THE IMPACT OF ROTATION AND DYNAMOS ON THE MULTI-MESSENGER EMISSION OF CORE-COLLAPSE SUPERNOVAE

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Abstract. The gravitational collapse of a massive star leads to the strong emission of gravitational waves and neutrinos during the first few seconds of the supernova event. Multi-messenger observations offer, thus, a unique window on the dynamics that regulate the explosion mechanism and the physical properties of the still-forming central proto-neutron star (PNS). In recent years, numerical models of core-collapse supernovae (CCSN) have started to produce quantitative predictions of both gravitational waves and neutrino emissions which provide the key ingredients necessary to constraint the physics of the explosion engine from actual observational data. Despite the fundamental role that strong magnetic fields play in the case of exceptionally energetic stellar explosions (e.g. long GRBs, hypernovae, superluminous supernovae), their impact on the multi-messenger emission from CCSN remains still largely unknown. We present results from recent studies aimed at quantifying the impact of dynamo-generated magnetic fields on the neutrino and gravitational waves emitted at the formation of a stellar compact object. We show how magnetic fields, by modifying the rotational profile of the proto-neutron star, weaken the development of large-scale instabilities connected to strong multi-messenger signals. However, this can also lead to a broadening of the spectral shape of the GW signal due to the magnetic field's impact on rotation and possibly the onset of the kink instability within the PNS. We finally display how current and upcoming neutrino detectors (e.g. KM3Net, DUNE, DarkSide) will be sensitive to the effects of rotation and strong magnetic fields predicted by our numerical models.

Keywords: supernovae, magnetic fields, gravitational waves, neutrinos, multi-messenger astronomy

1 Introduction

Core-collapse supernovae (CCSN) play a fundamental role in the formation of stellar-sized compact objects. The vast majority of CCSN can be explained by the so-called *neutrino-heating* mechanism, where a small fraction of the neutrinos emitted by the proto-neutron star (PNS) is absorbed by the shocked material (Janka 2012). At this stage of the explosion hydrodynamic phenomena such as the Standing Accretion Shock Instability (SASI) (Buellet et al. 2023; Walk et al. 2023) and the post-shock convection stirred by the neutrino absorption are crucial to aid the expansion of the shock further (Foglizzo et al. 2015). On the other hand, outstanding stellar explosions such as hypernovae, superluminous supernovae or long gamma-ray bursts require some additional energy reservoir to account for their exceptional kinetic energies and luminosities (Kasen & Bildsten 2010; Nicholl et al. 2013). A popular explanation relies on the *magneto-rotational* mechanism, where the combination of fast rotation (which provides an additional source of energy) and strong large-scale magnetic fields (which allow to tap into that reservoir) leads to powerful bipolar explosions with collimated outflows propagating along the rotational axis of the star (Bugli et al. 2020; Obergaulinger & Aloy 2021; Bugli et al. 2021).

Regardless of the specific explosion mechanism, the emission of both neutrinos and gravitational waves during this early stage of the explosion provides a unique window on the physical properties of the central PNS and the shock dynamics (Kuroda & Umeda 2010; Kuroda et al. 2016; Torres-Forné et al. 2019). Fast rotation can induce the onset of the so-called low-$T/|W|$ instability, whose action leads to large-scale non-axisymmetric

