Multi-scale and multi-physics numerical models of galaxy formation

N body module: Particle-Mesh method on AMR grids. Poisson equation solved using a multigrid solver.

Hydro module: unsplit second order Godunov method (MUSCL) with various Riemann solvers and slope limiters. MHD solver with Constrained Transport.

Time integration: single time step or sub-cycling.

Other: radiative transfer with moments method, star formation, sink particles, stellar and AGN feedback

MPI-based parallel computing using time-dependent domain decomposition based on Peano-Hilbert cell ordering.

Download at https://bitbucket.org/rteyssie/ramses
Magneto-Hydrodynamics
The origin of cosmic magnetic fields

• Biermann battery sets the initial field at $10^{-20}$ G (Naoz & Narayan 2013).

• Current magnetic fields in local galaxies reaches several $10^{-6}$ G.

• High-redshift galaxies seems to have 10x larger fields, probably even increasing with increasing redshift (Bernet, Miniati & Lilly 2013)

• Successful large-scale dynamos are slow with growth rate $\sim 0.1\Omega$ up to $\Omega$ Hanasz et al. (2004), Pariev et al. (2007), Gressel et al. (2008)

• Early galaxy formation MHD simulations with no or weak feedback show moderate field amplification: Wang & Abel (2009), Dubois & Teyssier (2010)
Recent simulations of magnetic fields in galaxy formation

- **Beck et al. (2012):** GADGET code, new MHD solver, small scale dynamo as a source of fast field amplification

- **Pakmor and Springel (2013):** AREPO code, new MHD solver, large scale field with fast amplification. See also Marinacci et al. (2015).

- **Rodrigues et al. (2015):** semi-analytical models of galaxy formation, small scale dynamo as a source of random fields, followed by mean field amplification for the large scale field
Supernovae feedback in dwarf galaxies

Supernovae feedback implemented using non-thermal energy dissipation (Teyssier et al. 2013) result in the formation of thick disks with V/\sigma \sim 1, and a strongly reduced SF efficiency (M_\text{s}/M_\text{h} \sim 0.01).

This is in striking agreement with the nearby isolated dwarf WLM (Eastman et al. 2012) although M_\text{s}/M_\text{h} \sim 0.001.
Turbulent dynamo in a dwarf galaxy

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Magnetic field generation in dwarf galaxies

no feedback

shear

dipole

quadrupole

magnetic field generation (feedback)

exponential

dipole

quadrupole

τ = 170 Myr

mean magnetic field (no feedback)

mean magnetic field (feedback)

initial dipole

initial quadrupole

initial dipole

initial quadrupole

height above midplane [kpc]

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A small scale dynamo?

kinetic energy spectrum

magnetic energy spectrum

no feedback

SN feedback

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Conclusions for the cosmic dynamo

In high-redshift, feedback-dominated galaxies with $\sigma \approx V_{\text{rot}}$, we obtain a small scale magnetic dynamo with growth rate set by the smallest scale, and reaching saturation on larger and larger scales.

If field reaches equipartition $B_{\text{equ}} \approx \sqrt{8\pi \rho_{\text{gas}} \sigma} \approx 10 \mu G (1 + z)^2 \left( \frac{M_{200}}{10^{10} M_\odot} \right)^{1/3}$

Saturation of the small scale dynamo is closer to 10% of equipartition.

Around redshift 2, for more massive galaxies, we have a transition from dispersion-dominated spheroids to rotation-dominated discs.

Formation of razor-thin discs, with competition between amplification through collapse and dissipation through reconnection. Final field strength ?

Later time evolution: magnetic energy is slowly decaying, or is slowly maintained by a large-scale dynamo.
Radiation Hydrodynamics
Radiation plays a role in shaping galaxies

Radiation driven feedback is invoked to model stellar feedback in current galaxy formation simulations. Only implemented through sub-grid models.

Different modes of radiation feedback, modelled self-consistently using radiation hydrodynamics in RAMSES-RT (Rosdahl et al. 2011, 2015)
Galaxies that shine

Isolated galaxy with 5 different photons groups, photo-ionisation and dust absorption.

- $10^{11}$ solar masses halo
- $3 \times 10^9$ solar masses baryonic disk
- 50% gas fraction.

- $10^6$ stellar and DM particles
- 18 pc resolution
- 0.1 solar metallicty

Feedback processes:
- thermal SN energy injection (no trick)
- HI and dust opacities

Radiative processes:
- photo-ionisation heating
- direct pressure from UV
- IR pressure from dust scattering

Rosdahl et al. (2015)
The interplay between radiation and supernovae

Rosedahl et al. (2015)
Photo-chemistry of Hydrogen

Total Hydrogen density

Molecular fraction
Conclusions

• Small-scale dynamos appear as a viable mechanism to amplify primordial fields in feedback dominated galaxies

• Saturation of the dynamo at 1/10 equipartition with turbulence

• Late time evolution: collapse back to razor-thin disks in which large scale dynamos shape the magnetic fields

• In the future: possible paradigm-shifting role of magnetic fields and cosmic rays?

• We are entering the era of radiation hydrodynamics of galaxy formation.

• Dynamical effect through photo-heating and radiation force.

• Current sub-grid models of radiation feedback are probably optimistic.

• Radiation hydrodynamics allows self-consistent chemistry (line excitation, molecular, neutral fraction...) and a detailed comparison to observations.
Photo-chemistry of Hydrogen

- Total Hydrogen density
- Molecular fraction
Suppressed feedback in dwarf galaxies

Magnetic energy growth (dwarf galaxy)

- SN feedback
- Suppressed feedback

Magnetic energy vs. Age [Gyr]
Suppressed feedback in dwarf galaxies

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Suppressed feedback in dwarf galaxies

mean magnetic field (suppressed feedback)

\[ \frac{\langle B \rangle}{B_{\text{RMS}}} \]

-2 -1 0 1 2

initial dipole

height above midplane [kpc]

\[ \frac{\langle B \rangle}{B_{\text{RMS}}} \]

-2 -1 0 1 2

initial quadrupole

toroidal
radial
vertical

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