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EFFECTS OF A MODERATELY STRONG MAGNETIC FIELD IN CORE COLLAPSE SUPERNOVAE

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Abstract. Most studies of core collapse supernovae either neglect any magnetic effect, or assume a very rapid rotation that can amplify the magnetic field enough to produce a magnetically driven explosion (the magnetic pressure is then comparable to the thermal pressure). The effects of a moderate magnetic field that would not be capable of driving an explosion by itself are thus mostly unknown. We suggest that the fluid dynamics could be significantly affected by a magnetic field, which energy is comparable to the kinetic energy. In a very subsonic flow, this condition can be fulfilled even if the magnetic pressure remains small. We study the effect of such a moderately strong magnetic field on the standing accretion shock instability (SASI), using a simplified model of this instability. SASI can be stabilized or strengthened depending on the geometry of the magnetic field. We then describe the dynamics of the singular Alfvén surface where the Alfvén velocity equals the advection velocity (which is equivalent to the magnetic energy being comparable to the kinetic energy). Alfvén waves created by SASI are amplified near this surface. This amplification sends a positive pressure feedback toward the shock, which could be significant to the shock dynamics.

Keywords: supernovae: general, magnetic fields, magnetohydrodynamics, instabilities, shock waves

1 Introduction

The combined effects of rotation and magnetic fields might be able to produce a core collapse supernova explosion exhibiting magnetic jets (Bisnovatyi-Kogan et al. 1976; Shibata et al. 2006). In this scenario the magnetic field is supposed to be amplified via the MRI (Akiyama et al. 2003; Obergaulinger et al. 2009) to a strength such that the magnetic pressure becomes as high as the thermal one, thus enabling the launch of the jets (Burrows et al. 2007). However this requires a very fast rotation, corresponding to the formation of a neutron star rotating typically with a millisecond period. In order to explain the explosion of more slowly or non rotating stars, several hydrodynamical mechanisms have been proposed: the delayed neutrino-driven mechanism (Bethe & Wilson 1985; Marek & Janka 2009), as well as the recently proposed acoustic explosions (Burrows et al. 2006). The work presented here aims at filling the gap between the studies neglecting the magnetic field, and those assuming a fast enough rotation for violent magnetic effects to take place.

We suggest that the multidimensional fluid dynamics can be affected by a magnetic field when the magnetic energy is comparable to the kinetic energy, or equivalently when the Alfvén speed v_A is comparable to the fluid velocity v. This criterion is related to the one comparing the magnetic and thermal pressure through the Mach number $\mathcal{M}$:

$$\frac{P_{\rm mag}}{P_{\rm th}} = \frac{\gamma}{2}\mathcal{M}^2\left(\frac{v_{\rm A}}{v}\right)^2. \tag{1.1}$$

In the subsonic flow below the standing accretion shock the pressure ratio is thus smaller than $(v_{\rm A}/v)^2$, by a factor ~ 0.06 at the shock if $\mathcal{M}_{\rm sh} \sim 0.3$, and as low as 10^{-3} if $\mathcal{M} \sim 0.05$ closer to the proto-neutron star. A moderate magnetic field with $v_{\rm A} \sim v$ thus has a modest or negligible pressure, and does not contain enough energy to trigger an explosion. It could however affect the fluid dynamics through the magnetic tension. In the following, we describe two such effects: the influence of the magnetic field on the standing accretion shock instability in Section 2 (following Guilet & Foglizzo (2010)), and the dynamics of an Alfvén surface in Section 3 (following Guilet et al. (2010)).

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2 SASI in a magnetized flow

The Standing Accretion Shock Instability (SASI, e.g. Blondin et al. (2003); Foglizzo et al. (2007); Scheck et al. (2008); Iwakami et al. (2009); Guilet et al. (2010b)) produces large scale non radial shock oscillations. These induce a global asymmetry that could be of crucial importance to the explosion mechanism (in both the acoustic and the neutrino-driven mechanisms) and to accelerate the forming neutron star to a high velocity (Scheck et al. 2006). Endeve et al. (2010) have shown that SASI can also amplify the magnetic field, highlighting the importance of understanding SASI in a MHD context.

