OpenGadget CAMELS
Based on the Magneticum model

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### The Magneticum simulations

#### Magneticum Pathfinder & Magneticum

<table>
<thead>
<tr>
<th>[Mpc/h]</th>
<th>Box0</th>
<th>Box1a</th>
<th>Box2b</th>
<th>Box2</th>
<th>Box3</th>
<th>Box4</th>
<th>Box5</th>
</tr>
</thead>
<tbody>
<tr>
<td>mr</td>
<td>$2 \times 4536^3$</td>
<td>$2 \times 1512^3$</td>
<td>$2 \times 2880^3$</td>
<td>$2 \times 594^3$</td>
<td>$2 \times 1584^3$</td>
<td>$2 \times 216^3$</td>
<td>$2 \times 576^3$</td>
</tr>
<tr>
<td>hr</td>
<td>2688</td>
<td>896</td>
<td>640</td>
<td>352</td>
<td>128</td>
<td>48</td>
<td>18</td>
</tr>
<tr>
<td>uhr</td>
<td>$2 \times 4536^3$</td>
<td>$2 \times 1512^3$</td>
<td>$2 \times 2880^3$</td>
<td>$2 \times 594^3$</td>
<td>$2 \times 1584^3$</td>
<td>$2 \times 216^3$</td>
<td>$2 \times 576^3$</td>
</tr>
<tr>
<td>xhr</td>
<td>$2 \times 1512^3$</td>
<td>$2 \times 1512^3$</td>
<td>$2 \times 2880^3$</td>
<td>$2 \times 594^3$</td>
<td>$2 \times 1584^3$</td>
<td>$2 \times 216^3$</td>
<td>$2 \times 576^3$</td>
</tr>
</tbody>
</table>

Table 1: Number of particles used in the Magneticum Pathfinder and Magneticum simulations for the different resolution levels mr, hr, uhr and xhr. The blue entries mark simulations which have been stopped before reaching $z=0$. Box2b/hr has been stopped very close to $z=0$ (e.g. $z=0.2$). The gray entries mark future, planned simulations.

<table>
<thead>
<tr>
<th>mr</th>
<th>$m_{\text{dm}}$</th>
<th>$m_{\text{gas}}$</th>
<th>$\epsilon_{\text{dm}}$</th>
<th>$\epsilon_{\text{gas}}$</th>
<th>$\epsilon_{\text{stars}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$1.3 \times 10^5$</td>
<td>$2.6 \times 10^5$</td>
<td>$10$</td>
<td>$10$</td>
<td>$5$</td>
</tr>
<tr>
<td>hr</td>
<td>$6.9 \times 10^5$</td>
<td>$1.4 \times 10^5$</td>
<td>$3.75$</td>
<td>$3.75$</td>
<td>$2$</td>
</tr>
<tr>
<td>uhr</td>
<td>$3.6 \times 10^5$</td>
<td>$7.3 \times 10^5$</td>
<td>$1.4$</td>
<td>$1.4$</td>
<td>$0.7$</td>
</tr>
<tr>
<td>xhr</td>
<td>$1.9 \times 10^5$</td>
<td>$3.9 \times 10^5$</td>
<td>$0.45$</td>
<td>$0.45$</td>
<td>$0.25$</td>
</tr>
</tbody>
</table>

Table 2: Mass of dm and gas particles (in M$_{\text{sol}}$/h) at the different resolution levels and the according softenings (in kpc/h) used.
Why the large boxes?

