THE COALESCENCE RATES OF DOUBLE BLACK HOLES

BELCZYNSKI K.1,2, BULIK, T.1, DOMINIK., M.1, PRESTWICH, A.3
1 Astronomical Observatory, University of Warsaw, Al. Ujazdowskie 4, 00-478 Warsaw, Poland
2 Center for Gravitational Wave Astronomy, University of Texas at Brownsville, Brownsville, TX 78520, USA
3 Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA

We present the summary of the recent investigations of double black hole binaries in context of their formation and merger rates. In particular we discuss the spectrum of black hole masses, the formation scenarios in the local Universe and the estimates of detection rates for gravitational radiation detectors like LIGO and VIRGO. Our study is based on observed properties of known Galactic and extra-galactic stellar mass black holes and evolutionary predictions. We argue that the binary black holes are the most promising source of gravitational radiation.

1 Population Synthesis Coalescence Rates

We employ the StarTrack population synthesis code (Belczynski et al. 2002, 2008) to perform several Monte Carlo simulations of binary evolution with a range of metallicity. We base the calculations on recent results from the Sloan Digital Sky Survey observations (Panter et al. 2008) indicating (∼300,000 galaxies) that recent star formation (within the last 1 billion years) is bimodal: half the stars form from gas with high amounts of metals (solar metallicity), and the other half form with small contribution of elements heavier than Helium (∼10−30% solar). Additionally, we use the recent estimates of mass loss rates producing much heavier stellar black holes than previously expected (∼30−80 M⊙; Belczynski et al. 2010a). The results of these calculations were presented for the first time by Belczynski et al. (2010b). We have evolved a population of 2 million massive binary stars, and investigated the formation of close double compact objects: double neutron stars (NS-NS), double black hole binaries (BH-BH), and mixed systems (BH-NS). Our modeling utilizes updated stellar and binary physics, including results from supernova simulations (Fryer & Kalogera 2001) and compact object formation (Timmes et al. 1996), incorporating elaborate mechanisms for treating stellar interactions like mass transfer episodes and tidal synchronization and circularization. We put special emphasis on the common envelope evolution phase, which is crucial for close double compact object formation as the attendant mass transfer allows for efficient hardening of the binary. This orbital contraction can be sufficiently efficient to cause the individual stars in the binary to coalesce and form a single highly rotating object, thereby aborting further binary evolution and preventing the formation of a double compact object. Due to significant radial expansion, stars crossing the Hertzsprung gap (HG) very frequently initiate a common envelope phase. HG stars do not have a clear entropy jump at the core-envelope transition (Ivanova & Taam 2004); if such a star overflows its Roche lobe and initiates a common envelope phase, the inspiral is expected to lead to a coalescence (Taam & Sandquist 2000). In particular, it has been estimated that for a solar
### Table 1: Galactic Merger Rates [Myr$^{-1}$]

| Type   | $Z_\odot$ (100%) | 0.1 $Z_\odot$ (100%) | $Z_\odot + 0.1 Z_\odot$ (50% + 50%) |
|--------|------------------|----------------------|-----------------------------------|
| NS-NS  | 40.8 (14.4)      | 41.3 (3.3)           | 41.1 (8.9)                        |
| BH-NS  | 3.2 (0.01)       | 12.1 (7.0)           | 7.7 (3.5)                         |
| BH-BH  | 1.5 (0.002)      | 84.2 (6.1)           | 42.9 (3.1)                        |
| TOTAL  | 45.5 (14.4)      | 138 (16.4)           | 91.7 (15.4)                       |

### Table 2: LIGO/VIRGO Detection Rates [yr$^{-1}$]

| Sensitivity ($d_{0,nsns}=$) | Type   | $Z_\odot$ (100%) | 0.1 $Z_\odot$ (100%) | $Z_\odot + 0.1 Z_\odot$ (50% + 50%) |
|-----------------------------|--------|------------------|----------------------|-----------------------------------|
| 18 Mpc                      | NS-NS  | 0.01 (0.003)     | 0.01 (0.001)         | 0.01 (0.002)                      |
|                             | BH-NS  | 0.007 (0.00002)  | 0.04 (0.02)          | 0.02 (0.01)                       |
|                             | BH-BH  | 0.02 (0.00005)   | 9.9 (0.1)            | 4.9 (0.05)                        |
|                             | TOTAL  | 0.03 (0.003)     | 10.0 (0.1)           | 5.0 (0.06)                        |

metallicity environment (e.g., our Galaxy), properly accounting for the HG gap may lead to a reduction in the merger rates of BH-BH binaries by $\sim 2-3$ orders of magnitude (Belczynski et al. 2007). The details of the common envelope phase are not yet fully understood, and thus in what follows we consider two models, one which does not take into account the suppression (optimistic model: A), and one that assumes the maximum suppression (pessimistic model: B).

