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A MODEL OF THE GALACTIC X-RAY BINARY POPULATION. I. HIGH-MASS X-RAY BINARIES[1]

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ABSTRACT

Using a numerical scenario code which is based on the current theory of stellar evolution and on a semiempirical birth function for binary stars, a model for the Galactic high-mass X-ray binary (HMXB) population is constructed. There is general agreement between predictions of the theoretical model and observed properties of HMXBs with respect to numbers and with respect to space velocity, mass, and orbital period distributions. Accretion by a close neutron star or black hole from the wind emitted by an OB star companion produces intense X-ray emission for 3×10^3–3×10^5 yr; the precise duration depends on the semimajor axis of the system and on the donor mass. The average HMXB lifetime is 14,000 yr. The model gives an HMXB birthrate $\sim 2.6 \times 10^{-3}$ yr^{-1}, with one out of 6–11 systems containing a black hole of mass $\sim 10\ M_\odot$. The total number of bright ($L_X > 1000\ L_\odot$) HMXBs is, according to the model, about 40, and the median peculiar velocity of these systems is ~ 60 km s^{-1}. Reasonable agreement with the observed distribution in number versus space velocity is achieved without invoking a "kick" other than the recoil velocity associated with mass loss in a supernova explosion.

Approximately 10% of all HMXBs with an OB star donor are predicted to evolve into close binaries with Wolf-Rayet donors and with mass-exchange rates large enough to make them observable in X-rays throughout the Galaxy. Cyg X-3 is the only such system known. The discrepancy between observed and predicted numbers can possibly be ascribed, if the accretor is a neutron star, to a magnetic propeller mechanism which inhibits accretion, and, if the accretor is a black hole, to the absence of an accretion disk.

Following the HMXB phase, some systems evolve into very close binary black holes and neutron stars which merge under the influence of gravitational wave radiation. The merger rate of black holes in the Galaxy is estimated to be $\sim 2 \times 10^{-5}$ yr^{-1}, and the merger rate of neutron star pairs is estimated to be $\sim 3 \times 10^{-4}$ yr^{-1}. The volume of space that produces merger events which are potentially detectable as pulsed gravitational wave sources of large energy depends strongly on the masses of the merging components, and, if the black hole mass is taken to be $\sim 10\ M_\odot$, the frequency of detectable black hole mergers may be about 10 times larger then the frequency of detectable mergers of binary neutron stars.

Subject headings: accretion, accretion disks — binaries: close — stars: evolution — stars: interiors — stars: statistics — X-rays: stars

1. INTRODUCTION

X-ray binaries are among the most popular objects of modern astronomy. Accretion in binary stars was introduced by Novikov & Zeldovich (1966) and by Shklovski (1967) to explain observed X-ray sources. The origin of massive X-ray binaries was described by van den Heuvel & Heise (1972), and the post–X-ray stage of evolution of massive binaries was described by Tutukov & Yungelson (1973). Different aspects of the origin and evolution of these systems have been studied over the past twenty years in many papers (e.g., Tutukov 1981; Rappaport & van den Heuvel 1982; Kornilov & Lipunov 1983a, b; Hellings & deLoore 1986; van den Heuvel & Rappaport 1987; Meurs & van den Heuvel 1989; Pols et al. 1991; Lipunov et al. 1994). X-ray binaries have been recently reviewed by van den Heuvel (1987, 1992), Bhattacharya & van den Heuvel (1991), and Webbink (1992). The main observational properties of well-studied X-ray binaries are described in catalogs by Bradt & McClintock (1983), Aslanov et al. (1989), and van Paradijs (1995).

The estimated mass $M_{\rm opt}$ of the optical component of a selection of X-ray binaries is shown in Figure 1 as a function of orbital period $P_{\rm orb}$. The binary data have been taken from the catalog of Aslanov et al. (1989), and the pictured systems with $M_{\rm opt} \gtrsim 10\ M_\odot$ comprise about one-third of all known bright high-mass X-ray binaries (van Paradijs 1995). Binaries in which the X-ray source is an accreting neutron star (Fig. 1*a*) can be divided into two quite distinct families: high-mass X-ray binaries (HMXBs) in which the mass of the optical component is larger than $\sim 10\ M_\odot$; and low-mass X-ray binaries (LMXBs) in which the mass of the optical component is less than $\sim 1\ M_\odot$. Only one known source, Her X-1, lies in the gap between the two families.

HMXBs may be divided into two groups according to the time dependence of their X-ray flux. "Stationary" or "persistent" sources have periods less than ~ 10 days and show significant fluctuations in X-ray luminosity about the average, but the X-ray emission never disappears. "Nonstationary" or

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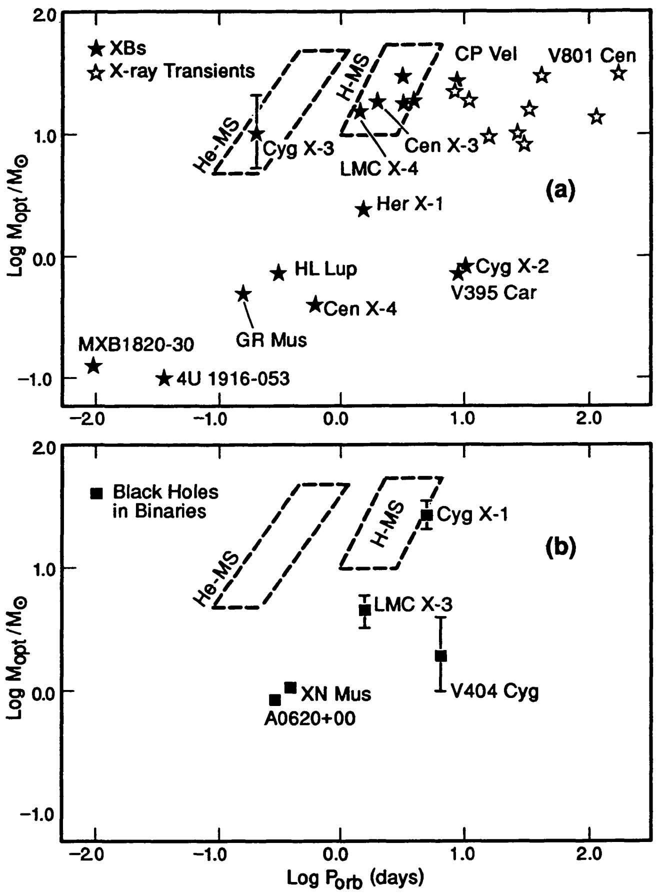

FIG. 1.—Mass of the optical component vs. orbital period for X-ray binaries in which the accretor is a neutron star (*upper panel*) or a black hole (*lower panel*); binary parameters are taken from Aslanov et al. (1989) and, for some HMXBs with black holes, from Tutukov & Cherepashchuk (1992). In the upper panel, stationary (persistent) sources are shown as filled five-rayed stars and hard transients are shown as open five-rayed stars. Closed polygons outline theoretical positions of binaries with different types of donors: an evolved hydrogen main-sequence star (H-MS) or a helium main-sequence star (He-MS) transferring matter via a wind. For more details about LMXBs, see Paper II.

"transient" sources exhibit pronounced spikes in their X-ray luminosity and periods of quiescence during which X-ray emission is below the limit of detectability. The stationary sources are close systems (Fig. 1*a*), and the optical component nearly fills its Roche lobe. The transient sources are of longer orbital period (larger semimajor axis) than the stationary ones, with the dividing line being at an orbital period of about 8–10 days. The orbits of the transient sources are usually eccentric with $e \sim 0.1$–0.8. Transients display recurrent X-ray bursts with a hard spectrum (Rappaport et al. 1978; Rappaport & van den Heuvel 1982; Stella, White, & Rosner 1986). The optical component is typically a Be star which is rotating near breakup velocity at the surface. Be stars typically blow a very nonstationary wind and eject matter in discrete, sporadically appearing clumps. The ejected matter appears to be strongly collimated into the equatorial plane and moves with a velocity which may be substantially less than the escape velocity from the surface of the optical component. At least one X-ray burst in the X-ray binary 4U 0115+63 (V635 Cassiopeia) was the result of a discrete mass-loss event experienced by the Be component (Kriss et al. 1983). The 60 day delay between the onset of the optical activity and the month-long X-ray outburst was attributed by these authors to the time required to form an accretion disk of critical mass for discharge onto the neutron star. Another interpretation is that 60 days is a measure of the time for the mass ejected by the Be star to reach the neutron-star component. In this interpretation, the velocity of the ejected clump is ~ 14 km s^{-1}, about 2 orders of magnitude smaller than the typical wind velocity of a Be star.

The high rotation rate of a typical Be star component and the relatively wide separation of the components are evidence that the secondary in the primordial system has been spun-up by mass accretion from the primary in a mass-conservative event which converts the primary into the helium-star precursor of the neutron-star component (Rappaport & van den Heuvel 1982). The relatively wide separation of components in the present system and the low mass ratio prevent tidal torques from braking the rotation of the Be star and from circularizing the orbit (Zahn 1975, 1977; Lecar, Wheeler, & McKee 1976; Tassoul 1988; King 1993). The rather large orbital eccentricities are a result of the supernova explosion and associated mass loss (Boersma 1961).

It is usually assumed that the optical components of LMXBs (typically main-sequence or subgiant stars) fill their Roche lobes; the neutron star or black hole component is thought to accrete because the main-sequence or subgiant component is forced to maintain contact with its Roche lobe and transfer mass through this lobe due to (1) evolutionary expansion of the Roche lobe–filling star (Webbink, Rappaport, & Savonije 1983; Taam 1983b), (2) the loss of angular momentum from the system by either a magnetic stellar wind (MSW) (Verbunt & Zwaan 1981) or gravitational wave radiation (GWR) (Paczyński 1967; Faulkner 1971; many others), or (3) by some combination of these processes (Taam 1983a; Iben & Tutukov 1984c). Recently it has been found that, if the donor in a close binary is the remnant of an intermediate-mass component with a CO or ONe degenerate core and a thick nondegenerate helium mantle, expansion related to nuclear burning at the base of the mantle can help drive mass exchange (Iben & Tutukov 1993). If the donor is a low-mass helium star or a degenerate dwarf, GWR can help drive mass transfer (e.g., Tutukov & Yungelson 1979a; Savonije, de Kool, & van den Heuvel 1986; Tutukov & Fedorova 1989). In a companion paper (Iben, Tutukov, & Yungelson 1995, hereinafter Paper II), it is argued that a wind from the donor, induced by the absorption of X-ray radiation from the accretor, may remove donor mass much more rapidly than mass is transferred to the accretor.

