A New Twist on the Core Collapse Supernova Mechanism?

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Abstract. We present results from the first numerical stability analysis of a stationary accretion shock in the core collapse supernova context during the critical shock reheating phase. We discuss the potential ramifications accretion shock instability may have for the supernova mechanism and supernova phenomenology.

1 Introduction

Rapidly increasing and ever more detailed observations of core collapse supernovae together with increasingly sophisticated stellar core collapse and postbounce simulations are uncovering a richness, a variety, and a veritable continuum of possibilities that future observational and modeling efforts must contend with (see, for example, [13]).

Past modeling efforts suggest that core collapse supernovae may be neutrino driven, MHD driven, or both[16,17,8,4,11,12,6,7], but uncertainties in the models prevent us from making firm conclusions at this point. Furthermore, in a scenario in which a supernova is neutrino driven, the magnetic fields in the proto-neutron star will likely have an impact on the dynamics of the explosion. Even small magnetic fields can be expected to qualitatively alter the fluid flow. Similarly, in a scenario in which a supernova is MHD-driven, the neutrino transport in no small part will dictate the dynamics of stellar core collapse, bounce, and the postbounce evolution, which in turn will create the environment in which the MHD-driven explosion occurs.

Ultimately, three-dimensional, general-relativistic radiation magnetohydrodynamics simulations with state of the art nuclear and weak interaction physics will be required to pin down the core collapse supernova mechanisms over the entire range of core collapse supernova progenitors. The neutrinos, fluid instabilities, core rotation, magnetic fields, and potentially other phenomena will act in a concerted way to drive these explosions, perhaps in different ways for different progenitor classes. To determine the "recipes for explosion" and to understand supernova phenomenology across these progenitor classes will require a systematic approach in which the dimensionality and the physics are layered to determine what is responsible for the explosions themselves and what is responsible for other observable characteristics of the explosions[15].

This systematic approach should begin with hydrodynamics-only simulations, provided they can be constructed in a meaningful way, in order to explore the complex, nonlinear hydrodynamics of stellar core collapse and bounce and the postbounce stellar core flow, particularly beneath the supernova shock wave and with a focus on the interaction of this flow with the shock. Along these lines, we have constructed models of stationary accretion flow that mimic the conditions in a postbounce stellar core during shock reheating and have discovered an instability that may have important ramifications for the supernova mechanism and phenomenology.

2 Accretion Shock Instability

The stability of accretion shocks has been considered in other contexts[10], but never in the context of the core collapse supernova problem during the neutrino heating phase and shock revival. Full details can be found in [3]. We present a few highlights below.

We consider an idealized adiabatic gas in one dimension accreting onto a star of mass M. We assume the infalling gas has had time to accelerate to free fall and that the free-fall velocity is highly supersonic. Below the standing accretion shock we assume radiative losses are negligible (we will discuss the appropriateness of this assumption later) and the gas is isentropic. The assumption of steady-state isentropic flow implies there is a zero gradient in the entropy of the postshock gas, which in turn implies this flow is marginally stable to convection. This allows us to separate effects due to convection from other aspects of the multidimensional fluid flow. In the more general case where a negative entropy gradient would drive thermal convection[8,4,11,14,6], such convection could act as a seed for the instabilities we discuss here.

A reasonable fit to profiles from spherically symmetric stellar collapse and postbounce simulations[15] that include Boltzmann neutrino transport and a realistic equation of state is obtained with $\gamma = 1.25$, as shown in Fig. 1.

If spherically symmetric perturbations are introduced, the accretion shock "rings" and eventually settles to its original configuration[3]. On the other hand, if non-spherically symmetric perturbations are introduced, the accretion shock becomes unstable. This is evident in Fig. 2. In this case the initial perturbation consists of two rings of overdense material that advect onto the shock from above (this is an axisymmetric simulation, and the figure shows one slice through the data). It is important to note that the instability is insensitive to the way the shock is initially perturbed. Once the shock is perturbed, the $l = 1, 2$ modes grow, become nonlinear, and do not saturate, leading to an oscillating, bipolar outflow[3].

The time sequences in Fig. 3 of both tangential velocity and pressure show the fundamental coupling at work in the accretion shock instability. Vorticity is introduced by the nonspherical shock and advects inward and is trapped. A low-pressure region at the base of the postshock flow associated with these trapped vortices becomes pronounced at $t \sim 40$. Pressure waves generated at the center when the vortices advect inward [as they collide or rebound off of the inner boundary (or the density cliff in a more realistic model)] propagate outward to further distort the shock, completing the loop and leading to the feedback that ultimately drives the instability. In Fig. 3, the radii and time are scaled. The radii are scaled to the initial shock radius, and one unit of our scaled time corresponds to ~ 6 ms in the more realistic model used in Fig. 1.

