Neutron Star Mergers out of the blur: modeling turbulent scales in Large Eddy Simulations

Daniele Viganò, Carlos Palenzuela

The first simultaneous detection of gravitational waves and electromagnetic waves from a binary neutron star (BNS) merger [1] represents a wealth of data, and a long-awaited simultaneous detection of multi-wavelength electromagnetic radiation, ranging from radio to gamma. The associated short gamma-ray burst has at once confirmed the main features predicted by the kilonova scenario [10], and constrained the equation of state of nuclear matter [12], the maximum mass supported by a neutron star [9, 13], its radius [3], the contribution of BNS mergers to heavy elements production via r-processes [2], and the amount of ejecta [4].

While the dynamics are quite clear, some interesting and more subtle questions regard the roles of magnetic fields and the process they undergo during and after the merger. Given the intrinsic difficulties of numerical GRMHD, a few works have consistently included the full set of combined Einstein equations and MHD equations. In particular, during the merger, the Kevin-Helmholtz instability (KHI) is thought to play an important role in a fast growth of any seed magnetic field. The instability develops faster for small-scale perturbation, with a cut-off wavelength of the order of the discontinuity layer (the shock layer of the two colliding cores). The simulations with the maximum numerical resolutions are of O(10) m [8], but they are not yet able to fully capture the KHI, whose smallest and fastest-growing scales are of the order of the discontinuity layer (a few meters probably).

Numerical limitations in solving the instability are being slowly overcoming thanks to the growing computational capacity. However, the full capture of all scales (direct numerical simulation) is still relatively far out of reach even for the most advanced codes and infrastructures, thus it is well worth to study alternative approaches that try to simulate the physical mechanisms with a much lower computational cost, by means of short-cuts. One popular way to numerically simplify the problem is to take a temporal or spatial average of the MHD variables, and to model them differently for the unresolved scales through the introduction of extra terms in the momentum and induction equations. These approaches are called Large Eddy Simulations (LES), which consist in the inclusion of sub-grid scale (SGS) models in the MHD equations.

We borrow techniques from plasma physics and engineering applications, often used for the incompressible case, and compare different SGS models available in literature [5–7, 14]. We confirm and extend previous findings: the best model in fitting the unresolved components is the gradient model [11]. It is obtainable from any non-linear equation, and it does not contains any arbitrary ingredient, except a single free coefficient.

We present the full extension of the gradient model, generalizing the recipe for any system of equation. We show the applications of LESs with the SGS gradient model in box relativistic MHD simulations. Within the next months, we will publish such results in a dedicated series of papers.

This approach is a novel implementation of techniques well known in very different contexts and represents an improvement in accuracy compared to the SGS models introduced so far in the context of mergers. Given the expected wealth of future detections, the advance in the theoretical understanding and numerical simulation of the role of turbulence and magnetic field amplification in mergers is a key issue.

---

[1] B. P. Abbott et al. *Physical Review Letters*, 119(16):161101, October 2017.
[2] B. P. Abbott et al. *ApJL*, 850:L39, December 2017.
[3] A. Bauswein et al. *ApJL*, 850:L34, December 2017.
[4] B. Côté et al. *ApJ*, 855:99, March 2018.
[5] P. Grete et al. *Physics of Plasmas*, 23(6):062317, June 2016.
[6] P. Grete et al. *PRE*, 95(3):033206, March 2017.
[7] M. Kessar et al. *Physics of Plasmas*, 23(10):102305, October 2016.
[8] K. Kiuchi et al. *Phys. Rev. D*, 92(12):124034, December 2015.
[9] B. Margalit and B. D. Metzger. *ApJL*, 850:L19, December 2017.
[10] B. D. Metzger. *Living Reviews in Relativity*, 20:3, May 2017.
[11] W.-C. Müller and D. Carati. *Physics of Plasmas*, 9:824–834, March 2002.
[12] D. Radice, A. Perego, F. Zappa, and S. Bernuzzi. *ApJL*, 852:L29, January 2018.
[13] M. Ruiz, S. L. Shapiro, and A. Tsokaros. *Phys. Rev. D*, 97(2):021501, January 2018.
[14] J. Smagorinsky. *Monthly Weather Review*, 91:99, 1963.