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# THE RATE OF NEUTRON STAR BINARY MERGERS IN THE UNIVERSE: MINIMAL PREDICTIONS FOR GRAVITY WAVE DETECTORS

E. S. PHINNEY[1]
Theoretical Astrophysics, 130–33, Caltech, Pasadena, CA 91125; and Institute for Theoretical Physics, University of California, Santa Barbara
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## ABSTRACT

Of the many sources which gravitational wave observatories might see, merging neutron star binaries are the most predictable. Their waveforms at the observable frequencies are easy to calculate. And three systems which will merge in less than a Hubble time have already been observed as binary pulsars: two in the disk of our Galaxy, and one in a globular cluster. From the lifetimes and positions of these, we infer with confidence a lower limit to the merger rate in our Galaxy and globular cluster system. Taking the merger rate in other galaxies to scale with the star formation rate, we compute the merger rate expected in the local universe. An ultraconservative lower limit to the rate gives three per year within 1 Gpc. Our *best* estimate, still conservative in that it considers only systems like those already observed, gives three per year within 200 Mpc. An upper limit of three mergers per year within $23/h$ Mpc is set by the rate of Type Ib supernovae. The rates of black hole binary mergers and black hole–neutron star binary mergers are model-dependent, but could be comparable to the given rate of neutron-star binary mergers.

*Subject headings:* black holes — gravitation — pulsars — stars: binaries — stars: neutron

## 1. INTRODUCTION

Merging binary neutron stars are the one source of gravitational radiation so far identified whose waveform and amplitude at the frequencies of interest can be predicted with confidence (in contrast to supernovae and pulsars), *and* whose event rate can be determined from electromagnetic observations (in contrast to merging stellar-mass black-hole binaries). The merger rate per unit volume in the universe is thus of considerable importance to the design and funding of gravitational wave observatories (e.g., LIGO).

The properties of the " chirp " of gravitational wave emission from the late stages of the inspiral are easily calculated. The waves at frequencies ($\sim$10–300 Hz) to which a LIGO is most sensitive are emitted when the orbital separation of the stars is $\sim$100 km, when post-Newtonian theory is still applicable, and before hydrodynamic effects of tides on the $\sim$10 km stars have become significant. A pedagogical summary of the simple, but adequate, Newtonian waveforms is given by Thorne (1987).[2] The waveforms have been calculated to post-Newtonian order by Lincoln & Will (1990). Thus, for detectors with specified coincidence noise, the *only* uncertainty about the detectability of waves from merging neutron star binaries lies in the event rate.

Until recently, there was known just one binary neutron star system, PSR 1913+16 (Taylor & Weisberg 1989), whose stars will spiral together in less than a Hubble time. The prescient, but crude estimate of the merger rate from this one object by Clark et al. (1979) was based on a model-dependent scaling to single pulsars and a supernova rate. This was seriously flawed by neglect of the differences in lifetime, luminosity, and detection volume between PSR 1913+16 and single pulsars (using the methods outlined below on the data available then would give an event rate $10^3$ times lower than given by Clark et al. 1979). Schutz (1989) summarized more realistically the uncertainties in this single-object estimate.

Since then, two more systems have been discovered: PSR 2127+11C in the globular cluster M15 (Prince et al. 1991), and PSR 1534+12 nearby in the Galaxy (Wolszczan 1991). These show that the earlier discovery was not a statistical fluke, and makes it possible to consider a serious calculation of a lower limit to the cosmological rate of mergers. In § 2, we use the observed systems to estimate the rate of merging in the various parts of our own Galaxy. In § 3 we identify more easily observable tracers of the relevant populations in distant galaxies, and in § 4 extrapolate to the rest of the universe.

