Erratum and Addendum: Gravitational waves from black hole-neutron star binaries: Classification of waveforms

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A coding error was found in our original version of numerical-relativity code SACRA. We correct the results of [M. Shibata, K. Kyutoku, T. Yamamoto, and K. Taniguchi, Phys. Rev. D 79, 044030 (2009),] by simulations of the improved accuracy.

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In [1], we reported numerical results obtained by our SACRA code employing a simple $\Gamma$-law equation of state with $\Gamma = 2$. During subsequent studies [2,3], we noticed that we systematically underestimated disk masses in the original work. The reason is that we evolved hydrodynamic variables and estimated disk masses only in a domain of the size $\sim 200^3 \text{ km}^3$, though Einstein’s equations were solved in domains of size $\sim 1500^3–2000^3 \text{ km}^3$. A small-size domain for hydrodynamics is insufficient for the estimation of the disk mass, if tidal disruption occurs. In particular, for a large neutron star (NS) radius, the tidally disrupted material extends far away from the central region, and the disk mass was significantly underestimated. This problem was found during the writing of [3], and the erratum of [2,4] were already published.

For this reason, we reperformed simulations for the same models as those of [1], enlarging the computational domain of hydrodynamics. To estimate disk masses more accurately, in addition, we improved the grid resolutions from $N \leq 36$ (we use the same notations as used in [1]) to $N = 40, 50, \text{ and } 60$; with $N = 60$, the diameters of NSs are covered by $\approx 100$ grid points, and the diameters of apparent horizons of black holes (BHs) are by $\approx 20Q$ grid points. With this improved grid resolution, we also reanalyzed gravitational waves. In addition, the fitting formula for the quasinormal-mode frequency is updated to the latest, more sophisticated one derived in [5].

First, we show the convergence properties of our updated simulations. Figure 1 plots the merger time for $Q = 2$ models as a function of $1/N^2(\approx \Delta x^2)$, and indicates that it converges approximately at the second order, which is expected for SACRA. Thus, a reasonable convergence is indicated to be achieved in our new simulations. The convergence properties of other quantities are discussed below.

The corrected quantities for the merger remnant BH are in the convergent regime within $O(0.1\%)$ errors except for $a_{(1)}$, indicating a reasonable convergence.

![FIG. 1 (color online). The merger time normalized by the Arnowitt-Deser-Misner mass of the initial configuration for models with $Q = 2$ as a function of $1/N^2$. The left, middle, and right points correspond to the results of $N = 60, 50, \text{ and } 40$, respectively.](image-url)
The new SACRA can correctly estimate the mass of the remnant disk. However, we find that the disagreement between $a_{i1}$ and other two, $a_{i2}$ and $a_{i3}$, becomes smaller as the grid resolution is improved, and the error is $\leq 0.015$ for $N = 60$. We note that $M_{BH, f}$ and $C_e/4\pi$ always agree approximately with each other irrespective of $N$.

The corrected remnant disk mass for $N = 60$ is significantly larger than that in our previous simulations. The reason for the mistake in [1] is due to the fact that we did not follow the motion of the material which is ejected by tidal disruption and escapes outside the central domain of the size $\sim 200^3$ km$^3$, even when they are bound and supposed to eventually return to the neighborhood of the BH. The new SACRA can correctly estimate the mass of the returned material. Snapshots of the rest-mass density profiles for model M30.145 are displayed in Fig. 3, which shows that the hydrodynamics processes are solved appropriately in the far region. Figure 4 plots the time evolution of $M_{\>	ext{r}_{\text{rad}}}$ for all the models with $N = 60$. It is found that the remnant disk mass after $\sim 10$ ms of the merger exceeds $0.01M_\odot$ for a wider range of binary parameters (for a hypothetical NS mass $1.35M_\odot$). However, the remnant disk mass is still small for a large mass ratio, $Q = 5$ or for a compact NS, $\mathcal{C} = 0.178$ for which the tidal effect plays a minor role in the merger process.

