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On the galactic and cosmic merger rate of double neutron stars

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ABSTRACT

Previous calculations of the merging rate of double neutron star systems similar to the Hulse–Taylor binary pulsar B1913+16 have assumed lifetimes based on the sum of the radio pulsar spin-down age and the time-scale on which the binary system merges as a result of gravitational radiation losses. Here we demonstrate that this method underestimates the merging rate, and that a more reliable calculation can be made from the radio lifetimes of these systems which are shorter by a factor of about 3. Using the latest estimates for the number of double neutron star systems in the Galaxy, we find the rate of such mergers to be $\sim 8\times10^{-6}$ yr^{-1}. Following earlier extrapolations made by Curran & Lorimer for all galaxies out to 100 Mpc, we find the lower limit to the event rate of neutron star mergers detectable by the advanced LIGO gravitational wave detector to be approximately 0.3 per year.

Key words: binaries: general – stars: neutron – pulsars: general – Galaxy: stellar content.

1 DISCUSSION

Curran & Lorimer (1995) derived the galactic number of double neutron stars (NS–NS) using a detailed computer simulation of the galactic pulsar population. They included in their simulation all the pulsar surveys up until the present, and calculated the potentially observable galactic number of NS–NS systems to be 240. This number is essentially based on the three systems of this type detected in these surveys (B1534+12, B1913+16 and B2303+46). From the lifetimes τ of these systems, Curran & Lorimer then calculated the galactic merger rate $\mathscr{R}$ of observable NS–NS systems to be $\mathscr{R}\simeq10^{-7}$ yr^{-1}. Correcting for the beaming factor f ($f\approx3$) and for the fact that there is expected to be an order of magnitude more pulsars of low radio luminosity (only detectable when they are very nearby), they arrived at a realistic galactic merger rate $\mathscr{R}\simeq3\times10^{-6}$ yr^{-1}.

We point out here that the 'lifetime' concept used in their estimates of $\mathscr{R}$ needs some revision, which results in about a three-fold increase of the above merger rates, for the following reasons.

Curran & Lorimer (1995) calculated $\mathscr{R}$ by dividing the number of potentially observable galactic NS–NS systems by their 'lifetime' τ, which they, following Phinney (1991), assumed to be the sum of the pulsar characteristic age and the binary coalescence time. However, for NS–NS systems with a coalscence time much shorter than the Hubble time, this lifetime concept is not correct, for the following reason. As the star formation rate in the Galaxy has been approximately constant in the past 5×10^9 yr (cf. Schmidt 1959), one expects that for the population of such systems there will be a steady state in which the birth rate equals the merger rate $\mathscr{R}$. Thus to calculate the merger rate one should calculate the birth rate. In order to calculate the birth rate, one should use as the lifetime only the observable lifetime of the pulsar, as is well known for pulsars in general: the system is observable only as long as its pulsar is observable. The observable lifetime, from birth until the pulsar becomes undetectable, is related to the pulsar characteristic spin-down age $t_{sd}=P/2\dot{P}$ as follows. The pulsar luminosity L is expected to be proportional to its energy loss rate $\dot{E}$ in the form of magnetic dipole radiation combined with the relativistic pulsar wind, which is given by (see e.g. Manchester & Taylor 1977)

$$\dot{E}=KB^2/P^4. \quad (1)$$

Here, B and P are the surface dipole magnetic field strength and the rotation period of the neutron star, respectively, and K is equal to

$$\frac{32\pi^4R_0^6}{3c^3}, \quad (2)$$

where R_0 is the radius of the neutron star. The time-scale on which $\dot{E}$ (and thus L) decays can be derived from this equation, and is given by

$$\dot{E}/\ddot{E}=P/4\dot{P}=\frac{1}{2}t_{\rm sd}. \tag{3}$$

The evolution of the pulse period with time is simply derived by equating expression (1) to the rotational energy loss rate of the neutron star, which yields the well-known expression (Manchester & Taylor 1977)

$$(P\dot{P})=K_1B^2, \tag{4}$$

with

$$K_1=K/4I, \tag{5}$$

where I is the moment of inertia of the neutron star. Present observational evidence suggests that magnetic fields of non-accreting neutron stars do not decay (Bhattacharya et al. 1992). Assuming this, integration of equation (4) yields

$$\frac{P^2(t)}{2K_1B^2}-\frac{P^2}{2K_1B^2}=t, \tag{6}$$

where $P(t)$ is the pulse period at a future time t and P is the present pulse period. The characteristic age $t_{\rm sd}$ is equal to

