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ON THE FORMATION OF LOW-MASS BLACK HOLES IN MASSIVE BINARY STARS

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ABSTRACT

Recently, Brown & Bethe suggested that most stars with main-sequence mass in the range of ~ 18–$30\ M_\odot$ explode, returning matter to the Galaxy, and then go into low-mass ($\geq 1.5\ M_\odot$) black holes. Even more massive main-sequence stars would chiefly go into high-mass ($\sim 10\ M_\odot$) black holes. The Brown-Bethe estimates gave $\sim 5 \times 10^8$ low-mass black holes in the Galaxy. We here address why none of these have been seen, with the possible exception of the compact objects in SN 1987A and 4U 1700−37.

Our main point is that the primary star in a binary loses its hydrogen envelope by transfer of matter to the secondary and loss into space, and the resulting "naked" helium star evolves differently than a helium core, which is at least initially covered by the hydrogen envelope in a massive main-sequence star. We show that primary stars in binaries can end up as neutron stars even if their initial mass substantially exceeds the mass limit for neutron star formation from single stars ($\sim 18\ M_\odot$). An example is 4U 1223−62, in which we suggest that the initial primary mass exceeded 35 $M_\odot$, yet X-ray pulsations show a neutron star to be present.

We also discuss some individual systems and argue that 4U 1700−37, the only example of a well-studied high-mass X-ray binary that does not pulse, could well contain a low-mass black hole. The statistical composition of the X-ray binary population is consistent with our scenario, but due to the paucity of systems it is consistent with more traditional models as well.

Subject headings: binaries: close — black hole physics — stars: evolution — stars: neutron — stars: Wolf-Rayet

1. INTRODUCTION

The formation of compact objects from massive stars is a difficult topic, because it depends on a number of physical processes of which our theoretical understanding is not yet satisfactory, the sample of available objects to test the theory on is small, and it is very difficult to get accurate observational determinations of the fundamental data required. We therefore use a mixed approach here in trying to constrain the outcomes of massive stellar evolution, using a combination of observational and theoretical arguments, whichever appears more reliable in each situation.

Chief among the theoretical uncertainties are (1) convective and semiconvective mixing in massive stars, which influences the sizes of the helium to iron cores that a star of given mass gets, (2) a quantitative calculation of supernova explosions and fallback, which should tell us what fraction of a core will eventually end up in the compact remnant, (3) the influence of binarity on the evolution of a stellar core, which determines how single stars will differ from ones in close binaries, (4) the precise dynamics of mass transfer in close binaries, and (5) the equation of state of matter at and above nuclear density, which determines the maximum mass of neutron stars and therefore helps determine which stellar masses can be progenitors of which types of compact object. The Brown & Bethe (1994) scenario for formation of a large number of low-mass black holes in the Galaxy used a rather soft equation of state. We review the evidence for that here and in addition take account of new developments regarding the influence of binarity, using the best available treatments of uncertainties 1, 3, and 5. Until recently, the view was that loss of the hydrogen envelope in a close binary had very little influence on the eventual outcome of the evolution of a star, but recent work on mass loss of helium stars (Woosley, Langer & Weaver 1993, 1995) has prompted us to review this. We conclude that hardly any of the many low-mass black holes predicted by Brown & Bethe will be found in X-ray binaries (§ 2).

The observational uncertainties are mostly (1) that very few neutron stars have reliable mass determinations, and none of the ones in X-ray binaries have small errors (§ 3) and (2) that the optical companions of massive X-ray binaries seldom have well-known masses (§ 3.1).

The Brown & Bethe (1994) scenario was painted with broad strokes. Whereas the chief points may be correct, individual events have special features, such as the fluctuation of Fe cores with main-sequence mass. Even though quantitative calculations of the entire supernova have not been carried out to date, and it may take some time until accurate ones are completed, it is interesting to try to correlate observations with their general picture.

2. CORE EVOLUTION AND REMNANTS OF MASSIVE STARS

As the core of a massive star moves to more and more advanced burning stages it becomes hotter and denser, and the star becomes more centrally condensed. Density gradients above the core are so strong that the evolution of the

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central density and temperature become independent of what the envelope does. As a result, the more advanced burning stages of massive stars become more and more independent of the mass of the star, most of which is locked up in the envelope. This phenomenon, called convergence, has long led researchers in binary evolution to make a crucial simplifying assumption in their models: that a star may lose its envelope to a companion when it expands to become a giant without this event causing any alteration of the further evolution of its naked helium core.

The main new stellar evolution ingredient in this paper is the fact that strong mass loss of such naked helium cores implies that this is not quite true (Woosley et al. 1993, 1995). To form an X-ray binary, the star whose core later becomes the accreting compact object nearly always loses its envelope and evolves as a naked He star. This implies that the compact objects in X-ray binaries have formed in an essentially different way than compact objects from single stars. Therefore, all the black holes and many of the neutron stars that we know form a population whose characteristics are not derivable from single stellar evolution. In the next few sections, we detail and attempt to quantify this effect.