## 2. MERGER RATE IN THE GALAXY

If $d$ binary neutron star systems $i$, each of total lifetime $\tau(i)$, are detected in surveys $j$ which could have detected pulsar $i$ in a volume $V_{\max}(i) = \sum_j V_{j,\max}(i)$, the merger rate in the Galaxy can be estimated as

$$R = \sum_i^d \frac{1}{V_{\max}(i)\tau(i)} V_{\rm Gal} , \qquad (2.1)$$

where $V_{\rm gal}$ is the volume of the Galaxy. If the pulsars are not uniformly distributed, $V_{\max}(i)$ and $V_{\rm Gal}$ are to be weighted by pulsar density.

If the pulsar has constant torque, braking index $n = 3$, and pulse period $P$ much longer than at rebirth, the total lifetime of each binary (from resurrection to merger) can be estimated as

$$\tau = P/(2\dot{P}) + \tau_{\rm mrg} . \qquad (2.2)$$

The time $\tau_{\rm mrg}$ until gravitational radiation merges the two stars is calculated from the observed binary period $P_b$, orbital eccentricity $e$, and the masses of the pulsar $M_1$ and its companion $M_2$ by integrating the equations of Peters (1964). The results are summarized in Table 1. The assumption that $P/(2\dot{P})$ is a good estimate of the time since the pulsar was formed (known to be the case in binary pulsars with white-dwarf companions:

[1] Alfred P. Sloan Fellow and Presidential Young Investigator.
[2] Thorne notes that in his eqs. (42a) and (42b), $ft$ should be replaced by the true phase, $\int (df/dt)dt$. The characteristic amplitude of the waves, eq. (46b) should consequently be increased by $\sqrt{2}$.

TABLE 1

GALACTIC BINARY NEUTRON STAR SYSTEMS

| Parameter | PSR 1534+12 | PSR 1913+16 | PSR 2127+11C |
|---|---|---|---|
| Reference | Wolszczan et al. 1991 | Taylor & Weisberg 1989 | Prince et al. 1991 |
| Flux (400 MHz) | 36 mJy | 5 mJy | 0.6 mJy |
| Distance | 0.5 kpc | 7.3 kpc | 10.6 kpc (in M15) |
| $P_b$ | 10.098 hr | 7.7519 hr | 8.047 hr |
| $e$ | 0.27367 | 0.61713 | 0.68141 |
| $M_1 + M_2$ | 2.679 $M_\odot$ | 2.82837 $M_\odot$ | 2.71 $M_\odot$ |
| $q = M_1(\text{psr})/M_2$ | $0.97 \pm 0.03$ | 1.04 | $1.0 \pm 0.2$ |
| $P/(2\dot{P})$ | $2.5 \times 10^8$ yr | $1.1 \times 10^8$ yr | $1.0 \times 10^8$ yr |
| $\tau_{\rm mrg}$ (GR decay) | $2.73 \times 10^9$ yr | $3.01 \times 10^8$ yr | $2.20 \times 10^8$ yr |
| $\tau$ | $3.0 \times 10^9$ yr | $4.1 \times 10^8$ yr | $3.2 \times 10^8$ yr |

see Kulkarni 1986) can eventually be tested as described in the caption to Figure 1.

The volume within which each pulsar in Table 1 could have been detected depends on the assumed Galactic distribution of pulsars. For a simple, conservative estimate, assume that such systems are uniformly distributed in a cylinder of radius 12 kpc, and half-height $Z$. To estimate $Z$, we note that both PSR 1913+16 (Taylor & Weisberg 1989) and the recycled PSR 1957+20 (Fruchter et al. 1990) have transverse velocities $v_t \sim 100$ km s$^{-1}$. A population ejected isotropically would have $v_z \sim v_t/\sqrt{2} \sim 70$ km s$^{-1}$, and reach maximum heights $Z \sim 1.5$ kpc above the Galactic plane. It is implausible that $Z \gg 1$ kpc, since then PSR 1534+12 would have $V/V_{\rm max} = (36 \text{ mJy}/1.5 \text{ mJy})^{-3/2} = 0.008$—i.e., Wolszczan would have been very lucky to find it so nearby (1534+12 is unlikely to be much more distant than 0.5 kpc, since its $DM \sin b = 9$ cm$^{-3}$ pc, and it is surrounded by three pulsar-containing globular clusters, M13, M5 and M53, with respectively $DM \sin b = 20, 21, 24$ cm$^{-3}$ pc and $z = 5$, 6, and 18 kpc—see Bhattacharya & Verbunt 1991). We adopt $Z = 1$ kpc as a best guess, but quote results for other values as well.