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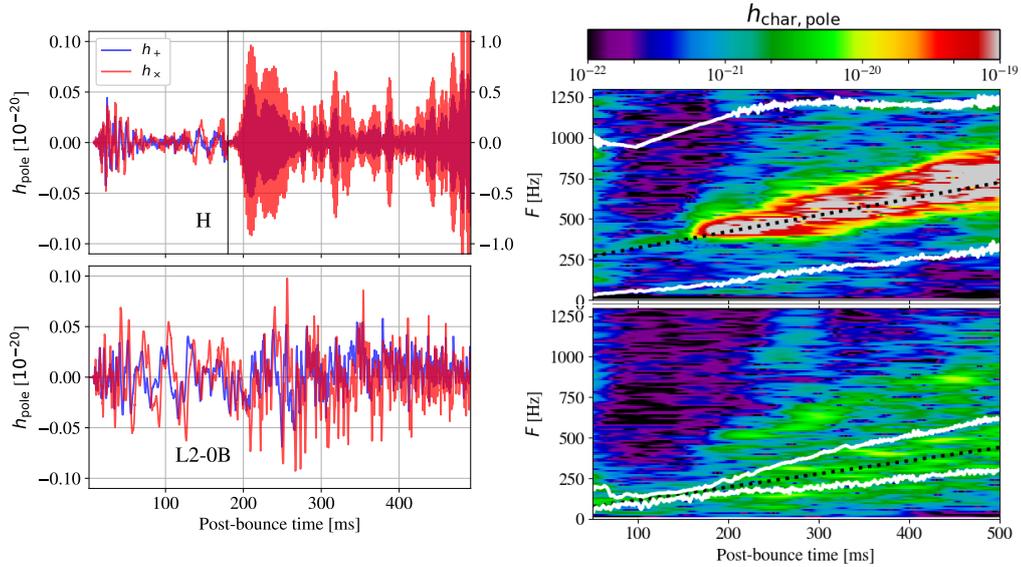
Fig. 1. On the left, GW strains observed along the polar axis for the unmagnetized model (top panel) and the model with an aligned quadrupolar magnetic field (bottom). On the right, time-frequency spectrograms for the corresponding characteristic strain $h_{\rm char}$. White lines represent twice the minimum and maximum rotational frequency of the PNS, while the black dotted line is twice the frequency of the $m = 1$ mode in the PNS density (from Bugli et al. 2023).

modes that can produce a strong emission of gravitational waves and modulations in the neutrino lightcurves (Takiwaki et al. 2021). However, the impact that strong magnetic fields can have on the multi-messenger emission of CCSN is still not very clear, due to the high computational cost of 3D magnetohydrodynamic (MHD) simulations of a stellar collapse and the consequent limitation in the number of models available. In the present work we show the analysis on the GW and neutrino emission from highly magnetized and fast rotating CCSN models (Bugli et al. 2023), highlighting in particular the signatures of fluid instabilities such as SASI and the low-$T/|W|$ instability. We will present the effects of the intense magnetic fields within the PNS on the neutrino luminosity curves and comment on their detectability with current and next-generation neutrino detectors (Bendahman et al. 2023). Finally, we will show the impact of strong magnetic fields on the ejecta composition and the effects on the explosive nucleosynthesis and the production of r-process elements (Bugli et al. 2023; Reichert et al. 2023).

2 Gravitational waves

The results shown here were obtained from 3D MHD numerical models of CCSN with the massive stellar progenitor 35OC in fast rotation. The different initial magnetic field configurations (an aligned dipolar, aligned quadrupolar, and equatorial dipolar field; for more details, see Bugli et al. 2021) are meant to take into account the complex field structures that typically arise during the dynamo processes that can occur within the PNS during the collapse (Raynaud et al. 2020; Reboul-Salze et al. 2021; Reboul-Salze et al. 2022; Guilet et al. 2022) but are not resolved in large-scale CCSN models.

