 (the central hydrogen abundance in the core at the beginning of mass transfer), and the star now has many of the characteristics of a nondegenerate helium star, except for the fact that the evolution, and hence mass transfer, is driven by hydrogen burning in an outward-moving shell. Unlike the case of early case B (see § 2.2), the star has now no tendency to become a giant, which would lead to mass transfer on a thermal timescale (we have tested this by evolving such a

star without further mass loss). The mass transfer rate is therefore determined by the timescale for hydrogen-shell burning and lies in the range of 2×10^{-9} – $7 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ (see the inset in Fig. 2*d*). This phase ends when the hydrogen-rich envelope has almost been exhausted and hydrogen burning stops. The star still continues to evolve, now as a detached star, burns helium in the core as an O subdwarf (with a luminosity $\sim 10 L_{\odot}$ and temperature $\sim 30,000$ K), and eventually ends its evolution as a CO white dwarf with an unusually low mass of $0.414 M_{\odot}$. The final neutron-star mass in this calculation is $1.64 M_{\odot}$.

The appearance of the secondary.—In the initial rapid phase (Fig. 1, *dashed portion of curve AB*), most of the transferred mass has to be ejected from the system. Since the mass-loss rate exceeds the Eddington rate by several orders of magnitude, the system is unlikely to look like a typical X-ray binary. Since this phase is rather short-lived ($\sim 10^6$ yr), relatively few systems should be found in this phase. One possibly related, somewhat more massive observed counterpart is the famous system SS 433, which appears to eject most of the transferred mass by means of two relativistic jets (e.g., Margon 1984).

On the other hand, in the two nuclear-evolution-driven phases, the system would in most respects resemble a typical low-mass X-ray binary (LMXB) and would almost certainly be observationally classified as a low-luminosity LMXB in the core-burning phase and a high-luminosity LMXB in the shell-burning phase. Both phases are also relatively long-lived (6×10^7 and 3×10^7 yr), and hence relatively more systems should be found in these phases than in the rapid phase (see § 3 for discussion).

In this particular model, the star spends a large fraction of the shell-burning phase near a location in the H-R diagram where Cyg X-2 lies (the dashed portion of track AB in Fig. 1). Indeed, during the phase when the orbital period increases from ~ 7 to ~ 10 days, the model provides an excellent description of the main observed properties of Cyg X-2 (see § 1; the mass of the secondary is in the range of 0.45 and $0.5 M_{\odot}$). An important prediction of this model is that the surface composition should be the same as the *core composition* of the secondary at the beginning of the first mass transfer phase, i.e., be severely hydrogen depleted (in this particular model, $X \simeq 0.1$) and show strong evidence of CNO processing. (We caution, however, that there are a sufficient number of uncertainties in the binary-evolution model, in particular associated with the angular-momentum loss from the system, that somewhat different initial binary parameters can almost certainly also reproduce the observed properties of Cyg X-2.)

2.2. An Early Case B Scenario?

An alternative model for Cyg X-2 is that it started to fill its Roche lobe in the Hertzsprung gap (early case B). This is essentially the model that was suggested by King & Ritter (1999; also see Kolb 1998). We have calculated this type of evolution for a $3.5 M_{\odot}$ star that has just left the main sequence (Fig. 1, *dashed curve marked "case B"*). The initial evolution is similar to the previous case. The mass transfer rate (Fig. 2*d*, *dashed curve*) reaches a peak of $\sim 10^{-5} M_{\odot} \text{ yr}^{-1}$ and starts to drop once the mass ratio has been reversed. In the subsequent somewhat, but not much, slower phase, mass transfer is driven by the thermal evolution of the envelope (the star is trying to evolve across the Hertzsprung gap to become a giant). This phase ends and

mass transfer stops completely once most of the hydrogen envelope has been lost and the hydrogen-burning shell has been extinguished. The secondary continues to evolve as a detached star, burning helium as an O subdwarf and finally becomes a CO white dwarf of mass $0.617 M_{\odot}$ (the neutron star has only a slightly increased final mass of $1.427 M_{\odot}$).