$$t_{\rm sd}=P^2/2K_1B^2. \tag{7}$$

The radio lifetimes of 'normal' (i.e. non-recycled) pulsars estimated from population studies are $\sim10^7$ yr (Lyne, Manchester & Taylor 1985). In order to estimate the radio lifetime of the NS–NS binary, we compare the evolution of $\dot{E}$ with that of a normal pulsar. This comparison is shown in Fig. 1, where we plot evolutionary tracks of $\dot{E}$ over the next 10^{10} yr of B1913 + 16, starting with its present-day spin parameters and a normal pulsar born spinning with a period of 30 ms and a magnetic field strength of 10^{12} G. Because the normal pulsar has a magnetic field about two orders of magnitude larger than that of B1913 + 16, its $\dot{E}$ is initially over four orders of magnitude larger. After 10^7 yr, however, whilst the value of $\dot{E}$ for B1913 + 16 is essentially unchanged, the value of $\dot{E}$ for the normal pulsar is now an order of magnitude below it. We therefore deduce the future radio lifetime of B1913 + 16 to be the epoch at which it reaches a similar value of $\dot{E}$ to that achieved by the normal pulsar after 10^7 yr. The evolutionary track of B1534 + 12 is similar.

Assuming thus that the NS–NS binary will no longer be observable at its present location after its luminosity has decayed by one order of magnitude below its present value (as suggested by Fig. 1), one finds that this will be the case when the pulse period has increased by a factor of 1.78, which occurs according to equation (6) at $t=2.2t_{\rm sd}$. Adding this time to their present age $t_{\rm sd}$, the total observable lifetime will be of the order of $3.2t_{\rm sd}$. This value we will therefore use to calculate their birth rates. Applying this, one obtains, from the data given in Curran & Lorimer's paper, a corrected merger rate for systems like B1534 + 12 of 2.1×10^{-7} yr^{-1}, and for systems like B1913 + 16 of 0.6×10^{-7} yr^{-1}, leading to a combined merger rate of observable NS–NS systems of 2.7×10^{-7} yr^{-1} instead of the 10^{-7} yr^{-1} calculated by Curran & Lorimer. Applying the above-mentioned upward correction by a factor of 30 one obtains the 'realistic' galactic merger rate $R\approx0.8\times10^{-5}$ yr^{-1}. This value is consistent with 'Bailes' upper limit of 10^{-5} yr^{-1} for the NS–NS birth rate, derived from general statistical considerations about pulsars (Bailes 1996). From the discussion in Curran & Lorimer's paper it is then clear that, from the collection of galaxies within 100-Mpc distance, one expects to observe with the Advanced LIGO detector more than one event per 3 yr, thus making LIGO an interesting endeavour. As Curran & Lorimer (1995) remarked, it

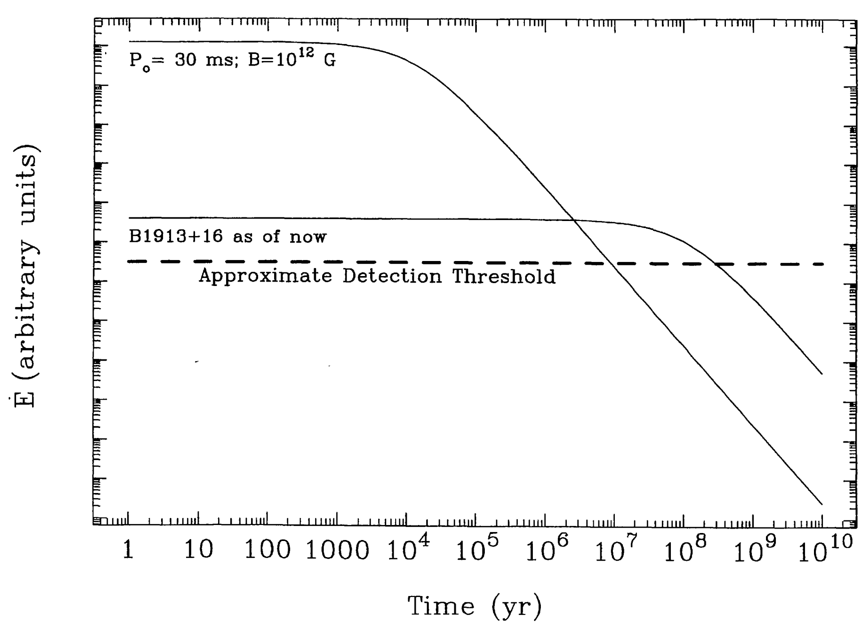

Figure 1. Evolution of the energy loss rate $\dot{E}$ of B1913 + 16 and a 'normal' radio pulsar that is born with a magnetic field of 10^{12} G and a rotation period of 30 ms. The radio luminosity of a pulsar is expected to be proportional to $\dot{E}$. The figure shows that, while the normal pulsar turns off after 10^7 yr, B1913 + 16 will remain observable for 3×10^8 yr from now. Further explanation can be found in the text.

should be stressed here that this merger rate is based purely on observations of the galactic pulsar population, and does not imply any theoretical assumption on how NS–NS systems have formed.

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