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ASYMMETRIC EXPLOSION OF CORE COLLAPSE SUPERNOVAE

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Abstract. The explosion of most massive stars depends on the revival of a stalled shock, a few hundred milliseconds after the birth of the central neutron star. Recent numerical simulations suggest that this revival is possible through an asymmetric explosion helped by a hydrodynamical instability named SASI. Its asymmetric character is also able to influence the kick and the spin of the resulting neutron star. We review the current status of these discoveries, and describe the advective-acoustic mechanism at work behind SASI.

1 Introduction

The explosion of massive stars is currently observed several hundred times per year as spectacular supernovae in external galaxies but yet, their explosion mechanism is still not satisfactorily understood. Numerical simulations have been able to reproduce a robust explosion only in the extreme cases where the progenitor is particularly light, or extremely magnetized, or rotates particularly fast. How does a standard massive star explode ? In the scenario proposed by Bethe & Wilson (1985), the success of the explosion depends on the efficiency of energy deposition by neutrinos below the stalled accretion shock, during the first second after core bounce. This mechanism is known to be inefficient in spherical symmetry (Liebendörfer et al. 2001). Hydrodynamical instabilities, however, may play an important role by breaking the symmetry and helping the revival of the stalled shock. Indeed, multidimensional simulations allowing for transverse motions, induced by neutrino-driven convection in the gain region, approached the explosion threshold (Burrows et al. 1995, Janka & Müller 1996), although this effect did not seem sufficient (Buras et al. 2003). The Standing Accretion Shock Instability (SASI) discovered by Blondin et al. (2003) has received considerable attention over the past 6 years, for its many unexpected consequences. SASI is distinct from neutrino-driven convection since it can even develop without neutrino-heating. It is characterized by large scale oscillations of the shock, dominated by the spherical harmonics l = 1, 2.

2 The unexpected -potential- consequences of SASI

(i) **Successful neutrino-driven explosion of a $15M_{\rm sun}$ progenitor.** The simulations of Marek & Janka (2009) showed the successful explosion of a $15M_{\rm sun}$ progenitor where neutrino energy deposition is efficient enough owing to the effect of SASI. A fraction of the postshock gas spends more time in the gain region in 2D than in 1D because of the convective motions. It is thus longer exposed to the neutrino flux (Murphy & Burrows 2008, Fernández & Thompson 2009b). The robustness of this scenario is still debated, more particularly its sensitivity to the softness of the equation of state inside the neutron star.

(ii) **A new mechanism of explosion driven by acoustic energy ?** SASI is the starting point of the acoustic explosion mechanism found by Burrows et al. (2006, 2007): SASI oscillations are able to excite g-modes inside the proto-neutron star, that generate in turn an acoustic flux which is powerful enough to revive the stalled shock. According to Weinberg & Quataert (2008) however, the energy of g-modes is likely to be dissipated locally by (unresolved) nonlinear coupling, instead of being redirected into an acoustic flux.

(iii) **Neutron star kick.** The asymmetric character of SASI can have important consequences on the birth conditions of the neutron star. Using 2D axisymmetric simulations, Scheck et al. (2004, 2006) estimated that

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the kick received by the neutron star during the first seconds of the explosion can exceed 1000 km/s. The distribution of kick velocities inferred from their parametric study is compatible with the observed velocity distribution of pulsars.

(iv) **Neutron star spin.** The first 3D simulations of SASI revealed that a spiral mode is able to affect the spin of the neutron star, in a direction opposite to the rotation of the progenitor (Blondin & Mezzacappa 2007, Iwakami et al. 2009). This result was confirmed by Yamasaki & Foglizzo (2008) using a perturbative approach. Whether a spiral mode could dominate the evolution of SASI, in a non-rotating collapsing core, is not clear yet.

(v) **Gravitational waves signature.** The asymmetric motions induced by SASI are a source of gravitational waves which, if detected, could help characterize the explosion mechanism (Ott et al. 06, Kotake et al. 07, Marek et al. 09, Ott 09, Murphy et al. 09). The sensitivity of near-future detectors is sufficient to detect the SASI signature of individual events taking place inside our own Galaxy.

