An experimental approach to shock instability during core collapse

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1- neutrino driven convection and the SASI: linear theory
2- a shallow water analogue of SASI, first experimental results
3- nonlinear interaction between SASI and buoyancy, 2D vs 3D
Theoretical framework (Bethe & Wilson 85)

neutrino-driven delayed explosion
Instabilities during the phase of stalled accretion shock

- Neutrino driven convection, l>5
  (Herant, Benz & Colgate 92, ...)

- SASI in an adiabatic flow l=1,2
  (Blondin et al. 03, ...)

What do we understand of convection and SASI?
Contribution of the neutrino-driven convection to a mode $l=1$?

Foglizzo, Scheck & Janka 06

$$\chi \equiv \frac{\tau_{\text{adv}}}{\tau_{\text{buoy}}} \sim \frac{H \omega_{\text{buoy}}}{v} \sim \left( \frac{GM}{r_{\text{sh}}v_v^2} \right)^{\frac{1}{2}} \left( \frac{H}{r_{\text{sh}}} \right)^{\frac{1}{2}} \sim 3.1 \left( \frac{u_1}{7v_2} \right) \left( \frac{H}{0.4r_{\text{sh}}} \right)^{\frac{1}{2}}$$

$\chi$ - threshold

$Hk_{\text{min}} \propto \frac{1}{\chi}$

$Hk_{\text{max}} \propto \chi$

-> the convective instability cannot be responsible for large scale oscillations (also Yamasaki & Yamada 07)

but non linear buoyancy may drive turbulence (Scheck et al. 08, Fernandez & Thompson 09)
Stationary Accretion Shock Instability: SASI

Mechanism of SASI: advective-acoustic cycle

(Foglizzo 02, Ohnishi et al. 06, Foglizzo et al. 07, Scheck et al. 08, Fernandez & Thompson 09, Guilet & Foglizzo 12)
Linear coupling between the acoustic wave and the entropy/vorticity wave

(Sato, Foglizzo & Fromang 09)

\[ \Omega_i^{\text{SASI}} \sim \frac{\log Q}{\tau_Q} \]
Linear coupling between the acoustic wave and the entropy/vorticity wave
(Sato, Foglizzo & Fromang 09)
Surprising spiral mode of SASI in 3D

Blondin & Mezzacappa 07
Fernandez 10

- too slow for slow rotators?
(Iwakami et al. 08, Wongwathanarat et al. 10,
Rantsiou et al. 11)

Need for more 3D simulations
of a rotating progenitor
(Iwakami et al. 09, Kotake 12?)

A spiral mode dominates the nonlinear evolution: why so robust?
From SN explosions to a shallow water experiment

**Observations of SN and pulsars**

- SN light curve, polarimetry, neutrinos, grav. waves, nucleosynthesis,
- Pulsar kick and spin

**Complex comprehensive simulations**

(Marek & Janka 09, Burrows et al. 06, Wongwathanarat 10, Suwa et al. 10, Müller et al. 12, Kuroda et al. 12, Sumiyoshi & Yamada 12)

- progenitor structure + nuclear EOS + neutrino "transport" & interactions + "GR" + "multi-D" hydro (no magnetic field)

**Multi-D hydro processes only**

Blondin & Mezzacappa 07

- stationary accretion, ideal gas, 3D adiabatic

**SWASI experiment**

Foglizzo et al. 12

- 2D shallow water inviscid
Hydraulic jumps = analog to shock waves

acoustic waves
shock wave
pressure

surface waves
hydraulic jump
depth
SWASI
Shallow Water Analogue of a Shock Instability
Analogues of Bondi accretion on a black hole

Bell-mouth spillway
of Monticello dam, lake Berryessa, CA

William Pye's water sculptures
SWASI: simple as a garden experiment

from May to Oct. 2010: 5 versions, 2k€
unstable oscillation and nonlinear symmetry breaking

irfu.cea.fr/Projets/SN2NS
Formal similarity between SASI and SWASI

accretion of gas (on a cylinder)

density $\rho$, velocity $v$, sound speed $c \propto \rho^{-\frac{1}{2}}$

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0
\]

\[
\frac{\partial v}{\partial t} + w \times v + \nabla \left( \frac{v^2}{2} + c^2 \log \frac{\rho}{\rho_0} + \Phi \right) = 0 \quad \text{isothermal}
\]

\[
\frac{\partial v}{\partial t} + w \times v + \nabla \left( \frac{v^2}{2} + \frac{c^2}{\gamma - 1} + \Phi \right) = \frac{c^2}{\gamma} \nabla S \quad \text{adiabatic}
\]

inviscid shallow water accretion

depth $H$, velocity $v$, wave speed $c = (gH)^{\frac{1}{2}}$

\[
\Phi = gz \quad \frac{\partial H}{\partial t} + \nabla \cdot (H v) = 0
\]

