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Incidence of stellar rotation on the explosion mechanism of massive stars

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Abstract. Hydrodynamical instabilities may either spin-up or down the pulsar formed in the collapse of a rotating massive star. Using numerical simulations of an idealized setup, we investigate the impact of progenitor rotation on the shock dynamics. The amplitude of the spiral mode of the Standing Accretion Shock Instability (SASI) increases with rotation only if the shock to the neutron star radii ratio is large enough. At large rotation rates, a corotation instability, also known as low-T/W, develops and leads to a more vigorous spiral mode. We estimate the range of stellar rotation rates for which pulsars are spun up or down by SASI. In the presence of a corotation instability, the spin-down efficiency is less than 30%. Given observational data, these results suggest that rapid progenitor rotation might not play a significant hydrodynamical role in the majority of core-collapse supernovae.

Keywords. hydrodynamics, instabilities, shock waves, stars: neutron, stars: rotation, supernovae: general

1. Introduction

A core-collapse supernova represents the death of a massive star and the birth of a neutron star. The initial spin period of the neutron star provides some insight on the explosion mechanism as well as the rotation of the progenitor. Neutron stars are expected to rotate slowly at birth with spin periods covering a range from tens to hundreds milliseconds (Faucher-Giguère & Kaspi 2006; Popov & Turolla 2012). This is at odds with 1D stellar evolution calculations which predict a maximum period of $10 - 15$ ms (Heger *et al.* 2005). However such calculations seem to overestimate the angular momentum contained in the cores of low-mass red giants (Cantiello *et al.* 2014).

Asymmetric explosions. The favored framework to explain the explosion of moderately rotating stellar cores relies on the delayed neutrino-driven mechanism proposed by Bethe & Wilson (1985). A spherical accretion shock stalls at a radius of about 150 km for a few hundreds milliseconds after the formation of a proto-neutron star (PNS) and is eventually revived thanks to neutrino absorption. Numerical simulations have shown that transverse motions induced by hydrodynamical instabilities play a decisive role in the explosions of progenitors above ~ 10 $M_\odot$. Two types of instabilities are able to break the spherical symmetry of the collapse: the neutrino driven convection (Herant *et al.* 1994; Foglizzo *et al.* 2006) and the Standing Accretion Shock Instability (SASI) (Blondin *et al.* 2003). Asymmetric explosions are supported by a number of observational evidence including a large pulsar kick that may be imparted by a global deformation $l = 1$ of the shock wave due to SASI (Scheck *et al.* 2004; 2006; Wongwathanarat *et al.* 2010).

Impact of rotation. Even if the first 3D explosions from ab initio models have been obtained in the last years, explosions are still slightly under-energetic and not yet routinely achieved (Janka *et al.* 2016). Moderate rotation may be an important ingredient to foster explosions. It reduces the critical neutrino luminosity required to revive the stalled shock (Iwakami *et al.* 2014). A SASI spiral mode is more easily destabilized by rotation (Blondin & Mezzacappa 2007; Yamasaki & Foglizzo 2008). In a non-rotating progenitor, such a spiral wave could spin the neutron star up to periods compatible with the observations (Blondin & Mezzacappa 2007; Foglizzo *et al.* 2012; Guilet & Fernàndez 2014). On the contrary, a SASI spiral mode may spin a pulsar down when the core is rotating (Blondin & Mezzacappa 2007). Such a scenario might lead to a counter-rotating neutron star depending on the efficiency of the angular momentum redistribution. When the rotation rate is high enough, a more vigorous one-armed spiral mode related to a corotation instability may arise and help the shock revival (Takiwaki *et al.* 2016). In this work, a simplified setup is used to investigate the role of progenitor rotation, regarding its impact on the shock wave dynamics and on the initial neutron star spin period.

2. A simplified model

Physical model. The stalled shock phase is studied by the mean of an idealized model which is dedicated to SASI in its simplest form. The numerical domain is restricted to the equatorial plane of a massive star described in cylindrical geometry, which enables non-axisymmetric motions in 2D. The flow, modeled by an idealized gas with an adiabatic index $\gamma = 4/3$, is decelerated by a shock wave of initial radius $r_{\rm sh\,0}$ and an incident Mach number $\mathcal{M}_1 = 5$. The matter accretes subsonically onto the surface of the PNS at a radius r_*. No heating function is employed in order to suppress the neutrino-driven convection. A cooling function is used to imitate the neutrino emission due to electron capture in the region surrounding the PNS with the approximation $\mathcal{L} \propto \rho P^{3/2}$ (Blondin & Mezzacappa 2006) where ρ and P respectively stand for the density and the pressure.

