Hydromagnetic instabilities in core-collapse supernovae

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Magnetic fields on scales from kilometres to kiloparsecs, Kraków, 18 May 2010

Contents

Progenitor and collapse

- Progenitor: a massive star ($\gtrsim 8M_\odot$) after exhaustion of nuclear full (onion-shell structure)
- gravitational collapse of the core to a proto neutron star: ρ_{max} increases from $\sim 10^9$ g/cm^3 to $> \rho_{\rm nuc} \sim 2 \times 10^{14}$ g/cm^3 within $\sim$ a free-fall time
- $e_{\rm core} \sim 10^{53}$ erg relased, mostly in neutrinos
- collapse stops when nuclear density is reached
  $\Rightarrow$ formation of a shock wave
- the shock propagates outwards, but stalls due to energy loss in dissociation reactions

¿ How is the stalled shock wave revived?

Ingredients

multi-scale problem

- star: blue or red giant
- pre-collapse core: few 1000 km
- PNS: few 10 km
- stalled shock: few 100 km
- large (magnetic) Reynolds number
- many dynamical time scales

multi-physics problem

- multi-dimensional (GR)(M)HD
- turbulence
- nuclear equation of state
- neutrino transport (from optically thick to transparent), neutrino-matter interactions
- nuclear burning

Exlosion mechanisms

How is the failed explosion revived?

Not a matter of energy ($e_{\text{core}} \gg e_{\text{env}}$), but of energy transfer.

- Spherical neutrino-driven explosion
- Standard model: neutrino heating aided by hydrodynamic instabilities
- Energy transfer by waves
- rotational mechanisms

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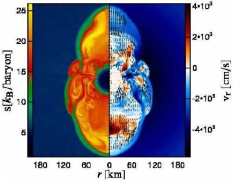
Exlosion mechanisms



Marek et al, 2008

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Neutrino mechanism

- Neutrinos diffuse out of the PNS
- they heat the matter behind the shock.

$\Rightarrow$ explosions for cores in a limited mass range (Kitaura et al., 2006)

- compatible with standard pre-collapse evolution

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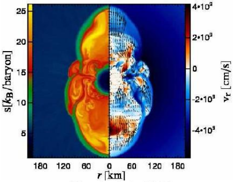

Marek et al, 2008

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Hydro instabilities

- Neutrino heating
- convection and standing accretion shock instability (Blondin et al., 2003, 2006; Foglizzo et al., 2007)

$\Rightarrow$ successful for $M \approx 11 \ldots 15 M_\odot$

- compatible with standard pre-collapse evolution

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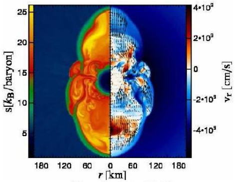

Marek et al, 2008

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Waves

- accoustic (Burrows et al., 2006, 2007) or Alfvén waves (Suzuki et al., 2008) generated at the PNS
- waves dissipate near the shock
- successful?
- compatible with standard pre-collapse evolution?

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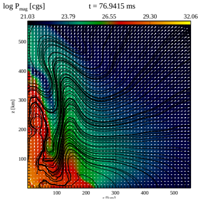

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Rotation

- tap into e_{rot} by magnetic fields (Thompson et al., 2004)
- successful?
- realistic?

$\longrightarrow$ MRI? (Akiyama et al., 2003)

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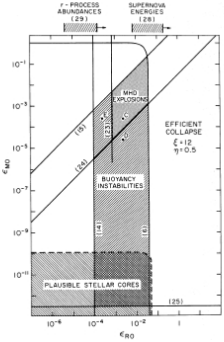
Contents

The rationale for studying instabilities

- magnetic fields need to be strong to have an effect on SNe
- But: stellar evolution theory predicts rather weak fields in the pre-collapse core

$\longrightarrow$ efficient amplification required

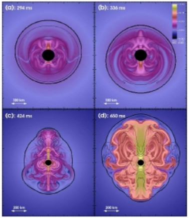
  - compression
  - linear winding by differential rotation
  - hydromagnetic instabilities: convection, magnetorotational instability (MRI), SASI

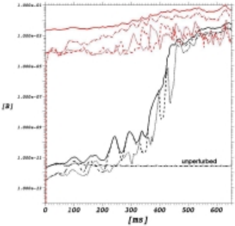


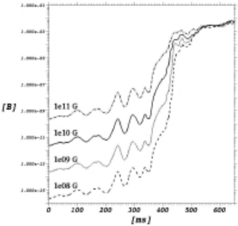
Meier et al., 1976

Instabilities: an overview

	SASI	convection	MRI
energy mechanism	accretion flow advective-acoustic cycle	thermal buoyant transport of energy/species	diff. rotation magnetic transport of angular momentum
role of $\vec{b}$	passive; turbulent dynamo	passive; turbulent dynamo	instability driver; turbulent dynamo







Endeve et al., 2008

MRI: Questions

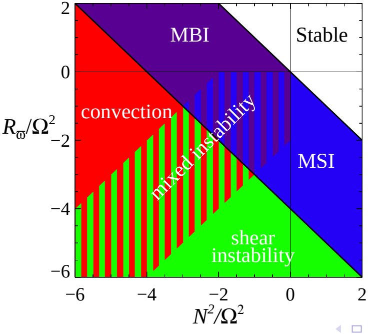
- physical issues
  - instability regimes unique to stellar environment
  - complex dependence of the turbulent saturated state on the initial conditions (huge parameter space)
  - interplay with supernova dynamics
- technical issues
  - resolution requirements: $\delta x \sim$ 1...100 cm to resolve the fastest growing mode
  - eliminate (or at least identify) the influence of numerical resistivity and viscosity