In Fig. 4 we see that the shock radius increases dramatically when the turbulent energy, as measured by the (scaled) kinetic energy in the angular direction in the postshock flow, increases.

3 Discussion

The accretion shock instability described here adds another potential ingredient to core collapse supernova models and perhaps the explosion mechanism itself. Given sufficient conditions, this instability will develop and could alter the energetics of the explosion as well as other observables, such as the explosion morphology. As described in detail in [3], the accretion shock instability acts as a conduit between gravitational binding energy and outgoing kinetic energy, much like the neutrinos do in more realistic models. In the explosions obtained in the idealized case, *in the absence of neutrinos*, the gravitational binding and kinetic energies increase in magnitude, while the thermal energy decreases, and at the end of the simulation a significant fraction of the material is unbound. Regarding explosion morphology, the instability may be the underlying mechanism producing the polarization observed in core collapse supernovae[9]. In one two-dimensional model (with $\gamma = 4/3$; other cases have not yet been analyzed in this context), the outflow resulted in *time-independent* aspect ratios (i.e., the outflow became self similar after some point in the evolution) that were ~ 2[3]. Aspect ratios of this size would provide at least one explanation for the spectropolarimetry observations, although much work remains to be done to determine if an accretion shock instability occurs and causes such gross asymmetries in supernovae.

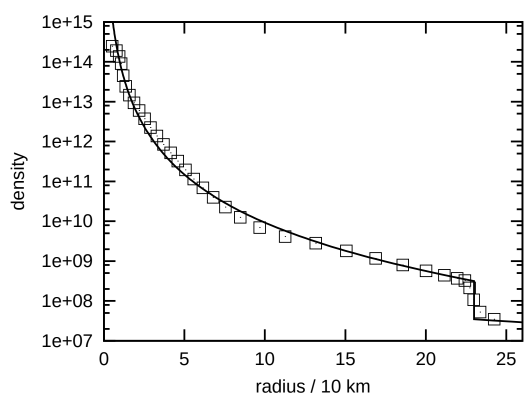

Fig. 1. For $\gamma = 1.25$, there is good agreement between the density profile in the spherically symmetric stationary accretion shock solution (solid line) and a postbounce profile taken from one of our simulations with neutrino transport and a realistic equation of state (squares).

We have presented the results of two-dimensional simulations in this paper. Three-dimensional simulations also exhibit the growth of $l = 1, 2$ modes and the same instability[2]. Therefore, the instability discussed here and its gross characteristics are not an artifact of the imposed axisymmetry and, more to the point, the imposed reflecting boundary conditions on the $\theta = 0$ axis used to numerically guarantee this axisymmetry. Indeed, while such boundary conditions may induce greater outflows on axis than off, they will certainly not lead to the unstable situation described here. Finally, in addition to our two- and three-dimensional simulations, linear stability analyses are planned. Linear stability analyses by Foglizzo[5] in a different context illuminated the existence of a vortical–acoustic feedback around accreting black holes.

Many questions must be answered before we can determine whether or not the instability described here plays a role in the dynamics of core collapse supernovae. Will neutrino cooling near the proto-neutron star surface dampen the feedback mechanism between the shock-induced vorticity and the resultant pressure waves by damping these waves? Will neutrino cooling below the shock drive the flow away from conditions in which an instability can develop—for example, by reducing the volume between the neutrinosphere and the shock? This seems to have occurred in the simulations documented in [14], where one can see the $l = 1, 2$ modes attempting to grow, but ultimately failing to do so as the shock recedes and the postshock volume shrinks. In light of these results, we investigated the growth of the instability in our model runs as (a) the adiabatic index was softened [which mimics to some extent the effects of radiative (neutrino) cooling] and (b) the ratio of the inner boundary radius to the shock radius was increased (a larger ratio would correspond to a smaller postshock volume in more realistic models). Figure 5 shows the results from case (b). In our model problem, an instability still develops as the postshock volume decreases, but takes longer to develop with decreasing volume. Finally, in the $\gamma = 4/3$ case we also included a cooling layer at the base of the postshock region, as discussed in [10]. This was done to investigate the effects of cooling and to consider the impact of different inner boundary conditions on the development of the instability. In this case too, the instability developed. However, only two- and three-dimensional radiation hydrodynamics simulations can definitively address the questions posed here.

