Contribution ID: **13** Type: **Oral Contribution**

Black hole simulations with the FO-CCZ4 formulation of the Einstein equations and ADER discontinuous Galerkin schemes

Thursday, 15 August 2019 11:30 (20 minutes)

We present FO-CCZ4, a strongly hyperbolic first-order formulation of the Einstein
equations based on the conformal and covariant Z4 system with constraint-violation damping. This formulation combines the advantages of a conformal and traceless formulation, with the suppression of constraint violations given by the damping terms, but being first order in time and space, it is particularly suited for a discontinuous Galerkin (DG) implementation. The strongly hyperbolic first-order formulation has been obtained by making careful use of first and second-order ordering constraints. A proof of strong hyperbolicity is given for a selected choice of standard gauges via an analytical computation of the entire eigenstructure of the FO-CCZ4 system. A key feature of our formulation is that the first-order CCZ4 system decouples into a set of pure ordinary differential equations and a reduced hyperbolic system of partial differential equations that contains only linearly degenerate fields. We implement FO-CCZ4 in a high-order path-conservative (ADER)-DG scheme with adaptive mesh refinement and local time-stepping, supplemented with a third-order ADER-WENO subcell finite-volume limiter in order to deal with singularities arising with black holes. We validate the correctness of the formulation through a series of standard tests in vacuum, performed in one, two and three spatial dimensions, and also present preliminary results on the evolution of binary black-hole systems. To the best of our knowledge, these are the first successful three-dimensional simulations of moving punctures carried out with high-order DG schemes using a first-order formulation of the Einstein equations.
Supported by European Research Council Grant No. 677912 EUROPIUM

Keywords

Compact Object Mergers

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Session Classification: Mergers