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NEUTRON STAR AND BLACK HOLE BINARIES IN THE GALAXY

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ABSTRACT

We present a statistical analysis of the number and birthrate of double neutron star (NS-NS) binaries. We estimate that there are $\sim 10^{4.5} z_0$ such systems in the Galaxy, with a birthrate $\sim 10^{-5} z_0$ yr^{-1}, where z_0 (kpc) is their scale height; we expect $z_0 \sim$ few kpc. We find that mergers of NS-NS binaries through gravitational radiation losses should be occurring roughly once a year in galaxies within $200/h$ Mpc. Also, we estimate that one out of $\sim 10^2/z_0$ massive stars in close binaries ends up in a NS-NS system.

Progenitor stars more massive than $\sim 50\ M_\odot$ probably form black holes (BHs). We estimate that the number and formation rate of BH-NS binaries in the Galaxy are comparable to the corresponding estimates for NS-NS binaries, and we predict that a BH-NS binary is likely to be discovered in pulsar surveys. Such an object may be an even better general relativistic laboratory than PSR 1913+16 or PSR 1534+12. BH-NS binaries may also be strong sources of gravitational radiation.

Subject headings: black holes — gamma rays: bursts — gravitation — pulsars — stars: binaries — stars: collapsed

1. INTRODUCTION

When the first binary pulsar, PSR 1913+16, was discovered (Hulse & Taylor 1975), it was not clear whether such double neutron star (NS-NS) systems are common or rare. The discovery of three more NS-NS systems, viz., PSR 2303+46 (Stokes, Taylor, & Dewey 1985), PSR 2127+11C (Anderson et al. 1990), and particularly the low-luminosity PSR 1534+12 (Wolszczan 1991), indicates that NS-NS binaries must constitute a large population.

In § 2 of this *Letter*, we estimate the number of NS-NS systems in the Galaxy and use this to obtain their formation rate. Phinney (1991) has done a comparable analysis and obtains similar results. These calculations improve on earlier work by Clark, van den Heuvel, & Sutantyo (1979) based only on PSR 1913+16. In §§ 3–5, we discuss the implications of these results for scenarios of binary evolution and explore some interesting possibilities with black hole neutron star (BH-NS) binaries.

2. NUMBER AND BIRTHRATE OF DOUBLE NEUTRON STAR SYSTEMS

We use the methods employed by Narayan (1987, hereafter N87) and Kulkarni & Narayan (1988, hereafter KN) in their study of the statistics of single radio pulsars and low-mass binary pulsars in the disk of the Galaxy.[2] In brief, we estimate what fraction of the density-weighted volume of the Galaxy has been searched by all surveys to date for NS-NS pulsars of a given period P and luminosity L. The reciprocal of this ratio is given by (N87)

$$S(P, L) = \frac{\iint \rho(R, z) R\, dR\, dz}{\iint_{(P, L)} \rho(R, z) R\, dR\, dz}, \quad (1)$$

where R is the Galactic radius (the Sun is taken to be at $R = 10$ kpc) and z is the height above the Galactic plane. The integral in the numerator is over the whole Galaxy, while that in the denominator is restricted to the part of the Galaxy where a pulsar of period P and luminosity L could have been detected by at least one of the pulsar surveys. Therefore, $S(P, L)$ gives, for each observed pulsar, the estimated number of similar pulsars in the Galaxy. Here $\rho(R, z)$, the number density of NS-NS binaries, is assumed to vary as $\exp[-(R/8 \text{ kpc})^2 - (z/z_0 \text{ kpc})^2/2]$ (cf. Narayan & Ostriker 1990, hereafter NO). The estimates obtained below are for $z_0 = 1$ kpc; the results scale almost linearly with z_0.

In computing $S(P, L)$, all pulsar surveys completed so far are modeled, taking particular care to include known selection effects in the searches. In addition to the surveys considered by KN, we have also included several recent surveys (Fruchter 1989; Wolszczan 1991; Johnston & Bailes 1991). As far as possible, our modeling and calculation procedures are identical to those used earlier for single pulsars (N87, NO). One exception is that somewhat more optimistic sensitivity limits have been assumed here for a few surveys. This is appropriate since the single pulsar calculations were based on a flux-limited sample, while in this *Letter* we consider all discoveries. The effect of this change is that the $S(P, L)$ values obtained here are reduced by a factor ~ 2 (our estimates are in this sense conservative).