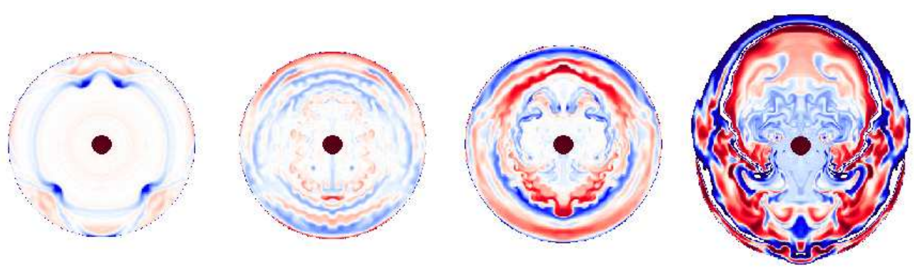

Fig. 2. In this sequence of two-dimensional entropy plots, both the growth of the accretion shock instability and the fact that the postshock region remains globally convectively stable—i.e., that entropy gradients are localized in radius and do not extend over a significant fraction of the postshock region—are evident.

We look forward to reporting on progress along these lines from the TeraScale Supernova Initiative (http://www.phy.ornl.gov/tsi/), whose goal it is to address these very questions, and others.

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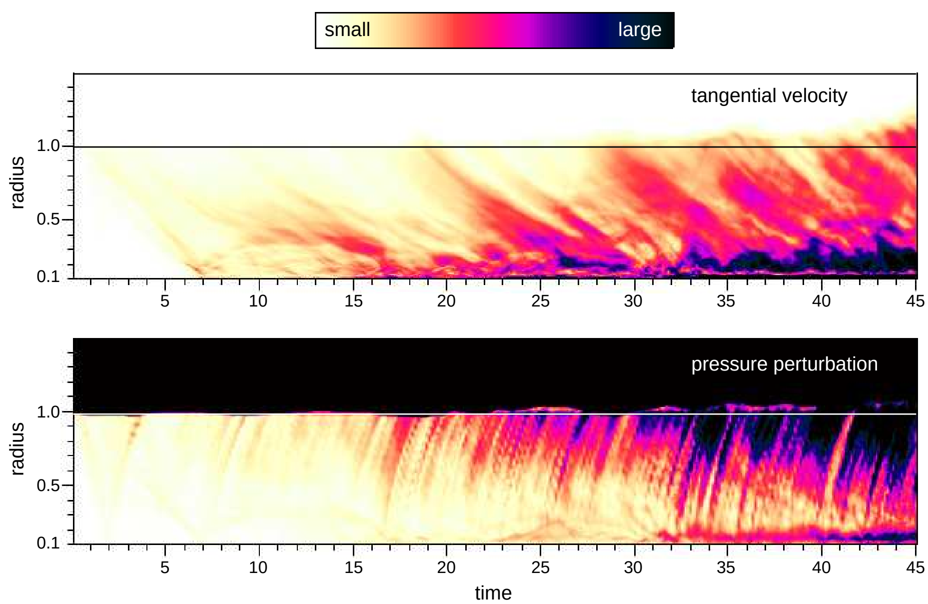

Fig. 3. Time sequences of tangential velocity and pressure show the feedback at work in the accretion shock instability. Tangential velocity introduced at the shock advects inward. Pressure waves caused by the advecting vortices propagate outward to further distort the shock. Deviations of the shock from its original radius are evident in both sequences.

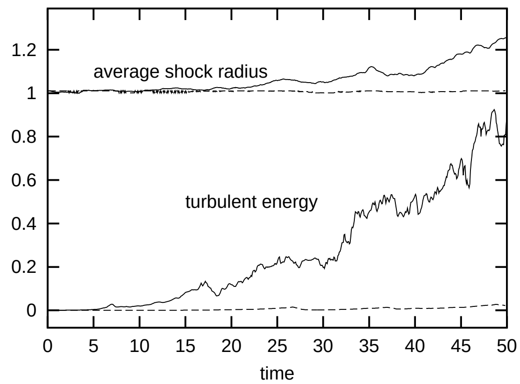

Fig. 4. The accretion shock begins to expand explosively when the turbulent energy beneath it begins to increase dramatically, as more and more vortices become trapped in the postshock flow. The dashed lines correspond to our two-dimensional simulation of the *unperturbed* spherically symmetric flow.

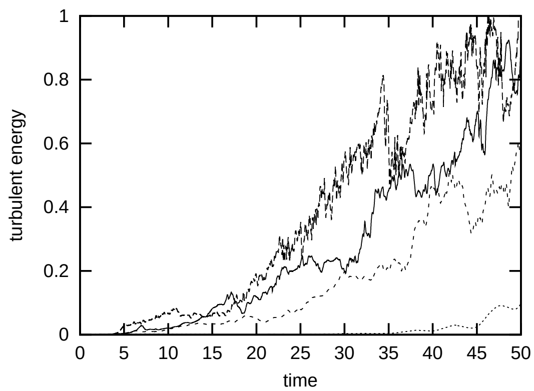

Fig. 5. The growth of the instability as a function of one model parameter is shown here by considering the growth of the interior turbulent energy for several different simulations with different inner boundary radii (from top to bottom: $R_i = 0.05$, 0.1, 0.2, and 0.4, where these radii are given as a fraction of the initial shock radius).