THE EFFECT OF METALLICITY ON THE DETECTION PROSPECTS FOR GRAVITATIONAL WAVES

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ABSTRACT

Data from the Sloan Digital Sky Survey (∼300,000 galaxies) indicate that recent star formation (within the last 1 billion years) is bimodal: half of 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). Theoretical studies of mass loss from the brightest stars derive significantly higher stellar-origin black hole (BH) masses (∼30–80 $M_\odot$) than previously estimated for sub-solar compositions. We combine these findings to estimate the probability of detecting gravitational waves (GWs) arising from the inspiral of double compact objects. Our results show that a low-metallicity environment significantly boosts the formation of double compact object binaries with at least one BH. In particular, we find the GW detection rate is increased by a factor of 20 if the metallicity is decreased from solar (as in all previous estimates) to a 50–50 mixture of solar and 10% solar metallicity. The current sensitivity of the two largest instruments to neutron star–neutron star (NS–NS) binary inspirals (VIRGO: ∼9 Mpc; LIGO: ∼18) is not high enough to ensure a first detection. However, our results indicate that if a future instrument increased the sensitivity to ∼50–100 Mpc, a detection of GWs would be expected within the first year of observation. It was previously thought that NS–NS inspirals were the most likely source for GW detection. Our results indicate that BH–BH binaries are ∼25 times more likely sources than NS–NS systems and that we are on the cusp of GW detection.

Key words: binaries: close – gravitation – stars: evolution – stars: neutron

Online-only material: color figures

1. INTRODUCTION

Gravitational waves (GWs) are a consequence of Einstein’s (1918) theory of general relativity. The first indirect evidence for the existence of GWs was presented by Hulse & Tylor (1974) through measurement of the orbital decay of a double binary pulsar. After four decades of effort, we have yet to directly detect GWs. In the past decade, two large interferometric observatories have been built to search for GWs: LIGO and VIRGO. The first observations have been collected, and although no positive detection has been made, some useful upper limits have been found (Abbott et al. 2008, 2009a). Both observatories will soon undergo major upgrades aimed to increase their sensitivity roughly 10 fold. In this Letter, we show that existing detectors are at the cusp of detecting GWs, and even modest improvements are likely to lead to the first direct detection of GWs.

We utilize the StarTrack population synthesis code (Belczynski et al. 2002) to perform a suite of Monte Carlo simulations of the stellar evolution of stars in environments with a range of metallicity. Our calculations are guided by recent results from the Sloan Digital Sky Survey observations (Panter et al. 2008), combined with recent estimates of mass loss rates (Belczynski et al. 2010a). Utilizing these latest results, we calculate a population of 2 million massive binary stars, tracking the ensuing formation of relativistic binary 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 (Belczynski et al. 2008), and tidal synchronization and circularization (Hut 1981). We put special emphasis on the common envelope evolution phase (Webbink 1984), which is crucial for 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 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 ∼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).

2. RESULTS

The merger and detection rates are presented in Tables 1 and 2, respectively. The merger rates are calculated for a Milky Way type galaxy, and therefore correspond to the rates within a limited volume (or a fixed star-forming mass). The detection rates are obtained via extrapolation of the Galactic rates to
an appropriate distance for GW observatories. The farthest
detectable distance for a given double compact object chirp
gmass is given by \( d = d_{0,\text{nsns}}(M_{c,\text{dco}}/M_{c,\text{nsns}})^{5/3} \),
where \( M_{c,\text{dco}} \) is the chirp mass of a given double compact object,
\( M_{c,\text{nsns}} = 1.2 M_\odot \) is a typical chirp mass of an NS–NS binary,
and \( d_{0,\text{nsns}} \) is the effective distance horizon for detection of
an NS–NS inspiral (Belczynski et al. 2007). VIRGO and LIGO have currently
reached \( d_{0,\text{nsns}} = 9.18 \text{ Mpc} \), respectively. This distance is sky
and angle averaged.\(^4\) The distance limit is significantly larger
for higher chirp mass double compact objects: BH–NS and

\(^4\) Our range is precisely the radius of a sphere with the same average detection
volume (i.e., \( d = ((VT)/T^3/4\pi)^{1/3} \)). For a single detector with
stationary noise, this average corresponds to a sky- and angle-averaged single-detector
range \( d_0 \); this value is quoted in the text. Other authors, such as Abadie et al.
(2010), describe network sensitivity using the “horizon distance” \( d_h \approx 2.26 d_0 \),
the range to which that detector can see a single optimally oriented binary.