2.1. *Formation of High-Mass X-Ray Binaries*

High-mass X-ray binaries consist of a compact object accompanied by an O- or B-type massive star, on or close to the main sequence. We briefly consider the standard model for their formation, to estimate the initial mass of the progenitor of the compact object given the mass of the current optical companion. We follow the work of van den Heuvel & Habets (1984) with small modifications and use the evolution tracks of Maeder (1990), since he used the same mass-loss prescription as in the work of Woosley and collaborators discussed later. A high-mass X-ray binary as observed now starts out as a close binary with primary mass M_p and mass ratio q. When the primary reaches the end of the main sequence, it expands and transfers its hydrogen envelope to its companion (so-called case B mass transfer); a fraction f of the transferred mass is lost from the binary. Then the now naked helium star primary evolves rapidly to a supernova and explodes. We neglect the short time this takes. The now more massive secondary evolves to the end of its main-sequence life. We accounted for rejuvenation by the added mass (van den Heuvel 1969; but see Braun & Langer 1995) when computing the time from mass transfer to core hydrogen exhaustion in the secondary. We assume that core hydrogen exhaustion in the secondary marks the start of the X-ray binary phase. This is reasonable because the observed high-mass X-ray binaries are in fairly close binaries, and the expansion of a star from the end of the main sequence across the Herzsprung gap is fast, so not much time will pass after the end of the main sequence until substantial accretion starts. (It is even possible that the optical companions are still burning hydrogen in their cores and thus are technically on the main sequence, but have a giant-like structure due to severe mass loss; see Ziółkowski 1979.) The value of q is unknown, of course, and the value of f is rather uncertain: while mass transfer between roughly equal-mass stars is often thought to be conservative, there are indications that it may not be in practice, especially if the donor is a giant. We will vary these unknown parameters to estimate their importance.

As an example, consider a binary with initial masses 45 and 36 $M_\odot$ ($q = 0.8$). When the primary reaches terminal age main sequence (TAMS), wind losses have reduced the masses to 40 and 33 $M_\odot$. The 22 $M_\odot$ envelope of the primary is now transferred, during which 20% (say) is lost from the system. Now the stars are 18 and 51 $M_\odot$, and soon thereafter the 18 $M_\odot$ helium star explodes, leaving a 1.5 $M_\odot$ compact object. When the rejuvenated secondary reaches TAMS, wind losses have reduced it to 48 $M_\odot$, implying that in this case an X-ray binary has formed with an optical companion of mass 48 $M_\odot$, precisely the minimum mass for 1223−62 (§ 3.1.5).

The lowest possible value for the initial primary mass (given a target value for the eventual optical companion mass) is obtained by maximizing the initial total mass $M_p(1 + q)$ and minimizing mass loss, which means setting $q = 1$ and $f = 0$. In Table 1, we give the masses of the initial primary required to get a given optical companion mass in an HMXB using the calculation outlined above for different values of q and f.

2.2. *Formation and Collapse of the Iron Core*

Stars of main-sequence mass $M > 12\ M_\odot$ collapse when the Fe core reaches the Chandrasekhar limit $M_{\rm CS} = 5.76 Y_e^2\ M_\odot$, where Y_e is the ratio of electrons to nucleons. The maximum stable mass can be increased by thermal pressure by the factor $1 + (\pi k T/\mu_e)^2$, where μ_e is the electron chemical potential, typically an $\sim 15\%$ enhancement. With $Y_{e,\rm final} = 0.43$–0.44 this gives a thermally modified Chandrasekhar gravitational mass of $\tilde{M}_{\rm CS} \simeq 1.25\ M_\odot$, scarcely dependent on the mass of the star. The $Y_{e,\rm final}$ is set by the strong β-decay of ^{63}Co, which opposes the electron capture proceeding to lower Y_e (Aufderheide et al. 1990; Timmes, Woosley & Weaver 1996, § 8.C of Bethe 1990).

Brown & Bethe (1994) developed the scenario, based on the kaon condensation equation of state of dense matter (Thorsson, Prakash, & Lattimer 1994), that in many cases in the collapse of massive stars the compact core is stable for a sufficient time for explosion and the return of matter to the Galaxy, and then goes into a black hole. This was estimated to happen for stars of ZAMS masses of $\sim$18–30 $M_\odot$. This possibility, that a star first explodes and subsequently

TABLE 1

MASS OF THE PROGENITOR OF THE COMPACT OBJECT IN A HIGH-MASS X-RAY BINARY WITH CURRENT OPTICAL COMPANION MASS $M_{\rm opt}$[a]

	$q = 1.0$			$q = 0.9$			$q = 0.8$			$q = 0.7$		
$M_{\rm opt}$	$f = 0.0$	$f = 0.2$	$f = 0.5$	$f = 0.0$	$f = 0.2$	$f = 0.5$	$f = 0.0$	$f = 0.2$	$f = 0.5$	$f = 0.0$	$f = 0.2$	$f = 0.5$
20……	11.7	12.9	15.1	12.5	13.9	16.4	13.4	15.0	18.0	14.5	16.3	19.9
30……	18.8	20.7	24.0	20.2	22.3	26.2	21.8	24.3	28.9	23.8	26.7	32.3
40……	26.9	29.4	33.9	29.1	32.0	37.3	31.7	35.1	41.4	35.0	39.1	46.7
50……	36.2	39.4	45.0	39.4	43.2	49.7	43.5	48.0	55.8	48.8	54.3	63.8

[a] The initial mass ratio is q, and f is the fraction of the envelope mass lost in the first mass transfer phase.

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drops into a black hole, had been suggested by Wilson et al. (1986) and Woosley & Weaver (1986). They had in mind the conventional scenario of a neutron star in which thermal pressure and neutrino pressure stabilize the compact object until it cools and collapses into a black hole. Prakash et al. (1995) show that this is possible for a small interval of $\Delta M \sim 0.05$–$0.1\ M_\odot$ in compact core masses. In addition to this "window" from thermal pressure and late time fallback, Brown & Bethe (1994) find approximately an additional $0.2\ M_\odot$ from the properties of the kaon condensed EOS, which implies a total window of $\Delta M = 0.25$–$0.3\ M_\odot$. Chiefly this results because at high densities the matter ends up as nuclear matter, not neutron matter. The former is much "softer" than the latter and sends the core into a black hole.