Rotation rates. Once the flow has relaxed on the numerical grid, a constant specific angular momentum j is injected through the outer boundary. The numerically relaxed 1D rotating flow is then perturbed by two counter-rotating density perturbations to trigger two spiral modes $m = \pm 1$ where m is the azimuthal wavenumber (see Kazeroni *et al.* 2017). The range of rotation rates considered in this study covers three orders of magnitude: $10^{13}\,{\rm cm}^2\ {\rm s}^{-1} \leqslant j \leqslant 10^{16}\,{\rm cm}^2\ {\rm s}^{-1}$. If the angular momentum were conserved down to the surface of a pulsar of 10 km radius, $j = 10^{16}\,{\rm cm}^2\ {\rm s}^{-1}$ would correspond to a spin period of 0.6 ms. The rotation rates considered are not high enough for the centrifugal force to greatly impact the dynamics. The stationary shock radius increases by less than 10% due to the centrifugal force (Fig. 1 & 2). Note that higher rotation rates are often considered in global simulations (e.g. Nakamura *et al.* 2014; Kuroda *et al.* 2014; Takiwaki *et al.* 2016). The angular momentum of the accreted material is poorly known since stellar evolution calculations predict values of $j \sim 10^{14} - 10^{15}\,{\rm cm}^2\ {\rm s}^{-1}$ if the magnetic field is taken into account and $j \sim 10^{16} - 10^{17}\,{\rm cm}^2\ {\rm s}^{-1}$ otherwise (Heger *et al.* 2005).

Non-rotating cases. Using non-rotating simulations of this model, Kazeroni *et al.* (2016) showed that a spiral mode prevails non-linearly only if the radii ratio $R \equiv r_{\rm sh\,0}/r_*$ is such that $R \gtrsim 2$. If this condition is fulfilled, a spiral mode emerges after three to five oscillations induced by a SASI sloshing mode. In the opposite case, the non-linear dynamics is dominated by a sloshing mode, irrespective of the shape of the initial perturbation.

Parametric simulations. A total of 140 simulations are used to cover the parameter space and the following radii ratio are used: $R = \{1.67,\ 2,\ 2.5,\ 3,\ 4,\ 5\}$. Periodic boundary

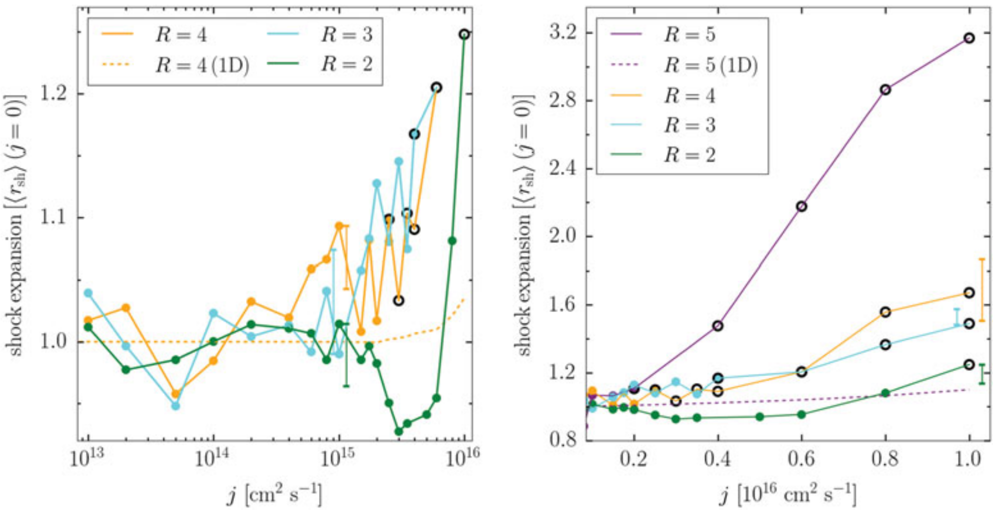

Figure 1. Influence of rotation on the non-linear regime of SASI (left panel) and the corotation instability (right panel) for different values of R. The solid lines represent the mean shock radius as a function of j in the 2D cases whereas the dashed lines show the effect of the centrifugal force in 1D simulations. The values are averaged in the non-linear regime and normalized by the ones measured in the non-rotating cases. The black circled points denote that a corotation emerges in the linear regime (empty circles) or in the non-linear regime (full circles). To reduce the variability of the results, the non-rotating simulations are repeated five times with slightly different initial perturbation amplitudes. The simulations where $j = 10^{15}\,\mathrm{cm^2\ s^{-1}}$ (left) and $j = 10^{16}\,\mathrm{cm^2\ s^{-1}}$ (left) are also repeated five times to assess the stochasticity of our results. The vertical bars indicate the minimum and maximum values obtained for each value of R.

conditions are employed in the azimuthal direction, a reflexive condition at the inner boundary and a constant inflow at the outer boundary which is placed far enough to prevent any interaction with the shock wave. The numerical resolution is 1600 cells in the azimuthal direction and from 1600 to 2730 in the radial one.