Model H represents a hydrodynamic benchmark without a magnetic field, and it is the only one amongst the simulations we are considering that develops the low $T/|W|$ instability within the first few hundreds of ms after shock formation. This is evident from Fig. 1 (top panel on the left), where the GW strain observed along the rotational axis exhibits a strong and long lasting emission after ~ 200 ms post-bounce (p.b.) which coincides with the formation of a spiral structure in the density distribution within the PNS. The frequency of this emission increases steadily with time (top right panel of Fig. 1), due to the contraction of the PNS and the conservation of angular momentum. On the other hand, none of the magnetized models show a distinctive sign of the onset of the instability. The GW emission remains overall weaker than the hydrodynamic case, with no clear bursts over time. The spectral shape of the signal is generally broader, with features appearing at frequencies higher than the PNS rotational one, suggesting a significant contribution by mechanisms not induced by rotation itself (e.g. proper oscillation modes of the PNS). The main reason behind this qualitative
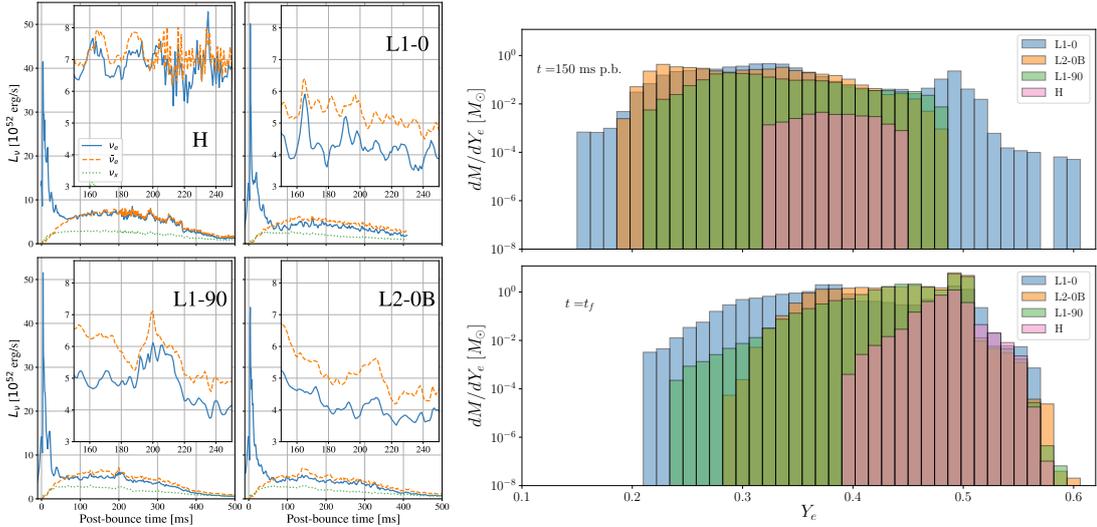
Fig. 2. Neutrino luminosities along the equatorial plane for all 3 neutrino species and four different magnetic field configurations (left) and ejecta compositions at two different times (right; from Bugli et al. 2023).

difference is the high efficiency of outward transport of angular momentum in presence of strong large-scale magnetic fields. As the rotation profile flattens, the PNS becomes stable against the low-$T/|W|$ instability and the formation of large-scale non-axisymmetric structures is disfavoured (Bugli et al. 2023).

3   Neutrinos and explosive nucleosynthesis

The neutrino emission from the magnetized models also presents qualitative differences w.r.t. the hydrodynamic case (left panels of Fig. 2). Similarly to GW, only for model H the luminosity curves observed along the equatorial plane have a distinctive high-frequency modulation at ~ 200 ms p.b. caused by the onset of the low-$T/|W|$ instability. Moreover, all magnetized models systematically have a lower luminosity in ν_e and $\bar{\nu}_e$, which stems from the more oblate shape of the PNS induced by the strong magnetic transport of angular momentum. Another effect of the extraction of rotational energy from the PNS via magnetic torques is a tendency to increase the amount of neutron-rich material in proximity of the PNS surface in the equatorial region, which would be otherwise accreted on the PNS without the additional rotational support. This phenomenon tends to increase the size of the region where ν_e are absorbed, pushing the electron neutrino-sphere further out, thus decreasing both the mean energy and the corresponding luminosity of ν_e w.r.t. $\bar{\nu}_e$.