For this purpose, we performed a linear analysis of a magnetized variant of the simplified toy model of SASI described by Foglizzo (2009). This planar and adiabatic flow comprises a shock and a potential step that decelerates the fluid at a distance below the shock, thus mimicking the deceleration of accreting material close to the proto-neutron star. We study the effect of a magnetic field that is either horizontal (parallel to the shock) or vertical (perpendicular to the shock).

In the presence of a magnetic field, the advective-acoustic cycle responsible for the hydrodynamical instability (Foglizzo et al. 2007) splits in up to five cycles. This stems from the separation of the advected entropy-vorticity wave into one entropy, two slow magnetosonic, and two Alfvén waves. The propagation of the Alfvén and slow waves at or close to the Alfvén speed causes a phase shift between the different cycles that is proportional to the magnetic field intensity. As a result the different cycles interfere, leading to oscillations of the growth rate as a function of the magnetic field strength (Fig. 1). Furthermore, a horizontal magnetic field increases significantly the efficiency of the cycles containing the vorticity (in the form of slow and Alfvén waves). This leads to an overall increase of the growth rate superposed to the oscillations due to the interferences (Fig. 1, right panel). By contrast a vertical magnetic field (which would correspond to a radial field in spherical geometry) does not affect each individual cycle efficiency, thus only the rather stabilizing effect of the interferences is present (Fig. 1, left panel).

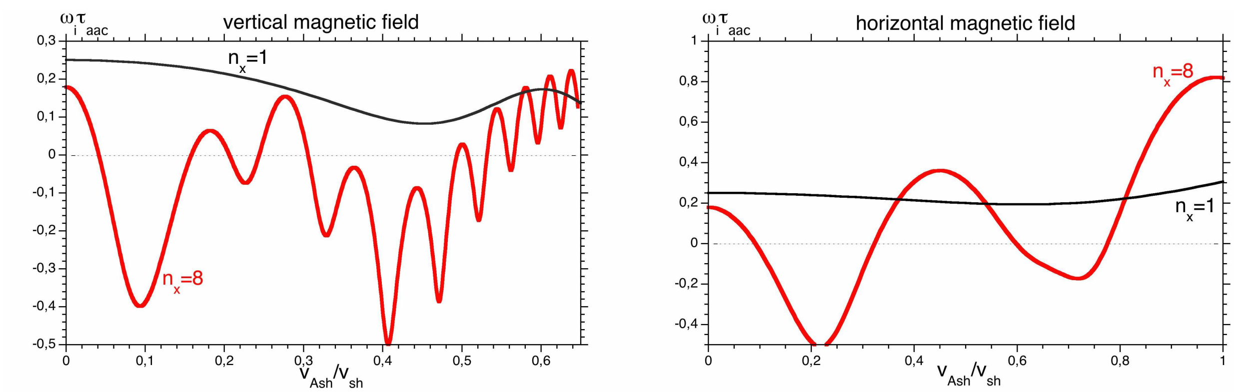

Fig. 1. The growth rate of SASI as a function of the magnetic field strength, parameterized by the ratio of Alfvén and advection speeds below the shock (from Guilet & Foglizzo (2010)). Black and red curves represent respectively the mode with one and eight wavelengths in the width of the box ($n_x = 1$ and $n_x = 8$). The left panel corresponds to a vertical magnetic field, while the right panel corresponds to a horizontal magnetic field (parallel to the shock). In both geometries, the interference between the vorticity and entropy cycles causes oscillations of the growth rate, which tend to stabilize SASI. In the case of a horizontal magnetic field, the vorticity cycle is amplified, which induces an increase of the growth rate.