Table 1 gives $S(P, L)$ for the three NS-NS systems discovered in the disk of the Galaxy; the estimate for PSR 1534+12 is large because it is fainter than the others. Assuming a lower luminosity cutoff for NS-NS binaries similar to that found in

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[2] We do not discuss NS-NS binaries in globular clusters, which make a minor contribution to the total birthrate in the Galaxy (Phinney 1991).

TABLE 1

PARAMETERS OF NS-NS PULSARS IN THE DISK OF THE GALAXY

Parameter	Pulsar		
	PSR 1534+12	PSR 1913+16	PSR 2303+46
Distance (kpc)	0.4	5	2.3
Luminosity (mJy kpc^2 at 400 MHz)	5.8[a]	150	15
Pulsar period (ms)	37.9	59.0	1066
Orbital period (days)	0.42	0.32	12.3
Orbital eccentricity	0.274	0.617	0.658
Spindown age, $P/2\dot{P}$ (yr)	...	1.2×10^8	3.0×10^7
Time to merge (yr)	2.7×10^9	3.0×10^8	...
Lifetime[b] (yr)	5×10^9	4×10^8	6×10^7
Number in the Galaxy, $S(P, L)$	$3600z_0$	$40z_0$	$590z_0$[c]
Birthrate in the Galaxy (yr^{-1})	$7 \times 10^{-7}z_0$	$10^{-7}z_0$	$10^{-5}z_0$[c]

[a] Flux from Wolszczan 1991, which differs from initial report (IAU Circ. 5073).

[b] PSR 1534+12: twice the merger time; PSR 1913+16: spin-down age plus merger time; PSR 2303+46: estimated age when the pulsar will cross the "death line."

[c] Includes a beaming factor of 3.2.

single pulsars, we estimate that there are $\sim 10^{4.5}z_0$ such systems in the disk of the Galaxy.

Given the probable lifetimes of the observed NS-NS systems (Table 1), it is straightforward to estimate their Galactic birthrate. We obtain a net formation rate of $\sim 10^{-5}z_0$ yr^{-1}. Table 1 further suggests that possibly a tenth of the NS-NS binaries have sufficiently short orbital periods to merge within a Hubble time through gravitational radiation losses, giving a merger rate $\sim 10^{-6}z_0$ yr^{-1}.

Apart from a large statistical uncertainty in the above estimates, there may also be systematic effects. For instance, we understand that the distance scale to many nearby pulsars may be revised upward by a factor ~ 2 (J. H. Taylor 1991, private communication). This will modify the results given here by a substantial factor ($\sim 2^3$ for PSR 1534+12). However, it will probably have a comparable effect on the single pulsar results as well. Therefore, quantitatively, we are most confident of the *relative* formation rate of NS-NS systems, expressed as a fraction of the single pulsar rate. Currently, the number of regular (i.e., nonmillisecond) single pulsars in the Galaxy is estimated to be $N_p \sim 10^{5.5}$ with a birthrate $R_p \sim 10^{-2}$ yr^{-1} (NO). The number of active pulsars in NS-NS binaries is thus $\sim 10^{-1}z_0 N_p$, and their birthrate is $\sim 10^{-3}z_0 R_p$. The exponents in these estimates are probably good to ± 0.5.

It is useful to establish a few scalings at this point. Consider first the lifetimes of the objects. Single pulsars are known to have radio lifetimes $\tau_p \sim 10^{7.5}$ yr (NO). NS-NS binaries, on the other hand, have gravitational radiation merger lifetimes $\tau_{gr} \sim 10^{9.5}$ yr (Table 1). Of the two neutron stars in the binary, the second-born will behave like a regular single pulsar and be visible for only $\tau_p \sim 10^{7.5}$ yr. However, the first-born neutron star is believed to undergo field decay and then to be spun-up during an accretion phase (Smarr & Blandford 1976) so that it is "recycled" (Radhakrishnan & Srinivasan 1981; Alpar et al. 1982) to become a long-lived fast pulsar, with $\tau_{rec} \sim 10^{9.5}$ yr. The increased lifetime of this pulsar by a factor $\sim 10^2$ relative to single pulsars explains the large number of binary pulsars estimated above even though their birthrate is relatively low. Note that the use of a characteristic age for the two populations is merely a convenient device to obtain quick estimates. In reality, of course, there will be a wide range of ages. Also, all recycled pulsars do not necessarily have such long lifetimes as we assume.

