LESSONS FROM 3D HYDRODYNAMIC CALCULATIONS OF BINARY NEUTRON STAR COALESCENCE

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The main lessons learned from several years of Newtonian (and post-Newtonian) numerical hydrodynamic calculations of neutron-star binary coalescence are briefly summarized and some important test calculations are suggested for fully relativistic 3D hydrodynamic codes now being developed.

1 Summary of Recent Work

Coalescing binary neutron stars (NS) are important sources of gravitational waves that should become detectable with the laser interferometers now being built as part of the LIGO, VIRGO and GEO projects. For recent reviews and references on the detection and sources of gravitational radiation, see Thorne[16].

Post-Newtonian (PN) approximation methods have been used to calculate waveform templates in the low-frequency, slow-inspiral phase of the binary evolution [3]. In this phase the two stars are still well separated and can be treated as point masses. Near the end of the coalescence, however, hydrodynamic effects and the interior structure of the stars play an increasingly important role. Hydrodynamics becomes dominant when the two stars finally merge together into a single object. The shape of the corresponding burst of gravitational waves provides a direct probe into the interior structure of a NS and the nuclear equation of state (EOS). In the Newtonian limit, the inspiral phase is quasi-hydrostatic, and the final merging is driven entirely by a global hydrodynamic instability caused by tidal effects [11]. After a brief episode of mass shedding, most of the fluid settles down into a new, nearly axisymmetric, hydrostatic equilibrium configuration [10].

Numerical hydrodynamic calculations of binary NS coalescence have now been performed by a number of different groups, using a variety of numerical methods. Unfortunately, up until very recently, no direct comparison between the different published results was possible because different groups focused on different aspects of the problem. Nakamura and collaborators[8] were the first to perform 3D calculations of binary NS coalescence, using a traditional Eulerian finite-difference code. Rasio and Shapiro [10 11] have been using the Lagrangian method SPH and have focused on determining the stability properties of initial binary models in strict hydrostatic equilibrium and calculating the emission of gravitational waves from the coalescence of unstable binaries. Many of

their results have now been independently confirmed in the work of New [9], who used completely different numerical methods but also focused on stability questions. Zhuge et al. [17] have also used SPH and studied the dependence of the gravitational waveforms on the initial NS spins. Davies et al. [4] and Ruffert et al. [12] have incorporated a treatment of the nuclear physics in their calculations (done using SPH and PPM codes, respectively) and focus on NS mergers as sources of gamma-ray bursts.

For NS binaries, and particularly if the NS EOS is fairly soft, relativistic effects combine nonlinearly with Newtonian tidal effects so that close binary configurations can become dynamically unstable earlier during the spiral-in phase (i.e., at larger binary separation and lower orbital frequency) than predicted by Newtonian hydrodynamics alone. The combined effects of relativity and tidal interactions on the stability of close compact binaries have only very recently begun to be studied. Preliminary results have been obtained using both analytic approximations [15 6 7] (basically PN generalizations of the work done by Lai et al. [5]) as well as numerical 3D calculations incorporating simplified treatments of relativistic effects [18 13 1]. A NASA Grand Challenge project is under way [14] that will ultimately attempt a fully relativistic calculation of the final coalescence, combining the techniques of numerical relativity and numerical hydrodynamics in 3D.

2 Main Lessons for Future Fully Relativistic Calculations

In the context of future 3D relativistic calculations, some important lessons to be remembered from existing Newtonian and PN calculations are as follows.

- **Relevance of the Newtonian limit**. For stiff NS EOS (NS radius $R \sim 12-15\,\mathrm{km}$, $M/R \sim 0.1-0.2$), relativistic effects may in fact remain relatively unimportant during the entire hydrodynamic merger. Thus it should be kept in mind that fully relativistic codes may not be entirely necessary to calculate NS mergers numerically. Much simpler PN codes may be sufficient, even to obtain quantitatively accurate results.

- **Importance of the Newtonian limit as a test case**. Even if they were not so relevant for real NS binaries (e.g., because the NS EOS turned out to be rather soft), Newtonian or PN results would remain important to test relativistic codes. These codes, when run for very large R/M (cf. Ref. 1), should be able to reproduce all the features of the Newtonian results. In particular, they should be able to maintain binaries in stable quasi-equilibrium circular orbits at large binary separations $r \gg R$, and

they should be able to identify the onset of dynamical instability at $r/R \sim 3$.

- **Sensitivity to the mass ratio**. Newtonian calculations[10] have revealed a high sensitivity of the gravitational waveforms to the binary mass ratio, even for very small departures from the equal-mass case. Thus, although the equal-mass case may seem to be the most natural test case, it is *not* a realistic case.

- **Synchronized vs Nonsynchronized Binaries**. Hydrodynamic mergers of initially *nonsynchronized* binaries are far more challenging to calculate numerically, compared to mergers of initially synchronized (uniformly rotating) NS. This is because an unstable vortex sheet can form at the interface between the two stars during the merger[10]. This leads to small-scale Kelvin-Helmholtz instabilities and turbulence, which are basically intractable (particularly in 3D). Therefore, although they may not be the most realistic[2], synchronized initial conditions should be preferred, at least for test calculations.

1. T. Baumgarte, et al. in this volume.
2. L. Bildsten and C. Cutler, *ApJ* **400**, 175 (1992).
3. L. Blanchet et al., *Class. Quant. Grav.* **13**, 575 (1996).
4. M.B. Davies et al. *ApJ* **431**, 742 (1994).
5. D. Lai, F.A. Rasio, and S.L. Shapiro, *ApJ* **437**, 742 (1994). [LRS]
6. D. Lai and A.G. Wiseman, *Phys. Rev.* D **54**, 3958 (1997).
7. J.C. Lombardi, F.A. Rasio, and S.L. Shapiro, submitted to ApJ (1997).
8. T. Nakamura, in *Relativistic Cosmology*, ed. M. Sasaki (Universal Academy Press, 1994), and references therein.
9. K. New, PhD Thesis, Louisiana State University (1996).
10. F.A. Rasio and S.L. Shapiro, *ApJ* **432**, 242 (1994).
11. F.A. Rasio and S.L. Shapiro, in *Compact Stars in Binaries*, Proc. of IAU Symp. 165, eds. J. van Paradijs et al. (Kluwer, Dordrecht, 1996).
12. M. Ruffert, H.-T. Janka, and G. Schäfer, *A&A* **311**, 532 (1996).
13. M. Shibata, *Prog. Theor. Phys.* **96**, 317 (1996).
14. W.-M. Suen, in this volume.
15. K. Taniguchi and T. Nakamura, *Prog. Theor. Phys.* **96**, 693 (1996).
16. K.S. Thorne, in *Compact Stars in Binaries*, Proc. of IAU Symp. 165, eds. J. van Paradijs et al. (Kluwer, Dordrecht, 1996).
17. X. Zughe et al., *Phys. Rev.* D **50**, 6247 (1994); **54**, 7261 (1996).
18. J.R. Wilson et al., *Phys. Rev.* D **54**, 1317 (1996).