The Brown & Bethe (1994) scenario indicated that most single stars with main-sequence masses between 18 and 30 $M_\odot$ explode, returning matter to the Galaxy, and leave low-mass black holes. In Table 2 we list the baryon number masses of remnants computed by Woosley & Weaver (1995), together with the gravitational masses obtained from the Lattimer & Yahil (1989) binding energy correction $E = 0.084(M/M_\odot)^2\ M_\odot$, where M is the gravitational mass of the compact core. Since supernova explosions giving quantitative results have not yet been carried out, they chose mass cuts outside the neutronized iron core and at the location of an abrupt entropy jump if one were nearby. The resulting behavior of remnant mass on initial stellar mass is complicated and not very certain.

The Fe core mass will not give the entire mass of the compact object, as there will be fallback from out to the bifurcation radius. Following Thielemann, Hashimoto, & Nomoto (1990) and Bethe (1990), we can estimate this radius from the fact that a small amount, $\sim 0.075\ M_\odot$, of Fe came off from SN 1987A. This means that bifurcation had to come at a radius slightly inside of that up to which oxygen and silicon were burned to ^{56}Ni, which later went into Fe through weak decays. To form ^{56}Ni from ^{28}Si by successive addition of α particles, the temperature must be above $T = 350$ keV $= 4 \times 10^9$ K. Given that the energy is mostly in radiation and electron pairs, $T = 350$ keV corresponds to a blackbody energy density of $w = 3.5 \times 10^{24}$ ergs cm^{-3}. The shocked system is approximately isothermal, so the energy density is also $w = 3E/(4\pi R^3)$, where R is the shock radius. It is then straightforward to find that

$$R = (4100\ \text{km}) E_{51}^{1/3}\ , \tag{1}$$

where E_{51} is the total energy in foes. Estimates for SN 1987A give E_{51} in the range of 1–1.5; therefore 4100 km $< R <$ 4700 km. Detailed calculations of Bethe & Brown (1995) give $R = 3900 \pm 400$ km, not very different from equation (1). Hence, it may be reasonable to choose the enclosed mass somewhere in this range as the mass that will end up in the compact core. The M_{3500} and M_{4500} for Wolf-Rayet cores in Table 3 were kindly furnished us by Stan Woosley (1994, private communication).

Woosley et al. (1995) find that for 10 explosions of Wolf-Rayet stars of various masses in the range of 4–20 $M_\odot$, the mass of ejected ^{56}Ni is small, lying in the narrow range 0.07–0.15 $M_\odot$. Thus, our procedure of obtaining the bifurcation radius near the edge of the iron core, as was done in SN 1987A, finds support. Woosley et al. (1993) also find that the helium core mass and further outcome is influenced by the uncertain ^{12}C(α, γ)^{16}O rate, but the variation is only a few percent.

The compact core mass for the 40 $M_\odot$ star evolved by Woosley et al. (1993) is similar to that for the 60 $M_\odot$ one, so there is presumably little difference in the region of masses 40–60 $M_\odot$. In fact, Woosley et al. note that all of their models, with the exception of the 85 $M_\odot$ model, have strikingly similar iron cores, cores that are also similar in mass to lighter presupernova stars arising in the 12–35 $M_\odot$ range. And they note "Thus it seems likely that whatever mechanism functions to explode the common Type II supernova will also operate for at least some of these stars. There is no apparent mass limit above which one can say that a black hole mass remnant is very probable." According to Brown & Bethe (1994), the dividing line for high-mass black hole formation lies at a gravitational mass of 1.84 $M_\odot$, i.e., baryon number mass 2.09 $M_\odot$. In Woosley et al. (1993) only their highest mass star (85 $M_\odot$) satisfies this, but the later results of Woosley & Weaver (1995) in Figure 1 do indicate that this limit can be exceeded at a mass as low as 30 $M_\odot$ in single stars. Four good candidates for high-mass black holes are listed by van den Heuvel (1992), and many more have been found recently (see review by Wijers 1996). While our considerations may make their formation somewhat more difficult, there are a number of known very massive

TABLE 2

COMPACT CORE MASSES FOR SOLAR METALLICITY, FROM WOOSLEY & WEAVER 1995[a]

Main-Sequence Mass ($M_\odot$)	Baryon Number Mass ($M_\odot$)	Gravitational Mass ($M_\odot$)
15	1.43	1.30
18	1.76	1.56
20	2.06	1.78
25	2.07	1.79
30	4.24	4.24?
35	7.38	7.38?

[a] Question marks indicate that the conversion to gravitational mass is uncertain for objects that immediately collapse to black holes.

TABLE 3

IRON CORES IN THE EVOLUTION OF WOLF-RAYET STARS, WITH MASS LOSS, FROM WOOSLEY, LANGER, & WEAVER 1995[a]

Initial He Star Mass/$M_\odot$	Final He Star Mass/$M_\odot$	Fe Core Mass/$M_\odot$	$M_{3500}/M_\odot$	$M_{4500}/M_\odot$
5	2.82	1.38	1.55 (1.39)	1.59 (1.42)
7	3.20	1.42	1.67 (1.485)	1.71 (1.52)
10	3.51	1.49	1.69 (1.50)	1.73 (1.53)
20	3.55	1.49	1.70 (1.51)	1.77 (1.56)

[a] When several cases for a star are given, we have taken only case A. Metallicity 0.02 was considered. Numbers in parentheses are gravitational masses. Masses are baryon number masses. The M_{3500} and M_{4500} are the enclosed masses at 3500 and 4500 km, respectively. They were kindly furnished us privately by Stan Woosley.