Figure 1*b* shows that, when the accreting star is a black hole, a designation inferred from its high mass ($\sim 10\ M_\odot$) relative to the mass of a typical neutron star (Cowley 1992 and references therein; see also Tutukov & Cherepashchuk 1992 for a discussion), a division into two groups on the basis of donor mass is not obvious. The smallness of the sample could be partly responsible for the absence of a well-defined mass gap. Probably more responsible is the fact that the mass of a black hole accretor is so much larger than the mass of a neutron star that the upper limit on the ratio of donor mass to accretor mass for stable mass transfer through a Roche lobe is considerably larger than 1 $M_\odot$. Among the five X-ray binaries containing a black hole, only Cyg X-1 has an optical component which clearly does not fill its Roche lobe (although it is close to filling it), and it may be defined as an HMXB. The other four are accreting matter through the Lagrangian point L1 from a less massive companion, and they may be defined as LMXBs.

The modern theory explains the origin and evolution of X-ray binaries of both types (van den Heuvel & Heise 1972; Tutukov & Yungelson 1973; Bhattacharya & van den Heuvel 1991). For those binaries in which the accretor is a neutron star, the discontinuity between the two types in the mass of the optical component relative to the mass of the accretor can be understood in part because main-sequence stars of mass in the 1–8 $M_\odot$ range do not support either an MSW or a strong radiatively driven wind, and in part because stable mass transfer through a Roche lobe on a long ($\sim$nuclear-burning) timescale requires that q, the ratio of donor mass to accretor mass, be less than $\sim\frac{2}{3}$ when the donor has a deep convective envelope and be less than ~ 1.2 when the donor has a radiative envelope (see Tutukov, Fedorova, & Yungelson 1982; Iben & Tutukov 1984c; Hjellming & Webbink 1987). For values of q larger than these critical values, mass transfer is on a thermal timescale (if $q \lesssim 1.2$ and the envelope of the donor is radiative) or on a dynamical timescale, and, since the system develops a common envelope (CE) which is very short lived, the mass-transfer event is not often observed. Possible examples of pre-CE binary stars are SS 433, Her X-1, and Cen X-3, and a possible example of a CE binary star is η Carinae.

The objective of this paper and Paper II is to present a theoretical model of the origin and properties of X-ray binaries which is based on the modern theory of close binary star evolution and which differs in approach from several other studies in which the initial parameters and the lifetime of individual systems are modeled by the Monte Carlo method (Kornilov & Lipunov 1983a, b; Dewey & Cordes 1987; Bailes 1989; Lipunov et al. 1994). The approach used here is a systematic study having a broad observational and evolutionary background (including the evolution of single and binary stars from the main sequence to the formation of white dwarfs, neutron stars, and black holes) which is accumulated in a scenario code. In this paper, a model of the HMXB population is presented.

The scenario approach to the study of binary star evolution has been used with reasonable success to understand both qualitatively (e.g., van den Heuvel & Heise 1972; Tutukov & Yungelson 1973) and quantitatively (within the observational and selection-effect uncertainties) the formation frequency and evolution of a wide class of binary systems (e.g., Kornilov & Lipunov 1983a, b; Iben & Tutukov 1984a, d, 1985, 1986; Tutukov & Yungelson 1986, 1987, 1993a, b).

The specific numerical scenario program which is used in this paper was developed at the Institute of Astronomy in Moscow several years ago. It incorporates the main known facts concerning single and binary star statistics. Also incorporated are the results of theoretical computations concerning the evolution of single and binary stars, including the effects of CE events, supernova explosions, and the like. The authors of this paper have been involved for many years in the numerical modeling of single and binary star evolution, and much of this modeling has been generated with the aim of providing the input necessary for the construction of a scenario code tightly constrained by the modern theory of stellar evolution. The code produces models of various populations of single and binary stars in the Galaxy, giving mass, semimajor axis, and space velocity distributions as well as the evolutionary status of binary components.

The scenario program has been applied to construct models of Wolf-Rayet (W-R) stars (Yungelson & Tutukov 1991), degenerate dwarfs (Tutukov & Yungelson 1992), neutron stars and black holes (Tutukov & Yungelson 1993a), supernovae (Tutukov, Yungelson, & Iben 1992), binary planetary nebula nuclei (Yungelson & Tutukov 1993; Yungelson, Tutukov, & Livio 1993), merging relativistic binaries (Tutukov & Yungelson 1993b), and other stellar objects. In all cases, there has been reasonable agreement between the models and the observations. In this paper, it is demonstrated that this is also the case for HMXBs in which the mass-donor is an OB star. This is important in the light of the fact that basic agreement between model predictions and observations does not occur in the case of LMXBs unless the assumption that mass is transferred conservatively is suspended (Paper II).

According to the model, observed short-period ($P_{\rm orb} < 10$ days) HMXBs (Fig. 1*a*) originate from systems in which the secondary is in the mass range 10–30 $M_\odot$, the primary is in the mass-range 11.4–50 $M_\odot$, and the orbital separation is small enough that the primary can make Roche lobe contact when it leaves the main sequence (semimajor axis A_0 less than 2000 $R_\odot$). Long-period ($P_{\rm orb} \gtrsim 10$ days) HMXBs originate from initial systems in which the mass ratio is near 1; mass-conservative mass transfer increases the mass of the secondary and causes an increase in the orbital separation. Since neither component develops an extended envelope, initially close systems with masses of components larger than 50 $M_\odot$ evolve like wide binaries.

In § 2, some of the stellar evolution input to the scenario code is described. In § 3, the simple model of an HMXB used in the code is presented, and the main characteristics of observed HMXBs which any scenario code should attempt to reproduce are discussed. In § 4, the birthrate of bright sources is estimated, and predicted distributions in period, mass, and space velocity are compared with observed distributions. In § 5, the evolution of post-HMXBs into close pairs of relativistic objects which can merge due to GWR is discussed, and in § 6, a summary is presented.

2. STELLAR EVOLUTION INPUT

When it does not fill its Roche lobe, each component is assumed to evolve as a single star. Evolutionary characteristics are taken from a variety of different sources which are too numerous to list.

The program takes into account stellar wind mass loss from massive main-sequence stars according to equation (7) in Vanbeveren (1991) and from helium stars as suggested by Langer (1989). The evolution of helium stars of different masses in binaries with mass exchange is taken into account according to Habets (1985a, b) and Avila Reese (1993).

There is possibly only one way to form a neutron star in an HMXB, and this is by a supernova explosion. Here it is assumed that all close binary components with initial masses larger than 11.4 $M_\odot$, but less than 40 $M_\odot$ (van den Heuvel

& Habets 1984), become supernovae with the formation of a neutron star. For binaries wide enough that the primary never fills its Roche lobe, the lower limit on the mass of a component which can become a neutron star is assumed to be 10 $M_\odot$, but such binaries cannot evolve into X-ray binaries. Stars with an initial mass larger than 40 $M_\odot$ are assumed to evolve into black holes of mass $\sim 10\ M_\odot$.

The initial eccentricities e of orbits are assumed to be related to the orbital period $P_{\rm orb}$ by

$$e = 0.1 \log P_{\rm orb}(\text{days}) . \quad (1)$$

If the orbit is elliptical when a primary first fills its Roche lobe, it is assumed that the orbit immediately becomes circularized, with orbital angular momentum remaining constant. If, after circularization, the primary can still fill its Roche lobe, the system is considered to be a close binary. Otherwise, it is considered to be a wide binary with $e = 0$. In a close binary, after a symmetric supernova explosion in which a neutron star is formed, orbital parameters are chosen according to the instantaneous mass-loss formulation of Boersma (1961) (see also McCluskey & Kondo 1971; Sutantyo 1974a, b; Bhattacharya & van den Heuvel 1991). For example, after the first explosion of a supernova in a close binary in a circular orbit, the eccentricity becomes $e = M_{\rm lost}/M_{\rm rem}$, where $M_{\rm lost}$ is the mass lost from the system and $M_{\rm rem}$ is the mass of the remnant binary. If the binary is to remain bound following a neutron star–forming supernova explosion, the amount of mass lost in the explosion must be less than the mass of the binary after the explosion, a condition which can be written as

$$M_{\rm precursor} - M_2 < 2M_{\rm NS} \simeq 2.8\ M_\odot , \quad (2)$$

where $M_{\rm precursor}$, M_2, and $M_{\rm NS}$ are, respectively, the mass of the primary just prior to the supernova explosion, the mass of the companion, and the mass of the neutron star.

After a neutron star–forming explosion in a wide binary, the change in the eccentricity is taken according to Hills (1983). Some massive binaries are disrupted by the first explosion (see, e.g., Tutukov & Yungelson 1993a for a quantitative estimate), and some systems achieve $e \sim 1$. At least two systems of the latter sort are known: one containing PSR 1253−63 (Johnston et al. 1992), and one in the SMC containing PSR J0045−7319 (Kaspi et al. 1994). Orbital periods of these binaries are 3.4 yr and 51 days, respectively.

Very close binaries can efficiently circularize their orbits by tidal interactions during the main-sequence lifetime of the primary (Zahn 1977). Wider binaries retain nonzero eccentricities until the primary leaves the main sequence and starts to fill its Roche lobe. In reality, all known HMXBs with orbital periods $\lesssim$ 10 days have almost zero eccentricities, and longer period HMXBs have $e > 0.1$. This difference has been explained in the framework of a theory developed by Zahn (1975, 1977) and others (Lecar et al. 1976; Tassoul 1988; King 1993; Prince et al. 1994) of circularization of orbits and synchronization of rotation and orbital periods.

A supernova explosion in a close binary will impart to the remnant system a rather large peculiar space velocity (Zwicky 1957), even in the case when the explosion is itself highly symmetric (see, e.g., the formulation of Boersma 1961). Blaauw (1961) has used this fact to account for the "runaway OB star" population (see also Stone 1982, 1991), and Gunn & Ostriker (1970) and Gott, Gunn, & Ostriker (1970) have used it to understand the velocity and space distributions of radio pulsars. It is of interest to note also that rotational velocities of runaway stars seem to be correlated with their peculiar space velocities (Tutukov & Yungelson 1989), suggesting that the rotation and orbital periods of massive presupernova binaries may be synchronized.