(vi) **Seed for subsequent mixing instabilities.** The asymmetric shape of the shock deformed by SASI is able to trigger mixing instabilities during its propagation through the envelope of the star (Kifonidis et al. 2006). The numerical simulations of Hammer et al. (2009) have revealed that the outward radial mixing of heavy elements and inward mixing of hydrogen is even more efficient in 3D than in 2D, leading to a better agreement with the observations of SN 1987A.

(vii) **Magnetic field amplification ?** According to the MHD simulations of Endeve et al. (2009), the development of SASI could amplify the magnetic field to 10^{15}G even in the absence of core rotation. This preliminary result obtained with adiabatic axisymmetric simulations has not been confirmed yet.

3 What do we really understand of SASI ?

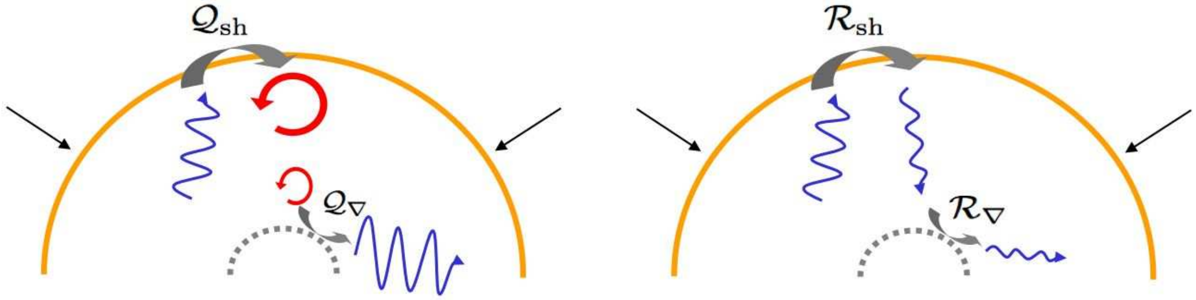

Fig. 1. Schematic views of the "advective-acoustic cycle" (left) and the "purely acoustic cycle" (right). Entropy/vorticity perturbations (circular arrows) are advected downward with the flow, and coupled to acoustic ones (wavy arrows) at the shock and in the decelerating flow. The linear coupling between these perturbations is described by coupling coefficients $\mathcal{Q}_{\rm sh}$, $\mathcal{Q}_\nabla$, $\mathcal{R}_{\rm sh}$, $\mathcal{R}_\nabla$. Growing evidence suggests that the advective-acoustic cycle can be unstable, while the purely acoustic cycle is stable.

In view of the spectacular possible consequences of SASI, a fundamental understanding of its mechanism is desired and has been a source of debate. In the subsonic flow between the shock and the neutron star, the interplay of advected and acoustic waves can be decomposed linearly onto two cycles illustrated by Fig. 1. Although the possibility of an unstable "purely acoustic cycle" has been invoked (Blondin & Mezzacappa 2006, Blondin & Shaw 2007), the only theoretical support for this explanation (Laming 2007) has been revised (Laming 2008). By contrast, the "advective-acoustic cycle" has been recognized as the driving mechanism by several authors who have gathered increasing evidence for this explanation (Blondin et al. 2003, Burrows et al. 2006, Ohnishi et al. 2006, Foglizzo et al. 2007, Scheck et al. 2008, Yamasaki & Foglizzo 2008, Fernández & Thompson 2009a). Part of the difficulty in recognizing the advective-acoustic mechanism in numerical simulations, even in the simplified set up proposed by Blondin et al. (2003), came from the lack of simple reference models where its properties would be fully understood.