Thus $V_{\rm gal} = 900(Z/1 \text{ kpc})$ kpc$^3$. To compute the volumes in which these disk pulsars could have been discovered, we considered 12 pulsar surveys $j$: the nine described in Kulkarni & Narayan (1988), plus the one described in Wolszczan (1991), and the two Caltech-Arecibo surveys (Navarro & Kulkarni 1991, private communication). We find $\sum_j V_{j,\rm max}(1534 + 12) = 0.3$ kpc$^3$, and $\sum_j V_{j,\rm max}(1913 + 16) = 20$ kpc$^3$.

Using equation (2.1) and the $V_{\rm max}$ values of § 2.2, we find a

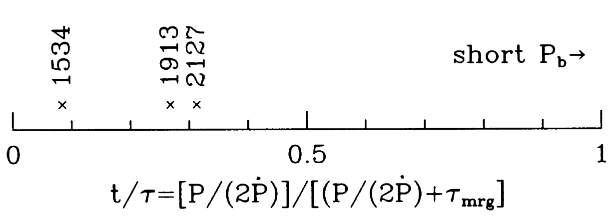


FIG. 1.—Where in their total lifetimes $\tau$ are each of the three neutron star binary pulsars. In the absence of luminosity or torque decay, old binaries should be uniformly distributed on the line. Binaries close to the right-hand edge would have short orbital periods and be hard to detect. Pulsars would be bunched at the right if there were torque decay, or if many still had periods close to their birth periods, so $P/(2\dot{P}) \gg t$. If the radio luminosity $L$ decreases as the pulsar spins down [e.g., $L = L_0(1 + t/t_0)^{-1}$], a flux-limited sample would be bunched at the left [$\langle t \rangle \simeq \tau/\ln(\tau/t_0)$ for $t_0 \ll \tau$], as observed. As more binaries are discovered, these luminosity and period selection effects can be removed without modeling by giving each pulsar a weight $1/V_{\rm max}$. A uniform distribution of weights would indicate that $P/(2\dot{P})$ was a good estimate of age.

Galactic disk merger rate

$$R = 10^{-6}\text{yr}^{-1} + 10^{-7}\text{ yr}^{-1} . \tag{2.3}$$

The first term comes from 1534+12, the second from 1913+16 (a slightly higher rate is found by Narayan, Piran, & Shemi 1991, who use an optimistic distance scale, a pulsar distribution concentrated to the Galactic center, and do not consider the Caltech surveys). Since the pulsar luminosity function is steep [$N(>L) \propto L^{-1}$], it is not surprising that luminous PSR 1913+16 should be the tip of an iceberg: 1534+12 is 30 times less luminous than 1913+16, and one of the faintest recycled pulsars known. There are undoubtedly many more systems not detected because: (1) they are still fainter than 1534+12, (2) the pulsar beam does not cross Earth, (3) both neutron stars have magnetic fields so low that they do not shine in the radio, or (4) have a larger merger rate but low space density, e.g., because they are born with $\tau_{\rm mrg} \ll 10^8$ yr, or have magnetic fields so high that their radio lifetime is much less than the lifetime to gravitational radiation (Figure 1 suggests that this may be true for the observed systems).

