GRMHD with Athena++ and its Application to MAD

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Summary

- Extending Athena++ framework to general relativity, while maintaining its advantages in speed and accuracy for ideal MHD
- Goal: Studying accretion flows near black holes in high resolution
- See arxiv:1511.00943 for code details

Magnetically Arrested Disks at Different Resolutions

- Test of code: Can we reproduce results in a relativistic, turbulent, magnetized flow?
- Exploring MAD at high resolutions: Are there non-axisymmetric instabilities that prevent choking of flow?
- Initial conditions of Tchekhovskoy, Narayan, & McKinney 2011
- Resolutions \( N_r \times N_\theta \times N_\phi \): 96 \times 32^2, 192 \times 64^2, 384 \times 128^2
- Preliminary results below

Preliminary results below

Equatorial slice of \( \beta \) at \( t = 14,000 \ M \) for low (left), medium (center), and high (right) resolutions.

Mesh Refinement and Polar Coordinates

- Static and adaptive mesh refinement supported
- Coarsen grid near poles \( \rightarrow \) larger timestep
- Cells communicate across polar boundary \( \rightarrow \) no need for artificial boundary condition

Example polar grid with equatorial refinement.

Performance

- Zone updates per second, single core, 2.5 GHz Ivybridge

<table>
<thead>
<tr>
<th></th>
<th>SR</th>
<th>GR</th>
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</thead>
<tbody>
<tr>
<td>Hydro LLF</td>
<td>1,300,000</td>
<td>380,000</td>
</tr>
<tr>
<td>HLLC</td>
<td>860,000</td>
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<tr>
<td>MHD LLF</td>
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</tr>
<tr>
<td>HLLD</td>
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<td>120,000</td>
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</tbody>
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Flat scaling to many cores

Constraint Transport

- Staggered mesh: \( \vec{B} \)
defined on faces
- GR formulation: Evans & Hawley 1988
- Cartesian: Athena (Gardiner & Stone 2005, 2008)
- Now implemented in GR with Athena++

Schematic showing how \( \vec{E} \) is calculated on an edge (center) self-consistently with the Riemann fluxes.

Better solvers \( \rightarrow \) less diffusion

Density of hydro blast wave in “snake” coordinates, using HLLE (left) and HLLC (right).

HLLC: Captures contact in hydrodynamics

HLLD: Captures contact and Alfvén in MHD

Entropy wave convergence tests in metric with time-space cross terms.

- Transform into orthonormal frame at each face
- Use SR Riemann solvers
- Transform fluxes back

Constrained Transport

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