Scaling Information for
"Three Projects in Astrophysical Magnetohydrodynamics"

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The three projects presented in this proposal will be using the code Enzo (Bryan et al. 2014). Enzo is an open source adaptive mesh refinement (AMR) code that has been used in hundreds of astrophysical works. These studies include the formation of the first stars (Abel et al. 2002), clusters of galaxies (Xu et al. 2011) and the large scale structure of the universe. It employs several hydrodynamics solvers, including the piecewise parabolic method (PPM, Colella & Woodward 1984), two implementations of magnetohydrodynamics (MHD), self-gravity, and Lagrangian particles that can be used for collisionless dark matter, stars, dust, and passive tracers. One of the primary advantages of Enzo over other codes is its use of structured AMR, which allows it to add resolution elements adaptively as dictated by the problem. A variety of refinement criterion are available. The present studies will use the divergence-preserving MHD module (Collins et al. 2010). For the patch solver we use the second order MHD method of Li et al. (2008) and the constrained transport method of Gardiner & Stone (2005) to preserve the divergence-free constraint ($\nabla \cdot \mathbf{B} = 0$) to machine precision. For the AMR, the divergence-free reconstruction of Balsara (2001) is used to interface magnetic fields with the adaptive mesh. For chemistry and radiative cooling used in the *cores* project, Grackle is used (Smith et al. 2017). For the burning operator in the *supernova* project, we use the implementation of (Hristov et al. 2018). The *turbulence* project will use only the isothermal MHD package.

To measure the behavior of the solvers, we ran a weak scaling test with the main physics packages for the three projects. A constant amount of work, 128^3 zones per task, was used for each node, and the refinement was forced to occupy the inner 1/8 of the domain volume. Scaling was done from 8 through 4096 processors, with 64 threads per node (when possible). The packages in question do not depend heavily on the regime of physics in question, so uniform gas was taken in each case. The results can be seen in Figure 1. Here we plot updates-per-core-second. for ideal scaling, this will be independent of the number of nodes or zones.

The blue curve, applicable to the *turbulence* suite, contains only the MHD solver and random forcing. This is extremely parallelizable, as the work is entirely local. The orange curve, applicable to the *supernovae* project, uses the MHD solver and nuclear burning machinery. The performance of this package sharply declines at 4096 threads. This decrease in performance will be addressed in the near future, but does not pose a threat to the successful completion of the simulations. The green curve is a uniform box with MHD, cooling, and self gravity. Being a non-local operator, the self gravity does not scale perfectly. This curve is relevant for the *cores* project.

If Z is the number of updates-per-core-second in the Figure, the cost per simulation in node-hours, $SU_{zu} = 1/(Z * 3600 * N_{\mathrm{core-per-node}})$. We will use 64 threads-per-node where possible.

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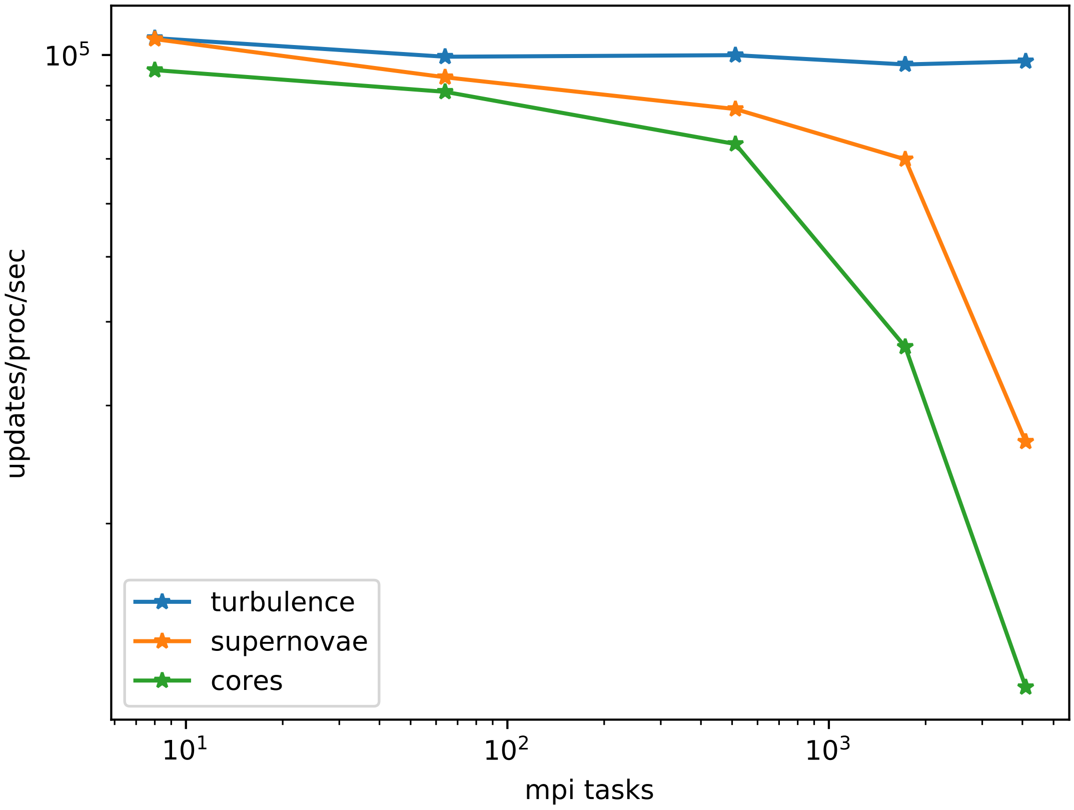

Figure 1: Updates per core-second for weak scaling with one level of AMR on Stampede 2. The three curves correspond to the three different sets of physics packages for each suite of simulations. The blue curve only employs the MHD solver, in the configuration used for the *turbulence* simulations. The orange curve employs the MHD solver as well as the burning operator, and will be used for the *supernovae* simulations. The green curve employs self gravity and cooling, and will be used for the *cores* simulations.

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