MRI: preliminary results

- instability regimes
- saturation
- large-scale dynamics

theoretical analysis of the dispersion relation of MHD modes in a differentially rotating fluid with or without thermal stratification

- growth rates of the MRI: few ms possible
- (de)stabilisation by thermal stratification: overlap with convection



MRI: preliminary results

- instability regimes
- saturation
- large-scale dynamics

1. local simulations of simplified models
2. confirm linear analysis: $\surd$
3. identify mechanism of MRI saturation: uncertain
4. scaling relations for the turbulent state: unclear

- ideal MHD
- simplified EOS
- no neutrinos
- shearing-disk boundary conditions
- high resolution
- 2d and 3d

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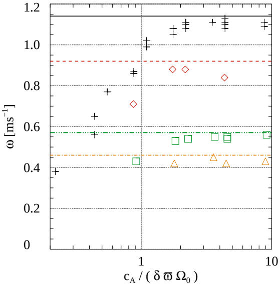

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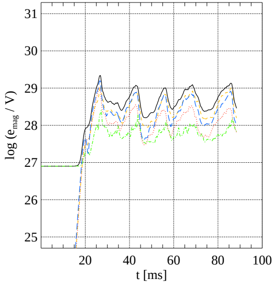

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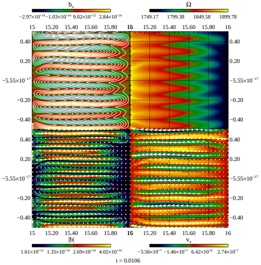

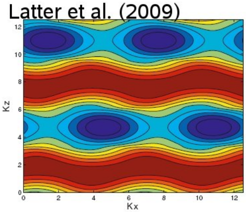

channel flows $\longrightarrow$ parasitic instabilities

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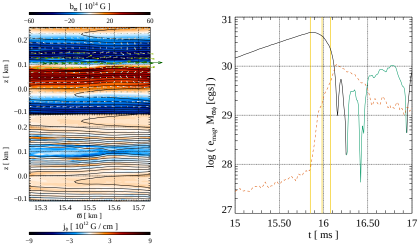

parasitic instabilities in our models

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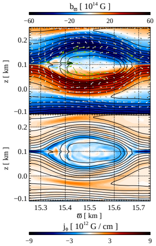

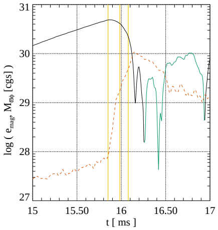

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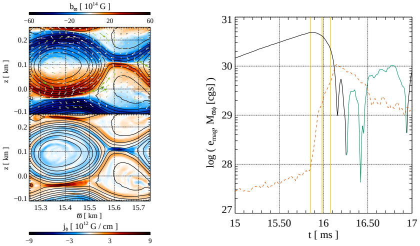

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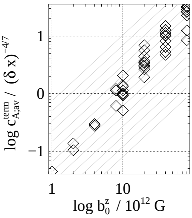
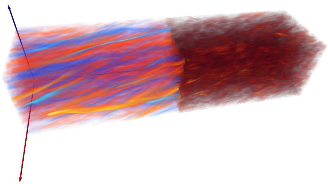
How strong is the field? What about topology and correlation between components?





MRI: preliminary results

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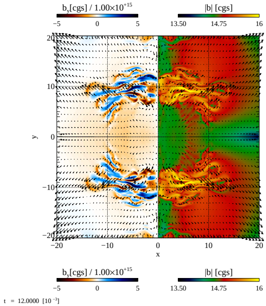
global simulations of cores in rotational equilibrium



avoid artificial boundary conditions

MRI present, but modified w.r.t. box models

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MRI: preliminary results

- instability regimes
- saturation
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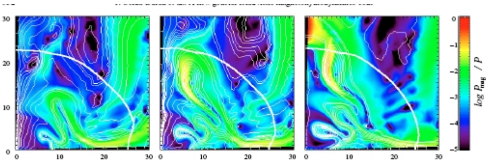
1. global simulations of magneto-rotational collapse
2. artifically enhanced initial field
3. varying degrees of sophistication for the microphysics
4. follow dynamics of magneto-rotational explosions



Cerdá-Durán et al., 2009

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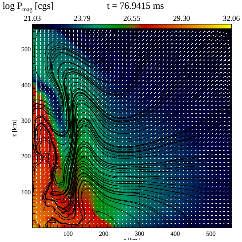

Contents

Summary

- Three instabilities potentially leading to field amplification: SASI, convection, MRI
- studied MRI and magneto-convection by analysis of the dispersion relation and simulations
- different approaches are required to understand the MRI/convection:
  - box simulations
  - global simulations with simplified physics
  - global simulations with the best possible treatment of physics
- MRI may grow in rapidly rotating cores
- field strength $\sim 10^{15}$ G achievable
- saturation mechanism still not understood

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