There are uncertainties in equation (2.3). (1) If the distances to the pulsars were underestimated by a factor of 2 (very unlikely), $V_{\rm max}$ would (for $Z = 2$ kpc) be increased by 4 and 6 (for 1534+12 and 1913+16, respectively), reducing their inferred merger rates by 4 and 6, respectively. (2) As $Z$ varies from 0.5 kpc to 3 kpc, $V_{\rm max}/V_{\rm Gal}$ increases and the merger rate decreases: for 1534+12 by a factor of 3 and for 1913+16 by a factor of 2.

## 3. EXTRAPOLATION TO THE UNIVERSE

Since the binary pulsars like PSR 1913+16 and PSR 1534+12 have lifetimes much less than a Hubble time, and are the result of the evolution of massive stars, the rate of formation of such systems ought to be proportional to the rate of formation of massive stars. This is made reasonable by the fact that there is no evidence for a strong dependence (i.e., more than a factor of 3) on metallicity of binary fraction (Latham et al. 1988; Duquennoy & Mayor 1990; Pryor et al. 1989) or initial mass-function (Scalo 1987; Phinney 1991).

The $B$-band luminosity density of the universe is (Efstathiou, Ellis, & Peterson 1988; see also Phillips & Shanks 1987) $\mathscr{L}_B(\text{obs}) = 1.9 \times 10^8 h\, L_{\odot,B}$ Mpc$^{-3}$. The $B$-band luminosity of our Galaxy is $L_{{\rm Gal},B} = 2 \times 10^{10}\, L_{\odot,B}$, of which $\sim 95\%$ is from the disk, and only $\sim 5\%$ is from the old spheroid population (van der Kruit 1987).

The cosmological $B$-band luminosity density arises mainly from 1–3 $M_\odot$ stars in the disks of spiral galaxies, formed in the past 5 Gyr. The extrapolation required is thus that the average rate of formation of 1–3 $M_\odot$ stars is proportional to that of the stars which make neutron stars, perhaps 8–25 $M_\odot$. One must further assume that the fraction of massive stars in binaries which evolve into close binary neutron stars is on average the same as in our Galaxy.

Two small corrections should be considered. First, not all the starlight emitted in $B$-band emerges there: some is absorbed by dust. The absorbed energy emerges in the infrared. The far-infrared luminosity density of the universe is (Soifer et al. 1987) $\mathscr{L}_{\rm FIR} = 1.2 \times 10^8 h\, L_\odot$ Mpc$^{-3}$. The spectral-synthesis program of Bruzual (1983, but 1988 version of code used) gives, for a star-formation rate constant over 15 Gyr and *no* extinction, $L_B/L_{\odot,B} \simeq 0.5 L_{\rm bol}/L_\odot$, for both Salpeter and Scalo IMFs. The effective $\mathscr{L}_B$ "hidden" by dust is thus $\sim 6 \times 10^7 h/sL_{\odot,B}$ Mpc$^{-3}$, where $s \leq 1$; $s = 1$ for black or gray absorption, and $s \simeq 0.4$ for conventional selective extinction models.

Second, about 20% of the cosmological $B$-band starlight is contributed by E and S0 galaxies, which have not formed massive stars recently, and thus should not be counted in the extrapolation of the birthrate of young neutron star binaries.

Thus, the net $B$-band luminosity density attributable to recent star formation is

$$\mathscr{L}_B = [(1 - 0.2) \times 1.9 \times 10^8 + 6 \times 10^7/s]h = 2.1 \times 10^8 h\, L_{\odot,B}\ {\rm Mpc}^{-3}\ . \quad (3.1)$$

A merger rate $R$ yr$^{-1}$ in the star-forming disk of the Galaxy hence extrapolates, with the assumptions listed above (similar IMF from 2–10 $M_\odot$, similar binary fraction and evolution in all galactic disks) to a merger rate density of

$$\mathscr{R}_{\rm sf} = R\mathscr{L}_B/L_{{\rm Gal},B} = (0.75 + 0.3/s) \times 10^{-2} hR\ {\rm Mpc}^{-3}\ {\rm yr}^{-1}\ . \quad (3.2)$$

The rate density would be *higher* if some galaxies had IMFs more heavily weighted toward massive stars, as some have proposed (e.g., Larson 1986).

