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The Merger Rate of Neutron Star Binaries in the Galaxy

Abstract

The major uncertainties in the merger rates of neutron star binaries are discussed, as well as a method of placing an upper limit on the binary neutron star population using simple ratios. We find that the merger rate is most unlikely to be greater than 10^{-5} yr^{-1} in our Galaxy, but is almost certainly greater than 10^{-7} yr^{-1}. The prospects for hardening the merger rate in the near future are relatively bleak, with recent deep surveys failing to discover any systems capable of merging within a Hubble time. Other possible mergers involving black holes are briefly discussed.

I Introduction

Observations of the 8-hour binary pulsar PSR B1913+16 have given strong experimental support for Einstein's General Theory of Relativity. In this fascinating system, the orbital period has been shown to decrease at the rate predicted by Einstein's theory if the neutron star binary is emitting gravitational waves (Weisberg & Taylor 1984, Taylor & Weisberg 1989). Thus, although we have not "seen" gravitational waves, we have good evidence that they exist. There is another exciting implication of the decay of PSR B1913+16's orbit. In roughly 300 million years from now the system will completely coalesce. In the last few seconds before coalescence the orbital period will only be a few milliseconds and the system will emit a large fraction of its remaining orbital energy in the form of gravitational waves. The Galactic population of relativistic neutron star binaries is therefore of great interest to physicists hoping to detect gravitational waves (Abramovici et al. 1992). The advanced LIGO detector is capable of detecting these merger events out to at least a few 100 Mpc, and so the Galactic population of neutron star binaries is of great importance.

The first reasonable attempts to estimate the merger rate of relativistic binaries (from here on the term "relativistic binary" will refer to neutron star binaries where the companion is thought to be another neutron star and will coalesce in less than a Hubble time) in our Galaxy were made by Phinney (1991) and Narayan, Piran and Shemi (1991; hereafter, P91 and NPS91 respectively). They obtained lower limits on the merger rate of neutron stars in our Galaxy of around 10^{-6} yr^{-1}, but hinted that these estimates were extremely conservative, and that the event rate was much higher than the lower limit and probably greater than 10^{-5} yr^{-1}. Curran and Lorimer (1995; hereafter, CL95) repeated these calculations taking into account the revised pulsar distance scale and the results of more recent surveys and concluded that a lower limit on the merger rate was more like 10^{-7} yr^{-1}.

II The limitations of merger rate calculations

The same recipe for calculating the merger rate was followed by all of the authors mentioned above. For each binary pulsar known that will coalesce in a Hubble time, they computed a "scale factor" indicative of the number of similar pulsars that exist in the Galaxy but which are unobserved due to the finite sensitivity and sky coverage of pulsar surveys. These scale factors were based upon relatively straight-forward computations involving the observed physical parameters of the pulsar, the sensitivity of pulsar surveys, and the assumed distribution of the parent population of relativistic binary pulsars. This gives an estimate of the number of potentially observable binary pulsars with similar luminosities and periods to those we already know about. These estimates are considered a lower limit because it seems reasonable to assume that there exist binary pulsars which are fainter than those we know about due to some combination of beaming and/or intrinsically lower luminosity.

While the computation of the scale factors and modeling of the pulsar surveys is straightforward, some of the assumptions that need to be made are not, and there are a number of limitations that we should remain aware of.

The first of these is small-number statistics. Unfortunately, there are only three binary neutron star systems known that will coalesce in a Hubble time, and one of these, PSR B2127+11C, was discovered in a targeted search of the globular cluster M15, and is thought not to greatly influence the merger rate (P91). The major computations were thus primarily concerned with just two systems, PSR B1913+16 and PSR B1534+12. The coalescence rate for our Galaxy was dominated by the low-luminosity object PSR B1534+12 in the studies of P91 and NPS91. In fact its merger rate was roughly 10 times that of the PSR B1913+16 system. The minimum merger rate computed by CL95 is much lower, primarily because of the reduced importance of PSR B1534+12 in the merger rate calculations for reasons we discuss below. We should note however, that even if the three binary pulsars we know of were the only ones in the entire Galaxy, the merger rate would still be of order 10^{-8} yr^{-1}. This could be viewed as an extremely conservative lower limit.

The second major uncertainty involves the luminosities of the objects in question. The scale factors are crucially dependent upon d the assumed distance to the source, with the number of implied sources in the Galaxy scaling as d^{-3} for very low-luminosity objects, and d^{-2} for higher luminosity objects. Since the initial scale factor calculations were made the pulsar distance scale has been extensively revised (Taylor and Cordes 1993), moving PSR B1534+12 from its initial estimate of 400 pc to 680 pc from the Sun. This has had the effect of decreasing its scale factor by a factor of a few. PSR B1913+16 has also had its distance increased from 5.2 to 7.1 kpc, again lowering the implied number of similar systems in the Galaxy. Unfortunately the distances to individual objects cannot be trusted to better than a factor of ~ 2.

The third major uncertainty is the underlying distribution of relativistic binaries in the Galaxy, with the total population scaling in rough proportion to the assumed scale height (see NPS91). The scale height depends upon the assumed velocities of the parent population, which can be estimated from the effects of mass loss and kick velocities on the pre-supernova system (Cordes & Wasserman 1984). Given that we only know of two relativistic binaries thought to be formed from massive binaries, we cannot realistically constrain their scale height. This leads to a factor of at least two uncertainty in the merger rate.

