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# NUMERICAL MODELING OF DYNAMOS IN COMPACT OBJECTS: MAGNETIC FIELD AMPLIFICATION AND DISSIPATION

M. Bugli[1,2], J. Guilet[2], R. Raynaud[2], A. Reboul-Salze[3], P. Barrère[2], A. Mignone[1], V. Berta[1], G. Mattia[4] and L. Del Zanna[4]

**Abstract.** The amplification of magnetic fields via dynamo mechanisms is a fundamental process that not only shapes the dynamics of stars, but also deeply affects the evolution of compact objects from their formation throughout their activity. Understanding how magnetic fields are dissipated and amplified in the environment surrounding neutron stars and black holes can thus disclose the connection between the properties of the central object and the multi-messenger emission related to the accretion process. We present results from recent studies aimed at quantifying the properties of dynamo-generated magnetic fields in proto-neutron stars and their potential impact on the explosion and the neutrino and gravitational waves signals emitted at the formation of the compact object. We also show how mean-field dynamos can modify the dynamics of accreting black holes, as weak magnetic seeds are amplified to strong large-scale fields that can reshape the properties of the accretion flow. Finally, we present some recent models of resistive relativistic jets and high-order numerical schemes for (relativistic) magnetohydrodynamics (RMHD) that showcase the importance of reducing the numerical dissipation of magnetic fields observed in simulations, thus enhancing the robustness of their predictions.

Keywords: magnetic fields, neutron stars, black holes, dynamo, MHD, numerical algorithms

## 1 Introduction

The combination of rapid rotation and large-scale magnetic fields provides the perfect conditions to power-up high-energy astrophysical sources such as gamma-ray bursts, compact binaries and accreting black holes. However, the large scale separation between the sites where amplification (or dissipation) of magnetic fields takes place and the accretion flows (or relativistic jets) from compact objects still poses a serious challenge for numerical models. In the following we present a series of recent results from (general relativistic) MHD models of accreting compact objects that demonstrate the challenges and main features of simulations of astrophysical plasmas within (or in proximity) of either proto-neutron stars (PNS) or black holes.

## 2 Multi-scale approach: PNS dynamos and magneto-rotational explosions

While the exact origin of the large-scale magnetic fields of magnetars remains uncertain, a possible scenario is represented by the action of dynamos occurring within a still-forming PNS during the gravitational collapse of a massive star. Using global MHD models exploring different layers of the PNS, we showed how PNS convection can efficiently amplify weak small-scale magnetic seed up to magnetar-like levels ($\sim 10^{15}$ G; Raynaud et al. 2020) and lead to significant emission of gravitational waves (GW; Raynaud et al. 2022). The magnetorotational instability can also take over as driving dynamo mechanism (Guilet et al. 2022), producing large-scale magnetic fields with dynamics that resemble typical mean-field dynamo processes (Reboul-Salze et al. 2021; Reboul-Salze et al. 2022). Finally, the fallback of material onto the PNS can trigger the onset of the Tayler instability, exciting

[1] Dipartimento di Fisica, Università di Torino, via Pietro Giuria 1, 10125 Torino, Italy
[2] Université Paris-Saclay, Université Paris Cité, CEA, CNRS, AIM, 91191, Gif-sur-Yvette, France
[3] Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Potsdam, D-14476, Germany
[4] INFN, Sezione di Firenze, Via G. Sansone 1, I-50019 Sesto Fiorentino, Italy

large-scale non-axisymmetric perturbations and closing dynamo cycle (Barrère et al. 2022, 2023). All these dynamo models predict the amplification of magnetic fields with a multipolar and generally non-axisymmetric spatial structure. Bugli et al. (2021) explored the effects that such fields could have on core-collapse supernovae, showing that aligned dipolar fields are the most efficient at launching bipolar outflows (also in 2D; see Bugli et al. 2020). Moreover, magnetic fields can quench the onset of rotationally-driven instabilities and suppress the corresponding multi-messenger signatures (Bugli et al. 2023).

## 3 Sub-grid modeling: black hole accretion disks and resistive jets

An alternative approach to the investigation of magnetic fields amplification and dissipation are sub-grid models. An example is given by the *mean-field dynamo* closure, where unresolved small-scale fluctuation of velocity and magnetic fields produce both a large-scale electromotive force and an enhanced turbulent dissipation Brandenburg & Subramanian (2005). Accretion disks and relativistic jets can be highly affected by such dynamics (Mattia & Fendt 2020, 2022). When applied to the general relativistic (GR) MHD framework (Bucciantini & Del Zanna 2013), a mean-fied dynamo can reshape the properties of accretion disks around black holes. The emergence of dynamo waves (Bugli et al. 2014) can not only induce large-scale non-axisymmetries in the gas accreting onto the black hole (Del Zanna et al. 2022), but also amplify an initially weak magnetic seed and reproduce results from ideal GRMHD models (Porth et al. 2019) that include from the beginning intense magnetic fields (Tomei et al. 2020, 2021). The effects of numerical dissipation on the properties of astrophysical flows in simulations (which are unavoidable in all grid-based models) can be mitigated by using explicit prescriptions for the turbulent resistivity. Mattia et al. (2023) showed how reproducibility of MHD simulations of relativistic jets increases significantly when the resistive RMHD regime is adopted. Moreover, a substantial decrease of numerical magnetic dissipation can be obtained using high-order integration schemes (Berta et al. 2023), which increase the effective resolution of a given model and can produce large speedups w.r.t. $2^{\mathrm{nd}}$-order methods.

## 4 Conclusions

We presented results from a series of studies that focus on the modeling of magnetic field amplification and dissipation in accreting compact objects. Our results showcase the importance of connecting all the scales relevant for both the magnetic field dynamics and the astrophysical outflow evolution, highlighting also the common traits that can characterize different stages of the activity of a compact object.

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