If the initial primary mass M_{10} is $\lesssim 50\ M_\odot$, the primary attempts to expand to giant dimensions after hydrogen has been exhausted over a central region, but, in a close enough binary, it fills its Roche lobe and begins to transfer mass to its companion. If the initial mass ratio is sufficiently larger than unity ($\gtrsim 1.2$ when the donor envelope is radiative), a CE is formed and most of the mass lost by the primary is also lost from the system. Mass loss continues until most of the hydrogen-rich envelope of the primary has been ejected from the system, giving $M_{\rm precursor} \sim M_{\rm He}$, where $M_{\rm He}$ is the mass of the helium core. After mass exchange, the primary has a mass similar to the mass of its helium core, an approximation for which is given by (e.g., Tutukov & Yungelson 1973; Iben & Tutukov 1984a, 1985)

$$M_{\rm He} \sim 0.1 M_{10}^{1.4} . \quad (3)$$

Here both masses are in solar units. Since the optical component in an HMXB is typically of mass $M_2 \sim$ 10–30 $M_\odot$, and since $M_{\rm precursor}$ is typically less than M_2, equation (2) is usually satisfied.

Semidetached binaries with black holes can arise only if $M_{\rm BH,min}$, the minimum initial mass of a star which can form a black hole, is smaller than $M_{\rm exp}$, the maximum initial mass of a star which can expand to giant dimensions. Otherwise, a CE will not be formed, and the companion of the black hole will remain too far away for mass transfer at appropriate rates to occur. The values of neither $M_{\rm BH,min}$ nor $M_{\rm exp}$ have been reliably established theoretically, so one cannot categorically exclude the possibility that $M_{\rm exp} < M_{\rm BH,min}$, and one can certainly not make reliable theoretical predictions about the probability of forming LMXBs with black hole components. However, the existence of semidetached binaries such as A0620+00, XN Mus, and LMC X-3 (see Fig. 1*b*), in which one component is a low-mass donor and the other appears to be a black hole of mass $\sim 10\ M_\odot$, could be taken as direct evidence that $M_{\rm exp} > M_{\rm BH,min}$. This argument would be weakened if the three observed systems have been formed in globular clusters in consequence of inelastic collisions between black holes and low-mass main-sequence binaries or single stars. But, since the three observed systems are not concentrated to the Galactic center, they probably belong to the Galactic disk population, and, therefore, formation from a primordial binary is a more probable scenario.

Only binaries in which the initial mass of the primary is in the range $M_{\rm BH,min}$–$M_{\rm exp}$ can form observed X-ray binaries with short orbital periods and black hole components. In the scenario program, it is assumed that $M_{\rm BH,min} = 40\ M_\odot$ (van den Heuvel & Habets 1984) and that $M_{\rm exp} = 50\ M_\odot$. The choice of $M_{\rm exp} \sim 50\ M_\odot$ is motivated by the near absence of bright red supergiants in the H-R diagram (Humphreys 1978; Humphreys & Davidson 1994) at luminosities corresponding to the luminosity of a 50 $M_\odot$ main-sequence star. The paucity of bright red supergiants suggests that initially very massive stars experience such extensive mass loss via a wind that the possibility of expansion after the formation of a helium core is effectively prevented (e.g., Massevich et al. 1979; Maeder 1980). Hubble-Sandage variables are in the "forbidden" region, but they are very few in number, and their apparent giant size is presumably due to the fact that optical depth unity occurs in the emitted wind. Because of the high rate of mass loss from the primary, the semimajor axes of orbits of binary systems with very massive primaries will increase during the core nuclear-burning phase. A supernova explosion increases the component separation still further.

In the evolution of many close binaries, a CE phase develops when the accretor cannot absorb matter at the same rate as it is provided by the donor and must expand (Paczyński 1976; Ostriker 1976, cited in Taam, Bodenheimer, & Ostriker 1978). An important paper bearing on the initiation of the CE phase is that of Flannery & Ulrich (1977). The evolution of binaries during this stage has been studied numerically by Taam et al. (1978), Meyer & Meyer-Hofmeister (1979), Tutukov & Yungelson (1979b), Taam (1979), Bodenheimer & Taam (1984), Livio & Soker (1984a, b, 1988), de Kool (1987), Taam & Bodenheimer (1989), Hjelming & Taam (1991), Taam, Bodenheimer, & Rozyczka (1994), and Terman, Taam, & Hernquist (1994). The main results of these studies have recently been reviewed by Iben and Livio (1993).

In the scenario program, a highly simplified algorithm is adopted to approximate the results of evolution during the CE stage. The energy necessary to eject the CE is assumed to come entirely from the energy of orbital motion. When the primary in the initial system achieves Roche lobe contact, an amount of mass equal to

$$\Delta M = (\tau_1/\tau_2)M_{20} \tag{4}$$

is transferred to the main-sequence secondary. Here τ_1 and τ_2 are, respectively, the thermal timescales of the envelopes of the initial primary and of the initial secondary, and M_{20} is the initial mass of the secondary. Orbital angular momentum is assumed to be conserved during mass exchange, so that

$$M_1^2 M_2^2 A_V = M_{10}^2 M_{20}^2 A_0 , \tag{5}$$

where A_0 and A_V are, respectively, the semimajor axis of the orbit before and after mass exchange, $M_1 = M_{10} - \Delta M$, and $M_2 = M_{20} + \Delta M$. If $\Delta M < M_{10} - M_{1R}$, where M_{1R} is the mass of the final remnant of the primary, the resulting pair of stars is called a "virtual" pair; the rest of the mass lost by the primary is assumed to go into a CE, with the degree of orbital shrinkage given by

$$\frac{G(M_1 + M_2)(M_1 - M_{1R})}{A_V} = \alpha_{\rm CE} G M_{1R} M_2 \left(\frac{1}{A_f} - \frac{1}{A_V}\right) . \tag{6}$$

In equation (6), A_V is the semimajor axis of the virtual system, A_f is the semimajor axis after the CE event, and $\alpha_{\rm CE}$ is a parameter of order unity. Numerical results show that, for an initial mass ratio q_0 (the mass of the less massive component divided by the mass of the more massive component) between 0.0 and about 0.8, because of the smallness of ΔM, the result of using the algorithm in the program is essentially equivalent to the result of nonconservative evolution. For $q_0 = 0.8$–1.0, a system evolves almost conservatively with respect to both mass and angular momentum.

For detached systems in which a main-sequence or helium-star component loses mass due to a wind, the semimajor axis A and the total system mass $M_{\rm tot}$ are assumed to be related by $M_{\rm tot}A$ = constant. This is the so-called Jeans approximation.

The adopted procedures for handling mass transfer and mass loss are probably still the most uncertain element of the scenario program. In particular, orbital periods of evolved binaries are very sensitive to the parameter $\alpha_{\rm CE}$. Previous semiempirical estimates of this parameter suggest that $\alpha_{\rm CE}$ is in the range 0.6–1.0 (e.g., Iben & Tutukov 1989; Tutukov & Yungelson 1993b). Some theoretical attempts to model the CE phase suggest $\alpha_{\rm CE} \sim 0.3$–0.6 (e.g., Livio & Soker 1988; Taam & Bodenheimer 1989). In this paper, the consequences of choosing $\alpha_{\rm CE} = 0.5$ and 1.0 are investigated.

3. AN ELEMENTARY MODEL OF WIND-FED X-RAY SOURCES AND A SUMMARY OF THE MAIN OBSERVED PROPERTIES OF HMXBs

Since X-ray emission from HMXBs is thought to be the result of the accretion by a compact relativistic star of matter from the radiatively driven wind of an OB star (Davidson & Ostriker 1973), many papers have been devoted to hydrodynamical studies of the accretion process (e.g., Livio et al. 1986; Anzer, Boerner, & Monaghan 1987; Matsuda, Inone, & Sawada 1987; Fryxell, Taam, & McMillan 1987; Taam & Fryxell 1988, 1989; Fryxell & Taam 1988; Sawada et al. 1989; Blondin et al. 1994; Ruffert & Anzer 1994; Ruffert 1994). The process is very complicated, and existing models indicate that flow patterns are highly nonstationary, with even the sense of rotation of an accretion disk fluctuating. Nevertheless, as many of the cited papers demonstrate (e.g., Fryxell et al. 1987), the average accretion rate is very close to that given by the Bondi-Hoyle-Lyttleton (Hoyle & Littleton 1939; Bondi & Hoyle 1944) approximation. McCray and Hatchett (1975) have pointed out that abundant elements such as carbon, nitrogen, and oxygen in the wind are ionized by X-ray radiation from the accretor. Since these ions are very important in the acceleration of the radiatively driven wind, the speed and mass-loss rate of the wind might be expected to be highly time dependent (Blondin et al. 1990). The scenario program does not take into account the complications of nonstationary flow, but assumes that accretion from the wind is steady and can be approximated after the manner of Bondi & Hoyle (1944).

The bright X-ray stage of persistent HMXBs is thought to begin when the optical component approaches its Roche lobe in size and the fraction of the donor-emitted wind matter captured by the relativistic component increases toward a maximum. The presence of a well-developed accretion disk in systems such as Cen X-3, LMC X-3, and SMC X-1 is evidence that the optical component in these systems is *very* close to filling its Roche lobe (Bhattacharya & van den Heuvel 1991).

If the accretor is a black hole, an accretion disk can in principle extend to the radius of the last stable orbit ($\sim$3 times the Schwarzschild radius) around the black hole (Abramovicz, Jaroszyński, & Sikora 1978; Paczyński & Wiita 1980). If an accretion disk is formed, X-rays are presumably emitted from the base of this disk. The conditions for the formation of a disk are regulated by the angular momentum of the intercepted matter (see, e.g., Shapiro & Lightman 1976, Appendix A), and there are, in principle, situations in which radial (sometimes called "spherical") accretion is possible.

If the accretor is a neutron star, the location of the base of the disk is presumably determined by a balance between the ram pressure of the wind and the energy density in the magnetic field of the neutron star (e.g., Lamb, Pethick, & Pines 1973; Shapiro & Lightman 1976; Börner et al. 1987). For typical conditions, this location has been estimated to be several hundreds of neutron-star radii from the surface of the neutron star. Matter from the disk presumably flows along magnetic field lines toward the magnetic poles, with X-rays being generated in an accretion column above the magnetic poles (e.g., Langer & Rappaport 1982).