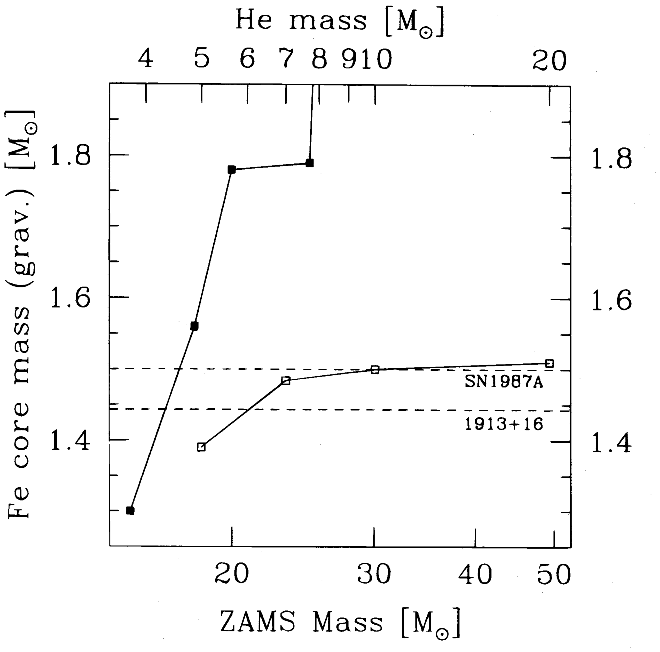

FIG. 1.—A comparison of the compact core masses resulting from the evolution of single stars (*filled symbols*) and naked helium stars with masses equal to the corresponding case B core masses of those same stars. Data are from Tables 2 and 3. The horizontal dashed lines indicate the mass of the heaviest known well-measured pulsar (PSR B1913+16; see Fig. 2) and the probable core mass of SN 1987A (see text).

W-R stars (Cherepashchuk 1991, and references therein) of which it is hard to imagine that they would not form massive black holes.

Given the very many uncertainties in the evolution of heavy stars with mass loss, it might appear unreasonable to consider the fact that most of the M_{3500} and M_{4500} masses exceed the Brown-Bethe 1.50 $M_\odot$ limit for neutron star masses. However, given the Bethe & Brown (1995) determination, as an exercise, we will do just that. But first, we must consider the effect of mass loss in helium stars, since all primaries in X-ray binaries spend some time prior to their explosion as naked helium stars (§ 2.1).

2.3. *Wind Mass Loss: The Difference an Envelope Makes*

When the primary in a close binary transfers its envelope to its companion it becomes a pure helium star. This helium star does not, however, evolve like the helium core of the original main-sequence star with hydrogen envelope. The core evolution and nucleosynthesis are altered if substantial mass loss continues, as it usually does, after the helium core is uncovered. According to Woosley et al. (1993) mass loss can lead to final helium star masses as small as 4 $M_\odot$ for a wide range of initial masses, such as the 35–85 $M_\odot$ range studied. This occurs because the mass-loss rate is mass-dependent. Simply integrating their mass-loss formula,

$$\dot{M}_{\rm WR} = 5 \times 10^{-8} \left(\frac{M_{\rm WR}}{M_\odot}\right)^{2.6} M_\odot \ {\rm yr}^{-1} , \qquad (2)$$

over 10^6 yr we find that 20, 10, and 4 $M_\odot$ helium stars end up at 4.6, 4.1, and 2.8 $M_\odot$, respectively. These numbers are not far from those arrived at by the full evolution calculation, so it is clear that the final masses are almost completely determined by the mass-loss rate $\dot{M}_{\rm WR}$. This result cannot yet be considered very well established, because measurements of masses and mass-loss rates are usually quite uncertain. The available data sometimes yield a much shallower dependence of mass-loss rate on mass, in which case the strong mass convergence noted here does not occur (see, e.g., Langer 1989; Schmutz, Hamann, & Wessolowski 1989; Smith & Maeder 1989). We shall nevertheless stick to this mass-loss prescription, since detailed calculations are available for it.

The chief result of Woosley et al. (1993) is that a presupernova star is not uniquely specified by its initial helium core mass. In order to show why a naked helium star ends up with a smaller Fe core mass than an initially "covered" helium core of the same mass, which resulted by loss of mass by wind from a massive main-sequence star, they evolve a 4.25 $M_\odot$ naked helium core and a 4.25 $M_\odot$ helium core that resulted after mass loss by wind from a 60 $M_\odot$ main-sequence star. Their chief point is that the latter core retains a chemical memory (although not a thermal memory) of its earlier history when it was covered up. The convective core size at the end of helium core burning is similar ($M_{\rm CC} \simeq 2\, M_\odot$) in the two cases. However, the chemical composition just outside this core is very different. In the case of the initially covered core, most of the matter just above the convective core has been burned to carbon and oxygen (presumably the "wraps" have kept the region hotter) so that there is very little helium left. In the case of the naked helium core, the helium concentration rises to 100% immediately beyond the convective zone. In the case of the initially covered helium core, the helium burning shell that develops at core helium exhaustion moves rapidly outward, through the small helium concentration, but for the naked star with $Y \simeq 1$, it remains almost fixed in mass at the edge of the convective core. Consequently, the carbon-oxygen core masses of the presupernova models are very different in the two cases, 3.03 $M_\odot$ for the initially covered case and 2.12 $M_\odot$ for the always naked case. This leads to a smaller Fe core for the naked case and a better chance that it will end up as a neutron star.