As is clear from Figure 2*d*, apart from the initial phase, the mass transfer history is very different from the case AB scenario above. In the slower phase, mass transfer is driven by the thermal expansion of the secondary rather than the nuclear evolution of the core or shell. Since the thermal timescale is much shorter than the evolutionary timescale during the hydrogen shell-burning phase in the case AB scenario, the mass transfer rate in the case B scenario is $\sim 3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$, an order of magnitude above the Eddington rate. It is not clear whether such a high mass transfer rate would be consistent with the observed properties of Cyg X-2. This problem is somewhat reduced if the initial secondary mass was somewhat lower ($\sim 3 M_{\odot}$). However, all case B scenarios suffer from the generic problems that the mass transfer rate is significantly super-Eddington and that the characteristic lifetime of this phase is very short (of order the thermal timescale of the star, $\sim 10^6$ yr). In all the case B models we have calculated, the secondaries spend very little time in the H-R diagram in the general neighborhood of Cyg X-2. For even lower masses, the thermal timescale would be longer, but the star would have a tendency to evolve toward the Hayashi line, which again would be inconsistent with the inferred parameters of the secondary in Cyg X-2. We have performed a whole series of early case B binary sequences. None of them was able to reproduce all of the observationally inferred parameters of Cyg X-2 simultaneously (i.e., the position in the H-R diagram, the constituent masses, and \dot{M}). While we cannot strongly rule out an early case B scenario for Cyg X-2, keeping in mind the general uncertainties in modeling non-conservative mass transfer, we conclude that it is more likely that Cyg X-2 is at present in a hydrogen shell-burning phase in a case AB scenario.

3. THE IMPORTANCE OF INTERMEDIATE-MASS X-RAY BINARIES

An important implication of our modeling of Cyg X-2 is that it suggests that there may be a whole class of X-ray binaries which either have intermediate-mass secondaries now or had them in the past. Such systems have received hardly any attention in the past (see, however, Pylyser & Savonije 1988, 1989; Kolb 1998). This started to change only recently when Davies & Hansen (1998) showed that IMXBs are relatively easy to form in globular clusters and suggested that they may provide an important channel for the formation of millisecond pulsars. The reason why IMXBs had not been studied in any detail in the past is, at least in part, observational, since previously only one such system (Her X-1/HZ Her) had been unambiguously identified. In addition, the theoretically predicted large initial mass transfer rates are much higher than those typically inferred for observed X-ray binaries. However, as our calculation show, this rapid phase is relatively short-lived, and very few systems should be found in this phase. It is also not clear what they would look like. A further theoretical uncertainty is how the mass is lost in this rapid phase. As noted earlier, SS 433 may provide an observational answer to both of these questions (the appearance initially and the

mass-loss mechanism). On the other hand, from an evolutionary point of view, IMXBs should be relatively common, since they are much easier to form and do not require the same amount of fine-tuning as LMXBs (see, for example, Bhattacharya & van den Heuvel 1991). The observational properties of IMXBs would vary significantly, depending on the initial mass of the secondary and the evolutionary phase at the beginning of the mass transfer phase.

We have initiated a systematic investigation of IMXBs and found that, in the longer-lasting evolutionary phases, they typically resemble “classical” LMXBs (Podsiadlowski & Rappaport 2000). This suggests that perhaps a significant fraction of X-ray binaries, presently classified as LMXBs, are actually IMXBs or their descendants. This may have important implications for our understanding of X-ray binaries. For example, it may help to explain some of the systematic differences between Galactic and globular-cluster LMXBs, the observed period and luminosity distributions, and may help to resolve the apparent discrepancy between the number of millisecond pulsars and their putative progenitors (e.g., Kulkarni & Narayan 1988).

4. IMXBs AND RECYCLED PULSARS

IMXBs provide an additional channel for the production of recycled pulsars, both in the Galaxy and in globular clusters. This has been discussed most recently by Davies & Hansen (1998) and King & Ritter (1999), and we refer the reader to these papers for their different perspectives and analyses.

There is a group of about two dozen radio pulsars that are found in nearly circular orbits with low-mass white dwarf companions (see, e.g., Taylor, Manchester, & Lyne 1993; Rappaport et al. 1995). The orbital periods of these systems range from less than 1 to 1232 days. It has been conjectured that this type of system evolves from a low-mass ($\sim 1 M_{\odot}$) subgiant or giant donor star which transfers its envelope to a neutron star via stable Roche lobe overflow (see, e.g., Joss, Rappaport, & Lewis 1987; Rappaport et al. 1995). What remains is a low-mass white dwarf (the core of the giant) in a wide, nearly circular orbit about the neutron star which has been spun up by the accretion process.