3. Influence of rotation

SASI dominated regime. The simulations of the linear regime reproduce the growth rates computed by Yamasaki & Foglizzo (2008) with a perturbative analysis with discrepancies of less than 10% (Kazeroni *et al.* 2017). The linear increase of the growth rates with rotation does not seem to depend on the geometry and the dimensionality (Blondin *et al.* 2017). In the non-linear regime of the instability, the shock wave expands with rotation only if the radii ratio is such that $R \gtrsim 2$. In that case, the shock radius is increased by 10% to 20% compared to situations where rotation is absent (Fig. 1, left panel). If $R < 2$, the averaged shock radius diminishes by 10% in the range of rotation rates in which spiral modes dominate the non-linear regime. This surprising result may be a consequence of the influence of rotation on the competition between the fundamental mode and higher harmonics. Note that this radii ratio threshold is similar to the critical ratio below which a sloshing mode dominates systematically the non-linear dynamics in non-rotating simulations (Kazeroni *et al.* 2016). The case-to-case stochasticity of the results may be as large as the effect of rotation on the shock dynamics (vertical bars in Fig. 1).

Overlap with a corotation instability. In cases with a large enough rotation rate, a corotation radius can emerge above the PNS surface. It delimits the region in which the flow

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has a higher rotational frequency than the spiral mode. In this case another instability known as low-T/W † can overlap with SASI (Kuroda *et al.* 2014; Takiwaki *et al.* 2016). This additional instability can produce a strong acoustic wave in the post-shock region with an open one-armed spiral pattern and may ease the shock revival (Takiwaki *et al.* 2016). While the mechanism of SASI has clearly been interpreted as an advective-acoustic cycle (Foglizzo *et al.* 2007; Guilet & Foglizzo 2012), the origin of low-T/W is uncertain. In the case of a differentially rotating neutron star, it has been suggested that the instability could be due to an energy transfer occurring across a band around a corotation radius where acoustic waves are amplified (Watts *et al.* 2005; Passamonti & Andersson 2015). In our study, an overlap between a corotation instability and SASI could be responsible for a more robust spiral mode. Indeed, the shock radius is increased by 50% to 200% compared to a non-rotating case (Fig. 1, right panel).

Angular momentum redistribution. The rotation profile induced by a SASI spiral mode is able to redistribute angular momentum and impact the spin of the neutron star. In an idealized scenario, some angular momentum is stored in the SASI spiral wave and expelled in the explosion while the opposite quantity is accreted onto the surface of the neutron star. If the progenitor is not rotating, this mechanism can induce a spin-up of the neutron star (Blondin & Mezzacappa 2007; Fernàndez 2010) which may reach periods of a few tens milliseconds (Guilet & Fernàndez 2014). This process has been reproduced experimentally in a shallow-water analogue of SASI where the dynamics of a hydraulic jumps is similar to the one of a shock wave in the equatorial plane of a massive star (Foglizzo *et al.* 2012; 2015). Concerning rotating cases, (Blondin & Mezzacappa 2007) proposed that a SASI spiral mode could reduce the neutron star spin compared to an estimate based on angular momentum conservation during the collapse. If enough angular momentum is redistributed, this process could lead to a counter-rotating neutron star compared to its progenitor.

Neutron star spin. The efficiency of the spin-up and the spin-down generated by spiral modes can be assessed by comparing the idealized angular momentum redistribution to a spherically-symmetric collapse leading to a rotational frequency $f_{\rm CORE}$ (Fig. 2). If the radii ratio is such that $R \lesssim 2$, the saturation amplitude of the spiral is too low to drive a significant redistribution and the neutron spin is barely affected by SASI. For higher radii ratios, rotation impacts the initial neutron star spin throughout the range of rotation rates considered. If the rotation is low, i.e. $f_{\rm CORE} \lesssim 10 - 30$ Hz, the angular momentum redistribution proceeds very similarly to the non-rotating case. The neutron star periods obtained are close to the ones derived from non-rotating cases and the direction of rotation of the spiral mode is stochastic, so is the one of the neutron star. The amount of angular momentum required to balance the quantity redistributed by SASI is similar to the amount stored in a spiral wave of a non-rotating case. If $f_{\rm CORE} \lesssim 100$ Hz, the neutron star spin is mostly set by SASI which can induces a significant spin-down. Finally, if $f_{\rm CORE} \gtrsim 100$ Hz, a corotation instability can develop. The overlap between the two instabilities do not lead to a strong spin-down effect, the efficiency of the process is less than 30% (Kazeroni *et al.* 2017). Observational data indicate that $f_{\rm CORE} = 100$ Hz may represent an upper limit to initial neutron star spins. Our results suggest that a corotation instability may not be compatible with such a constraint, at least when magnetic fields are neglected.