The scenario code does not take into account the details of accretion and assumes that all of the gravitational potential energy released in the accretion process is converted into X-rays at a luminosity given approximately by

$$L_X \sim \frac{GM_X}{R_X}\dot{M}_X \sim 0.1\,c^2\dot{M}_X \sim 0.1\,c^2\frac{\dot{M}_w}{4\pi A^2}\pi r_{\rm acc}^2\,, \quad (7)$$

where M_X and R_X are, respectively, the mass and radius of the accretor, $\dot{M}_w$ is the mass-loss rate from the OB star, A is the semimajor axis of the orbit, and $r_{\rm acc}$ is an "accretion radius." If $r_{\rm acc}$ is chosen as (Bondi & Hoyle 1944)

$$r_{\rm acc} = \frac{2GM_X}{v_{\rm wa}^2}\,, \quad (8)$$

where $v_{\rm wa}$ is the speed of the wind at the location of the accreting star,

$$L_X \sim 0.1\,c^2\dot{M}_w\frac{G^2M_X^2}{A^2v_{\rm wa}^4}\,. \quad (9)$$

In the last two formulae, it has been assumed for simplicity that the orbital velocity $v_{\rm orb}$ of the accretor is much less than the wind velocity and can therefore be neglected. In the more general case, the relative velocity of an accretor and the wind gas is the vector sum of both motions.

In the case of single stars, it is known that the wind velocity at large distances from a wind emitter (large enough that no further acceleration occurs) is about 3 times the escape velocity $v_{\rm esc}$ from the star, almost independent of the rotational period of the emitter (see, e.g., Fig. 7 in Friend & Abbot 1986). In a close binary system, the situation can be quite different. The wind is accelerated over a region (the "near zone") which may not be small compared with the semimajor axis, and the wind velocity in the neighborhood of the accretor is smaller than its final value far from the system. This may be taken into account by setting

$$v_{\rm wa} = 3\alpha_w v_{\rm esc} = 3\alpha_w\sqrt{\frac{2GM_{\rm opt}}{R_{\rm opt}}}\,, \quad (10)$$

where $M_{\rm opt}$ and $R_{\rm opt}$ are, respectively, the mass and radius of the optical component, and α_w is a parameter which may, for very close systems, be considerably less than unity. Waters & van Kerkwijk (1989) estimate that $\alpha_w \sim 1 - R_{\rm opt}/A$. With these definitions, equation (9) becomes

$$L_X/L_\odot \sim \frac{4.1\times10^{11}}{\alpha_w^4}\left(\frac{M_X}{M_{\rm opt}}\right)^2\left(\frac{R_{\rm opt}}{A}\right)^2\dot{M}_w(M_\odot\,{\rm yr}^{-1})\,. \quad (11)$$

For small α_w, the contribution of the orbital motion to the velocity of the wind relative to the velocity of the accretor must be included [$v_{\rm esc}/v_{\rm orb} = (2M_{\rm tot}A/M_{\rm opt}R_{\rm opt})^{1/2}$, where $M_{\rm tot} = M_{\rm opt} + M_X$], but, for our purposes, equation (11) is an adequate approximation.

It is evident from equation (11) that, for typical values of $\dot{M}_w$ ($\sim10^{-6}\,M_\odot$ yr^{-1}), $M_X/M_{\rm opt}$ ($\sim$0.1), and $R_{\rm opt}/A$ ($\lesssim$0.5), the closer the optical component is to filling its Roche lobe, the larger is the accretion luminosity. However, in the real situation, the dependence on A may be much steeper than the inverse square; this has been taken explicitly into account by introducing the parameter α_w. In a close enough binary, the accretor may be in the near zone where the wind velocity is significantly less than its asymptotic value. Thus, equation (11) with $\alpha_w = 1$ provides an upper limit on the X-ray luminosity which becomes progressively less adequate, the closer the donor is to filling its Roche lobe.

Figure 1, which displays almost all persistent HMXBs with known masses and orbital periods, shows that only those optical components with masses larger than $\sim10\,M_\odot$ have a wind powerful enough to lead to X-ray emission which can be seen at large distances in the Galactic disk. The observations show that the OB component tends to be a rather evolved main-sequence star, with a radius typically about twice that of a zero-age main-sequence star of the same mass (Joss & Rappaport 1984). Choosing $M_{\rm opt} \sim 14\,M_\odot$, $M_X \sim 1.4\,M_\odot$, $R_{\rm opt}/A \sim 0.6$, and $\dot{M}_w \sim 10^{-6}\,M_\odot$ yr^{-1}, equation (11) gives

$$L_X \sim \frac{1500}{\alpha_w^4}L_\odot\,. \quad (12)$$

In general, the luminosity of even the brightest HMXBs (e.g., eq. [12]) is much less than the value corresponding to accretion at the Eddington limit for a neutron star. To achieve the largest possible X-ray luminosity, the OB component must be close to filling its Roche lobe (eq. [11]). This requirement simultaneously helps in the formation of an accretion disk around the accretor (see Appendix A). When the accretor is a black hole, whether or not an accretion disk forms determines the efficiency with which the kinetic energy of accreted matter is converted into escaping light.

The Galactic coordinates of 69 (mostly persistent) HMXBs, as given in the van Paradijs (1995) catalog of X-ray binaries, are shown in Figure 2. These systems are selected according to the apparent brightness of the optical component and thus include the brightest and therefore closest HMXBs. All known systems are clearly associated with the Galactic plane, and their distribution is highly nonuniform, or "clumpy." Comparing these with the (also clumpy) distribution of bright stars in the solar neighborhood (e.g., van den Bergh 1982; Conti et al. 1983; Efremov & Sitnik 1988), it is clear that the positions of

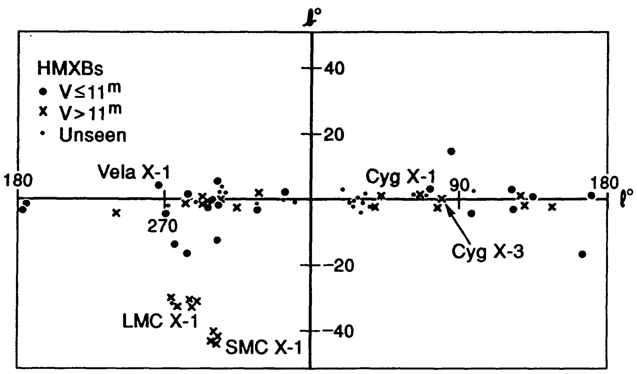

FIG. 2.—Positions of HMXBs on the sky in Galactic coordinates according to the van Paradijs (1993) catalog. The apparent visual brightness is indicated by symbols described in the legend in the upper left-hand corner of the figure.

the clumps of HMXB sources coincide (in projection) with the positions of the clumps of bright stars in spiral arms. This coincidence permits us to estimate distances to the known HMXBs as typically within ~ 2.5 kpc of the Sun. This estimate is supported by individual estimates of distances to well-studied HMXBs. With an estimated average distance, the height of an HMXB above the Galactic plane can be estimated, and it is found to be typically 100–300 pc (see Fig. 2), compared with a height ≤ 100 pc for a typical unevolved massive star (Stone 1982).

The space density of stars in the solar neighborhood is roughly equal to the average space density over the entire disk of the Galaxy (e.g., Iben & Tutukov 1984b), and since most of the known HMXBs are within 2.5 kpc of the Sun, one can infer that the total number of HMXBs in the Galaxy is $N_{\rm HMXB}^{\rm tot} \sim (10\,{\rm kpc}/2.5\,{\rm kpc})^2 (N_{\rm HMXB}^{\rm obs}) \sim 16 \times 69 \sim 1100$. However, only a small fraction of the observed sources are brighter than 1000 $L_\odot$ in X-rays. Using our distance estimates, only 3–5 out of the 69 cataloged sources have X-ray luminosities larger than 1000 $L_\odot$ (see Fig. 3), and this translates into only $\sim$50–80 "bright" HMXBs in the entire Galaxy. These binaries are the subject of our numerical model.

The van Paradijs catalog permits us to compare the distributions of HMXBs and LMXBs in number versus X-ray flux. About half of all LMXBs in the catalog are bulge sources (see Fig. 2 in Paper II) located within 20° of the Galactic center, and therefore at distances of ~ 8 kpc. Most of them have X-ray fluxes in the range 10–10^3 mJy. Only about half the HMXBs have fluxes in this range, the other half having lower fluxes. Since HMXBs are, on average, over 3 times closer than the bulge LMXBs, it may be concluded that the intrinsic X-ray luminosity of an average bright HMXB is at least an order of magnitude smaller than the X-ray luminosity of an average LMXB. This difference is a consequence of the difference in the mode of mass exchange—inefficient accretion from a wind in the case of HMXBs and efficient transfer through the Roche lobe throat in the case of LMXBs.

On the other hand, taken as a group, HMXBs are much brighter optical sources than are LMXBs. This is a natural consequence of (1) the low luminosity of the low-mass donor in LMXBs compared to the luminosity of the OB star donor in HMXBs, and (2) the larger average distance of LMXBs from the Sun as compared to that of HMXBs.

4. THE BIRTHRATE OF HMXBs: NUMBER-PERIOD, NUMBER-MASS, AND NUMBER-SPACE VELOCITY DISTRIBUTIONS

In order to construct a model of any family of evolved systems, estimates of the birthrates of precursor systems and estimates of their lifetimes are required. The scenario program assumes that the primordial birthrate function for binaries in our Galaxy can be approximated by (IT 1984a)

$$d^3\nu({\rm yr}^{-1}) = 0.2\, d \log A_0 \left(\frac{dM_{10}}{M_{10}^{2.5}}\right) dq_0 \,, \qquad (13)$$

where A_0, M_{10}, and q_0 are, respectively, the semimajor axis, the mass of the primary, and the ratio of the mass of the secondary to the mass of the primary in the primordial system.