### 3.1. *Rate in Globular Clusters*

To estimate the contribution from neutron-star binaries created in globular clusters (Phinney & Sigurdsson 1991), we assume that the globular clusters around early-type galaxies are similar to those around the Galaxy. We neglect globular clusters around irregular galaxies, since many appear to be young, and different in stellar content (Elson et al. 1989) from the Galaxy's clusters. We use the cluster specific incidence $S$ (number of globular clusters per $M_V = -15$ or $8.5 \times 10^7\ L_{\odot,V}$ of $V$-band galaxy luminosity) of van den Bergh (1984). His values are for galaxy magnitudes corrected for internal absorption, so for spiral galaxies, they should be applied to the optical luminosity density *including* the absorbed component estimated from the far-infrared luminosity density. The values adopted are given in Table 2. Adding the entries in the last column of Table 2, we get a globular cluster mean space density of

$$\phi_{\rm gc} = 10h^3\ {\rm Mpc}^{-3}\ . \quad (3.3)$$

Only 3% of the clusters are in galaxies like our own (Sb). We assume that globulars in early-type galaxies are similar to our own in that 20% have evolved to core collapse (Chernoff & Djorgovski 1989). We further assume that half of these collapsed clusters contain binary neutron stars like 2127+11C in M15, with lifetime $\tau$ from Table 1, giving

$$\mathscr{R}_{\rm GC} = 3 \times 10^{-9} h^3\ {\rm Mpc}^{-3}\ {\rm yr}^{-1}\ . \quad (3.4)$$

## 4. DISCUSSION

An ultraconservative lower limit to the event rate can now be derived as follows. (1) Suppose that in only 10% of all realizations of the pulsar distribution are pulsars like PSRs 1534+12 and 1913+16 as close to Earth as they are in the Galaxy. (2) Make no extrapolation to fainter pulsars. (3) Make no correction for pulsars beamed away from Earth, not radio luminous, or of short radio lifetime. (4) Assume that PSR 2127+11C is the only neutron star binary in the Galaxy's entire globular cluster system. (5) Take $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $s = 1$. Then by (1) and (4), we reduce the rates (2.3) and (3.4) by a factor of 10, and using equation (3.2) find the ultraconservative limit to the rate density:

$$\mathscr{R} > 6 \times 10^{-10}\ {\rm Mpc}^{-3}\ {\rm yr}^{-1}:\ \ 3\ {\rm yr}^{-1}\ {\rm at\ 1\ Gpc}\ . \quad (4.1)$$

A "best guess" rate from the known binary pulsars can be derived as follows. (1) Suppose that PSR 1534+12 and PSR 1913+16 are at distances typical of their density. (2) Make a factor of 3 correction for pulsars beamed away from Earth or not radio luminous. (3) Increase the "uniform galaxy" rate (2.3) by 2, appropriate if the pulsar formation rate is as centrally concentrated as an exponential disk with scale length $h = 0.5\ R_\odot$. (4) Assume that PSR 2127+11C is typical of core-collapsed clusters. (5) Take $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $s = 0.4$. Then by (2) and (3), we increase the rate (2.3) by 6, and by (4) and (5) adopt the rate (3.4). Thus the "best guess" rate

TABLE 2

SPECIFIC SUPERNOVA RATE $R$ AND GLOBULAR CLUSTER INCIDENCE $S$

| Type | $R$(Ib + Ic) | $S$ | $B-V$ | Contribution to $\mathscr{L}_B$ | Globular Cluster Space Density |
|---|---|---|---|---|---|
| E, S0 | 0 | $9h^2$ | 1.0 | adopt 20% | $5.6h^3$ Mpc$^{-3}$ |
| Sa | $0.1h^2$ | $7h^2$ | 0.9 | adopt 20% | $4.0h^3$ Mpc$^{-3}$ |
| Sb | $0.6h^2$ | $0.7h^2$ | 0.7 | adopt 20% | $0.3h^3$ Mpc$^{-3}$ |
| Sc | $1.3h^2$ | $0.2h^2$ | 0.6 | adopt 30%, plus all FIR | $(0.1 + 0.1/s)h^3$ Mpc$^{-3}$ |