A second factor is that regular pulsars are typically easier to detect than recycled pulsars because they are slower rotators and are brighter on average. Writing $\langle S(P, L)\rangle_p = (f/z_0)\langle S(P, L)\rangle_{rec}$, and combining the results given here (Table 1) with previous work (NO; KN), we estimate that $f \sim 10^{-1}$, that is, recycled pulsars are on average harder to detect by a factor $\sim 10z_0$. This is why, even though the estimated number of NS-NS systems in the Galaxy is $\sim 10^{-1}z_0 N_p$, the number of systems expected to be *detected* is $\sim 10^{-2}N_p$(obs) $\sim$ few, where N_p(obs) $\sim$ 500 is the number of observed pulsars. In most of the detected systems, the recycled pulsar will be observed. However, in roughly 1 out of $\sim 10^3/z_0$ observed pulsars, or 1 out of $\sim 10/z_0$ observed NS-NS binaries, the second-born nonrecycled pulsar should be seen. Indeed, one such system is probably known, viz., PSR 2303+46 (though one cannot rule out that this too is a recycled pulsar), which suggests that $z_0 \sim$ a few kpc. We return to this point below. Normally, in such a system, one would expect to observe both pulsars. This is not the case with PSR 2303+46, suggesting that in this wide binary the first-born neutron star may not have been spun-up to a fast period.

3. BINARY DISRUPTION

We now incorporate the results of the previous section into an evolutionary scenario (Srinivasan 1989; Bhattacharya & van den Heuvel 1991, and references therein). Neutron stars are presumed to form from progenitors with masses $\gtrsim 10\ M_\odot$. Binary NS-NS systems presumably arise from interacting binary progenitors. Since roughly half the massive stars occur in binaries, with a moderate fraction being close enough to interact (Abt 1983), it is a reasonable guess that b, the fraction of massive stars initially in close binaries, is ~ 0.1.

The initially more massive star in these systems, the primary, will end its life in a supernova and form a neutron star. Since the secondary will be quite massive, a close binary will not be disrupted in this explosion. As the secondary evolves, it will begin to transfer substantial mass to its companion neutron star through a strong wind or quasi-Roche-lobe overflow, and the system will be visible as a massive X-ray binary (MXRB). The estimated birthrate of these systems, $bR_p \sim 10^{-3}$ yr^{-1}, is consistent with having $\sim 10^2$ MXRBs in the Galaxy, with lifetimes probably $\sim 10^5$ yr (e.g., Meurs & van den Heuvel 1989).

When the secondary evolves to a supergiant and then a supernova, two important effects have to be considered. First, when the mass transfer rate becomes large enough, there is a

TABLE 2

EXPECTED RATES AND NUMBERS OF PULSARS

Parameter	Single (recycled)	NS-NS (regular)	NS-NS (recycled)	BH-NS (regular)	NS-BH (recycled)
(Rate/R_p)	b	bP_s	bP_s	bP_{bh}	bP'_{bh}
(N/N_p)	$b(\tau_{\mathrm{rec}}/\tau_p)$	bP_s	$bP_s(\tau^*/\tau_p)^{\mathrm{a}}$	bP_{bh}	$bP'_{\mathrm{bh}}(\tau^{**}/\tau_p)^{\mathrm{b}}$
(N/N_p) (obs)	$b(\tau_{\mathrm{rec}}/\tau_p)(f/z_0)$	bP_s	$bP_s(\tau^*/\tau_p)(f/z_0)^{\mathrm{a}}$	bP_{bh}	$bP'_{\mathrm{bh}}(\tau^{**}/\tau_p)f^{\mathrm{b}}$

[a] $\tau^* = \min(\tau_{\mathrm{rec}}, \tau_{\mathrm{gr}})$.
[b] $\tau^{**} = \min(\tau_{\mathrm{rec}}, \tau_{\mathrm{grbh}}, \tau_{\mathrm{H}})$.

dynamical instability, and the system is likely to undergo a common-envelope phase. The neutron star primary will spiral in close to the core of the secondary, ejecting the envelope in the process. Secondly, when the core finally explodes as a supernova, there is a strong possibility that the binary will become unbound because of the large mass loss (Blaauw 1961) and possible asymmetry in the explosion (Flannery & van den Heuvel 1975; Bailes 1989). Observational evidence in support of frequent disruption is provided by the large eccentricities of the four known NS-NS systems, viz., $e = 0.27, 0.62, 0.66, 0.68$, which indicates that most of these systems became nearly unbound when they formed.

An interesting question then is the following: what is the probability, P_s, that the system will survive as a binary? This can now be estimated by comparing the formation rate of NS-NS binaries with the birthrate of MXRBs, which gives $P_s \sim 10^{-2} z_0$. As with other numbers in this *Letter*, the estimate is probably good to plus or minus half a decade.

