HEAD-ON COLLISIONS OF DIFFERENT INITIAL DATA

ULRICH SPERHAKE, BERND BRÜGMANN, JOSÉ A. GONZÁLEZ, MARK D. HANNAM, SASCHA HUSA
Theoretical Physics Institute,
University of Jena, D-07743 Jena, Germany

We discuss possible origins for discrepancies observed in the radiated energies in head-on collisions of non-spinning binaries starting from Brill-Lindquist and superposed Kerr-Schild data. For this purpose, we discuss the impact of different choices of gauge parameters and a small initial boost of the black holes.

1. Introduction

The area of numerical relativity has made dramatic progress in the last two years and numerical simulations of black hole binaries performed by various groups have resulted in a wealth of literature on astrophysical topics and those related to gravitational wave data analysis. At the same time, laser-interferometric GW detectors, LIGO, GEO600, TAMA, VIRGO, have started collecting data at design sensitivity. The area of GW physics has thus entered a very exciting stage with vast potential for astrophysics, our understanding of the early universe and fundamental physics.

From the viewpoint of numerical relativity, though, a number of important questions still remain to be addressed. These largely concern the accuracy of the produced waveforms, the dependency of the results on numerical techniques, their detailed matching with results predicted by approximation theories as well as the mass production of waveforms covering the complete parameter space for use in GW observations and parameter estimation.

The purpose of this study is to address the dependency of the numerical results on the choice of black-hole binary initial data. In contrast to spacetimes containing single stationary black holes, there exist no uniqueness theorems guaranteeing that two data sets for binary black holes using different data types represent the same physical configuration. Indeed, such data sets are known to generally differ in the amount of gravitational radiation inherent in the initial data.

The dependency on initial data parameters (though not data type) has been studied in the case of binary black hole coalescence in Refs. 2,4,6. Using the moving puncture technique, the merger waveforms are found to agree well for different initial separations and algorithms to produce quasi-circular initial configurations. A comparison of GWs produced in the evolution of Cook-Pfeiffer and puncture data using different evolution techniques has been presented in Ref. 1 and shown good agreement. There remains a difficulty in the identification of free initial parameters in this case, however (cf. the non-vanishing spin in the Cook-Pfeiffer data set in this comparison). This identification of parameters represents a simpler and cleaner task in the case of head-on collisions of non-spinning black holes which has been studied in Ref. 11. That study observed systematically larger amplitudes by about 10% in the merger waveform resulting from Kerr-Schild data compared with those
of Brill-Lindquist data. Here we investigate two possible causes for this discrepancy: the dependency of the results on the gauge trajectories in the case of Kerr-Schild data and the impact of deviations from time symmetry of the initial data.

2. Results

The simulations presented in this work have been obtained with the Lean code\textsuperscript{7,11} which uses the BSSN formulation of the Einstein equations together with the moving puncture approach.\textsuperscript{3,5} It is based on the Cactus\textsuperscript{8} computational toolkit and the Carpet\textsuperscript{10} mesh-refinement package. For a detailed description of the code as well as the construction of initial data we refer the reader to Ref. 11.

We first discuss the gauge trajectories used in Ref. 11 for the Kerr-Schild data. There, algebraic gauge conditions are constructed which require trajectories for the (approximate) black hole positions (see 11 for details). These are prescribed as polynomials $x^i(t) = x^i_0 + v^i_0 t + a^i_0 t^2/2 + j^i_0 t^3/6 + q^i_0 t^4/24$ which are smoothly (up to fourth derivatives) matched to the static function $x^i(t) = 0$ in a time interval $t_1 < t < t_2$. Here $x^i_0$, $v^i_0$, $a^i_0$, $j^i_0$, $t_1$ and $t_2$ are free parameters which need to be chosen carefully to avoid numerical instabilities. In Table 1 we list the values for each (Kerr-Schild) model. In order to assess the impact of the particular choice of these parameters, we have evolved the initial data of model 1 with alternative gauge parameters as listed in the second row of the table. This alternative gauge trajectory is motivated by the initial coordinate velocity $v = -0.08$ of the central position of the apparent horizon as measured using Thornburg’s AHFinderDirect.\textsuperscript{12,13}

The resulting waveforms are shown in the left panel of Fig. 1. Both the waveforms and the radiated energies thus obtained for model 1 show excellent agreement. The differences in radiated energy are about 1.5 % and thus substantially smaller than the discrepancies between $E_{KS}$ and $E_{BL}$.

Second, we assess the impact of deviations from exact time symmetry of the initial superposed Kerr-Schild data. These deviations manifest themselves in a small but non-vanishing initial coordinate velocity of the superposed Kerr-Schild holes as measured by the central position of the apparent horizon. For the case of model 2
we have measured this velocity to be \( v = 0.067 \). In order to estimate what impact such an initial velocity has on the resulting waveforms, we have applied an initial linear momentum \( p_z = m v \) to the Brill-Lindquist version of this model, where \( m \) is the irreducible mass of a single hole. The resulting waveform is compared with its non-boosted counterpart in the right panel of Fig. 1. Again, the wave amplitudes show good agreement, as do the resulting values for the radiated energy in Table 1.

In summary, we find the observed differences in radiated energy resulting from modifications of the gauge trajectories and a possible initial boost of the black holes to be of the order of \( 1\% \) and thus substantially below the differences of about \( >20\% \) observed in Ref. 11 between the two types of initial data.

Acknowledgments

This work was supported by DFG grant SFB/Transregio 7 “Gravitational Wave Astronomy”, and the DEISA Consortium (co-funded by the EU, FP6 project 508830). Computations were performed at LRZ Munich and HLRS, Stuttgart.

References

1. J. G. Baker, M. Campanelli, F. Pretorius, and Y. Zlochower. 2007. \textit{gr-qc/0701016}.
2. J. G. Baker \textit{et al.} \textit{Phys. Rev. D}, 73:104002, 2006.
3. J. G. Baker, J. Centrella, D.-I. Choi, M. Koppitz, and J. van Meter. \textit{Phys. Rev. Lett.}, 96:111102, 2006.
4. B. Br"{u}gmann \textit{et al.} 2006. \textit{gr-qc/0610128}.
5. M. Campanelli, C. O. Lousto, P. Marronetti, and Y. Zlochower. \textit{Phys. Rev. Lett.}, 96:111101, 2006.
6. M. Campanelli, C. O. Lousto, and Y. Zlochower. \textit{Phys. Rev. D}, 74:041501, 2006.
7. J. A. González, M. D. Hannam, U. Sperhake, B. Br"{u}gmann, and S. Husa. 2007. \textit{gr-qc/0702052}.
8. T. Goodale \textit{et al.} \textit{In Vector and Parallel Processing - VECPAR’2002, 5th International Conference, Lecture Notes in Computer Science}, Berlin, 2003. Springer.
9. F. Pretorius. \textit{Phys. Rev. Lett.}, 95:121101, 2005.
10. E. Schnetter, S. H. Hawley, and I. Hawke. \textit{Class. Quantum Grav.}, 21:1465–1488, 2004.
11. U. Sperhake. 2006. \textit{gr-qc/0609079v1}.
12. J. Thornburg. \textit{Phys. Rev. D}, 54:4899–4918, 1996.
13. J. Thornburg. \textit{AIP Conference Proceedings}, 686:247–252, 2003.