† where T and W respectively stand for the rotational kinetic energy and the gravitational potential energy.

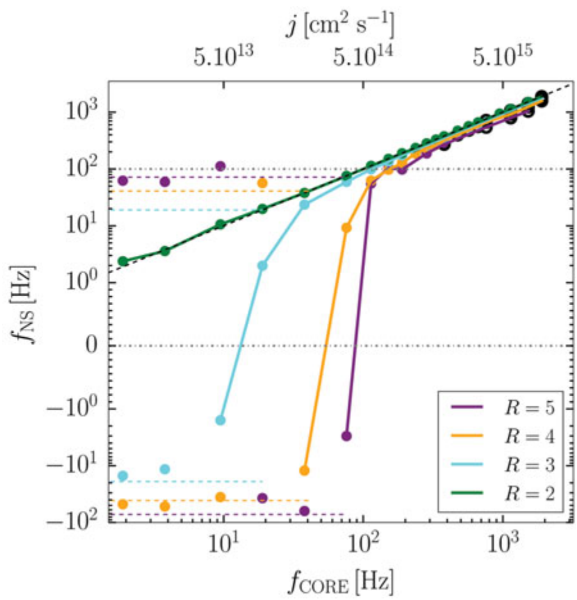

Figure 2. Relationship between the rotational frequency inferred from a spherically-symmetric collapse ($f_{\rm CORE}$) and the one which accounts for the development of spiral modes ($f_{\rm NS}$). The black dashed line illustrates the absence of angular momentum redistribution ($f_{\rm NS} = f_{\rm CORE}$). Neutron stars above and below this line are respectively spun up and down by SASI. The upper gray dot-dashed line indicates the maximal rotation frequency which seems compatible with the observations ($f \lesssim 100\,$Hz). Counter-rotating neutron stars correspond to the cases below the lower grey dot-dashed line. The horizontal dashed lines refer to the rotational frequencies obtained in simulations without rotation. The angular momentum redistribution at low rotation rates (isolated points) is very similar to the non-rotating cases.

4. Conclusion

A parametric study based on numerical simulations of an idealized model has been conducted to investigate the interplay between SASI and stellar rotation. Our approach enables to isolate the development of hydrodynamical instabilities from the complexity of physical effects at play in ab initio simulations of core-collapse supernovae and to perform a wide coverage of the parameter space.

Non-linear dynamics. Rotation is able to boost a SASI spiral mode only if the shock to the PNS radii ratio is large enough. This threshold is similar to the one above which a spiral mode prevails in a non-rotating progenitor (Kazeroni *et al.* 2016). The non-monotonic influence of the rotation rate on the shock radius as well as the stochasticity of the dynamics suggest that a single self-consistent 3D simulation including rotation may not fully capture the role of rotation on the shock dynamics. Above a specific angular momentum of $10^{15} - 10^{16}$ cm^2 s^{-1}, the emergence of a corotation above the PNS surface can dramatically impact the dynamics. The development of a corotation instability can lead to an increase of the shock radius of $50 - 200\%$ compared to a non-rotating case whereas SASI alone only induces an increase of $10 - 20\%$. The corotation instability seems to have a similar influence in the more realistic model of Takiwaki *et al.* (2016). However the mechanism of the instability remains unclear.

Pulsar spin. SASI has the potential to significantly impact the initial neutron star spin period if two conditions are satisfied (Kazeroni *et al.* 2017). The shock to the PNS radii ratio should be large enough, i.e. $R \geqslant 3$, to lead to a high saturation amplitude of the spiral mode. This quantity sets the amount of angular momentum redistributed by

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a spiral mode (Guilet & Fernàndez 2014). The second condition is that the progenitor rotation rate should correspond to a neutron star spin of less than 100 Hz inferred from a spherically-symmetric collapse. In that parameter space, the birth period is largely impacted by SASI which can either spin up or spin down the nascent neutron star and in the low rotation regime give birth to a counter-rotating object. The spin periods obtained are in agreement with observational data (Faucher-Giguère & Kaspi 2006; Popov & Turolla 2012). Finally, the maximal efficiency of the spin-down is less than 30% when a corotation instability develops. According to purely hydrodynamical simulations, the impact of one armed spiral modes on the natal pulsar spin is not strong enough to reconcile rapid progenitor rotation with neutron star periods of at least 10 ms derived from observations. Therefore our results question the role of rapid rotation in the majority of core-collapse supernovae.

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