It is instructive to make a crude first estimate of the birthrate of all systems which consist of a neutron star or black hole and an OB star, regardless of the luminosity and wind mass-loss rate of the OB star or of the accretion rate of the neutron star or black hole. Inserting in equation (13) the choices $\Delta \log A_0 \simeq 2.0$, $M_{10} = 11.4$–$50\ M_\odot$, and $\Delta q_0 \sim 0.3$, one obtains $\nu_{\rm HMXB} \sim 2 \times 10^{-3}\ {\rm yr}^{-1}$. An estimate of the total number in the Galaxy of some family of stars is usually given by the product of the theoretically estimated birthrate and the lifetime of an average representative of the family. Since the main-sequence lifetime of a star in the mass range 10–30 $M_\odot$ is ~ 3–10×10^6 yr (e.g., Chiosi & Maeder 1986), one may infer that the number of close binary systems consisting of an OB star and a relativistic component is $N_{\rm OB+RC} \sim 13000 \pm 7000$. Most of these systems are not currently observable X-ray sources, but eventually become such. The duration of the X-ray stage, especially the du-

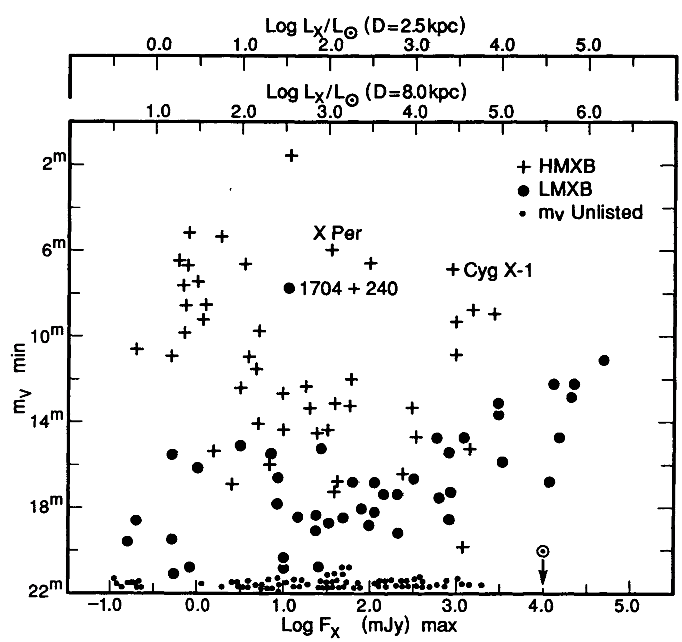

FIG. 3.—The apparent visual magnitudes of LMXBs (*large filled circles*) and HMXBs (*plus signs*) vs. their X-ray fluxes, as given by the van Paradijs (1993) catalog. For variable sources, F_X refers to the maximum flux over a long time interval. Dots located at the bottom of the figure represent LMXBs which are not seen at optical wavelengths. Numbers on the upper scales are estimates of X-ray luminosity (in the 2–10 KeV range) for two assumed distances.

ration of the brightest part of it, is much shorter than the main-sequence lifetime (Massevich et al. 1979; Savonije 1979), so that $N_{\rm HMXB} \ll N_{\rm OB+RC}$.

In order to make a more direct comparison with sources which have been better studied, the scenario code focuses attention on only the brightest persistent sources with an X-ray luminosity (estimated from eq. [11]) which is larger than 10^3 $L_\odot$. Mass loss via a stellar wind from the OB component is assumed to occur at the rate

$$\dot{M}_w = \frac{L_{\rm OB}}{v_\infty c}, \tag{14}$$

where $L_{\rm OB}$ is the luminosity of the OB star, and v_∞ is 3 times the escape velocity from the OB star (see eq. [10] with $\alpha_w = 1$). Massevich et al. (1979) and Savonije (1979) show that the duration of the bright X-ray phase is much shorter than the main-sequence lifetime of the optical component, because high mass-transfer rates occur only when this component nearly fills its Roche lobe (see eq. [11]). Analytical approximations have been constructed for the duration T of the bright X-ray phase in HMXBs in which a neutron star is an accretor (Massevich et al. 1979). If the optical component is a main-sequence star (case A) with mass greater than 10 $M_\odot$,

$$T_A({\rm yr}) = 1000 M_{\rm opt}^2 (1 + 0.000005 M_{\rm opt}^{3.5})^{-1}, \tag{15}$$

and, if the optical component is a shell hydrogen-burning star (case B),

$$T_B({\rm yr}) = 14000 M_{\rm opt}^{-0.44}, \tag{16}$$

where the mass of the optical component is in solar units. The same estimates are used for the duration of the X-ray phase for HMXBs with black hole accretors.

With these algorithms and the choice of $\alpha_{\rm CE} = 1$, the program generates $N_{\rm HMXB}^{\rm bright} \sim 35$ as the total number of Galactic HMXBs in which the optical component is an OB star close to filling its Roche lobe. This is not too different from the estimate of $N_{\rm HMXB} \sim 50$–80 based on the observations (see § 3). Dalton & Sarazin (1994, 1995) obtain a similar theoretical estimate based on scenario modeling. The theoretical estimate depends linearly on the assumed duration of the X-ray phase, and it is worth emphasizing that the duration of the X-ray phase, as predicted by the standard theory of stellar evolution, at least for massive binaries, is consistent with the observational facts. Savonije (1979) estimates the duration of the X-ray stage to be in the range 3×10^4–10^5 yr, depending on the evolutionary status of the donor. These values agree rather well with the durations given by equations (15) and (16). Hellings & de Loore (1986) give similar estimates for the duration of the X-ray phase for A and B systems: $T_A \sim 3 \times 10^5$ yr, and $T_B \sim 3 \times 10^3$ yr. Meurs & van den Heuvel (1989) assume the average lifetime of HMXBs to be 2.5×10^4 yr and estimate the number of bright X-ray sources to be several times 10.

The numerical model provides additional information. When $\alpha_{\rm CE} = 1$, the total birthrate of all persistent HMXBs is $\nu_{\rm HMXB} \sim 2.7 \times 10^{-3}$ yr^{-1}, and, when $\alpha_{\rm CE} = 0.5$, $\nu_{\rm HMXB} \sim 2.5 \times 10^{-3}$ yr^{-1}; both estimates are close to our first rough estimate and show that the estimated birthrate of HMXBs is only weakly dependent on $\alpha_{\rm CE}$. The scenario code does not attempt to find the total number $N_{\rm HMXB}^{\rm tot}$ to compare with the semiempirical estimate of 1100 in § 3, as this requires a choice of a lower limit on L_X and a consideration of many selection effects.

The estimated birthrate of bright HMXBs ($L_X \geq 10^3$ $L_\odot$) is only weakly dependent on the choice of black hole mass, if this mass is in the range 5–10 $M_\odot$. When it is assumed that all stars of initial mass larger than 40 $M_\odot$ produce black holes of mass 5 $M_\odot$, three of the predicted 35 bright sources contain black holes. When a black hole mass of 10 $M_\odot$ is adopted, the number of bright sources with black hole accretors increases to six, and the total number of bright sources increases to 38. These numbers may be compared with the estimate of 20–60 persistent HMXBs by Meurs & van den Heuvel (1989). Within the limits of existing uncertainties, all theoretical estimates are consistent with each other and with the observations.

The average duration of the X-ray stage in the case of a 10 $M_\odot$ black hole accretor is, according to our model, about 1.4×10^4 yr, or only a few tenths of a percent of the donor main-sequence lifetime. Among about 20 HMXBs with known masses listed in the compilation by Aslanov et al. (1989), in possibly only one, Cyg X-1, is the accretor a massive black hole. Because of the small statistics, one cannot claim either agreement or disagreement between the theoretical estimates and the observational one.

Several additional quantitative aspects of our model of the Galactic HMXB population are displayed in Figures 4–6. Figure 4 shows the distribution in number versus mass of the optical components of systems in which the X-ray luminosity is greater than 10^3 $L_\odot$. Optical components of the great majority of the X-ray bright theoretical systems have masses in the range 10–30 $M_\odot$, just as is the case with observed systems (Fig. 1*a*). The predicted distribution of the brightest stationary sources with regard to orbital period is shown in Figure 5*a*. Since a donor must almost fill its Roche lobe if it is to fuel a bright X-ray source, the orbital period is a good indicator of its size and

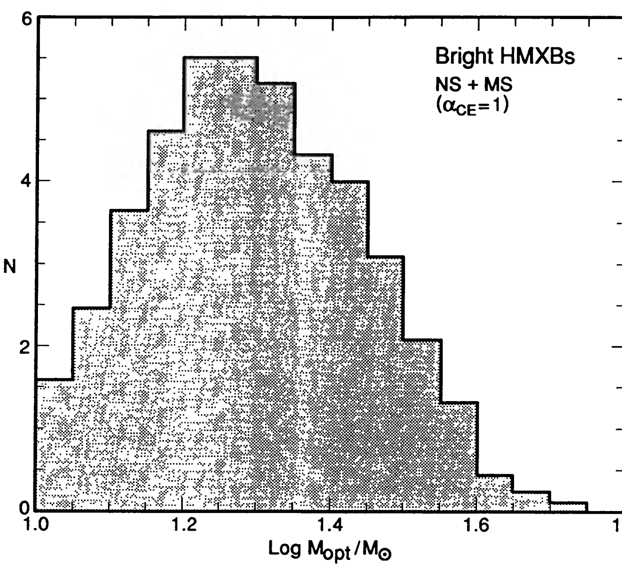

FIG. 4.—The distribution of optical components of bright HMXBs in number vs. mass according to the numerical model with $\alpha_{\rm CE} = 1$.