Table 1

| Type  | \( Z_0 \) (100%) | 0.1 \( Z_0 \) (100%) | \( Z_0 + 0.1 Z_0 \) (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)                     |

Notes. 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 an HG star.

Table 2

| Sensitivity | Type   | \( Z_0 \) (100%) | 0.1 \( Z_0 \) (100%) | \( Z_0 + 0.1 Z_0 \) (50% + 50%) |
|-------------|--------|-----------------|---------------------|---------------------------------|
| 4'18 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)  | 0.04 (0.04)         | 0.04 (0.05)                     |
|             | Total  | 0.03 (0.003)    | 0.04 (0.04)         | 0.05 (0.05)                     |
| 4'45 Mpc    | NS–NS  | 0.2 (0.05)      | 0.2 (0.01)          | 0.2 (0.03)                      |
|             | BH–NS  | 0.1 (0.0003)    | 0.5 (0.03)          | 0.3 (0.15)                      |
|             | BH–BH  | 0.3 (0.0007)    | 145.4 (1.0)         | 72.8 (0.82)                     |
|             | Total  | 0.6 (0.05)      | 146.1 (1.9)         | 73.3 (1.0)                      |
| 4'97 Mpc    | NS–NS  | 1.5 (0.5)       | 1.6 (0.1)           | 1.5 (0.3)                       |
|             | BH–NS  | 1.0 (0.003)     | 4.8 (2.9)           | 2.9 (1.5)                       |
|             | BH–BH  | 2.8 (0.007)     | 1454.6 (16.4)       | 728.7 (8.2)                     |
|             | Total  | 5.3 (0.5)       | 1461.0 (19.5)       | 738.3 (10.0)                    |
| 4'300 Mpc   | NS–NS  | 44.3 (15.1)     | 45.9 (4.0)          | 45.1 (9.5)                      |
|             | BH–NS  | 29.7 (0.1)      | 141.9 (85.4)        | 85.8 (42.8)                     |
|             | BH–BH  | 82.4 (0.21)     | 427680.8 (483.3)    | 214252.2 (241.7)                |
|             | Total  | 156.4 (15.2)    | 429550.8 (572.7)    | 215560.0 (294.0)                |

Notes. Detection rates for model A (B) as a function of sensitivity of a given
instrument. Sensitivity is defined as the sky and angle averaged distance horizon
for detection of a double neutron star inspiral. The rates are given for a local
universe consisting of only solar composition stars (unrealistically high), 0.1 \( Z_0 \) stars
(unrealistically low), and for a 50–50 mixture of the above (realistic local
universe; Panter et al. 2008). The sensitivity of \( d_{0,\text{nsns}} = 18 \text{ Mpc} \) and 300 Mpc

corresponds to the current and advanced (2015) LIGO detectors, respectively.

Figure 1. Chirp mass distribution for double compact objects. Top two panels:
model A. Note the strong effect of metallicity on chirp mass of binaries with
BHs. Low metallicity (second panel down) reduces the wind mass loss from
the BH progenitors, allowing more massive BHs to form. The maximum chirp mass
is \( \sim 8 M_\odot \) for solar composition, while it can reach \( \sim 30 M_\odot \) for 10% solar for
BH–BH mergers. Bottom two panels: model B. Note that BH binaries appear
(in significant numbers) only in the low-metallicity case (bottom panel). The
typical chirp mass in model B is significantly lower than in model A. This is the
result of progenitor elimination through common envelope mergers in model B.
In particular, high-mass stars (that can give birth to the highest mass BHs) reach
large radii and are prone to enter a common envelope phase while crossing the
Galaxy, thereby aborting further evolution even at low metallicity.

(A color version of this figure is available in the online journal.)

BH–BH. The predicted chirp mass distribution (as none of the
BH double compact objects are yet observed) is presented in
Figure 1.

For solar metallicity, the rates show a mixture of NS–NS,
BH–NS, and BH–BH binaries in the optimistic case (model A),
while BH–NS and BH–BH binaries virtually disappear from
the double compact object population in the pessimistic case
(model B), and even rates for NS–NS are lower. Although
NS–NS mergers dominate the rates by an order of magnitude
in model A, the detection rates are dominated by BH–BH binaries.
This is because the heavier BH–BH binaries \( (M_{c,\text{dco}} \sim 5 M_\odot) \); see
Figure 1) are “louder” in GWs in the appropriate band
(Flanagan & Hughes 1998), and are therefore visible farther than
NS–NS systems \( (d \sim 4 d_{0,\text{nsns}}) \), resulting in \( \sim 60 \) times increase in
sampled volume, and a similar rate increase in detection. In
model B, there are so few BH–BH systems that NS–NS inspirals
strongly dominate both the merger and detection rates.

