TeraScale Supernova Initiative

The Inherent Asymmetry of Core-Collapse Supernovae

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Abstract

Even under idealized conditions of spherical infall, the shock wave generated in the canonical core-collapse model for Type II and Type Ib/c supernovae does not remain spherical. We examine the inherent asymmetry of the stalled shock wave in core-collapse supernovae using an idealized model of a spherical accretion shock (SAS). Although this model is stable to radial perturbations, non-radial modes can grow due to a feedback between turbulence in the postshock gas and the nominally spherical shock front. The result is an expanding, aspherical blastwave with postshock flow dominated by low-order modes. We present one-, two-, and three-dimensional hydrodynamic simulations of this standing accretion shock model that illustrate the dynamical effects of the post-shock turbulence.

Modeling the Post-Collapse Phase with a Standing Accretion Shock

In the canonical model of core-collapse supernovae, the sudden stiffening of the imploded core generates a rebound shock that propagates to a radius of typically 100-150 km, where it stalls assuming a quasi-steady configuration with the ram pressure of the infalling outer core balanced by the thermal pressure of the shocked gas interior to the accretion shock. In the generic shock revival scenario, energy deposition from the intense neutrino flux escaping the core tilts this balance in favor of the thermal pressure and the shock is driven out through the infalling star.

The dynamics of this brief phase can be crudely modeled as a steady-state, spherically symmetric accretion shock, or **SAS**.