The systematic decrease in the equatorial ν_e and $\bar{\nu}_e$ fluxes due to the action of strong magnetic fields can have a clear impact on neutrino observations (Bendahman et al. 2023). The left panel of Fig. 3 shows the number of events expected in the ARCA detector from the KM3NeT experiment (Adrian-Martinez et al. 2016; Aiello et al. 2021; Bendahman et al. 2022) for a CCSN event located at a distance of 5 kpc. Even considering the finite efficiency of the instrument and the presence of significant background, there is a clear suppression of the neutrino fluxes between 200 and 400 ms p.b. for the model with an aligned dipolar magnetic field. The significance of this effect, measured for several next-generation neutrino detectors, is instead shown in the right panel of Fig. 3. While KM3NeT could observe the suppression up to the galactic center at 3σ, experiments such as Hyper-Kamiokande, DUNE, and DarkSide-20k will have full galactic sensitivity.

Magnetic fields can also have a strong impact on the nuclear composition of the ejecta and the prospects for the production of heavy elements via explosive nucleosynthesis. Fig. 2 shows how magnetized models tend to expel more neutron-rich material than the hydrodynamic case, with model L1 (aligned dipolar field) producing the ejecta with the lower electron fraction Y_e. This effect is mainly due to the magneto-rotational explosion mechanism being able to eject material on shorter time-scales than in the hydrodynamic scenario, thus preventing the accretion of this material on the PNS or its irradiation by ν_e, which would increase Y_e accordingly. Since the presence of more neutron-rich ejecta favours the production of r-process elements (Reichert et al. 2021, 2023), the magnetized models here presented also produce heavier elements than model H, with the aligned dipolar case being the most efficient and capable of producing, to a certain extent, elements up to the second
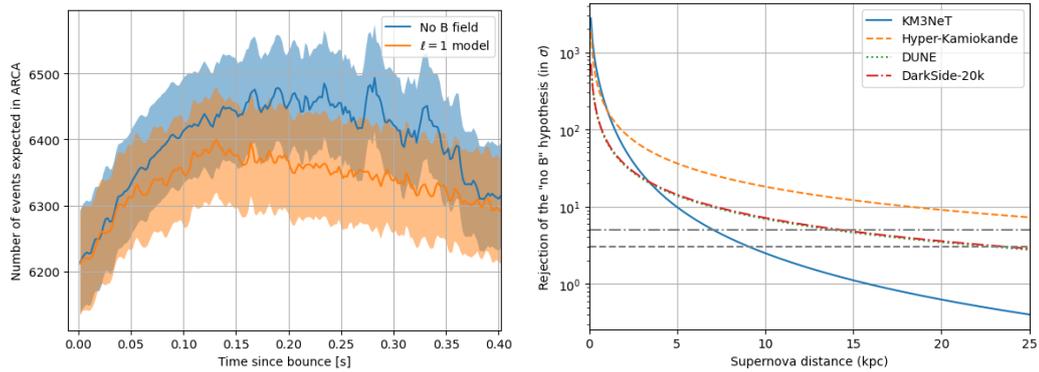
Fig. 3. On the left panel, neutrino event counts in the window 200-400 ms p.b. expected at KM3NeT-ARCA for the dipolar model L1-0. On the right panel, significance of the difference between the hydrodynamic model and the magnetic dipole model as a function of the CCSN distance (from Bendahman et al. 2023).

r-process peak (Reichert et al., in prep.).

4   Conclusions

We presented a series of 3D MHD models of fast rotating and highly-magnetized CCSN that showcase the impact of strong magnetic fields on the multi-messenger emission of CCSN. We have shown distinctive signatures arising both in GW and neutrinos (in some cases with similar features) and the qualitative effect that magnetic fields have on the production of new elements during the explosion. In forthcoming studies we will explore more in detail the correlations that GW and neutrino signals can display in virtue of common physical processes responsible for their production, while we will also quantitatively assess to what extent different magnetic fields configurations can have a role in the explosive nucleosynthesis.

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