The decrease of metallicity significantly affects rates for
binaries containing BHs. We find that inspirals of double
compact objects with BHs dominate both the merger and
detection rates for stellar populations with 10% solar metallicity,
independent of our choice of a model. The rate increase for
BH–BH binaries is dramatic: factors of \( \sim 50/3000 \) times for
merger rates and ∼500/2000 times for detection rates, for model A/B. These drastic enhancements, although not previously noted, are readily understood in terms of BH formation physics.

In model A, the rate increase is primarily due to larger BH masses at low metallicity. For these higher BH masses we expect little to no natal kick at BH formation, and this leads to the survival of large fractions of massive binaries through supernova explosions, resulting in a significantly enhanced formation of BH–BH systems. At low metallicity, the stellar wind mass loss is inefficient, and stars lose less mass than their higher metallicity counterparts (Vink 2008). On the atomic level this is understood in terms of interaction of radiation with matter. Winds for massive stars are radiation driven. The heavy elements in stellar atmosphere (large cross sections) intercept photons more efficiently than in stars with low metal content, and the mass outflow from the high-metallicity star is higher. For metal-poor stars the outflows are weaker, and in the end stars finish their evolution at higher mass. On average, in low-metallicity systems the BH mass in close BH–BH binaries is predicted to be about ∼15 $M_\odot$, roughly double the corresponding mass at solar metallicity. This is shown in Figure 1 in terms of chirp mass and has been noted in recent observational BH mass estimates. While BHs in our Galaxy (approximately solar metallicity) reach only ∼15 $M_\odot$ (Casares 2007), in galaxies of low-metallicity stars form more massive BHs, e.g., ∼20 $M_\odot$ in NGC300 (40% $Z_\odot$; Crowther et al. 2010) or ∼30 $M_\odot$ in IC10 (30% $Z_\odot$; Prestwich et al. 2007).

These heavier masses affect binary retention. One of the most disruptive processes in the formation of double compact object binaries is a supernova explosion, and any asymmetries leading to natal kicks for the newly formed NSs, and possibly BHs. Since NSs and BHs originate from massive stars, they form on wide (weakly bound) orbits. Hence, the first supernova tends to disrupt most ($>90\%$; Belczynski et al. 2010c) progenitor binaries. The magnitude of natal kicks was established for Galactic single pulsars at the level of 200–300 km s$^{-1}$ (Hobsb et al. 2005). There is growing observational evidence that, although low-mass BHs may receive small-to-moderate kicks, massive BHs are born in the dark (without attendant energetic supernova explosions) and without natal kicks (Mirabel & Rodrigues 2003; Dhawan et al. 2007; Martin et al. 2010). These observations fit with a model assuming that kicks are produced by asymmetric ejecta. Even if the total kick momentum was comparable for collapse to a BH, the higher the BH mass, the lower the kick velocity. Additionally, it is likely that for very high mass ($M_{\text{zams}} \gtrsim 40 M_\odot$) stars promptly collapse to massive BHs, with no mass ejection and possibly no natal kicks (Fryer & Kalogera 2001). We have utilized the above information and incorporated a low-mass BH/small kick and high-mass BH/no kick scheme into our population synthesis calculations. This approach was folded in with metallicity-dependent BH formation, leading to new estimates of the corresponding BH–BH rates. The increase in the BH–BH merger rate is due to the lack of natal kicks in the formation of the majority of BHs at low metallicity, and thus a high binary survival rate through collapse. The detection rates are further boosted by the high BH–BH chirp mass, allowing detections to much farther distance.

The results for model B show a particularly dramatic increase in the merger rates with decreasing metallicity. BH binaries, almost non-existent at solar metallicity, become the dominant population at low metallicity. This striking increase in the rate is the direct result of small stellar radii at low metallicity. This trend, noted in stellar models (Hurley et al. 2000) and included in our calculations, is driven by the decreased opacity in matter with fewer heavy elements; the stars are less puffed up by photons emerging from the core. The smaller radial expansion of stars may also be caused by the high rotation that is usually induced by binarity or low stellar metallicity (Vazquez et al. 2007; de Mink et al. 2009), but the effects of rotation on stellar evolution are not included in our analysis. These smaller stellar radii at low metallicity cause some fraction of massive stars to bypass mass transfer early in their evolution and thus avoid coalescing in the common envelope phase. These stars survive to form a population of close BH–BH binaries. Figure 2 demonstrates how the evolution of a typical BH–BH progenitor alters with the change of metallicity.