3 Dynamics of an Alfvén surface

An Alfvén surface is defined as a surface where the flow velocity equals the Alfvén velocity. In core collapse supernovae, such a surface exists during the phase of accretion onto the proto-neutron star even for a weak magnetic field, because the infall velocity vanishes at the center of the star. An interesting property of this Alfvén surface is that Alfvén waves propagating against the flow accumulate, and are amplified as they approach it in the sense that their energy flux increases (Williams (1975), and see Fig. 2 of this proceeding). The amplification

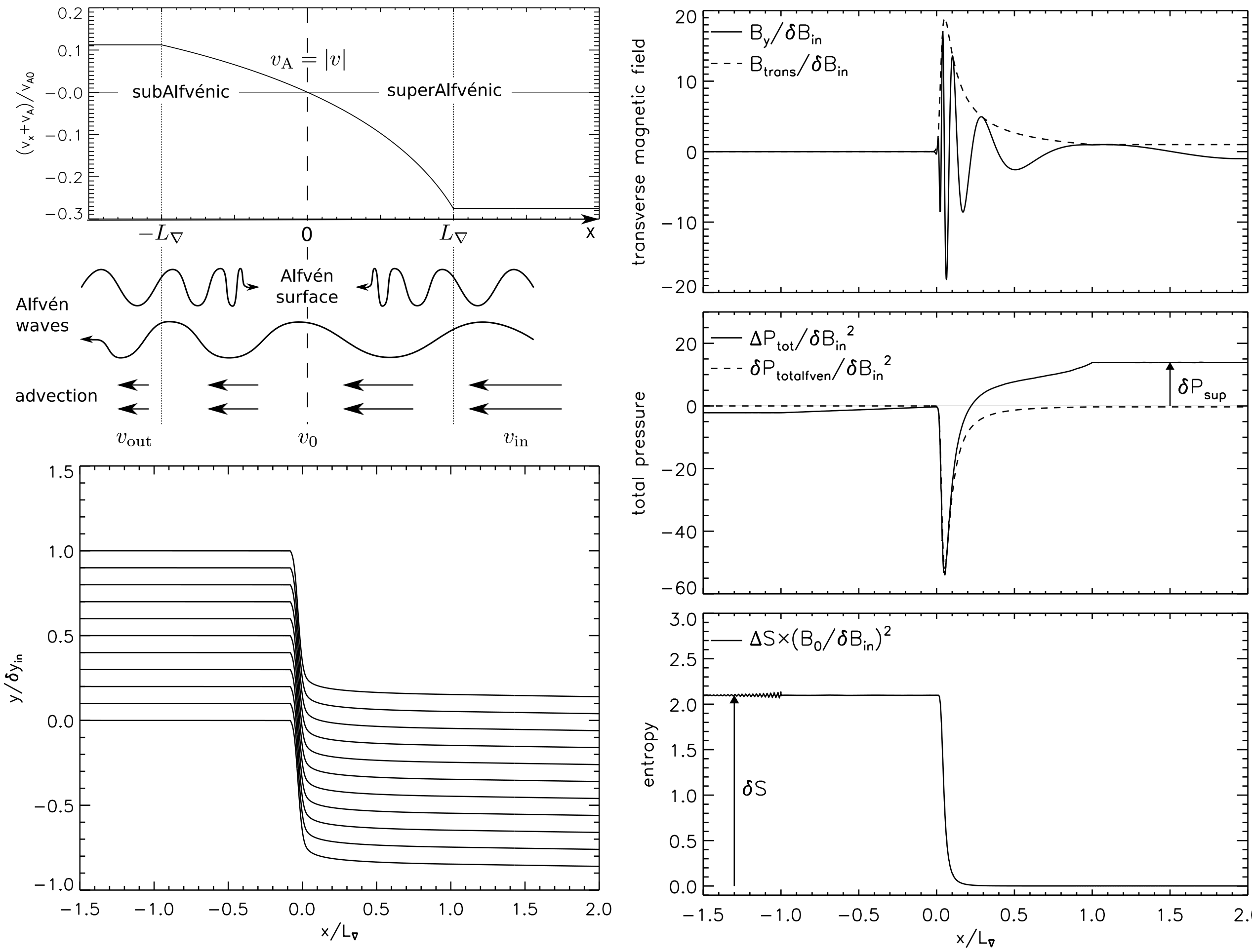

Fig. 2. Upper left panel: Schematic view of the setup of the Alfvén surface simulations. An external potential step located in $-L_\nabla < x < L_\nabla$ decelerates the flow from a superAlfvénic to a subAlfvénic velocity. An Alfvén wave propagating against the flow is sent from either the lower or the upper boundary, and accumulates at the Alfvén surface. The upper part of the figure represents the propagation speed of this wave ($v+v_A$), which vanishes at the Alfvén surface located in $x=0$. On the contrary, Alfvén waves propagating in the same direction as the flow are not affected by the Alfvén surface as their propagation velocity $v-v_A$ does not vanish. **Bottom left panel:** Magnetic field lines for a small amplitude Alfvén wave in the low frequency regime. The scale in the y direction has been normalized by the displacement of the incident wave $\delta y_{in} = \delta B_{in}/(k_{in}B_0)$. **Right panel:** Profiles of the perturbed transverse magnetic field (upper plot), total pressure (middle plot), and entropy (bottom plot) for a small amplitude high frequency Alfvén wave. The pressure and entropy have been normalized by δB_{in}^2 and $\delta B_{in}^2/B_0^2$ in order to define dimensionless quantities that are independent of the incident wave amplitude in the linear regime.

timescale is controlled by the strength of the gradients, whose lengthscale is noted L_∇:

$$\tau = \left(\frac{\partial(v+v_A)}{\partial x}\right)^{-1} \sim \left(\frac{\mathrm{d}v}{\mathrm{d}r}\right)^{-1} \sim \frac{L_\nabla}{v}. \tag{3.1}$$

The amplification is fast enough to take place before the explosion if the Alfvén surface lies in the strong gradients slightly above the proto-neutron star surface, which requires a magnetic field strength of $B \sim 3.10^{13}$ G. While substantially lower than the magnetic field needed for a magnetic explosion, this remains a rather large value and should lead to a magnetar strength magnetic field once compressed to the size of a cold neutron star.