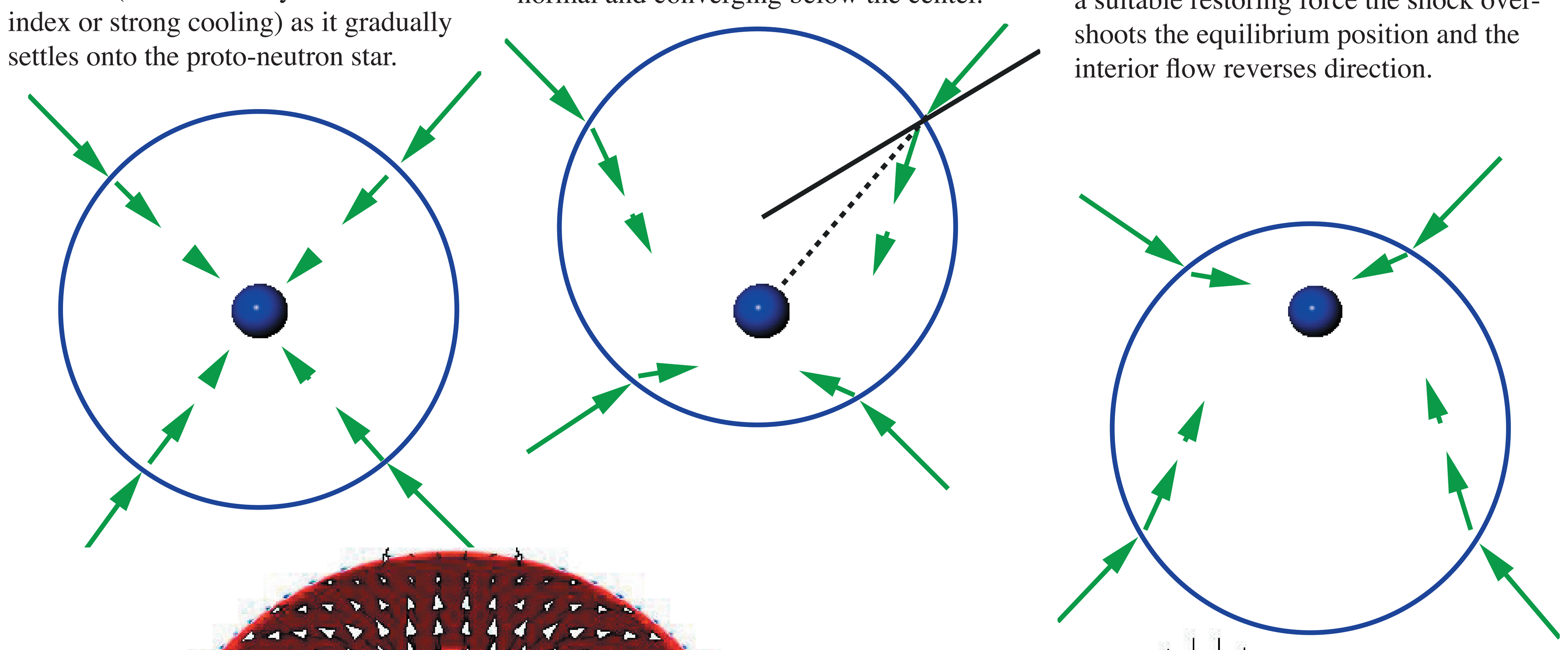
Overstability of a SAS

While a SAS is stable to radial perturbations (Houck & Chevalier; BMD), it is overstable to nonradial perturbations, specifically an *l=1* mode in which the roughly spherical accretion shock sloshes back and forth in a linear direction. This overstability is driven by the dynamics of an oblique shock - once the spherical shock is perturbed, the postshock flow is no longer radial. Foglizzo identified this feedback between the large-scale vorticity generated by an oblique shock and the subsequent pressure waves generated by the vorticity, and termed it the ***vortical-acoustic instability***. The diagram below illustrates the dynamics of this overstability.

For a spherical accretion shock, the radial inflow strikes the shock head on. The postshock flow remains spherical and decelerates (for sufficiently small adiabatic index or strong cooling) as it gradually settles onto the proto-neutron star.

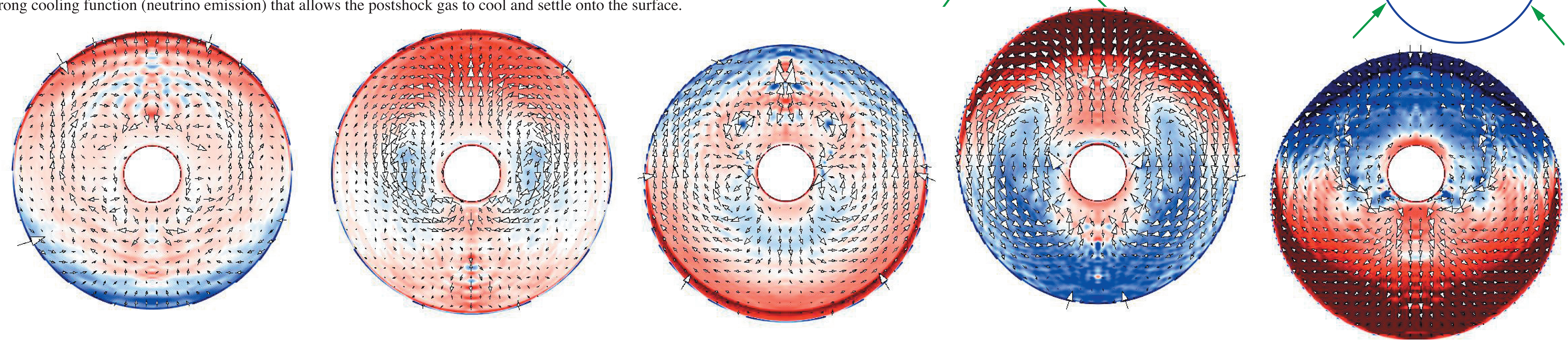
If that same spherical shock were displaced vertically, the radial inflow would then strike the shock obliquely, with the post-shock flow deflected away from the shock normal and converging below the center.

The converging postshock flow in the previous frame will drive the shock down toward its original position, but without a suitable restoring force the shock over-shoots the equilibrium position and the interior flow reverses direction.