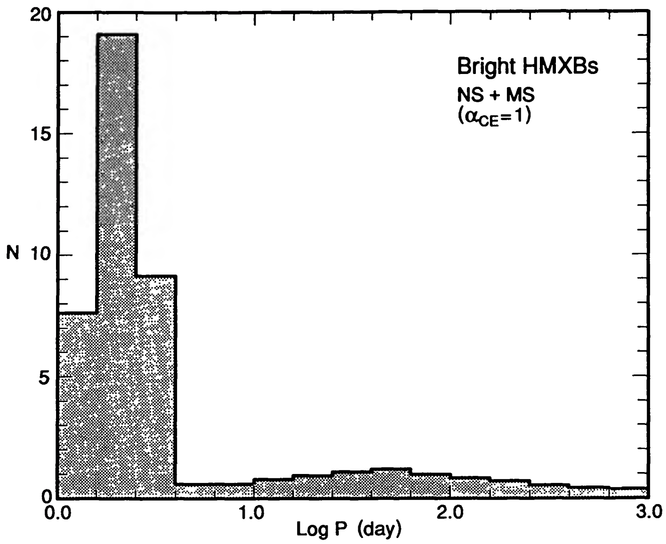

FIG. 5*a*

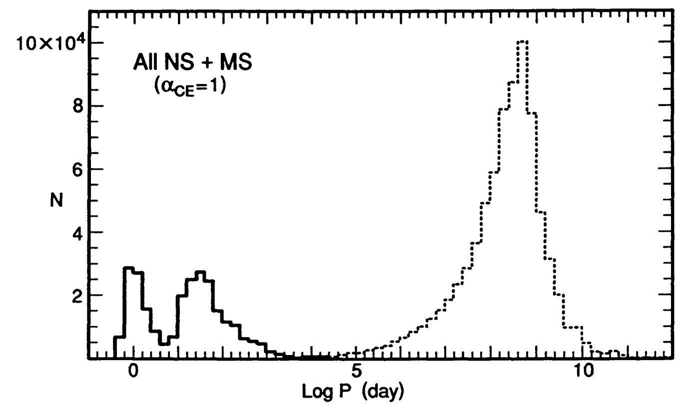

FIG. 5*b*

FIG. 5.—(*a*) The distribution of bright HMXBs ($L_X \geq 10^3\ L_\odot$) with respect to orbital period according to the numerical model with $\alpha_{CE} = 1$. (*b*) The distribution with respect to orbital period of all binaries consisting of a neutron star and a main-sequence star (TY 1993a, $\alpha_{CE} = 1$).

therefore of its evolutionary state. There are clearly two kinds of systems. The more highly populated kind consists of close binaries in which the optical component is close to the main sequence. The other kind consists of wider binaries in which the optical component has left the main sequence. The closer systems outnumber the wider systems by about four to one. In the sample of six bright persistent HMXBs with OB components (see Fig. 1*a*), four have orbital periods shorter than 4 days and two have longer periods. Thus, there is qualitative agreement between the observations and theoretical expectations.

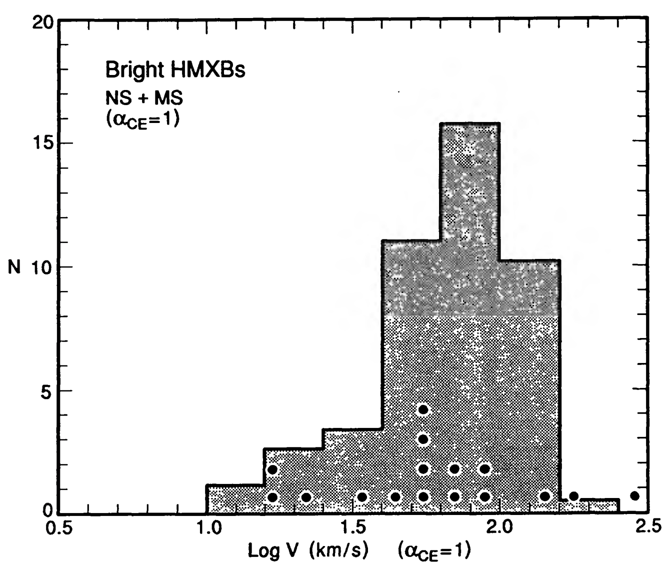

FIG. 6.—The distribution of bright HMXBs with respect to the space velocity achieved during the supernova explosion which converted the initial primary into a neutron star. Also shown are the peculiar radial velocities obtained by van Oijen (1979) multiplied by 2 to convert radial velocities into space velocities.

The predicted distribution in number versus period of all detached binaries consisting of a neutron star and a main-sequence star is given in Figure 5*b* (Tutukov & Yungelson 1993a). In this distribution, there is no restriction on the mass of the main-sequence component (other than that a bound system has remained after the formation of the neutron star, see eq. [2]), and there is no restriction on the brightness of either the main-sequence star or on the possible X-ray luminosity of the neutron star. A comparison between Figures 5*a* and 5*b* emphasizes the rarity of the HMXB phenomenon; only about one out of 1000 close systems with a neutron star accretor is in the HMXB phase at any time.

There are three "humps" in the distribution of Figure 5*b*. Systems in the broad hump at very long period (centered at $\sim 5 \times 10^8$ days) have not experienced mass exchange. Because of the large mean eccentricity of wide initial systems consisting of two main-sequence stars, about half of all wide systems in which the primary becomes a neutron star remain bound after the explosion which produces the neutron star (it is most likely that the explosion occurs near apastron [e.g., Hills 1983] when most of the orbital energy is in gravitational potential energy). Systems in the two neighboring humps at short period (centered at ~ 1 day and ~ 30 days, respectively) are progeny of systems which have experienced mass exchange and mass loss during the formation of the helium-star precursor of the neutron star. The shorter period hump consists predominantly of systems which have evolved through one or two CE phases (initial mass ratio $q_0 = 0.0$–0.8); a large fraction ($\sim 30\%$) of similar systems have evolved into single stars during the CE phase. The longer period hump consists predominantly of systems which have evolved through a mass-conservative mass-exchange phase (components with initial $q_0 \approx 0.8$–1.0).

Stationary bright HMXBs (Fig. 5*a*) are in the short-period half of the hump centered at 1 day in Figure 5*b*. Comparing the model number of bright HMXBs with the estimate of $\sim$6000–20,000 for the total number of binary stars with relativistic components derived on the assumption that the HMXB lifetime is equal to the main-sequence lifetime of the donor, it is evident that, on average, systems consisting of a neutron star and a main-sequence star are bright stationary HMXBs for only ~0.2%–0.7% of the main-sequence lifetime. In most systems consisting of a neutron star and an optical component, either the optical component is considerably less massive than 10 $M_\odot$, or the orbital separation is too large to permit the secondary to fill a significant fraction of its Roche lobe until it has evolved well beyond the main sequence. Transient HMXBs are to be found among the systems in the hump centered at 30 days (Figs. 5*a*–5*b*). The 10–1000 day range in orbital period in this hump is not inconsistent with the range in orbital period (~10–200 days) in the observed distribution (Fig. 1*a*), given the fact that, the wider the system, the shorter is the X-ray stage and the smaller is the fraction of the matter ejected by the OB component which can be accreted by the neutron-star or black hole component and, therefore, the lower is the probability of discovering it. These long-period systems can retain a large post–supernova explosion eccentricity for almost the entire main-sequence lifetime of the OB companion, as is found to be the case for HMXBs with Be optical components.

At the moment of formation of the first neutron star in a massive binary, the bound system which survives achieves a large peculiar space velocity because of the necessity to conserve linear momentum between the surviving system and the mass ejected in the explosion (Zwicky 1957; Blaauw 1961; van den Heuvel & Heise 1972; Tutukov & Yungelson 1973). Such fast, massive stars have long been known as "runaway" stars. The runaway velocity is calculated in the scenario program, and the resulting theoretical distribution of HMXBs versus peculiar space velocity is shown in Figure 6. The velocity is in the range 40–150 km s^{-1}, which is sufficient for the average system to move ~10^3 pc from its birthplace over the main-sequence lifetime of the massive optical component. According to Conti, Leep, & Lorre (1977), about 10% of all observed O stars have space velocities this high; according to Stone (1982), approximately half of all observed O stars have space velocities this high, and some of them are known to have a low-mass (probably highly evolved, relativistic) companion (e.g., Aslanov et al., 1989). Since most HMXBs are in very close systems, their space velocities certainly entitle them to membership in the family of runaway stars.

Van Oijen (1989) has determined the peculiar radial velocities of a sample of 33 HMXBs and states that he has "found strong indications that the massive X-ray binaries are indeed high-velocity objects." Assuming symmetry between radial and transverse velocities, the peculiar radial velocities given in van Oijen's Table 6 have been multiplied by a factor of 2 and inserted as filled circles in Figure 6. It is evident that (within the uncertainties) there is excellent agreement between the predicted and the observed distributions.

Van Oijen also estimates the height above the Galactic plane and the distance from the nearest OB association for his sample of HMXBs. Some HMXBs are at a large distance above the Galactic plane, e.g., 4U 0728−25 ($z \sim -327$ pc) and X Per ($z = -235$ pc), and eight out of the 33 systems studied are separated from the nearest OB association by over 1 kpc.

The magnitude of the recoil velocity acquired during a supernova explosion is inversely proportional to the mass of the remnant system and is directly proportional to the orbital velocity of the exploding component. It is because of this latter dependence that the brightest HMXBs constitute a high space velocity population. Wide binary progenitors of HMXBs evolve into low space velocity HMXBs and are at their brightest in X-rays for only a very short time toward the end of their main-sequence lives (eq. [16]). Close binary progenitors evolve into high space velocity objects and are brighter for a longer portion of their main-sequence lives (eq. [15]).

The theory also predicts a correlation between the rotational velocity of a massive runaway star and the space velocity of this star. The shorter the orbital period of the precursor system, the larger will be the space velocity of the runaway star after the supernova explosion; if the optical component of the precursor system rotates about its own axis with a period near the orbital period, which is reasonable to expect in a close system, there will clearly be a correlation between the rotational velocity and the space velocity of the runaway star. A statistical analysis of observed space and rotational velocities of runaway stars (Tutukov & Yungelson 1989) verifies the predicted correlation, and this is additional quantitative support for the binary scenario of the origin of runaway stars.

5. AFTER THE HMXB STAGE: MERGERS AND GRAVITATIONAL WAVE PULSES

Since it tends to be a highly evolved main-sequence star or an early post–main-sequence star close to filling its Roche lobe, the donor in a bright stationary source does not lose much mass between the onset of the bright X-ray phase and the moment when it has expanded to fill its Roche lobe. Hence, when Roche lobe–filling occurs, the ratio of donor mass to accretor mass is still large, and a CE is formed, leading to orbital shrinkage by a factor of 30–60 (eq. [6]).

Some of the systems in Figures 1*a* and 5*b* with $P_{\rm orb} \sim 100$ days and $M_{\rm opt} \gtrsim 25\ M_\odot$ might be expected to evolve through a CE phase into HMXBs in which the optical component is a W-R star. However, among the six persistent HMXBs with known orbital parameters (Fig. 1*a*), only one system, Cyg X-3, at a distance of ~12 kpc (Dickey 1983), is of this type (van Kerkwijk et al. 1992). From the observed rate of period change, van Kerkwijk et al. (1992) infer a mass-loss rate of ~$10^{-5}\ M_\odot$ yr^{-1}, which is typical of W-R stars. Assuming component masses of 1.4 $M_\odot$ and 10 $M_\odot$, the orbital semimajor axis is ~3.25 $R_\odot$, and, according to equation (11), $L_{\rm X} \sim 8000\alpha_w^{-4}\ L_\odot$. There are 46 W-R stars within a 2.5 kpc circle about the Sun (van der Hucht et al. 1988), and this corresponds to about 1000 in the entire Galaxy. The scenario code (Yungelson & Tutukov 1991) predicts that about 11% of all W-R stars should have close ($A < 10\ R_\odot$) relativistic components, and equation (11) predicts a luminosity greater than 800 $L_\odot$ if $\alpha_w = 1$, $\dot{M}_w = 10^{-5}$ $M_\odot$ yr^{-1}, and $M_{\rm X} = 1.4\ M_\odot$. Thus, the scenario program predicts the existence in the Galaxy of about 100 massive binaries with W-R components, compared with one known example, and five bright HMXBs with W-R donors within 2.5 kpc of the Sun, where none has been observed.