To study the consequences of the Alfvén wave amplification, we performed 1D simulations of a simplified model of Alfvén surface, which are summarized in Fig. 2. We find that the amplification stops either by non linear effects (for large enough amplitudes of the incident wave), or when the wavelength becomes as small as the resistive or viscous scale (for incident waves of small amplitude). The amount of entropy created by this dissipation corresponds to an energy flux that can be much larger than that of the incident Alfvén wave if the flow is weakly dissipative. We also find that the amplification of the Alfvén wave creates an acoustic signal that increases the upstream pressure (Fig. 2, middle plot of the right panel). Using analytical estimates, Guilet et al. (2010) concluded that the Alfvén wave created by SASI could be amplified to a large amplitude ($\delta B \sim 10^{15}$ G) and create a significant pressure increase below the shock.

4 Conclusions

We have described two magnetic effects that become important when the magnetic energy is comparable to the kinetic energy, or equivalently when the Alfvén speed is comparable to the fluid velocity. Interestingly this condition can be fulfilled in the very subsonic part of the accretion flow (close to the proto-neutron star) even if the magnetic pressure remains modest. The propagation of vorticity through Alfvén and slow waves can alter the growth of SASI in a way that depends on the magnetic field geometry. A vertical magnetic field has a rather stabilizing influence due to the interference between the different cycles. On the other hand a horizontal magnetic field favors the growth of SASI by amplifying the vorticity cycles. We also studied the amplification of Alfvén waves in the vicinity of an Alfvén surface, where the Alfvén and advection velocity coincide. This amplification creates an acoustic feedback that increases the upstream pressure. This pressure increase might affect significantly the shock dynamics if the magnetic field is strong enough for the Alfvén surface to lie above the proto-neutron star surface. One should note that an important caveat of the studies described above is that they assume a given magnetic field strength without explaining its origin. Strictly speaking the results thus apply only for a magnetic field already present in the progenitor star. If the field is created in situ the results might not directly apply as they could be affected by the turbulent character of such a field.

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