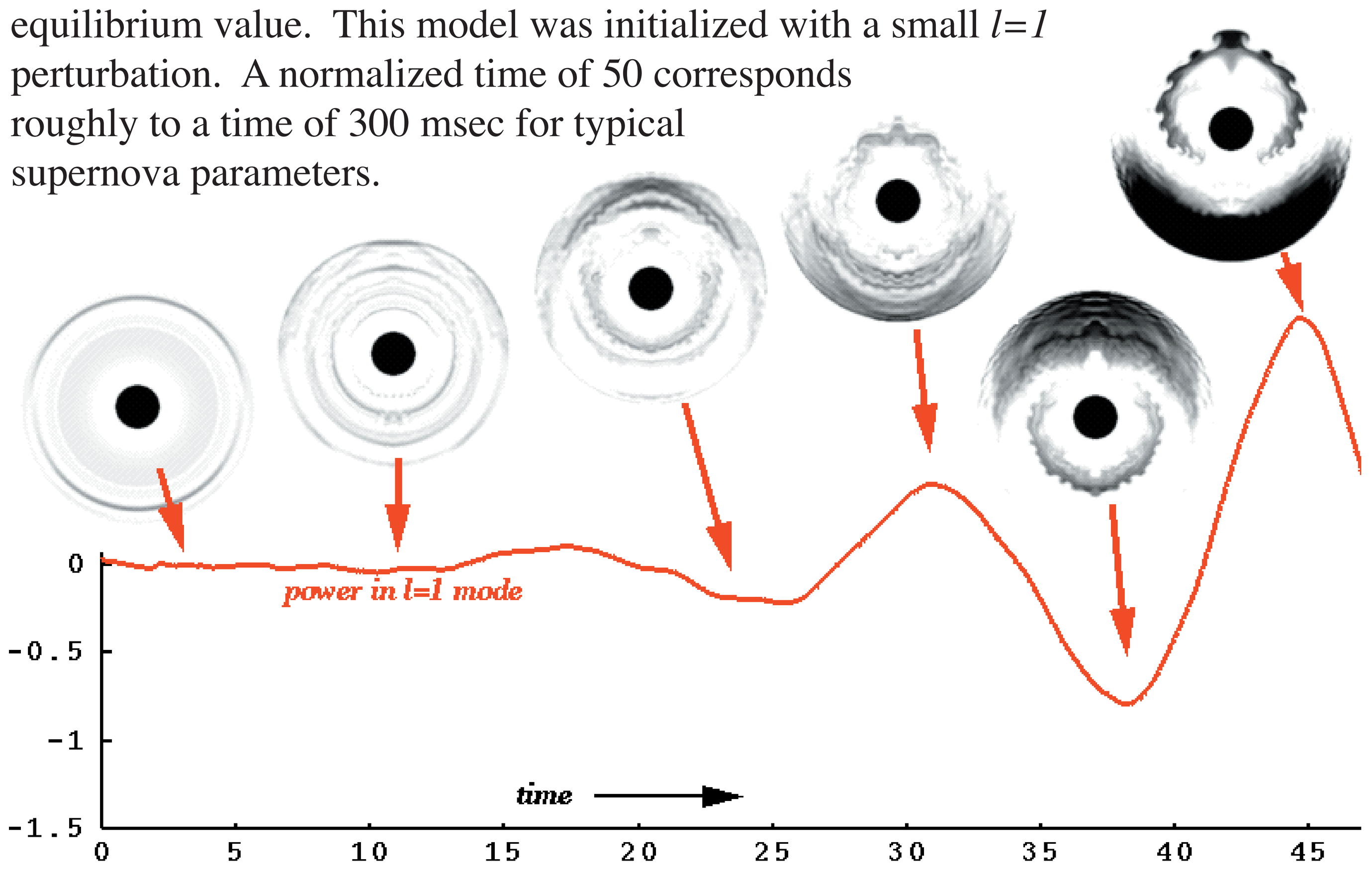
2D Hydrodynamic Simulations

Below we show the perturbations to the velocity (shown as vectors) and pressure (red is high, blue is low) from a 2D axisymmetric simulation, demonstrating the overstability of an SAS. These 2D models start with the steady-state model of Houck & Chevalier, which assumes a reflecting inner boundary (the surface of the proto-neutron star) and a strong cooling function (neutrino emission) that allows the postshock gas to cool and settle onto the surface.



Growth of *l=1*

Below we plot the evolution of the amplitude of the *l=1* mode from a 2D axisymmetric simulation, showing the rapid growth of this overstable mode. The black and white images show the deviation of entropy from the radially constant equilibrium value. This model was initialized with a small *l=1* perturbation. A normalized time of 50 corresponds roughly to a time of 300 msec for typical supernova parameters.



Overstable in 3D

This overstabile *l=1* mode is still dominant in 3D! At right is a volume rendering of the entropy of the shocked gas in a 3D simulation using a cartesian grid with 320 zones on a side. The evolution proceeds very similar to the 2D axisymmetric models. Note that simulating a 3D 'wedge' would miss this overstability: 3D supernova models must include the full 4π Steradians; 2D models must include a full hemisphere.

Application to Supernovae

This is a robust, shock-driven instability (nothing to do with convection!) that leads to an expanding, asymmetric shock. It ***will*** play a role in the dynamics of core-collapse supernovae provided:

* The rebound shock stalls at a radius at least twice that of the protoneutron star in the center
* The stalled shock survives long enough for the overstability to become nonlinear: at least a few infall times.

Computational Method:

The time-dependent hydrodynamic simulations presented here were computed with an MPI version of VH-1, an ideal gas dynamics code based on the PPM algorithm and available at ***http://astro.physics.ncsu.edu/pub/VH-1***

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