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

- Inviscid shallow water: analogue to an isentropic gas $\gamma=2$
  (intermediate between "isothermal" and "$\gamma=2$ without entropy"

expected scaling

\[
\frac{t_{sh}}{t_{\text{IP}}} \equiv \left( \frac{r_{sh}}{r_{\text{IP}}} \right) \left( \frac{r_{sh} gH_{\text{IP}}}{GM_{\text{NS}}} \right)^{\frac{1}{2}} \sim 10^{-2}
\]

shock radius $\times 10^{-6}$ 200 km $\rightarrow$ 20 cm
oscillation period $\times 10^2$ 30 ms $\rightarrow$ 3 s
Comparison to a 2D shallow water model

No free parameter:
- laminar viscous drag measured in the stationary flow
- inner boundary: free spillover

Foglizzo, Masset, Guilet, Durand
PRL (2012)
Angular momentum budget

rotating wave + advected vorticity = 0
Angular momentum budget

rotating wave + advected vorticity = 0

irfu.cea.fr/Projets/SN2NS
Surfing SWASI?
- test the saturation mechanism of SASI. Growth of parasitic instabilities? (Guilet et al. 10)

- timescale for spiral domination?
  Blondin & Mezzacappa 07, Fernandez 10, Foglizzo et al. 12
  Iwakami et al. 08, Wongwathanarat et al. 10, Rantsiou et al. 11

- how is SASI destabilized by rotation?
  Blondin & Mezzacappa 07, Yamasaki & Foglizzo 08
  - quadratic centrifugal force $\propto \Omega^2$,
  - linear Doppler shift of the frequency $\omega-m\Omega$
nonlinear interplay of SASI and buoyancy in 2D/3D (in preparation)

If neutrino heating is strong enough to drive turbulence on the scale of the gain region \((l>5)\)

> stabilisation of the advective-acoustic mode by turbulent damping of vorticity waves (turbulent viscosity) and entropy waves (turbulent diffusion of heat)

\[
\nu_{\text{turb}} \equiv \alpha \frac{\omega_{BV}}{k_{\text{gain}}^2}
\]

\[
\omega_{i,\text{turb}} \sim -\nu_{\text{turb}} k_{\text{SASI}}^2
\]

\[
\chi \equiv \omega_{BV} \tau_{\text{gain}} \omega_{i,\text{SASI}} \equiv \frac{\log Q}{\tau_Q}
\]

\[
\chi > \left( \frac{\tau_Q}{\tau_{\text{gain}}} \right)^2 \frac{\log Q}{\alpha}
\]

> stochastic excitation of the stable advective-acoustic mode: random walk (e.g. solar p-modes)

\[
E_{nlm}(t) \sim \left| \sum_{0<t-t_k<\tau_d} a_{nlm}^k e^{i \phi_{nlm}} \right|^2
\]

(e.g. Foglizzo 98)

consequences
- stochastic direction of oscillation (Kotake et al. 10)
- larger SASI amplitude in 2D vs 3D (Iwakami et al. 09, Hanke et al. 12)
- the interplay of SASI and buoyancy depends on the core structure (Müller et al. 12)

-> Need to characterize the linear strengths of buoyancy \((\chi)\) and SASI \((Q)\) in the collapsing core \((\sim 1D)\)
Conclusions

SWASI: first experimental view on SASI
- complementary to analytical and numerical approaches
- makes asymmetric explosions more intuitive

Several hydro questions:
- saturation mechanism ?
- spiral domination ?
- destabilized by rotation ?
- interplay of SASI and convection ?
- 2D/3D properties of SASI ?

Two new prototypes built at CEA Saclay (end 2012)
- improved accuracy + global rotation for research
- simplified model for public outreach