Asymmetric explosion of core-collapse supernovae

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A very narrow window in space and time

Massive star

600 millions km

Hydrogen
Helium
Oxygen
Iron

3000 km
1.4 $M_{\odot}$

Iron

1 sec

40 km

Collapse of the iron core

Neutrino emission

Iron

300 km

$\gamma$-sphere

Shock
Observational constraints on the asymmetry of the explosion mechanism

Velocity distribution of pulsars

Kick-spin alignment (Wang, Lai & Han 06, Ng & Romani 04)

Explosion asymmetry deduced from
- spectropolarimetry (Leonard et al. 06, Wang et al. 03, ...)
- oxygen spectroscopy (Maeda et al. 08)

SNR composition gradients? (Katsuda et al. 08)
Core-collapse supernovae since 2003

What do we understand of SASI?

From the kettle to supernovae
Improved Models of Stellar Core Collapse and Still No Explosions: What Is Missing?


- 90° wedge
- computer time
Stationary Accretion Shock Instability: SASI

Mechanism of SASI: advective-acoustic cycle?
(Foglizzo 2002, Galletti 05, Foglizzo et al. 07)

\[ \nu_e^+ + e^- \rightarrow n + \nu_e \]
**Numerical simulations: SASI has been ubiquitous since 2003**

<table>
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<th>Initial</th>
<th>Sym.</th>
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The unexpected possible consequences of SASI

- successful explosion driven by neutrino energy
  \[15M_{\text{sol}}\] (Marek & Janka 09)

- new explosion mechanism driven by acoustic energy
  \[11-25M_{\text{sol}}\] (Burrows et al. 06, 07, but Weinberg & Quataert 08)

- pulsar kick (Scheck et al. 04, 06)

- pulsar spin (Blondin & Mezzacappa 07)

- H/He mixing in SN1987A
  (Kifonidis et al. 06, Hammer et al. 09)

- gravitational waves
  (Ott et al. 06, Kotake et al. 07, Marek et al. 09, Ott 08, Murphy et al. 09)

- magnetic field amplification ?
  (Endeve et al. 2008)
A new explosion mechanism based on acoustic energy

SASI

g modes

acoustic emission

unresolved nonlinear mode coupling (Weinberg & Quataert 08)
Classical explosion mechanism based on neutrino energy aided by 2D hydrodynamical instabilities
Classical explosion mechanism based on neutrino energy aided by 2D hydrodynamical instabilities

Marek & Janka 09
How does SASI help the neutrino-driven explosion?

- non radial motions induced by SASI and convection
  - longer advection time
  - longer exposure time to the neutrino flux

also,
- increased shock radius  ➡️  larger gain region
- production of entropy gradients  ➡️  seeds convection

but,
- predictive criterion for a successful explosion?  
  (equation of state? 3D?)
What is the mechanism at work behind SASI?

- Growing evidence for the advective-acoustic mechanism
  - cycle efficiency of the cycles, wkb (Foglizzo et al. 07)
  - timescales in simulations (Scheck et al. 08)
  - timescale of the dominant mode (Fernandez & Thompson 09)
Why bother about the mechanism of SASI?

- Knowing the mechanism

  → optimal grid size in simulations? (Sato et al. 09)

  → why is SASI a low $l=1,2$, low frequency instability? (Foglizzo 09)

  → which saturation amplitude? (Guilet et al. 09)
Linear coupling between the acoustic wave and the entropy/vorticity wave

(Sato, Foglizzo & Fromang 09)
Aero-acoustic instabilities

- advected perturbations
- acoustic feedback

- vortical-acoustic cycle

whistling kettle
Chanaud & Powell (1965)

vibrations in Ariane 5

- entropic-acoustic cycle

combustion
rumble instability of ramjets
Abouseif, Keklak & Toong (1984)
Why is SASI a low frequency instability? (Foglizzo 09)

\[ \tau_\nu \sim \frac{\Delta z_\nu}{\nu} \]

low freq:
\[ \omega < \frac{1}{\tau_\nu} \]
no phase mixing

high freq:
\[ \omega \gg \frac{1}{\tau_\nu} \]
acoustic phase mixing

\[ Q_\nu = \int_{bc} \frac{\delta \rho_\nu}{\rho \nu} \frac{\delta \rho_{\nu z}}{\rho \nu z} dz \]

where
\[ b_0 = \frac{1}{2} \left( 1 + \frac{M_0^2 - \rho_{sh}}{\rho} \right) \left( 1 - R_{\nu z} - \frac{1 + R_{\nu z}}{\rho_{sh} M_{sh}} \right) \]
\[ = \frac{1 - M_\nu^2}{1 - M_{sh}^2} \frac{M_{sh}^2}{M_\nu^2} \left( \frac{\delta \rho_{\nu z}}{\rho \nu z} \right)^{-1} e^{-i \omega \frac{\Delta z_\nu}{\nu}} \]

\[ b_\nu = \frac{v_{\nu}}{c_{\nu} M_{sh}^2} \frac{\omega - 2 \pi k \nu}{\frac{\omega}{\nu} - 2 \pi k \nu} \frac{\Delta z_\nu}{\nu} \]

\[ \Delta z_\nu \]
3D effects on SASI evolution

sloshing SASI mode
l=1, m=0

spiral SASI mode
l=1, m=±1

First order effect of rotation:
- negligible centrifugal force $\propto \Omega^2$
- Doppler shifted frequency $\omega-m\Omega$

Can the spiral mode dominate even for slow rotators?

Dominant spiral mode when the core is rotating
(Iwakami et al. 08, 09)

Nature 09

Blondin & Mezzacappa 07

Yamasaki & Foglizzo 08
The saturation of SASI by parasitic instabilities

- propagate against the flow
- their effective growth rate exceed the SASI growth rate

PhD J. Guilet
Comparison with numerical simulations

Fernandez & Thompson 09 (no heating)

interaction with \( \nu \)-driven convection?
A shallow water SASI experiment: Lab. Astro. at low cost?

acoustic waves
shock wave
sound speed
Mach number

gravity waves
hydraulic jump
wave speed \((gh)^{1/2}\)
Froude number

\[
\Phi = g\zeta \\
c^2 = gh
\]

St Venant approximation

\[
\frac{\partial \Phi}{\partial t} + w \times v + \nabla \left( \frac{v^2}{2} + c^2 + \Phi \right) = 0 \\
\frac{\partial h}{\partial t} + \nabla \cdot (hv) = 0
\]

Vorticity-driven advective-acoustic instability

+ energy and angular momentum budgets ?
+ destabilizing effect of rotation ?
+ spiral mode ?
+ non linear saturation ?

Perturbative analysis
Potential consequences of SASI are numerous:

- neutrino driven explosion
- acoustic explosion
- NS kick
- NS spin
- mixing
- grav. waves
- magnetic field

Still large uncertainties concerning 3D & EOS

Understanding SASI can be helpful:

- perturbative analysis: code accuracy, mechanism
- toy model: SASI properties
- first insight into non linear saturation
- SASI experiment in shallow water?