3 DISCUSSION

Recent observational data indicate that about half of recent star formation arises in low-metallicity galaxies (Panter et al. 2008). We have created a synthetic model of the local universe that assumes half of the stars are forming at solar metallicity, and the other half are forming at 10% solar. This range of metallicity has profound effects on the detectable rate of GWs from binary systems. The predicted detection rates are presented in Table 2, as a function of gravitational detector sensitivity. LIGO (with its sensitivity of about 18 Mpc) has yet to detect a binary
inspiral (Abbott et al. 2009b). Our optimistic model (A), with a predicted detection rate of 5 yr\(^{-1}\) for \(d_{\text{obs}} = 18\) Mpc, is thus already excluded by LIGO. Our pessimistic model (B), with a much lower detection rate of 0.05 yr\(^{-1}\) for \(d_{\text{obs}} = 18\) Mpc, is consistent with observations. This hints that some fraction of massive binaries cannot be surviving the common envelope phase.

We employ the results of our pessimistic model (B) to estimate the sensitivity at which instruments like LIGO or VIRGO would detect 1 and 10 inspirals per year. Assuming a local density of Milky Way size galaxies of \(\rho_{\text{gal}} = 0.01\) Mpc\(^{-3}\) (O'Shaughnessy et al. 2008), we extrapolate to a distance sufficient to contain enough star-forming mass to generate the desired merger rate (our calculated rate of mergers per Milky Way size galaxy is listed in Table 1). It is found that instruments need to reach a sensitivity of \(d_{\text{obs}} = 45\) Mpc and 97 Mpc to provide 1 and 10 detections per year, respectively. We also note that the detections will be most likely dominated by BH–BH binaries (\(\sim 80\%\)), with a smaller contribution from BH–NS systems (\(\sim 15\%\)), and a negligible contribution from NS–NS inspirals (\(\sim 5\%\)).

Our results are subject to a number of uncertainties. First, the star formation rates may be different from those presented in Panter et al. (2008). Stars which formed in the remote past but are merging at present day may manifest themselves as an additional and significant component to the detection rates. In-depth study of the overall cosmic star formation rate, and the contribution of mergers from stars born at high redshift, using existing tools (Belczynski et al. 2010b) is underway. Second, the process of BH formation is still somewhat uncertain. Evolutionary effects like wind mass loss rates may alter the final BH mass, while natal kicks (or lack thereof) or the disputed mass delineation between NS and BH formation may substantially affect the rates. Although we have chosen the best available models to describe these processes, future theoretical and observational constraints may significantly affect our estimates. Finally, we can exclude 100% of stars following model A (ignoring suppression through the common envelope phase), since this produces rates that should have already been detected by LIGO. However, mixtures of model A and model B (e.g., 50–50 of each model) are still consistent with observational limits. The physical interpretation of this sort of mixture model is that massive stars begin developing core–envelope structure halfway through the HG, and the survival through common envelope phase depends not only on the donor type, but also on its evolutionary state. Therefore, a fraction of binaries survive the common envelope phase.

Our results suggest a very high potential for the detection of gravitational radiation from a binary inspiral in the near future. Our merger rates for the most likely source to be detected, a BH–BH binary, are significantly higher than previous estimates in the literature. For example, Abadie et al. (2010) estimated the realistic level of BH–BH detection at the level of 20 yr\(^{-1}\) for the advanced LIGO, while our realistic prediction is of the order of \(\gtrsim 200\) yr\(^{-1}\). Note that we have not included the potentially significant contribution of dynamically formed BH–BH binaries in globular clusters (e.g., Sadowski et al. 2008; Downing et al. 2010). Our prediction is based on the most recent observational and theoretical results, and employs a standard stellar evolutionary model. Further support for our enhanced theoretical predictions is the existence of high-mass X-ray binaries, such as IC10 X-1 and NGC300 X-1, that are expected to form close BH–BH binaries on a very short timescale (set by the evolution of the massive Wolf–Rayet companion). These systems have formed massive BHs in low-metallicity environment (consistent with our results), but also using their nearby locations leads to a semi-empirical estimate of merger rates that are comparable to the rates presented here (Bulik et al. 2008). Extending the sensitivity of existing instruments by factors of only a few, to about 50–100 Mpc, should result in the first detection of GWs. The lack of detections at increased sensitivity will put stringent constraints on the BH–BH formation (BH natal kicks) and/or on the star formation (metallicity) in the local universe.

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