The number of close ($A \leq 10\ R_\odot$) NS+W-R pairs produced by the scenario program depends rather weakly on the assumed value of $\alpha_{\rm CE}$. This number decreases from 60 for $\alpha_{\rm CE} =$ 1 to 35 for $\alpha_{\rm CE} = 0.1$. It has been argued that NS+W-R binaries should not be strong X-ray emitters because the strong magnetic field of the rapidly spinning neutron star prevents accretion (Lipunov 1982; Lipunov et al. 1994) due to a "propellor" mechanism (Illarionov & Sunyaev 1975).

However, the model also produces a significant number of close BH+W-R binaries, and this mechanism cannot be invoked to explain the apparent absence of observed counterparts. According to equation (11) with $R_{WR} = 1\ R_\odot$, $M_X = M_{WR} = 10\ M_\odot$, and $\dot{M}_w = 10^{-5}\ M_\odot\ yr^{-1}$, BH+W-R binaries will be bright ($L_X \geq 10^3\ L_\odot$) X-ray sources if $A \leq 63\ R_\odot$. The number of such close BH+W-R systems produced by the scenario program increases smoothly from 100 for $\alpha_{CE} = 1.0$ to 122 for $\alpha_{CE} = 0.1$.

Some understanding as to why these predicted numbers are so large compared with the observed number (zero) follows from an examination of the conditions required for the formation of an accretion disk around a black hole (Appendix A). Taking $\alpha_w = 1$, the formation of a Keplerian disk around the black hole requires the semimajor axis of the binary to be less than $\sim 3.6\ R_\odot$ (eq. [A2] in Appendix A). The scenario population model for $\alpha_{CE} = 1.0$ has only three BH+W-R binaries with $A \leq 6.3\ R_\odot$. Accretion in wider systems is probably mostly radial (White, Swank, & Hoft 1983), and this probably excludes strong X-ray emission (e.g., Shapiro & Teulkolsky 1983). Most of the thermal and kinetic energy acquired by gas as it is being accreted enters the black hole horizon before it can be radiated away, the rate of energy release being less than $\sim 10^{-4}\ \dot{M}c^2$ (Park 1990a, b). Thus, in spite of the possible existence of a large number of relativistic remnants around apparently single W-R stars in our Galaxy, only a few systems, those with orbital periods less than ~4.2 hr, can be bright X-ray sources like Cyg X-3. The problem of disk formation in BH+W-R systems is a very complicated one which deserves much more sophisticated numerical modeling.

Most systems with characteristics shown in Figure 5*b* are disrupted during the second supernova explosion (Tutukov & Yungelson 1993a). This is a simple consequence of the fact that the exploding component is usually far more massive than its companion (see eqs. [2] and [3]). The scenario code finds that massive binaries produce several families of neutron stars with space velocities ranging from ~ 10 km s^{-1} up to ~ 800 km s^{-1} (Tutukov & Yungelson 1993b). The existence of a family of radio pulsars with low space velocities has been inferred from observed samples (e.g., Tutukov, Chugai, & Yungelson 1984; Narayan & Ostriker 1990). Examining a homogeneous sample of 301 radio pulsars, Narayan & Ostriker (1990) conclude that there are probably two almost equal populations of pulsars with mean one-dimensional peculiar space velocities of about 50 km s^{-1} and 150 km s^{-1}, respectively. Thus, the observed distribution of radio pulsars over their space velocities (Taylor, Manchester, & Lyne 1993) can be understood as the result of the formation of most, if not all, radio pulsars in close binaries with interacting components.

A currently popular explanation of high pulsar space velocities is that, in consequence of an asymmetric supernova explosion, the remnant neutron star (or binary containing the remnant neutron star) receives a "kick" (Shklovski 1970). If most radio pulsars were the result of the evolution of single massive stars (with typical peculiar velocities of only ~ 10 km s^{-1}), it is understandable how one might find it necessary to introduce such a kick to explain the observed high space velocities. The value assumed for the kick varies from about 90 km s^{-1} (Dewey and Cordes 1987), through 100–200 km s^{-1} (Bailes 1989), to about 450 km s^{-1} (Lyne and Lorimer 1994).

A kick of the envisioned sort is not mandated by the observations, and such a kick is not included in the scenario code. A small kick (less than about 50 km s^{-1}) would not change the pulsar space velocity distribution significantly relative to that given by the scenario code, and a larger "universal" kick would destroy the low-velocity population of radio pulsars (Tutukov, Chugai, & Yungelson 1984; Narayan & Ostriker 1990). A universal kick exceeding about 50 km s^{-1} also creates a problem in understanding the existence of neutron stars in globular clusters for which escape velocities are typically ~ 10 km s^{-1}. It is usually assumed that an LMXB in a globular cluster is formed in consequence of tidal capture (Hills 1975) or an exchange collision (Fabian, Pringle, & Rees 1975) involving a neutron star formed earlier in the life of the cluster. The introduction of a ~ 450 km s^{-1} kick (Lyne & Lorimer 1994) would disrupt most binaries with orbital periods larger than several days at the moment of the first supernova explosion. Then, the existence of wide HMXBs with Be donors and orbital periods of about 100 days (see Fig. 1*a*) would be hard to understand. Such a large kick would also impart an excessively large space velocity to HMXBs which remain bound, destroying the otherwise good agreement between space velocities given by the scenario model and observed ones (Fig. 6).

Components in persistent X-ray sources of periods less than about 3 days will merge during a CE phase initiated by the optical component; the result will be a Thorne-Żytkow object (a supergiant with a neutron-star core [Thorne & Żytkow 1975, 1977; Cannon et al. 1992] or a black hole core). Their birthrate is 4×10^{-4} yr^{-1} when $\alpha_{CE} = 1$. Transient HMXBs with longer orbital periods either become unbound when the optical component explodes as a supernova ($M_{opt} \gtrsim 14.2\ M_\odot$, eq. [2]) or, when $M_{opt} \lesssim 14.2\ M_\odot$, they evolve into pairs of neutron stars or neutron stars bound to black holes, but with periods in the range ~0.1–1000 days (TY 1993a). If a final system consists of two neutron stars with an orbital period shorter than ~15 hr or consists of two black holes with orbital period less than ~51 hr, GWR will cause the components to merge in less than a Hubble time.

The birthrate of the closest final systems consisting of two compact relativistic stars merits special attention. The largest energy which can be emitted by stars in the form of gravitational waves, and possibly in some other forms as well, occurs during the mergers of these systems (e.g., Smarr & Blandford 1976; Clark & Eardley 1977). Estimates of the frequency of such events are of basic importance for planning experiments for the direct detection of pulses of GWR (e.g., Evans, Iben, & Smarr 1987; Hils, Bender, & Webbink 1990). Several semiempirical estimates have been made. Clark, van den Heuvel, & Sutantyo (1979) estimate the frequency of merging of neutron star pairs in our Galaxy as 3×10^{-4} yr^{-1}. Narayan, Piran, & Shemi (1991) estimate a value 10 times smaller, and, assuming that most HMXBs are not disrupted during the second SN explosion, estimate the frequency of black holes plus neutron star mergers in our Galaxy to be the same as that of double neutron star mergers, 3×10^{-5} yr^{-1}. Hils et al. (1990) estimate the birthrate of neutron star pairs in our Galaxy to be $\sim 10^{-4}$ yr^{-1} and the birthrate of black hole plus neutron star binaries to be $\sim 2 \times 10^{-4}$ yr^{-1}. Using the ages and distances of three known pulsars which are likely to have a neutron star companion, Phinney (1991) estimates the merging rate of such systems to be $\sim 10^{-6}$ yr^{-1}. It is possible that Phinney's low value is due to an underestimate of the space density of binary neutron stars. Phinney also argues that the birthrates of close binary black holes and of black holes and neutron stars are comparable with the birthrate of merging neutron stars.

The scenario code provides independent estimates of these frequencies. Assuming a black hole mass of 5 $M_{\odot}$, Tutukov & Yungelson (1993b) estimate that the frequencies of mergers in our Galaxy are (NS = neutron star, BH = black hole): $\nu_{\rm NS+NS} \sim 3.2 \times 10^{-4}$ yr^{-1}, $\nu_{\rm NS+BH} \sim 1.5 \times 10^{-5}$ yr^{-1}, and $\nu_{\rm BH+BH} \sim 1.4 \times 10^{-6}$ yr^{-1}. When the mass of the black hole is taken to be 10 $M_{\odot}$, which is possibly a more characteristic value (e.g., Cowley 1992; Tutukov & Cherepashchuk 1992), the scenario code finds that the frequency of NS+NS mergers remains the same, the frequency of NS+BH mergers becomes $\nu_{\rm NS+BH} \sim 6 \times 10^{-5}$ yr^{-1}, and the frequency of BH+BH mergers becomes $\nu_{\rm BH+BH} \sim 1.7 \times 10^{-5}$ yr^{-1}. The increase in the NS+BH and BH+BH merger frequencies is due in part to a wider permissible range for the mass of the precursor of the second relativistic star remaining in a binary (eq. [2] with $2M_{\rm NS}$ replaced, respectively, by $M_{\rm NS} + M_{\rm BH}$ and $2M_{\rm BH}$); this translates into larger intervals of initial semimajor axes and initial mass ratios for systems which remain bound after the second supernova explosion. In addition, for a given orbital separation when a relativistic pair is formed, a more massive black hole means a shorter time between formation and merger, and this also translates into a wider range in initial semimajor axes.

Comparing the results found here with those of other authors, it appears that most merger frequency estimates agree within a factor of 2–3 with the values $\nu_{\rm NS+NS} \sim 1 \times 10^{-4}$ yr^{-1}, $\nu_{\rm NS+BH} \sim 4 \times 10^{-5}$ yr^{-1}, and $\nu_{\rm BH+BH} \sim 2 \times 10^{-5}$ yr^{-1}. The BH+BH and BH+NS merging rates are the result of a balance between an intrinsically relatively small black hole birthrate and a large range in initial semimajor axes which is due to the fact that, at a given orbital separation, the timescale for merging depends inversely on the mass of each component and on the total mass of the system.