Joss, Rappaport, & Lewis (1987) and Rappaport et al. (1995) showed that there is a nearly unique relation between the final orbital period, P , of such a “recycled” binary pulsar and the mass of the white dwarf, M_{wd} (see also Savonije 1987, and Refsdal & Weigert 1970, 1971 for related discussions). In short, this relation results from the fact that the radius of a low-mass giant is a nearly unique function of its core mass. It then follows for a Roche lobe filling star in a binary that P , at the end of mass transfer, is a function of only the core mass of the donor. Thus, the binary remains as a fossil relic of the giant donor star and its degenerate He core. The theoretical relation between P and M_{wd} is found to be roughly consistent with the inferred masses of the white dwarf companions in these systems. Unfortunately, this model cannot be confirmed to the level of confidence that one would like. First, for most of these systems, only the mass function is measured, and thus the uncertainty in the white dwarf mass is rather large. Second, there are a number of these systems for which the orbital period is really too short to be explained by this scenario (i.e., < 3 days). Finally, there are a few systems where the lower limit on the mass of the white dwarf is only marginally consistent with the theoretical relationship.

The last of these difficulties could be mitigated if some of these systems formed with donors of intermediate mass. We have shown in this work that neutron stars with intermediate-mass donor stars can attain a final evolutionary state which is very much like that of the binary radio pulsars discussed here. In particular, the system which we use to model Cyg X-2 would end its evolution with a $0.42 M_{\odot}$ CO white dwarf in a nearly circular 12 day orbit about a spun-up neutron star. Since the initial mass transfer in this system occurred when the $3.5 M_{\odot}$ donor star was late in its main-sequence phase (late case A), the core was neither completely hydrogen depleted nor degenerate. This combination enables the final orbital period to remain relatively short for a white dwarf mass as large as $0.42 M_{\odot}$. By contrast, in the more standard low-mass giant scenario the corresponding final orbital period with this same white dwarf mass would have been ~ 400 days. Put another way, in this same scenario, a system with a 12 day orbital period would be expected to have $M_{\text{wd}} \sim 0.21 M_{\odot}$. In the future, deep spectroscopy of the companion white dwarfs (see, e.g., van Kerkwijk & Kulkarni 1995), as well as the possible detection of the Shapiro delay in the arrival times of the radio pulses (see, e.g., Kaspi, Taylor, & Ryba 1994), could substantially improve the determination of the white dwarf masses and thereby discriminate between low-mass and intermediate-mass progenitors.

It is also possible that neutron stars accreting from intermediate-mass donor stars could attain a final evolutionary state consisting of a very low mass white dwarf in a short orbital period binary (e.g., < 1 days) and help explain binary radio pulsars with such properties. We plan to explore such scenarios in future work.

Thus, evolutionary scenarios and population synthesis studies which are employed to reproduce the distribution of orbital periods and white dwarf masses in binary radio pulsars must include consideration of intermediate-mass donor stars.

5. CONCLUSIONS

We have shown that the observationally inferred parameters of the X-ray binary Cyg X-2 can be understood if the secondary had an initial mass of $\sim 3.5 M_{\odot}$ and started to transfer mass near the end of the main sequence (or less likely just after leaving the main sequence). Cyg X-2 is therefore related to a class of intermediate-mass X-ray binaries that has been little studied before. In our favored model for Cyg X-2, mass transfer started at the end of the secondary’s main-sequence phase (case AB) rather than in the Hertzsprung gap (early case B, as has also been suggested by King & Ritter 1999). The model predicts that the secondary should, at present, be severely hydrogen depleted. We suggest that perhaps a significant fraction of X-ray binaries that are presently classified as LMXBs could be related to this class. This could have far-reaching implications for our understanding of X-ray binaries. Detailed future observations of the secondaries in X-ray binaries as well as systematic binary population synthesis studies should help to assess the importance of this relatively unexplored evolutionary channel.

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