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An acoustic mechanism for core-collapse supernova explosions

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Abstract

We present a new mechanism for core-collapse supernova explosions that relies upon acoustic power generated in the inner core as the driver. In our simulation using an 11-solar-mass progenitor, a strong advective-acoustic oscillation à la Foglizzo with a period of 25–30 ms arises 200 ms after bounce. Its growth saturates due to the generation of secondary shocks, and kinks in the resulting shock structure funnel and regulate subsequent accretion onto the inner core. However, this instability is not the primary agent of explosion. Rather, it is the acoustic power generated in the inner turbulent region and most importantly by the excitation and sonic damping of core g-mode oscillations. An $l = 1$ mode with a period of 3 ms grows to be prominent around 500 ms after bounce. The accreting protoneutron star is a self-excited oscillator. The associated acoustic power seen in our 11-solar-mass simulation is sufficient to drive the explosion. The angular distribution of the emitted sound is fundamentally aspherical. The sound pulses radiated from the core steepen into shock waves that merge as they propagate into the outer mantle and deposit their energy and momentum with high efficiency. The core oscillation acts like a transducer to convert accretion energy into sound. An advantage of the acoustic mechanism is that acoustic power does not abate until accretion subsides, so that it is available as long as it may be needed to explode the star.

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Contents

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1. Introduction

The essence of the mechanism of core-collapse supernovae must be the conversion of a fraction of the reservoir of gravitational energy into the kinetic and internal energy of the exploding mantle of the Chandrasekhar core whose instability inaugurates core collapse. However, despite decades of work on the direct hydrodynamic and the neutrino mechanisms, both in 1D and multi-D, these mechanisms have yet to be shown to lead robustly to explosion for a healthy range of progenitor masses and the best physics. If the energy transfer from the core to the mantle necessary to explode the star is by neither direct hydrodynamics nor neutrino heating, what is left? How do core-collapse supernovae explode? Burrows et al. (2006) propose a new alternative, the generation in the core and the propagation into the mantle of strong sound waves. Acoustic power is, potentially, an efficient means to transport energy and momentum into the outer mantle to drive the supernova explosion. Unlike neutrinos, sound is almost 100% absorbed in the matter. As sound pulses propagate outward down the density gradient they steepen into multiple shock waves that catch up to one another and merge. If sufficient sound is generated in the core, it would be a natural vehicle for the gravitational energy of infall to be transferred to the outer mantle and could be the key missing ingredient in the core-collapse explosion mechanism. Furthermore, periodic shocking due to multiple sound pulses can lead naturally to entropies in the debris of hundreds of units, just what is required for r-process nucleosynthesis (Woosley and Hoffman, 1992; Woosley et al., 1994; Hoffman et al., 1996).

Through our recent 2D radiation/hydrodynamic simulations, we have identified a vigorous source for the necessary acoustic power: the excitation and oscillation of core pulsation modes in the deep interior of the PNS. We have discovered that turbulence and anisotropic accretion in the inner 40–100 km can excite and maintain vigorous core g-mode oscillations which decay by the radiation of sound. The inner core acts as a transducer for the conversion of accretion gravitational energy into acoustic power. The associated acoustic power seen in our simulations is sufficient to drive the explosion >550 ms after bounce.

2. Appealing features of acoustic power

There are certain virtues to acoustic driving that bear mentioning. First is that while the acoustic luminosity is much smaller than the neutrino luminosity, almost all of the sound is absorbed in the mantle matter. At late times in our simulation, less than a percent of the ν_e and $\bar{\nu}_e$ neutrino luminosity is absorbed. This amounts to an neutrino absorption power of $\leqslant 10^{50}$ erg s^{-1}, compared with an estimated core acoustic power at the end of our calculation near $\sim 10^{51}$ erg s^{-1}.

Second, sound carries not only energy, but momentum, and this factor seems to be important in our simulations. The momentum flux for sound with the same energy flux as neutrino radiation is larger by the ratio of the speed of light to the speed of sound, which in the inner mantle regions is as much as a factor of ten. Third, acoustic power propagates from where it is generated to where it is needed; it fulfills the central requirement of a core-collapse supernova mechanism that it involve energy transfer from the bound interior PNS to the outer exploding mantle. If the acoustic power is large enough, it is the ideal transfer agent. Fourth, the acoustic source seems to grow just when the neutrino luminosity is ebbing and, importantly, it continues until explosion ensues. Fifth, the successive merger of trains of sound waves that steepen into shocks provides a non-neutrino way to entropize some of the matter and naturally achieve r-process conditions.

3. Simulation code: VULCAN/2D

We have used the code VULCAN/2D for our 2D supernova simulations. VULCAN/2D uses the hydrodynamic approach described in Livne (1993), with the transport methods discussed in Livne et al. (2004) and Walder et al. (2005). The Multi-Group, Flux-Limited Diffusion (MGFLD) variant is a Newtonian, 2D, multi-group radiation/hydrodynamics code with an Arbitrary-Lagrangian–Eulerian (ALE) structure (with remap). Velocity terms in the transport sector, such as Doppler shifts, are not included in the code, though advection is. The flux limiter is a vector version of the one found in Bruenn (1985). The code can handle rotation. In 2D, the calculations are axially/azimuthally symmetric, and we use cylindrical coordinates (r and z), but the grid points themselves can be placed at arbitrary positions. This allows us to employ a Cartesian grid at the center (inner ~20 km) and transition to a spherical grid further out. The grid resolution is essentially uniform everywhere within ~20 km. A version of this grid structure is plotted in Ott et al. (2004). The Cartesian format in the interior allows us to avoid the severe Courant problems encountered in 2D by all other groups employing grid-based codes due to the inner angular Courant limit and, thereby, to perform the calculations in full 2D all the way to the center.

4. Simulation results

Burrows et al. (2006) have recently focussed on the 11-$M_\odot$ progenitor without rotation of Woosley and Weaver (1995). The calculations were done from ~200 ms before bounce to ~1.0 s after bounce, significantly longer than any other previous multi-D simulations.

At ~50 ms after bounce the shock has stalled, is roughly spherical, and is at a spherical radius (R) of ~115 km. Neutrino-driven convection has begun in the region ~50 km wide interior to the shock wave. By ~150 ms, the average shock radius has reached ~150 km, and the convection is encompassing the region down to $R \sim 75$ km. In the full angular region of 180°, we see 5–6 dominant turbules