Hydrodynamic instabilities

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The possible consequences of hydro instabilities: SASI, buoyancy and shear

- successful explosion of $15M_{\odot}$ driven by neutrino energy
  (Marek & Janka 09, Suwa+10, Müller+12)

- pulsar kick
  (Scheck+04, 06, Nordhaus+10, Wongwathanarat+10)

- pulsar spin ?
  (Blondin & Mezzacappa 07, Yamasaki & Foglizzo 08, Iwakami+09, Fernandez 10, Rantsiou+11)

- H/He mixing in SN1987A
  (Kifonidis+06, Scheck 07, Hammer+09)

- gravitational waves
  (Ott+06,+08, Kotake+07,+09,+11, Marek+09, Murphy+09, Müller+12)

- neutrino signal
  (Marek+09, Lund+10, Brandt+11, Müller+12)

- magnetic field amplification
  (Endeve+10,+12, Guilet+11, Obergaulinger & Janka 11)
- What is SASI, what is $\nu$-driven convection?
- Can SASI be disentangled from $\nu$-driven buoyancy?
- What is left of SASI in 3D "realistic" simulations?
- Connexion between SASI and ...
  - the $\nu$-driven explosion mechanism?
  - the acoustic mechanism?
  - pulsar kick?
  - pulsar spin?
  - gravitational waves?
  - $\nu$-signature?
  - explosion anisotropies, mixing?
Instabilities during the phase of stalled accretion shock

neutrino driven convection $+$ SASI

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

Foglizzo, Scheck & Janka 06

\[ \chi \equiv \frac{\tau_{\text{adv}}}{\tau_{\text{buoy}}} \sim \frac{H \omega_{\text{buoy}}}{v} \sim \left( \frac{GM}{r_{\text{sh}}v_{\text{sh}}^2} \right)^{1/2} \left( \frac{H}{r_{\text{sh}}} \right)^{1/2} \sim 3.1 \left( \frac{v_{1}}{7v_{2}} \right) \left( \frac{H}{0.4r_{\text{sh}}} \right)^{1/2} \]

- 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)

\[ H k_{\text{min}} \propto \frac{1}{\chi} \]

\[ H k_{\text{max}} \propto \chi \]

\[ \chi \sim 3 \]

hydrostatic equilibrium
(Chandrasekhar 61)
Stationary Accretion Shock Instability: SASI

No neutrino heating

= No confusion with neutrino-driven convection
  (not an explosion model)

\[ p^+ + e^- \rightarrow n + \nu_e \]
Linear coupling between the acoustic wave and the entropy/vorticity wave
(Sato, Foglizzo & Fromang 09)

\[ \omega_i^{\text{SASI}} \sim \frac{\log Q}{\tau_Q} \]
The saturation of SASI by parasitic instabilities

- propagate against the flow
- grow as fast as SASI

Guilet et al. 2010
Can SASI be disentangled from $\nu$-driven convection?

Blondin et al. 03

No neutrino heating
  =
No confusion with neutrino-driven convection

But still, some nonlinear buoyancy effects
Guilet+12

shock
~150km

Blondin et al. 03

Buoyant Plumes
Can SASI be easily disentangled from $\nu$-driven convection?

With neutrino heating

$=$

SASI + neutrino-driven convection

No neutrino heating

$=$

SASI alone

What are the properties of SASI driven turbulence?

(e.g. Endeve+12)
Instabilities and the explosion threshold

SASI amplitude seems weaker in 3D compared to 2D (Hanke+12, Burrows+12), but the explosion threshold is unchanged (even slightly easier in 3D)

-> influence of SASI on the explosion ?

-> is the 3D turbulence triggered by SASI ?

-> 3D explosion of the 27$M_{\odot}$ progenitor ?

-> Expected spiral SASI mode ? With rotation ?
Drawing conclusion from a single model? Nordhaus+10 vs Burrows+12

Burrows+12

Nordhaus+10

Hanke+12
nonlinear interplay of SASI and buoyancy in 2D/3D (in preparation)

If neutrino heating is strong enough to drive turbulence in 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)

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

\[
\omega_i^{\text{turb}} \sim -\nu_{\text{turb}} k_{\text{SASI}}^2
\]

\[
\chi \equiv \omega_{BV} \tau_{\text{gain}}
\]

\[
\omega_i^{\text{SASI}} \equiv \log \frac{Q}{\tau_{Q}}
\]

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

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

\[
\frac{A_{2D}}{A_{3D}} \sim \frac{N_{2D}^{\frac{1}{2}} < a_{2D} >}{N_{3D}^{\frac{1}{2}} < a_{3D} >} \propto \left(1 - \frac{R_{\text{gain}}}{R_{\text{sh}}} \right)^{-\frac{1}{2}}
\]

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

-> Need to characterize the linear strengths of buoyancy ($\chi$) and SASI ($Q$) in the collapsing core (~1D)
The spiral mode of SASI in 3D

A spiral mode dominates the nonlinear evolution: why so robust?

- how is SASI destabilized by rotation?
  Blondin & Mezzacappa 07, Yamasaki & Foglizzo 08

- quadratic centrifugal force $r \Omega^2$,
- linear Doppler shift of the frequency $\omega - m\Omega$

Timescale for symmetry breaking?

- too slow for slow rotators?
  (Iwakami+08, Wongwathanarat+10, Rantsiou+11, Hanke+12, Burrows+12)

Need more 3D simulations with a rotating progenitor
  (Iwakami et al. 09, Kotake 12?)
Angular momentum budget

rotating wave + advected vorticity = 0
Angular momentum budget

rotating wave + advected vorticity  = 0
Diversity of progenitors: 8.1, 11.2, 15, 27 $M_{\text{sol}}$ (e.g. Ugliano+12, Müller+12)

-> no direct generalization (e.g. Burrows+12, Murphy+12?)
-> 3D simulations are still too few (dM/dt, rotation)
  e.g. 27$M_{\text{sol}}$ in 3D ? with rotation ?

Some parameters can help characterize the hydro properties
  - strength of $\nu$-driven buoyancy ($\chi$ parameter)
  - strength of SASI (Q parameter)
  - others ?

-> dependence on rotation, EOS ?
-> stabilization of spiral SASI by turbulence: $\Omega(\chi)$ ?
-> explosion threshold $\chi(L, dM/dt)$ ?

27$M_{\text{sol}}$ in 2D (Müller+12)
Thanks for this stimulating program