The results are presented in Table 1 (Galactic merger rates) and 2 (LIGO/VIRGO detection rates). In Table 1 the rates are calculated for a Milky Way type galaxy (10 Gyr of continuous star formation at a rate of $3.5 \, M_\odot \, \text{yr}^{-1}$), with the assumption that all stars have either solar metallicity or 10% solar, or a 50-50 mixture of both types of stars. The rates are presented for the optimistic model (A) where progenitor binaries survive through the common envelope phase, while the results in parentheses represent the pessimistic model (B), where the binaries do not survive if the phase is initiated by a Hertzsprung gap star. In Table 2 the detection rates are given for model A (B) for a given sensitivity of LIGO/VIRGO instrument. Sensitivity is defined as the sky and angle averaged distance horizon for detection of a NS-NS inspiral. The rates are given for a local Universe consisting of only solar composition stars (unrealistically high), 0.1 $Z_\odot$ stars (unrealistically low) and for a 50-50 mixture of the above (realistic local Universe; Panter et al. 2008). The sensitivity of $d_{0,nsns} = 18 \text{Mpc}$ corresponds to the expected initial LIGO/VIRGO detector.

The results show two clear trends. First, the rates are generally larger for model A than B. This is the direct consequence of our assumptions on common envelope outcome in both models as mentioned earlier and discussed in detail by Belczynski et al. (2007). Since black hole progenitors are the most massive stars and thus experience the most dramatic expansion (CE mergers in model B) the BH-BH rates are affected in the largest extent. Second, we note that the rates are higher for the low metallicity model ($Z = 0.1 \, Z_\odot$) as compared with high metallicity model ($Z = \, \text{Z}_\odot$). The major reason behind this trend is the smaller radii of stars at low metallicity. This directly leads back to CE evolution; the smaller the radius of a given star the later in evolution the star overflows its Roche lobe. Thus for low metallicity, massive stars tend to initiate CE phase after HG, and so they have a chance of surviving this phase and forming a double compact object independent of assumed model of CE evolution. The increase
of rates with decreasing metallicity is additionally connected with the fact that low metallicity stars experience low wind mass loss and thus form more massive compact objects. This leads to a shorter merger times and higher merger rates.

Had the initial configuration of LIGO/VIRGO instruments reached its design sensitivity of \( d_{0,\text{nsns}} \approx 18 \text{ Mpc} \) for its entire lifetime (averaged horizon for NS-NS merger) we would be able to exclude model A from our considerations. This model generates about 5 BH-BH inspirals per year within this horizon (of course the actual horizon for BH-BH detection was accordingly extended with the increased mass of each BH-BH merger). So far there was no report of detection in LIGO/VIRGO data so one would be tempted to exclude this model from further considerations. However, the time averaged sensitivity of the last LIGO/VIRGO run (S5, the most recently released) has reached only about \( d_{0,\text{nsns}} \approx 9 \text{ Mpc} \). Therefore, the rates should be decreased by factor \((18/9)^3 \approx 8\) and the expected detection rate for BH-BH binaries would drop below 1 yr\(^{-1}\) and consequently model A cannot be yet excluded.

2 Empirical Coalescence Rates

The optical followup of X-ray sources revealed the nature of several X-ray binaries in the galaxies in the Local Group. Two objects: IC10 X-1 and NGC300 X-1 are of particular interest. The identification of optical counterparts and their spectroscopy allowed to estimate the properties of these two binaries. Both host massive black holes on a tight orbit with WR stars. Both reside in low metallicity environments (Crowther et al. 2007, Crowther et al. 2010, Prestwich et al. 2007, Silverman and Filipenko 2008). In the future the accretion in these binaries will continue and the WR stars will loose mass through stellar winds. The typical lifetime of the WR stars in such systems is from 100 to 300 kyrs. After that time the WR stars will explode as supernovae leading to formation of a BH, or a NS in the case of extremely large mass loss. The systems will most likely survive the explosions and remain bound since the current orbital velocities are above 500 km s\(^{-1}\). Both systems will end up as binary black holes in a few hundred thousand years.