The final and perhaps most severe limitation is the question of how many relativistic binary pulsars are fainter than those we observe—and thus unseen but still potential mergers. One can imagine that we only ever see the brighter members of the pulsar population and therefore the Galaxy contains a huge population of incredibly low-luminosity binary pulsars. Whilst this is a tantalizing prospect, until we find one it remains conjecture. One can also postulate the existence of all kinds of other potentially observable (with gravitational wave detectors) systems, such as black hole-black hole binaries, or black hole-neutron star binaries, or neutron star binaries so relativistic at birth that their merger time is significantly shorter than a typical pulsar's lifetime. These will all increase the event rate for gravitational wave detectors but by how much is difficult to gauge.

Rather than repeat in detail the calculations of scale factors by previous authors, or speculate about potential populations of ultra-low luminosity neutron stars, I will restrict the immediate discussion to a lower limit on the merger rate. Curran and Lorimer claimed a lower limit to the merger rate one tenth of that of the previous authors. There were two major reasons for this. The first was the adoption of the new pulsar distance model. The distance to PSR B1534+12 has changed, leading to a factor of few *decrease* in the merger rate. This seems entirely reasonable. Whilst the 1993 Taylor and Cordes distance model is probably not the final word in pulsar distance models, there were good reasons for its adoption, especially for nearby pulsars such as PSR B1534+12, the distances of which were systematically underestimated.

The second major cause for Curran and Lorimer's lower merger rate was the increased volume of the Galaxy that had been searched for relativistic binaries without success. They claimed that this leads to a lowering of the scale factor by a further factor of six for PSR B1534+12. Perhaps a quick way to assess the increase in Galactic volume surveyed for these pulsars is to look at the increase in the number of millisecond pulsars known between the time of the computations. When PSR B1534+12 was discovered, there were only 6 other millisecond pulsars known in the disk. At the time of CL95's calculations the number was closer to 25, which implies a factor of 4 increase in the volume of sky effectively surveyed, near the factor 6 that they claimed. However, since then, the number of millisecond pulsars known has steadily increased to $\sim$ 35–40 (depending upon your definition of "millisecond pulsar") with still no new detections of relativistic binaries. We therefore conclude that a factor of ten decrease in the lower limit for mergers is reasonable, and that this lower limit is indeed near 10^{-7}yr^{-1}.

A different approach relies on the simple fact that at least one of the neutron stars in a "disk" relativistic binary must be just a normal pulsar, and we know of about 700 "normal" pulsars in the disk of the Galaxy but no "normal" pulsars in relativistic binaries (Bailes 1996). The first-born neutron star in a relativistic binary has the opportunity to be spun-up to a period of a few tens of milliseconds, and its magnetic field reduced, probably by mass accretion (Bhattacharya & van den Heuvel 1991). In both of the neutron star binaries in the disk, we see the first-born or recycled neutron star. A limit to the binary neutron star birthrate can therefore be obtained by comparing the relative birthrate of normal (unrecycled) pulsars in neutron star binaries to that of normal single pulsars. The only assumption here is that the second-born pulsars in relativistic binaries possess similar luminosities to normal pulsars in the disk. Since there are no normal pulsars observed in "relativistic" neutron star binaries (this excludes PSR B2303+46 since it is irrelevant in merger rate calculations) we conclude that their birthrate is at most 1/700th that of the general pulsar population. Taking Lorimer et al. 's (1993) estimate of the pulsar birthrate of 1 per $\sim$ 150 years, we find a maximum birthrate of $\sim 10^{-5}$ for relativistic binaries (we note in passing that most of the other recent computations of the single pulsar birthrate would yield similar values if the new distance model is adopted). The advantage of this limit over the scale-factor estimates is that it is based on the properties of 700 objects, not two.

NPS91 discussed the relative populations of neutron star binaries to single pulsars, but concluded that the observable binary neutron star population should be of order a few percent of the single pulsar population. This is clearly not the case, 3% would imply an observed population of relativistic neutron stars of about 20, where we see none. The upper limit discussed above is the most assumption-free method of limiting the merger rate, and similar to the "conservative" merger rates of most authors. It is ten times the best estimate of Lipunov et al. (1995) which was based on binary evolution codes! Whilst the use of these so-called "scenario machines" can be an interesting way of gaining insights into the relative importance of different phases of binary evolution, I feel they have no value in computing accurate merger rates. There are simply too many highly uncertain assumptions required. To obtain some idea of the uncertainties involved, an independent analysis by Portegies Zwart and Spreeuw (1997) obtained a merger rate of $\sim 10^{-5}$ yr^{-1}, one tenth that of Lipunov et al.

The same argument used to restrict the birthrate of relativistic binaries with neutron star companions can be used to limit the birthrate of neutron star-black hole binaries. None of the 700 pulsars we know of are orbiting a black hole. We therefore conclude the formation rate of black hole-pulsar binaries is less than 10^{-5} yr^{-1}. Through simulations, it is probably possible to gain an order of magnitude estimate of the relative formation rates of black hole-black hole binaries to black hole-neutron star binaries. This is probably the most effective method of limiting the merger rate of all classes of mergers that would give rise to detectable gravitational wave emission.

III Conclusions

The merger rate of neutron star binaries in our Galaxy is probably between 10^{-7} and 10^{-5} yr^{-1}. Without the discovery of large numbers of relativistic binaries in the near future, it is unlikely that this number will firm significantly. Perhaps the best estimate of the merger rate will ultimately come from gravitational wave detectors.

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