The iron cores of Woosley et al. (1995) are given in Table 3. Note that these iron core masses are substantially less than those given in Table 2, where the cores were evolved with hydrogen envelope present. For example, the value of 1.67 $M_\odot$ for M_{3500} of a 7 $M_\odot$ helium star should be compared with the 2.07 $M_\odot$ remnant mass for a 25 $M_\odot$ main-sequence star in Table 2. In Figure 1 we show a comparison between the core resulting from covered and naked helium cores. It is evident that the difference increases rapidly with core mass above ~8 $M_\odot$, where mass loss according to equation (2) becomes important. Consequently, we see that "naked" primaries in binaries are much more likely to end up as neutron stars than single stars of the same initial main-sequence mass.

2.4. *Neutron Star Mass Accretion and Survival*

Neutron star masses can be accurately measured only when the neutron star occurs in a binary, and there are many situations in which it can accrete mass from the companion. This was generally not thought to increase the neutron star mass appreciably, because the accretion was assumed to be less than the Eddington limit, $\dot{M} \simeq 1.5 \times 10^{-8}\, M_\odot \ {\rm yr}^{-1}$. However, it has been known for some time that if neutrinos can carry off the bulk of the energy, accretion can proceed at a much greater rate (Colgate 1971; Zeldovich, Ivanova, & Nadezhin 1972; Bisnovatyi-Kogan & Lamzin 1984). Chevalier (1993) pointed out that during the common envelope phase of binary evolution, photons would be trapped and accretion could occur at much higher rates, typically 10^{-4}–10^{-3} $M_{\odot}$ yr^{-1}, and that neutron stars that have to go through this phase generally will go into black holes. Since the standard scenario for binary pulsar evolution has neutron stars going through a common envelope phase,[4] in the usual situation the neutron star may have the opportunity to accrete up to 1 $M_{\odot}$ of matter. Terman et al. (1994) and Taam, Bodenheimer, & Różyczka (1994) have found, in a three-dimensional treatment of the neutron star in the common envelope, that the neutron star may survive spiral-in. This possibility arises when the neutron star ends up in a low-density region just outside a hydrogen burning shell with the massive companion in its red giant phase. Consequently, the standard scenario of binary pulsar evolution is expected to involve various gradations in the amount of matter accreted onto the neutron star. Thus, the fact that neutron stars of mass greater than the larger one of 1.44 $M_{\odot}$ in PSR 1913+16 have not been observed might be interpreted as evidence that neutron stars heavier than this do not exist. The best test of this issue will be the measurement of the mass of a millisecond pulsar with a white dwarf companion, since in the standard scenario such a pulsar will easily have accreted a few tenths of a solar mass of material (Phinney & Kulkarni 1994).

3. LIMITS TO LOW-MASS BLACK HOLES

Tests of the above scenario and the mass limits suggested by theory for the formation of neutron stars, low-mass black holes, and massive black holes can be obtained both from considering individual systems with special properties (§ 3.1) and from statistical analysis of the population of X-ray binaries as a whole (§ 3.2).

3.1. *Individual Systems*

The current mass of the optical companion in an X-ray binary constrains the mass of the progenitor of the compact object (§ 2.1). Other systems with special properties may likewise provide tests of the mass cuts derived above (§ 2). Here we discuss five such cases in turn.

3.1.1. *GRO J0422+32*

This object is one of the newly discovered X-ray novae with *GRO*. Most of these turn out to have rather high lower limits on the mass of the compact object in them. It is therefore generally assumed that these compact objects are black holes; a typical mass of these black holes is ∼6 $M_{\odot}$ (Wijers 1996). It might therefore be tempting to take the low-mass function of GRO J0422+32, $f(M) = 1.21 \pm 0.06$ $M_{\odot}$ (Filippenko, Matheson, & Ho 1995), as evidence that it contains a low-mass black hole. However, the mass function is also proportional to $\sin^3 i$, where i is the angle between the orbital plane and the plane of the sky. If one takes the whole set of six X-ray novae with measured mass functions, then it would be surprising not to find a mass function as low as 1.2 $M_{\odot}$ among them if they were all 6 $M_{\odot}$ in reality.

3.1.2. *Supernova 1987A*

It has been suggested that if SN 1987A had left a neutron star, it should have showed up due to a very large accretion luminosity within a year (Chevalier 1989; Brown & Weingartner 1994). Based on its nondetection, Brown, Bruenn, & Wheeler (1992) suggested that a black hole was formed instead. Bethe & Brown (1995) obtained an upper limit on the mass of the compact core in SN 1987A of 1.56 $M_{\odot}$ from the 0.075 $M_{\odot}$ of Fe production (see § 2.2) using the presupernova core evolved by Woosley. The presupernova core of Thieleman, Nomoto, & Hashimoto (1995) would have given ∼1.443 $M_{\odot}$, just above the mass of the Hulse-Taylor pulsar. This latter mass may be somewhat too small because of the use of Schwarzschild, rather than Ledoux, convection in the calculations of the Nomoto group. On the other hand, using evolutionary calculations of Woosley et al. (1993) together with the evolution of the Hulse-Taylor pulsar by Burrows & Woosley (1986), the pulsar mass comes out as 1.50 $M_{\odot}$, somewhat larger than the observed 1.44 $M_{\odot}$. Therefore, we believe that the upper limit on the compact core mass in SN 1987A is somewhat too high, and we shall adopt the estimate of 1.50 $M_{\odot}$ of Brown & Bethe (1994), keeping in mind that it may be wrong, in either direction, by a few percent. Based on the reasoning that the compact object in SN 1987A went into a black hole but only barely so, we adopt the core mass in 1987A as the maximum possible neutron star mass:

$$M_{\text{NS,max}} = 1.50\ M_{\odot}. \tag{3}$$

In Figure 2 and Table 4 we show the known masses of compact objects. The masses of radio pulsars, at the bottom of Figure 2, all fit nicely in with our estimate of $M_{\text{NS,max}}$. While the errors are large, it is interesting to discuss 4U 1700−37 and Vela X-1, as the central values of their masses exceed our $M_{\text{NS,max}}$ the most.

3.1.3. *Vela X-1*

Because of the pulses in the X-ray spectrum, the compact object in Vela X-1 is known to be a neutron star. Its high nominal mass (Fig. 2 and Table 4) may therefore be a worry in view of our low maximum neutron star mass. Van Kerkwijk et al. (1995b) find that observed velocities in Vela X-1 deviate substantially from the smooth radial-velocity curve expected for pure Keplerian motion. The deviations seem to be correlated with each other within one night, but not from one night to the other. The excursions suggest something like pulsational coupling to the radial motion and make it difficult to obtain an accurate mass measurement. The lower limit for the mass of the compact object in Vela X-1 is now found to be 1.43 $M_{\odot}$ at 95% confidence lower limit or

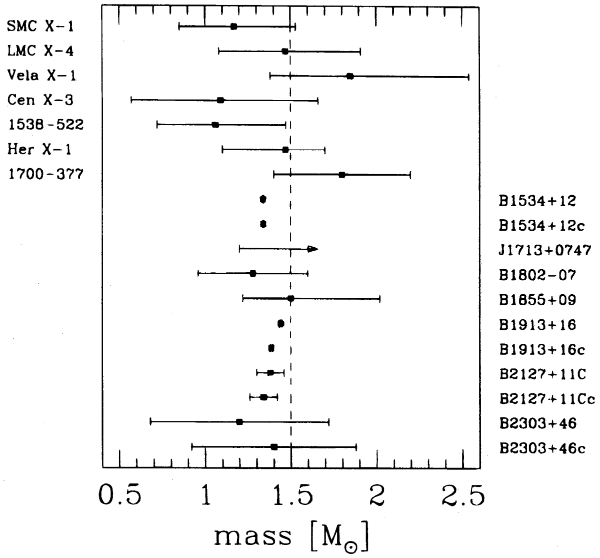

FIG. 2.—Measured masses of 18 compact objects. X-ray binaries are at the top, radio pulsars and their companions at the bottom. The vertical dashed line indicates our preferred value of $M_{\text{NS,max}} = 1.50\ M_{\odot}$.

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[4] An alternative scenario is given by Brown (1995).

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TABLE 4

Measured Masses of 18 Compact Objects

Source	Type[a]	Mass ($M_\odot$)[b]	Reference
SMC X-1	HMXB	$1.17^{+0.36}_{-0.32}$	1
LMC X-4	HMXB	$1.47^{+0.44}_{-0.39}$	1
Vela X-1	HMXB	$1.85^{+0.69}_{-0.47}$	1
Cen X-3	HMXB	$1.09^{+0.57}_{-0.52}$	1
1538 − 522	HMXB	$1.06^{+0.41}_{-0.34}$	1
Her X-1	IMXB	$1.47^{+0.23}_{-0.37}$	1
1700 − 37	HMXB	1.8 (4)[c]	2
B1534 + 12	BPSR	1.3378 (34)	3
B1534 + 12c	BPSR	1.3405 (34)	3
J1713 + 0747	BPSR	> 1.2	4
B1802 − 07	BPSR	1.28 (32)	3
B1855 + 09[b]	BPSR	$1.50^{+0.52}_{-0.28}$	5
B1913 + 16	BPSR	1.442 (6)	6
B1913 + 16c	BPSR	1.386 (6)	6
B2127 + 11C	BPSR	1.38 (8)	7
B2127 + 11Cc	BPSR	1.34 (8)	7
B2303 + 46	BPSR	1.20 (52)	3
B2303 + 46c	BPSR	1.40 (48)	3

[a] The abbreviations mean high mass X-ray binary, intermediate-mass X-ray binary, and binary pulsar, respectively. A lowercase c appended to a pulsar name denotes the unseen companion, which is also thought to be a neutron star.

[b] All errors or limits refer to the 95% confidence region. Numbers in parentheses are errors in the last digits. If a 1 σ error was specified in the quoted reference, it was simply doubled. In case of pulsar B1855 + 09 this is somewhat dubious, because it is the only such case with asymmetric errors. Nonetheless, the confidence contours in the reference show that the limits we quote are roughly correct.

[c] This mass is rather less rigorous and reliable than the others, but it is included because it features in our discussion.

References.—(1) van Kerkwijk et al. 1995a; (2) Heap & Corcoran 1992; (3) Arzoumanian 1995; (4) Camilo 1995; (5) Kaspi et al. 1994; (6) Taylor & Weisberg 1989; (7) Deich 1996.

1.37 $M_\odot$ at 95% confidence interval around the most probable value (van Kerkwijk et al. 1995b). Hence the data do not yet contradict equation (3) but may do so if the observations on this system improve.