One consequence of this result is that for every one recycled pulsar discovered in a binary, there should be $\sim 10^2/z_0$ single pulsars that are really recycled pulsars from disrupted close binaries (Table 2). These would have fast periods ($P \lesssim 100$ ms), relatively low magnetic fields ($B \sim 10^{10}$ G), and lower than average luminosities. Since recycled binaries make up $\sim 10^{-2}$ of the observed pulsars, the recycled single pulsars with these characteristics should constitute a fraction $\sim 1/z_0$. While some such pulsars are observed (Radhakrishnan & Srinivasan 1981; Alpar et al. 1982), they do not constitute a large fraction of the known pulsars. (Note that there may indeed be many recycled single pulsars in the observed sample, e.g., the "injected" pulsars in N87 and the S pulsars in NO, but most of these pulsars do not have such a low field or long lifetime as PSR 1913+16; the point here is that there are only a few single pulsars with these particular characteristics.) This leads us to suggest that the scale height of the recycled systems may be several kpc rather than 1 kpc. This is not unreasonably large, considering that after the second supernova the vertical velocity of a surviving tight NS-NS binary, or the neutron stars from a disrupted binary, could be as large as ~ 200 km s^{-1}. Assuming a conservative $z_0 \sim 3$ kpc, the binary survival probability is $P_s \sim 10^{-1.5}$. The number of NS-NS binaries in the Galaxy then becomes $\sim 10^5$, and their formation rate is $\sim 10^{-4.5}$ yr^{-1}.

4. BLACK HOLE NEUTRON STAR BINARIES

The existence of black hole candidates such as Cyg X-1 and LMC X-3 among the MXRBs is empirical evidence that black holes may form from certain classes of massive stars (McClintock 1991). In the following discussion we assume that all stars more massive than some critical initial mass M^*_{BH} end their lives as black holes and explore some of the consequences.

What is the value of M^*_{BH}? As mentioned above, it appears that a fraction $P_{\mathrm{bh}} \sim 10^{-1.5}$ of the MXRBs have a black hole rather than a neutron star as their primary. Assuming that the X-ray lifetime of black hole MXRBs (BHMXRBs) is similar to that of neutron star MXRBs, and taking a Salpeter initial mass function, we estimate M^*_{BH} to be $\sim 50\ M_\odot$ and the birthrate of BHMXRBs in the Galaxy to be $\sim 10^{-4.5}$ yr^{-1} (see also van den Heuvel & Habets 1984).

Using the mass estimates of black holes in BHMXRBs as a guide, we assume that all binary black holes have masses $\sim 10\ M_\odot$. When BHMXRBs evolve to the second supernova, we then expect that most of these systems will *not* suffer orbital disruption since the larger mass of the black hole compared to a neutron star increases the residual gravity in the binary significantly. Assuming that the probability of making a BH-BH system is small, we thus obtain a surprisingly large birthrate of $\sim 10^{-4.5}$ yr^{-1} for BH-NS binaries.

If BH-NS systems form with sufficiently short orbital periods to merge within a Hubble time—this is unclear at the present time, but see Lattimer & Schramm (1976)—then they are important for gravitational radiation detectors. Equally interesting is the possibility of detecting one of these systems as a binary pulsar. In the above scenario, the neutron star is formed in the second explosion and lives for only $\sim 10^{7.5}$ yr as a visible pulsar. Using the approximate scalings of § 2, we predict that BH-NS systems should turn up in pulsar surveys at the rate of about 1 for every $10^{2.5}$ pulsars discovered. Equivalently, since a NS-NS system with a second-born pulsar may have been found (PSR 2303+46), a representative of the comparably numerous BH-NS population should be discovered soon.

A BH-NS binary will emit gravitational radiation, spiral in, and ultimately merge, just as in the case of a NS-NS binary. The lifetime for spiraling in, τ_{grbh}, is proportional to a^4/MM_1M_2, where M_1, M_2 are the masses of the two stars, $M = M_1 + M_2$, and a is the initial orbital separation. Because of lack of knowledge of a, it is difficult to estimate τ_{grbh} with any reliability, but we do think that it is likely to exceed τ_p so that the estimate given above for the probability of detecting the pulsar is not affected. However, for BH-NS binaries to be important as sources of gravitational radiation, τ_{grbh} has to be smaller than the Hubble time, $\tau_{\mathrm{H}} \sim 10^{10}$ yr; we are less confident on this point.