Coulton et al. 2022
The simulation code: OpenGadget3

- Updated version of the popular code P-Gadget3.
- Gravity is solved via the TreePM method in cosmological simulations.
- Variety of different solvers for hydrodynamics (density-entropy SPH, pressure-entropy SPH, pressure-energy SPH and MFM).
- If SPH is used the code adopts a higher order Wendland kernel, if MFM is used we adopt a cubic spline.
- Since MFM is Riemann based method we implemented several Riemann solvers (exact, Roe-solver, HLL, HLLE, HLLC, HLLD pending for MHD).
- The code supports magnetic fields and cosmic rays.
- The code supports anisotropic heat conduction and viscosity.
The Hydro-solvers in the code

Groth, Steinwandel et al. (in prep)
Magnetic fields in the code

- Equations of ideal Magnetohydrodynamics (Cauchy equations)

\[
\frac{\partial \rho}{\partial t} + \nabla (\rho \cdot \mathbf{v}) = 0 \quad (1)
\]

\[
\rho \left( \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{v} = -\nabla p + \mathbf{g} + \frac{(\mathbf{J} \times \mathbf{B})}{c} \quad (2)
\]

\[
\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{u} = \frac{p}{\rho} (\nabla \cdot \mathbf{v}) + \frac{\mathbf{B}^2}{8\pi \rho} (\nabla \cdot \mathbf{v}) \quad (3)
\]

\[
\frac{ds}{dt} = 0 \quad (4)
\]

\[
\left( \frac{\mathbf{J} \times \mathbf{B}}{c} \right) = \frac{\mathbf{B} \cdot \nabla \mathbf{B}}{4\pi} - \nabla \left( \frac{\mathbf{B}^2}{8\pi} \right) \quad \text{1st term: magnetic tension}
\]

\[
\text{2nd term: magnetic pressure}
\]

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \Delta \mathbf{B} \quad (5) \quad \text{Induction equation}
\]

\[
\nabla \cdot \mathbf{B} = 0 \quad (6) \quad \text{Solenoidal constraint}
\]
Currently we adopt SPMHD for magnetic fields:

- In principle it is trivial to derive the basic SPMHD equations.
- Just take the MHD Lagrangian and to exactly the same as in HD.

\[
\mathcal{L}_{\text{MHD}} = \int \left[ \frac{1}{2} \rho \mathbf{v}^2 - \rho u(\rho, s) - \frac{\mathbf{B}^2}{8\pi} \right] d^3r \approx \sum m_i \left[ \frac{1}{2} \mathbf{v}_i^2 - u_i(\rho, s) - \frac{1}{8\pi} \frac{\mathbf{B}_i^2}{\rho_i} \right]
\]

- To obtain the basic SPMHD-EOM plus discretization of the induction equation.

\[
\frac{d\mathbf{v}_i}{dt} = - \sum m_j \left[ \frac{P_i + \frac{\mathbf{B}_i^2}{8\pi}}{\rho_i^2 \Omega_i} \nabla_i W_{ij}(h_i) + \frac{P_j + \frac{\mathbf{B}_j^2}{8\pi}}{\rho_j^2 \Omega_j} \nabla_j W_{ij}(h_j) \right] + \frac{1}{4\pi} \sum m_j \left[ \frac{\mathbf{B}_i (\mathbf{B}_i \cdot \nabla_i W_{ij}(h_i))}{\rho_i^2 \Omega_i} + \frac{\mathbf{B}_j (\mathbf{B}_j \cdot \nabla_j W_{ij}(h_j))}{\rho_j^2 \Omega_j} \right]
\]

\[
\frac{d}{dt} \left( \frac{B_i}{\rho_i} \right) = \sum m_j (\mathbf{v}_i - \mathbf{v}_j) \frac{B_i}{\rho_i^2 \Omega_i} \cdot \nabla_i W_{ij}(h_i)
\]
Magnetic fields in the code

Steinwandel et al. (2022)

Steinwandel (in prep)
Cosmic rays in the code

Boess, Steinwandel et al. (in press)

Boess, Steinwandel et al. (in prep)
This can be coupled to the galaxy formation model

- Metals, stellar populations and chemical enrichment SNIa, CCSN, AGB stars (Tornatore et al. 2007).
Running a CAMELS box with magnetic fields

Steinwandel & Teyssier (or vice versa in prep)
Running the same box with RAMSES

Steinwandel & Teyssier (or vice versa in prep)
The state of Magneticum-CAMELS

- There is a small latin hyper cube set present that consists out of 50 simulations.
- The CV set is running now, but is almost finished.
- Subfind data for these runs will be available soon.
- Planning to run more simulations.