3.1.4. *4U 1700 − 37*

The other object in Figure 2 that lies beyond our 1.5 $M_\odot$ limit is 4U 1700 − 37. Its mass determination (Heap & Corcoran 1992) is the poorest in the whole set because it is based on the spectral type and wind properties of the optical companion. Yet with a nominal mass of 1.8 ± 0.4 $M_\odot$ it is interesting to note the peculiarity of this source. Contrary to all other high-mass systems with such a low-mass compact star, it is not pulsing in X-rays (Bhattacharya & van den Heuvel 1991), so it does not appear like a rotating magnetized neutron star. Also, its spectrum extends to very high energies, significantly beyond 60 keV (Rubin et al. 1993)[5] and may well be harder than that of other high-mass X-ray binaries. Such a hard spectrum is often associated with black holes, even though some proven neutron stars seem capable of it (Tanaka & Lewin 1995).

The companion star HD 153919 in 4U 1700 − 37 is an O6f star with a very uncertain mass. Conti (1978) chose a value of 27 $M_\odot$ for this star, although he noted that the value was uncertain. Heap & Corcoran (1992) derive a much higher value, 52 ± 2 $M_\odot$. The situation is unsatisfactory, and we settle on an estimate of 40 ± 10 $M_\odot$ with error bars large enough to encompass both of the above estimates. Indeed, Heap & Corcoran say that HD 153919 is much like λ Cep. Herrero (1995) finds a mass for λ Cep in the central part of this range. This then leads to a minimum progenitor mass of the compact object of 19–36 $M_\odot$, and a more plausible range of 24–48 $M_\odot$. If it is a black hole, then its likely lower progenitor mass than 1223 − 62 (§ 3.1.5) indicates a possible nonmonotonic behavior of the remnant mass with initial mass of the star or the influence of other parameters (such as how far the star evolved to the giant stage before it lost its envelope).

In any case, it is worth considering whether the absence of pulsation cannot simply be the result of a low field of a neutron star, despite the fact that in all other high-mass X-ray binaries the neutron star does manage to pulse. Taam & van den Heuvel (1986) have shown that empirically field decay is inversely correlated with mass accretion (although there is up to now no fundamental theoretical basis for this correlation). Applying a direct proportionality between field and accreted mass given that millisecond pulsars are thought to have accreted 0.01–0.1 $M_\odot$ of material and thereby decreased their magnetic field by 4 orders of magnitude, one finds $B_0/B \sim \Delta M/(10^{-5.5}\ M_\odot)$. 1700 − 37 may have been accreting material for up to 5×10^4 yr, at a rate of perhaps 10% of the Eddington rate, implying $\Delta M < 10^{-4}\ M_\odot$. This means that its field could have decayed to a few percent of its initial value, possibly putting it at $\sim 3 \times 10^{10}$ G now. Other pulsars that descended from massive binaries, e.g., PSR 1913 + 16 (the Hulse-Taylor binary pulsar), have fields even lower than that, so a low field is quite possible in 1700 − 37. However, the X-ray spectrum should then be softer than that of X-ray pulsars, rather than harder as observed. With some reserve, we therefore advocate the view that the compact object in 1700 − 37 is indeed a low-mass black hole.

3.1.5. *4U 1223 − 62*

This X-ray pulsar (White et al. 1976) has the highest-mass optical companion known. Sato et al. (1986) determined the mass of the companion, Wray 977, to be $M_{\rm opt} \simeq 38\ M_\odot$, accounting for the limit on the inclination angle due to the absence of X-ray eclipses. More recently, Kaper et al. (1995) revised the spectral classification of Wray 977, claiming it is a hypergiant and thus further away from us. This more than doubles the star's radius and thus forces a smaller inclination ($i \leq 62°$) in order to avoid eclipses. Consequently, the minimum mass is 48 $M_\odot$. From Table 1 and § 2.1, we infer that the mass of the progenitor of the neutron star must have exceeded 36 $M_\odot$. A more plausible progenitor mass, adopting $q = 0.8$ and $f = 0.2$, would have been 45 $M_\odot$. Such massive stars leave helium stars of 13 and 18 $M_\odot$, which according to Table 3 leave compact objects just above our 1.5 $M_\odot$ limit for neutron stars. Given the uncertainties, we may still say that the presence of a neutron star is consistent with our understanding of the evolution of this binary.

Incidentally, a 36 $M_\odot$ star is already close to the range where binarity ceases to matter much to a star's evolution. Above $\sim 45\ M_\odot$, stars become luminous blue variables and lose their envelopes without the help of a binary companion to become Wolf-Rayet stars (Chiosi & Maeder 1986). Woosley et al. (1993) find that rapid mass loss in the luminous blue variable phase determines the stellar mass at the

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[5] We thank D. Chakrabarty for pointing this out to us.

beginning of helium burning. The hydrogen-rich envelope is completely gone, and their situation is similar to that of the naked helium stars formed after mass transfer in a binary.

3.2. *Statistical Considerations*

Let us now gather up a plausible set of mass limits for stars to form neutron stars and black holes, both for the single and close binary case, to estimate how much difference it will make in the numbers we expect to see. In both cases, we shall deem compact objects to form from the mass range 8–100 $M_{\odot}$. In single stars, we take the mass range for low-mass black hole formation to be 18–30 $M_{\odot}$ after Brown & Bethe (1994), in fair agreement with the Woosley et al. results (Fig. 1). Neutron stars are formed below this range and high-mass black holes above it. In binary stars, we face the problem that the theoretical curve of core mass versus stellar mass intersects the critical mass of 1.5 $M_{\odot}$ at a very shallow angle, so we do not get a good value for the dividing mass. The uncertainty is even greater because, as we noted earlier, the Woosley et al. (1995) masses give an ~ 0.06 $M_{\odot}$ too high a mass for PSR 1913+16. If we lower the curve for naked helium stars by that amount, we would get no low-mass black holes at all in the mass range shown. Instead we set the cut at 36 $M_{\odot}$, the lowest value for the progenitor mass of the neutron star in 4U 1223−62 (§ 3.1.5.). As the upper limit for low-mass black hole formation we choose 50 $M_{\odot}$, somewhat arbitrarily.