NOTES.—Fractions of $B$-band light from Fig. 1 of Binggeli et al. 1988, adopting mean of the field and Virgo fractions—see also Davis & Huchra 1982. Type Ib Supernova rates are per century, per $10^{10}\ L_{\odot,B}$ of *observed* galaxy luminosity. Rates are from Table 8 of van den Bergh & Tammann 1991, multiplied by the mean extinction correction applied by Sandage & Tammann 1981 to that galaxy type: 2.4 for Sa,Sb; 1.7 for Sc,Sd; 1.3 for Im. Last column computed using eq. (3.1) and fifth column, converting $\mathscr{L}_B$ to $\mathscr{L}_V$ using the color in fourth column, and the cluster incidence in the third column (see text).

density is

$$\mathscr{R} = 8 \times 10^{-8}\ \mathrm{Mpc^{-3}\ yr^{-1}}:\ \ 3\ \mathrm{yr^{-1}\ at\ 200\ Mpc}\ . \quad (4.2)$$

In both equations (4.1) and (4.2), disk binaries dominate $\mathscr{R}$.

Even the ultraconservative lower limit to the rate density gives a rate of 3 $\mathrm{yr}^{-1}$ within a distance where the proposed LIGOs, with advanced detectors (see eqs. [124]–[126] and Fig. 9.4 of Thorne 1987), would be able to distinguish real mergers from 3 $\mathrm{yr}^{-1}$ noise coincidences. The more reasonable "best guess" gives an event rate from known types of merging neutron stars 100 times higher. Several effects might raise this still further: (1) Conditions in galactic nuclei are similar to those in the cores of post-core collapse clusters, but involve much larger numbers of stars. They might contain a large population of exchange binaries like those in the globulars. Pulse smearing in the ISM makes it impossible to detect these in our own Galactic nucleus. (2) Neutron stars with dipole surface fields $B < 10^8$ G will neither have pair cascades, nor shine as radio sources; those with $B > 10^{12}$ G will have radio lifetimes much less than the orbital decay time scale. Both populations, and systems born with $\tau_{\mathrm{mrg}} \ll 10^8$ yr, could have a large birthrate, without appearing in pulsar samples. (3) The rate of star formation in galaxies appears to increase rapidly as one looks back even to redshift 0.3. Thus our local estimate of the star formation may underestimate the rates for LIGOs sensitive to sources at cosmological distances.

An upper limit to $R$ is half the rate of Type (Ib + Ic) supernovae (half because we assume that *both* neutron star progenitors lose their hydrogen envelopes in mass transfer, so formation of each binary neutron star system requires two Type Ib or Ic supernovae). This is a generous upper limit, since it assumes that all (Ib + Ic) supernovae occur in binaries whose other member is, or will become a neutron star, and it assumes that all the binaries remain bound, with orbits tight enough that the stars will merge in a Hubble time. Using Table 1, we find the rate of Type (Ib + Ic) supernovae in the universe to be

$$\mathscr{R}(\mathrm{Ib + Ic})/2 = 6 \times 10^{-5} h^3\ \mathrm{Mpc^{-3}\ yr^{-1}}:\ \ 3\ \mathrm{yr^{-1}\ at}\ 23/h\ \mathrm{Mpc}\ . \quad (4.3)$$

With the rates given by van den Bergh & Tammann (1991), the Type II supernova rate is about 4 times higher than equation (4.3), but most are presumably single stars, or in binaries too wide for mass transfer to occur.