The estimated frequency of mergers of binary black holes has very important observational consequences. The energy radiated in gravitational waves during a merger depends strongly on the masses of the merging components. Therefore, the volume of space-producing detectable merger events is also a strong function of the component masses (see, e.g., Abramovici et al. 1992), being proportional to $M^{2.5}$ (Tutukov & Yungelson 1993b) for components of the same mass M. Thus, when $M_{\rm BH} = 10\ M_{\odot}$, the volume of space that produces detectable BH+BH mergers is about 136 times larger than the volume of space that produces detectable NS+NS mergers. As a result, among detected events, BH+BH mergers may be about 10 times more common than NS+NS mergers, and the first detection of GWR may well be that of a BH+BH merger.

6. CONCLUDING SUMMARY

This paper has been devoted to modeling intrinsically bright HMXBs, a family of binary systems which has very few ($\sim$100–1000) members but which is very important from the standpoint of the theory of stellar evolution. It also describes some of the machinery which is used in Paper II to explore evolutionary links between LMXBs and binary radio pulsars and millisecond pulsars. The main results of the scenario model are summarized in this conclusion. It is to be emphasized that, although not all of these "results" (i.e., properties of a population of stars) are new, the way in which they have been achieved (by means of a self-consistent model of the binary population of the Galaxy) is new; known facts are predicted by means of a scenario model based on results of theoretical stellar evolution calculations and on a semiempirical birthfunction in a way which has not been done before.

1. Typical model HMXBs (in the "bright" set with $L_X > 10^3$ $L_{\odot}$) have luminosites significantly smaller than the Eddington limit for the accretor, and this is consistent with the fact that most known HMXBs are at distances less than $\sim$2.5 kpc from the Sun.

2. The numerical scenario model predicts that HMXBs are formed at the rate of $\sim 2.6 \times 10^{-3}$ yr^{-1}, but, since they have such a short average lifetime as bright X-ray stars ($\sim 1.4 \times 10^4$ yr, or about 0.2% of the main-sequence lifetime of the optical component), the total observable number of bright HMXBs (those with $L_X \gtrsim 10^3\ L_{\odot}$) is only $\sim$40. Known HMXBs include examples of nearly all possible theoretical evolutionary paths for forming HMXBs, including X-ray binaries with black hole accretors. The model predicts three ($M_{\rm BH} \sim 5\ M_{\odot}$) to six ($M_{\rm BH} \sim 10\ M_{\odot}$) bright HMXBs with black hole accretors when $\alpha_{\rm CE} \sim$ 0.5–1, and their birthrate in our Galaxy is $\sim$2–4 $\times 10^{-4}$ yr^{-1}. Because of the long main-sequence lifetimes of OB stars, the total number of massive binaries with relativistic components probably exceeds the number of bright HMXBs by a significant ($\gtrsim$400) factor, but only a small fraction of these are observable as X-ray sources. In the observed sample of persistent HMXBs, the number of persistent HMXBs with $L_X < 10^3\ L_{\odot}$ exceeds the number with $L_X \gtrsim 10^3$ $L_{\odot}$ by a factor of about 14.

3. The numerical model produces distributions with respect to the mass of the optical component, the orbital period, and the peculiar space velocity which are in agreement with the observations. The brightest HMXBs have large peculiar space velocities because (a) the linear momentum of the binary remnant of the supernova explosion must balance the linear momentum of the ejected supernova material, (b) the recoil velocity of the binary remnant is proportional to the orbital velocity of the supernova precursor, and (c) the brightest systems evolve from close binaries in which this orbital velocity is large. No arbitrary ad hoc "kick" associated with an asymmetrical supernova explosion is invoked. The model predicts that the peculiar space velocity of bright HMXBs is in the interval 40–160 km s^{-1}. This high peculiar space velocity permits them to move a significant distance from their place of birth, in and above the Galactic plane, in spite of their relatively short lifetimes prior to the X-ray stage.

4. According to the scenario model, a significant fraction of apparently single Wolf-Rayet stars may have a close neutron-star or black hole companion. The existence of such systems would be supported by the spectroscopic discovery of close unseen components of appropriate masses in circular orbits around Wolf-Rayet stars. The absence of strong X-ray emission from NS+W-R binaries may be due to the fast rotation of a highly magnetized neutron star, preventing efficient accretion, and the absence of strong X-ray emission from BH+W-R

binaries may be due to the failure of accretion disks to form around black holes. It is estimated that only a few of the ~ 100 BH+W-R binaries produced by the scenario code (those with orbital periods smaller than ~ 10 hr) have an accretion disk around the black hole and appear as strong X-ray sources.

5. The birthrate of black hole pairs which can merge in less than a Hubble time under the influence of gravitational wave radiation depends sensitively on the mass of a typical black hole, being 10 times larger for $M_{\rm BH} = 10\,M_\odot$ than for $M_{\rm BH} = 5\,M_\odot$. Since the detectability of the pulse of GWR emitted in the merger increases as the 2.5th power of the component masses, BH+BH mergers with $M_{\rm BH} = 10\,M_\odot$ can be seen within a volume over 100 times larger than NS+NS mergers can be seen, and therefore the probability of detecting a BH+BH merger is 10 times larger than the probability of detecting an NS+NS merger. This provides additional motivation for current projects designed to detect pulsed GWR events in relatively nearby galaxies.

In conclusion, the numerical evolutionary scenario code which has been used before to construct models of several stellar populations such as single W-R stars, neutron stars, white dwarfs, and supernovae, as well as of some highly evolved binaries such as binary radio pulsars and binary white dwarfs, can also explain most of the main observed properties of bright massive X-ray binaries. Because the lifetime of the X-ray stage is very short compared with the total lifetime of the mass donor, only a very small fraction of the mass of the donor can be accreted by the compact component. With an average lifetime of $\sim 1.4 \times 10^4$ yr for the X-ray stage, and with accretion at a rate even as large as $\sim 4 \times 10^{-8}\,M_\odot\,{\rm yr}^{-1}$ (the Eddington limit rate for a neutron star), the accreted mass is less than $\sim 0.6 \times 10^{-4}$ times the initial mass of the donor. This implies a final equilibrium spin period for a neutron star accretor larger than ~ 0.5 s (see Paper II).

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APPENDIX A
CONDITIONS FOR THE FORMATION OF A DISK

Conditions for the formation of accretion disks from stellar wind matter have been studied numerically (e.g., Livio et al. 1986; Anzer et al. 1987; Taam & Fryxell 1988, 1989; Sawada et al. 1989). Here the conditions for the formation of a Keplerian disk are examined in a much more elementary way. The discussion may be relevant to accretion by a black hole, which cannot support a magnetic field, and to accretion by neutron stars in wide HMXBs, where the donor is far from filling its Roche lobe. Nature provides examples of systems with well-developed accretion disks, e.g., Cen X-3 and SMC X-1 (Bhattacharya & van den Heuvel 1991) as well as systems in which accretion may be approximately radial, e.g., X Per and 4U 1145−61 (White et al. 1983). These latter sources are dim and highly variable and have long orbital periods.

If matter from the wind of the optical component were to fall on the relativistic component radially, most of the released gravitational potential energy would be converted into γ-rays. To obtain X-rays, it is necessary that either (1) an accretion disk be present for converting released gravitational potential energy into X-rays (e.g., Shapiro & Lightman 1976) or (2) a strong ($\gtrsim 10^{12}$ G) magnetic field be present to channel accreted matter into optically thick polar columns (e.g., Langer & Rappaport 1982). One condition for the formation of a disk is that the specific angular momentum of accreted matter be larger than the specific angular momentum of matter in Keplerian orbit at the location of the base of the disk (a magnetosphere in the case of a neutron star and the radius of the last stable orbit in the case of a black hole). The minimum specific angular momentum of the matter accreted by the relativistic star is the specific spin angular momentum of matter leaving the rotating donor. It is possible that the efficiency of conversion of orbital angular momentum of accreted matter into angular momentum of a disk is less than 10% (Livio et al. 1986; Livio 1988), so, for rough estimates, the contribution of orbital angular momentum may be neglected.

In a system in which the donor rotates synchronously with the orbital period, a disk will form if the specific angular momentum of accreted donor matter exceeds the minimum specific angular momentum of a Keplerian disk at a radius $R_{\rm K}$. In the case of a black hole accretor, $R_{\rm K}$ is the radius of the last stable orbit, or $\sim 3R_{\rm Sch}$ (Abramovicz et al. 1978; Paczyński & Wiita 1980). In the case of a neutron star accretor, $R_{\rm K} = R_{\rm NS}$ if the magnetic field is weak enough, or equal to the so-called Alfvén radius (Lamb et al. 1973) when the field is strong. The Alfvén radius can be 10–100 times the radius of a neutron star, depending upon the strength of the magnetic dipole moment of the neutron star and on the mass transfer rate (e.g., Lamb et al. 1973). If the accreted wind matter has only the rotational specific angular momentum with which it left the donor, and if the donor rotates synchronously with the orbital period, the condition for disk formation for the donor is (Iben & Tutukov 1995)

$$\frac{R_d}{A} \gtrsim \alpha_w^{8/7}\left(\frac{R_{\rm K}}{R_d}\right)^{1/7}\left(\frac{M_d}{M_{\rm rel}}\right)^{3/7}, \tag{A1}$$

where R_d and M_d are, respectively, the radius and mass of the donor, $M_{\rm rel}$ is the mass of the relativistic component, and α_w is the same parameter used in equation (10). In the case of a black hole accretor and a W-R donor, $R_d = R_{\rm WR} \sim 1\,R_\odot$, $M_d = M_{\rm BH} \sim 10\,M_\odot$, and $R_{\rm K} = R_{\rm Sch} \sim 9 \times 10^6$ cm, and the criterion for the formation of a disk around the black hole becomes

$$\frac{R_d}{A} \gtrsim 0.28\alpha_w^{8/7} \quad \text{or} \quad A \lesssim 3.6R_\odot \quad \text{for } \alpha_w = 1\,. \tag{A2}$$

Since in this case $R/A \sim 0.4$, a disk can form only if the optical component is close to filling its Roche lobe.

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