We now assume that single stars and primaries in binaries have a Salpeter initial mass distribution, i.e., $N(>M) \propto M^{-1.35}$, to compute the fractions of stars that will yield each type of compact object. For single stars, we find that 69% form neutron stars, 17% low-mass black holes, and 14% high-mass black holes. For binaries, the results are starkly different: 90% neutron stars, 5% low-mass black holes, and 5% high-mass black holes.

Of course, compact objects are only seen in binaries (except radio pulsars), so this is the only place where we can test the numbers. The largest number of high-mass X-ray binaries are Be/X-ray binaries (15–20; see Tables 3, 5, and 8 of Bhattacharya & van den Heuvel 1991), where the companion is a rapidly rotating B star, i.e., lighter than 20 $M_{\odot}$. This implies that the initial primary was almost certainly below 18 $M_{\odot}$ (see Table 1), and thus the compact object should be a neutron star, as is observed, whether we use the numbers for binary or single stars. In high-mass X-ray binaries the situation is less clear. There are six with X-ray pulsars, possibly one with a low-mass black hole and two with massive black holes. This implies somewhat higher fractions of black holes than we just derived, but we should account for the fact that by looking only at high-mass X-ray binaries, which have very massive optical companions, we have implicitly limited ourselves to a smaller range of initial masses, probably starting at 20 $M_{\odot}$ or so rather than 8 $M_{\odot}$ (Bhattacharya & van den Heuvel 1991). For the single star mass cuts, this means virtually no neutron stars would be present in them. So the fact that we do see mainly neutron stars in high-mass X-ray binaries is indirect evidence for the increased mass limit for neutron star formation. (This is only true within the context of a soft EOS of neutron stars: stiffer neutron stars can form from stars more massive than 20 $M_{\odot}$.) The binary scenario mass cuts now would yield 60% neutron stars, 20% low-mass black holes, and 20% massive black holes. This is in reasonable agreement with the observed number ratio of 2:1:1 for nearby systems. It is difficult to compare the predicted formation rates with the observed numbers because the lifetimes may be different for the different types, as may the selection effects. The lifetimes for the neutron star and low-mass black hole systems will be similar, because the mass ratios are essentially the same, and thus mass transfer is unstable on the same timescale and they are both expected to live as X-ray sources for a thermal timescale of the envelope, i.e., a few times 10^4 yr. But the massive black holes are closer in mass to their optical companions; hence the mass transfer in systems like Cyg X-1 could be less unstable and their lifetimes longer, leading to some overrepresentation in the observed sample. There is also some bias in the observed sample toward high-mass black holes because the higher the mass of a black hole is, the more it can accrete: the accretion luminosity from Bondi-Hoyle type wind accretion increases with the square of the mass of the accreting object up to the Eddington luminosity. Above that, the luminosity is limited to the Eddington rate, which increases linearly with mass. High-mass black holes with $M \sim 10$ $M_{\odot}$ can thus give ~ 2 orders of magnitude more accretion than the low-mass ones with $M \sim 1.5$ $M_{\odot}$.

The number ratio of massive stars that form low-mass black holes to those that form neutron stars is thus low, 5%–20% depending on what fraction of stars are in binaries. This implies that it is not at all unlikely to find no low-mass black holes among the 10 well-studied X-ray binaries in globular clusters. Hence the absence of known low-mass black holes in the population of globular-cluster X-ray sources is quite consistent with the Brown-Bethe scenario for low-mass black hole formation, and statements to the contrary by Kulkarni, Hut, & McMillan (1993) are incorrect.

4. CONCLUSIONS

We have discussed the scenario in which the primary star in a binary, as long as its mass is less than ~ 40 $M_{\odot}$, will evolve quite differently from an isolated star of the same mass. This is due to transfer of its hydrogen envelope to the secondary, and subsequent large mass-loss rates of the helium core (which had hitherto not been taken into account). In this way, primaries corresponding to main-sequence masses as massive as 35 $M_{\odot}$ can evolve into neutron stars, whereas single stars in the mass range 18–30 $M_{\odot}$ would go into low-mass black holes. In addition, luminous blue variables in the ZAMS mass range 50–60 $M_{\odot}$ may end up as neutron stars, especially in close binaries. This leaves only a narrow region of masses around 35–50 $M_{\odot}$ for possible evolution into low-mass black holes, in addition, possibly, to some very massive stars above 60 $M_{\odot}$. Although several aspects of our discussion are uncertain, it does seem clear that few stars in binaries would be expected to go into low-mass black holes. The different behavior of "naked" helium cores may explain why only one possible low-mass black hole has been observed in high-mass X-ray binaries while the Brown-Bethe scenario, in which stars of main-sequence masses 18–30 $M_{\odot}$ explode and then go into low-mass black holes, may still be roughly correct.

We showed that 4U 1700−37, the only example of a well-studied X-ray binary that does not pulse, is a fair candidate for containing a low-mass black hole.

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