Given the estimate of the future evolution of the two binaries: IC10 X-1 and NGC300 X-1, we estimate the formation rate of such binaries. The estimated merger time is smaller than the Hubble time. Therefore assuming that the star formation rate was constant the merger rate of the binary black holes formed from such systems will be the same as their formation rate. For each system we estimate the volume in which it is detectable. Each binary was detected only because of its X-ray radiation, thus the observability is proportional to the X-ray active phase. The formation rate of each binary can be approximated as: \( R = (V_{\text{obs}} t_{\text{obs}})^{-1} \). A detailed statistical analysis is presented in Bulik, Belczynski and Prestwich (2010). We present the probability distributions of the formation and merger rates of the binary black holes corresponding to each binary IC10 X-1 and NGC300 X-1 in Figure 1. The thick line in Figure 1 represents the probability density of the sum of the two rates. This calculation implies a merger rate density of \( \mathcal{R} = 0.36^{+0.50}_{-0.26} \text{Mpc}^{-3}\text{Myr}^{-1} \). For the time averaged the sensitivity range of LIGO and VIRGO to binary black holes coalescence of \( \approx 100\text{Mpc} \), this implies the expected detection rate around one per year. This is in a striking agreement with the population synthesis results.

3 Conclusions

Both theoretical simulations and empirical estimate indicate that detection rates of BH-BH binaries are significantly higher than other double compact objects (NS-NS and BH-NS). The population synthesis predictions for our realistic model of local Universe with a mixture of high
Figure 1: The probability density of the binary black hole merger rate density. We present separately the contributions of IC10 X-1 and NGC300 X-1 and the total rate.

and low metallicity stars results in about 100 BH-BH detections per 1 NS-NS detection by LIGO/VIRGO. The empirical estimate presented here for BH-BH detection rate based on the observed extra-galactic BH binaries is $\approx 1 \text{ yr}^{-1}$, again much higher than the corresponding empirical detection rate for NS-NS inspiral ($\approx 0.06 \text{ yr}^{-1}$, Kim, Kalogera & Lorimer 2006). Thus it is likely that the existing LIGO/VIRGO data contains a coalescence signal that may be discovered with a more elaborate reanalysis.

Acknowledgments

Authors acknowledge support from MSHE grants N N203 302835 and N N203 404939.

References

1. Bauer, F. E., & Brandt, W. N. 2004, ApJ, 601, L67
2. Belczynski, K., Kalogera, V., & Bulik, T. 2002, ApJ, 572, 407
3. Belczynski, K., et al. 2007, ApJ, 662, 504
4. Belczynski, K., et al. 2008, ApJ Sup., 174, 223
5. Belczynski K., et al. 2010a, ApJ, 714, 1217
6. Belczynski, K., et al. 2010b, ApJ, 715, L138
7. Bulik, T., Belczynski, K., Pretwich, A., 2011, ApJ, 730, 140
8. Crowther, P. A., et al. 2010, MNRAS, 403, L41
9. Crowther, P. A., Carpano, S., Hadfield, L. J., & Pollock, A. M. T. 2007, A&A, 469, L31
10. Fryer, C., & Kalogera, V. 2001, ApJ, 554, 548
11. Ivanova, N., & Taam, R. E. 2004, ApJ, 601, 1058
12. Kim, C., Kalogera, V., & Lorimer, D. 2006, New Astronomy Rev. 54, 148
13. Panter B., et al. 2008, MNRAS, 391, 1117
14. Prestwich, A. H., et al. 2007, ApJ, 669, L21
15. Silverman, J. M., & Filippenko, A. V. 2008, ApJ, 678, L17
16. Taam, R. E., & Sandquist, E. L. 2000, ARA&A, 38, 113
17. Timmes, F., Woosley, S., & Weaver, T. 1996, ApJ, 457, 834