The toy model illustrated by Fig. 2 is simple enough to be characterized analytically (Foglizzo 2009). The results of the linear analysis, confirmed by numerical simulations (Sato et al. 2009), can help us build our physical intuition about the advective-acoustic coupling responsible for an unstable cycle. In particular, the

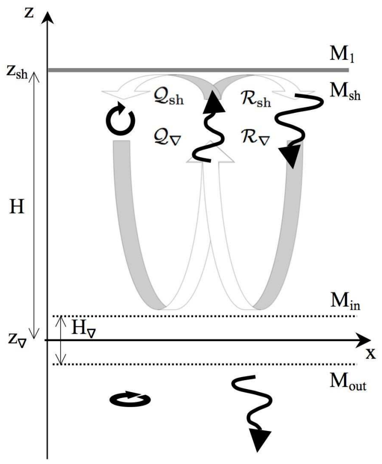

Fig. 2. Schematic view of the toy model. The unperturbed flow is planar, adiabatic, and decelerated through a stationary shock ($z_{\rm sh}$). The step-like external potential is uniform except in the deceleration region of size H_∇ around z_∇.

size H_∇ of the deceleration region is an important parameter responsible for a frequency cutoff $\omega_\nabla \sim v_\nabla/H_\nabla$ above which the advective-acoustic coupling is inefficient (Fig. 3a), due to incoherent acoustic emission (phase mixing). As a consequence, SASI is a low frequency, low-l instability.

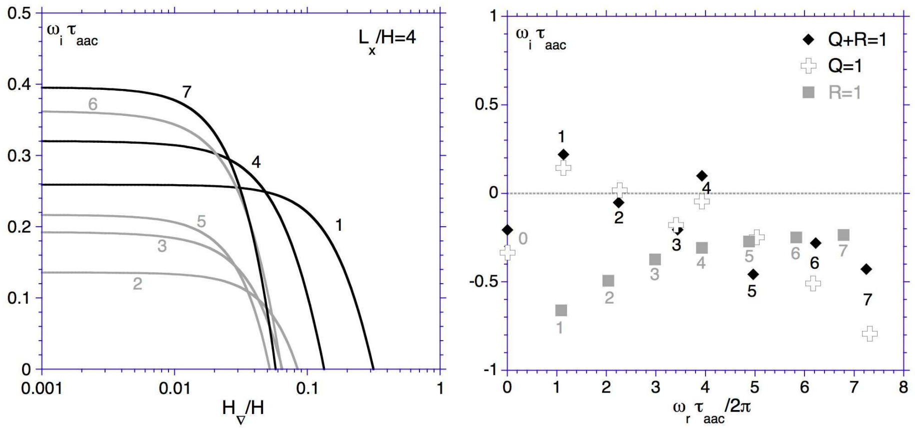

Fig. 3. Left (a): Dependence of the growth rate ω_i on the size H_∇ of the coupling region, when the amplitude $\Delta\Phi$ of the potential jump is kept constant. **Right (b):** For each value of the horizontal wavenumber $n_x = 0$ to 7, comparison of the most unstable modes associated to the advective-acoustic cycle alone (white crosses), the purely acoustic cycle alone (filled gray squares) and the full problem (filled black diamonds).

In this toy model, the efficiency $\mathcal{Q} \equiv \mathcal{Q}_\nabla \mathcal{Q}_{\rm sh}$ of the advective-acoustic cycle and the efficiency $\mathcal{R} \equiv \mathcal{R}_\nabla \mathcal{R}_{\rm sh}$ of the purely acoustic cycle can be calculated for all modes. The growth rate of the dominant mode is compared in Fig. 3b to the growth rates associated to each cycle considered separately: the growth rate associated to the advective-acoustic cycle alone is close to the growth rate of the toy model, while the purely acoustic cycle alone is always stable. As in Foglizzo & Tagger (2000), the influence of the purely acoustic cycle which can be either constructive (e.g. $n_x = 1, 4$) or destructive (e.g. $n_x = 2$).

The simple setup of this toy model can also be used to study the saturation mechanism of SASI: the acoustic feedback is decreased by the growth of parasitic instabilities on the advected wave of entropy/vorticity (Guilet et al. 2009).

4 Toward 3D simulations

The success of the neutrino-driven explosion, and its effect on the neutron star kick are among the most promising consequences of SASI. Yet these results still have to be confirmed by 3D simulations, whose computational cost preclude an accurate treatment of neutrino transport. Despite this difficulty, future parametric studies in 3D using a simplified transport should be able to elucidate the actual consequences of SASI on core-collapse supernovae. A detailed physical understanding of simple toy models can guide our interpretation of these complex simulations.

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