A minor twist in the black hole scenario is possible if we allow for significant mass transfer. It is conceivable that the original primary has a mass less than M^*_{BH} and forms a neutron star, but that the secondary has so much mass transferred to it that it is pushed above the M^*_{BH} limit and forms a black hole. Such a binary will again not be disrupted and will end up as a NS-BH binary. We write the probability of this channel as P'_{bh}, giving a formation rate of $10^{-2}bP'_{\mathrm{bh}}$ yr^{-1}. In this case, the neutron star will be of the recycled type, and its lifetime as a pulsar will be τ_{rec}, τ_{grbh}, or τ_{H}, whichever is smallest. Also, the binary receives very little velocity so that these systems will have a low scale height, making them easier to discover. Assuming a lifetime of $\sim 10^{10}$ yr, the fact that none of these systems has been found yet suggests that the birthrate through this route is $\lesssim 10^{-6}$ yr^{-1}, that is, $P'_{bh} \lesssim 10^{-3}$.

5. DISCUSSION

We estimate in this *Letter* that there are $\sim 10^{4.5} z_0$ NS-NS binary pulsars in the Galaxy, with a merger rate due to gravitational radiation emission $\sim 10^{-6} z_0$ yr^{-1}, where z_0 (kpc) ~ 3 (kpc) is the scale height of the systems. If we extrapolate this to other galaxies and use a galaxy density of $10^{-2} h^3$ Mpc^{-3} (Kirshner et al. 1983; see Phinney 1991 for a more detailed analysis), we predict $\sim 10^{-0.5} z_0 \sim 1$ NS-NS merger per year out to a distance $\sim 200/h$ Mpc. This will be a substantial event rate for advanced detectors like LIGO that are sensitive enough to detect gravitational radiation from the last cosmologically spiraling-in phase of cosmologically distant NS-NS binaries. Unfortunately, if the distance to PSR 1534+12 is larger by a factor ~ 2 (a possibility, see § 2), the rate will have to be revised downward by almost an order of magnitude. Apart from gravitational radiation, the merger of a NS-NS binary may also produce a γ-ray burst (Paczynski 1986; Eichler et al. 1989). If as little as 10^{-5} of the released energy is channeled into γ-rays (a conservative estimate), the burst fluence on Earth would be $\sim 10^5$ eV cm^{-2} (for 200 Mpc distance) which could be detected by GRO.

We estimate that a fraction $\sim 10^{-2} z_0 \sim 10^{-1.5}$ of close massive binary stars survive to become NS-NS binaries. This result should help sharpen discussions of common-envelope spiral-in, mass loss, and asymmetric supernova explosions in such binaries.

We estimate that the number of BH-NS systems in the Galaxy as well as their birthrate are comparable to the corresponding figures for NS-NS systems. We anticipate, therefore, that a BH-NS binary will be discovered in pulsar surveys being conducted now or being planned for the near future. The discovery of such a system will permit various precise measurements to be done. In particular, the periastron shift and the Shapiro time delay, which are post-Newtonian effects, can be de-ected even from systems with relatively wide orbits, for example, PSR 2303+46 (Taylor & Dewey 1988) and PSR 1855+09 (Ryba & Taylor 1991), both of which have long orbital periods ~ 12 days. Such effects will enable the masses of the two stars in the binary to be determined to a much greater accuracy than possible with BHMXRBs. Additional higher order general relativistic effects could be measured in a close BH-NS binary, which will permit the verification of the existence of the black hole to an unparalleled degree of certainty. A particularly interesting possibility is that multiple pulses with delays may be observed from the pulsar due to lensing by the black hole. (This requires a nearly edge-on binary like PSR 1855+09.) Indeed, it may even be possible to measure the orientation and magnitude of the spin of the black hole through its effect on light propagation.

For a given separation, the gravitational radiation luminosity of a BH-NS system is stronger ($\propto M_1^2 M_2^2/M$) and occurs at a higher frequency ($\propto M^{1/2}$) than with a NS-NS system. Whether the signal is easier or more difficult to detect will however depend on fine details of the last stages of the merger, and on the characteristics of the detector. Also, it is not clear that the merger lifetime of BH-NS binaries is short enough for these systems to be important as sources of gravitational radiation, or of γ-ray bursts. We leave such questions to a future analysis.

On a final note, we should mention that some MXRBs may merge during the common envelope phase and become Thorne-Zytkow (1977) objects. While the fate of such a composite star is not clear, it is unlikely that it will become a NS-NS binary. This is therefore an alternative scenario for the destruction of NS binary systems without invoking orbit disruption. This does not affect our estimates of the number of NS-NS binaries or their birthrate, which were based on observational data. However, if the majority of BHMXRBs form BH Thorne-Zytkow objects, then our estimates of the number of BH-NS binaries and their birthrate will have to be revised downward.

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