What of analogous binaries in which one or both neutron stars are replaced by a black hole? The "best guess" merger rate of neutron star (ns) binaries (see above) is $R = 10^{-5}\ \mathrm{yr}^{-1}$, about $10^{-2}$ the rate of Type (Ib + Ic) supernova explosions in the Galaxy (van den Bergh & Tammann 1991). Since the latter rate is comparable to the birth rate $R(\mathrm{Be}\text{-}X) \simeq 5 \times 10^{-4}\ \mathrm{yr}^{-1}$ of massive X-ray binaries (predominantly Be-ns systems; see Pols et al. 1991), most such systems seem to survive the first supernova explosion. The much smaller rate $R$ of ns-ns mergers suggests that only ~2% of such systems survive spiral-in and the mass loss and recoil kicks of the second supernova explosion (Bailes 1989). Collapse of a star to a black hole could have much less mass-loss and recoil velocity than that associated with neutron star formation. *Most* such systems could then remain bound.

Thus the birth rate of binaries with two black holes (bh-bh), or a black hole and a neutron star (bh-ns; scenarios are discussed by Narayan et al. 1991) could be high: fewer stars leave black hole remnants, but the binary is much less likely to be disrupted in their formation. A lower limit to the black hole binary birthrate follows from the fact that $\gtrsim 3$ of the $\sim 10^3$ X-ray binaries in the Galaxy (Pols et al. 1991) contain black holes or black hole candidates. The black holes' massive companions have lifetimes ~10 times less than those of the Be stars. Thus the (X-ray luminous) black hole binary birthrate is $\gtrsim 0.03$ that of Be-ns binaries, comparable to the merger rate $R$ of close ns-ns binaries.

Unfortunately, the rate of gravitational mergers among bh-bh and bh-ns binaries depends on the orbital periods after spiral-in, and hence on the ill-understood details of the process. For gravitational radiation to merge a binary of total mass $10 M_1\ M_\odot$, mass ratio $q$, and period $P_d$ days in a nearly circular orbit, takes

$$\tau_{\mathrm{mrg}} = 1.0 \times 10^9 P_d^{8/3} M_1^{-5/3} (1 + q)(1 + 1/q)\ \mathrm{yr}\ . \quad (4.4)$$

To merge in a Hubble time, spiral-in must thus reduce the orbital period to $\lesssim 1$ day. A black hole can have a mass exceeding its companion's helium core mass. Hence spiral-in need not occur, as it must except in very nonconservative transfer to a lower mass object like a neutron star. If the companion has a strong stellar wind, spiral-in might never begin; if it does, envelope ejection might be less efficient than that by a neutron star, since black hole accretion could have a very low efficiency ($L/\dot{M}c^2$). If spiral-in does occur, however, the subsequent evolution can be simpler than in the ns-ns case. Helium stars less massive than 3 $M_\odot$ (as needed for PSR 1913+16 and PSR 1534+12 if there is no recoil) expand their envelopes dramatically during core carbon burning (Habets 1986), requiring a *second* spiral-in to make a ns-ns binary which would merge in a Hubble time. The more massive He cores which could leave black hole remnants do not expand much, so a second spiral-in is not required.

Thus bh-bh and bh-ns binaries form at rates comparable to the ns-ns merger rate in equation (4.2), but the fraction which merge depends on the miasma of mass transfer and spiral-in which determine the final period distribution. Since the gravitational waveforms of any merging systems will allow the masses of the merging bodies to be determined accurately (Schutz 1986), the distribution of masses of merging bodies will shed light on this physics, as well as on the minimum black-hole mass (determined by post-collapse infall). The much more certain ns-ns mergers will also allow the mass distribution of neutron stars to be determined. The distances to the merging systems can be determined (Schutz 1986), allowing a determination of the Hubble constant, and the cosmography of massive stars, independent of the selection effects which plague galaxy surveys. Specially tuned detectors could follow the coalescence into the high-frequency phase of tidal disruption, giving further insight into the equation of state of nuclear matter. Gravity wave observatories should have an exciting life.

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