The CRASH Code

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CRASH is a radiation-hydrodynamic code with a laser package

- 1D, 2D or 3D
- Dynamic adaptive AMR
- Level set interfaces
- Self-consistent EOS and opacities
- Multigroup-diffusion radiation transport
- Electron physics and flux-limited electron heat conduction
- Laser package
  - 3D ray tracing for 2D or 3D runs

The genesis of CRASH was space-weather modeling

- We developed a practical high-resolution Godunov scheme for multi-dimensional MHD
- We built an efficient solution-adaptive parallel MHD solver (BATS-R-US)
- We tied a number of physics modules (some built on BATS-R-US) together to form the Space Weather Modeling Framework (SWMF)
The disparate scales of space-weather drove our need for solution-adaptive parallel code

- **Temporal scale range:**
  - $\sim2^{28} \approx 2.5 \times 10^8$

- **Linear spatial scale range:**
  - $\sim2^{28} \approx 2.5 \times 10^8$
BATSRUS can model many plasma processes

- Compressible fluid dynamics
- Ideal MHD
- Resistive MHD
- Hall MHD
- Semi-relativistic MHD
- Physics-based energy transport
  - Heat conduction
  - Wave energy transport
- Multi-fluid MHD
  - Each ionic species has its own continuity, momentum and energy equation
  - Electron momentum equation is replaced by Ohm’s law.

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The Space-Weather Modeling Framework comprises many modules!
SWMF has been extensively validated

- In late October and early November 2003 a series of some of the most powerful solar eruptions ever registered occurred.

- The “Halloween storm” simulation provided a unique opportunity for code/observation comparison.
CRASH is an extension of BATS-R-US to the high-energy-density domain

- Builds on the solution-adaptive, parallel framework of BATS-R-US
  - Adds new physics
    - Radiation transport
    - Electron physics and flux-limited electron heat conduction
    - Laser package
    - Tabular and self-consistent EOS and opacities
- Can tap into physics in BATS-R-US (e.g. MHD)
We model laser energy transport using a parallel ray-tracing algorithm for AMR grids.

Rays are traced by solving

\[
\frac{d\mathbf{r}^2}{ds^2} = \frac{d\mathbf{r}}{ds} \times \left( \frac{\nabla n}{n} \times \frac{d\mathbf{r}}{ds} \right)
\]

where \( \mathbf{r} \) is the ray direction, \( s \) is the distance along the ray, and \( n \) is the index of refraction.

\( \nabla n \) is determined from the plasma density distribution.

Laser energy is absorbed by electron-ion collisions.

The laser energy is smoothly deposited in the plasma by distributing it among the nearest cells.

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CRASH Radhydro Code: Hydro and Electron Physics

\[
\frac{\partial}{\partial t} \left\{ \mathcal{E} + \frac{\rho}{2} \| \mathbf{u} \|_2^2 \right\} + \nabla \cdot \left\{ \rho \mathbf{u} \left( \frac{1}{2} \rho \| \mathbf{u} \|_2^2 + \mathcal{E} + p \right) \right\} = S
\]

\[
S = \left\{ \begin{array}{l}
\nabla \cdot C_e \nabla T_e - S_{re} + S_L \\
- \rho_e \nabla \cdot \mathbf{u} + \nabla \cdot C_e \nabla T_e + \frac{\rho k_B (T_i - T_e)}{M_p A \tau_{ei}} - (S_{re} - S_{rm} \cdot \mathbf{u}) + S_L
\end{array} \right\}
\]

- Laser energy deposition
- Radiation/electron momentum exchange
- Electron heat conduction
- Compression work
- Collisional exchange
- Radiation/electron energy exchange

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CRASH Radhydro Code: Multigroup diffusion

- Radiation transport equation reduces to a system of equations for spectral energy density of groups.
- Diffusion is flux-limited
- For the $g^{th}$ group:

$$\frac{\partial E_g}{\partial t} + \nabla \cdot (E_g u) - p_g \nabla \cdot u - \frac{\nabla \cdot u}{\Delta (\log \varepsilon)} \Delta(p_g) = \text{diffusion} + \text{emission - absorption}$$

$$\text{diffusion} = \nabla \cdot (D_g \nabla E_g) \quad \text{emission-absorption} = c \chi_{abs_g} (B_g - E_g)$$

$$\Delta(\cdot) = (\cdot)_{g+\frac{1}{2}} - (\cdot)_{g-\frac{1}{2}}$$
Overview of Solver Approach

- Self-similar block-based adaptive grid
- Finite-volume scheme, approximate Riemann solver for flux function, limited linear interpolation
- Level-set equations used to evolve material interfaces; each cell treated as single-material cell
- Mixed Implicit/Explicit update
  - Hydro and electron equations
    - Advection, compression and pressure force updated explicitly
    - Exchange terms and electron heat conduction treated implicitly
  - Radtran
    - Advection of radiation energy, compression work and photon shift are evaluated explicitly
    - Diffusion and emission-absorption are evaluated implicitly
  - Implicit scheme is a preconditioned Newton-Krylov-Schwarz scheme
We extensively test our code

- New program units implemented with unit tests
  - Nightly execution of many unit tests for CRASH and its parent code
- New features implemented with verification tests
  - Daily verification & full system tests are run on a 16-core Mac.
  - Tests cover all aspects of the new feature, including restart, using grid convergence studies and model-model comparison.
- Compatibility & reproducibility checked with functionality test suite
  - Nightly runs. 9 different platforms/compilers on 1 to 4 cores: tests portability
- Parallel Scaling Tests
  - Weekly scaling test on 128 and 256 cores of hera.
  - Reveals software and hardware issues, and confirms that results are independent of the number of cores.
Multiple classes of tests are in our suite

- Hydrodynamics
- Radiation transport
- Radiation hydrodynamics
- Heat conduction
- Simulated radiography
- Material properties (EOS and opacities)
- Unit tests
- Full-system tests

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The hydro portion of the code scales well to tens of thousands of cores
(CRASH hydro Weak Scaling on BG/L)
Radiation-hydrodynamics scales well to ~ 1000 cores

CRASH rad-hydro strong scaling on Hera and Pleiades
The CRASH project itself is focused on radiative shocks

- 1 ns, 4 kJ laser irradiates 20 µm Be disk
- Drives shock into Xe-filled tube at 1.1 atm.
- Radiative precursor heats wall of tube, leading to ablation
- Complex interaction among laser-driven shock, ablation-driven shock, and Xe-Be interface
Full system with CRASH laser package

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We can now simulate the Year-5 Experiment!
CRASH simulation of Y5 experiment
CRASH simulation of Y5 experiment
CRASH has been used to model several HED experiments

Rayleigh-Taylor growth in a diverging system

Ablative flow of laser driven foil for collisionless shock experiments

Rayleigh-Taylor growth in the presence of a radiative shock

Creation of plasma jets using laser irradiation of conical foils

See Poster by M J Grosskopf for more details as well as information on other applications being modeled with the CRASH code.

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Concluding Remarks

- The CRASH code is now useful for applications
- We follow good practices on code development and verification
- We have simulated the experiments for the CRASH project
- We have simulated several other HED experiments
- The code is publicly available
  - But realistically requires knowledge and experience to run
  - We welcome visitors seeking these
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