By contrast, quantities associated with the remnant BH do not differ much from those obtained in [1]. This fact suggests that the disrupted material does not affect the remnant BH strongly. This is reasonable, because the mass of the remnant BH is always much larger than that of the remnant disk.

The gravitational waveforms for selected models are plotted in Fig. 5. As often found in our series of papers [2,3], the waveform agrees well with the Taylor-T4 formula.

![Figure 2](color online). Evolution of the rest mass of the material located outside the apparent horizon for different grid resolutions of models M20.145 and M20.178.
except for the first one orbit and for the final inspiral orbit just before the merger. For completeness, corrected results for the radiated energy and angular momentum are also listed in Table II.

The gravitational-wave spectra for selected models are shown in the left panel of Fig. 6 together with the spectra computed by the Taylor-T4 formula and of the phenomenological waveform proposed in [8] following the idea...
We also recomputed the cutoff frequency, $f_{\text{cut}}$, for each model, and the results are listed in Table I. We reconfirm the correlation between $C$ and $f_{\text{cut}}$ for the fixed $Q$ (the cutoff frequency converges approximately for $N = 60$ and 50). The right panel of Fig. 6 shows the spectrum for selected models with different grid resolutions. We do not match numerical data to the Taylor-T4 waveform unlike in our original paper.

Finally, we would like to apologize to readers of [1] for any inconvenience caused by our negligence.

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**TABLE II.** Corrected numerical results for gravitational waves: Compare with Table IV of [1].

<table>
<thead>
<tr>
<th>Model</th>
<th>$\Delta E/M_0$ (%)</th>
<th>$\Delta J/J_0$ (%)</th>
<th>(2,2)</th>
<th>(3,3)</th>
<th>(4,4)</th>
<th>(2,1)</th>
<th>$f_{\text{QNM}}M_{\text{BH}}$</th>
<th>$V_{\text{kick}}$ (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M20.145 ($N = 60$)</td>
<td>0.80</td>
<td>17</td>
<td>0.78</td>
<td>0.014</td>
<td>0.004</td>
<td>0.001</td>
<td>0.084</td>
<td>25</td>
</tr>
<tr>
<td>M20.160 ($N = 60$)</td>
<td>1.13</td>
<td>20</td>
<td>1.10</td>
<td>0.024</td>
<td>0.007</td>
<td>0.003</td>
<td>0.084</td>
<td>43</td>
</tr>
<tr>
<td>M20.178 ($N = 60$)</td>
<td>1.62</td>
<td>23</td>
<td>1.56</td>
<td>0.037</td>
<td>0.010</td>
<td>0.008</td>
<td>0.083</td>
<td>80</td>
</tr>
<tr>
<td>M30.145 ($N = 60$)</td>
<td>0.99</td>
<td>18</td>
<td>0.93</td>
<td>0.041</td>
<td>0.009</td>
<td>0.003</td>
<td>0.077</td>
<td>20</td>
</tr>
<tr>
<td>M30.160 ($N = 60$)</td>
<td>1.37</td>
<td>22</td>
<td>1.28</td>
<td>0.068</td>
<td>0.012</td>
<td>0.007</td>
<td>0.077</td>
<td>15</td>
</tr>
<tr>
<td>M30.178 ($N = 60$)</td>
<td>1.70</td>
<td>24</td>
<td>1.56</td>
<td>0.11</td>
<td>0.017</td>
<td>0.010</td>
<td>0.077</td>
<td>40</td>
</tr>
<tr>
<td>M40.145 ($N = 60$)</td>
<td>1.09</td>
<td>20</td>
<td>0.97</td>
<td>0.084</td>
<td>0.018</td>
<td>0.016</td>
<td>0.073</td>
<td>92</td>
</tr>
<tr>
<td>M50.145 ($N = 60$)</td>
<td>1.01</td>
<td>20</td>
<td>0.86</td>
<td>0.11</td>
<td>0.022</td>
<td>0.012</td>
<td>0.071</td>
<td>84</td>
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</tbody>
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