Using adaptive nested mesh code HydroBox3D for numerical simulation of Type Ia supernovae: merger of carbon-oxygen white dwarf stars, collapse, and non-central explosion

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The motivation: white dwarf evolution

**The progenitor of a Type Ia supernova**

- Two normal stars are in a binary pair.
- The more massive star becomes a giant...
  ...which spills gas onto the secondary star, causing it to expand and become engulfed.
- The secondary, lighter star and the core of the giant star spiral toward within a common envelope.
- The common envelope is ejected, while the separation between the core and the secondary star decreases.
- The remaining core of the giant collapses and becomes a white dwarf.
- The aging companion star starts swelling, spilling gas onto the white dwarf.
- The white dwarf’s mass increases until it reaches a critical mass and explodes...
  ...causing the companion star to be ejected away.
The motivation: white dwarf evolution (asymmetric explosion)

The mathematical challenges:
1. The numerical model construction
2. The numerical solver development
3. The efficiency parallel implementation

White dwarf expands less than in the Röpke et al. model, so the collision on the far side occurs at higher density and with less geometrical dilution. In the Chicago version, the temperature is sufficient to ignite a detonation that consumes the rest of the star.

*Jordan et al. (2008)*

The supernova explosion enriches interstellar medium with the elements of life: O, C, Fe, N, Si, Mg, Ca,…
The Hydrodynamic Model of White Dwarf

- The Euler hydrodynamics equations
- The gravity
- The stellar equation of state:
  - Ideal gas for low temperature
  - Adiabatic (non)relativistic degenerate gas for high temperature
  - Radiation term
- The carbon burning $^{12}\text{C} + ^{12}\text{C} \rightarrow ^{23}\text{Na} + p$
The numerical methods for hydrodynamics

SPH approach
- Robustness of the algorithm
- Galilean-invariant solution
- Simplicity of implementation
- Flexible geometries of problems
- High accurate gravity solvers
- Artificial viscosity is parameterized
- Variations of the smoothing length
- The problem of shock wave and discontinuous solutions
- Instabilities suppressed
- The method is not scalable

AMR approach
- Approved numerical methods
- No artificial viscosity
- Higher order shock waves
- Resolution of discontinuities
- No suppression of instabilities
- Correct turbulence solution
- The complexity of implementation
- The effects of mesh
- Problem of the minimal mesh
- Not Galilean-invariant solution
- The method is not scalable
## Top10 (November 11, 2018)

<table>
<thead>
<tr>
<th>Rank</th>
<th>System</th>
<th>Cores</th>
<th>TFlop/s</th>
<th>TFlop/s (kW)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Summit - IBM Power System AC922, IBM POWER9 22C 3.07GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband, IBM OSCI/Oak Ridge National Laboratory</td>
<td>2,397,824</td>
<td>143,500.0</td>
<td>200,794.9</td>
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<td>2</td>
<td>Sierra - IBM Power System S922LC, IBM POWER9 22C 3.1GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband, IBM / NVIDIA / Mellanox DOE/NWNL/NL</td>
<td>1,572,480</td>
<td>94,640.0</td>
<td>125,712.0</td>
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<td>3</td>
<td>TaihuLight - Sunway MP: Sunway SW26010 260C 1.45GHz, Sunway, NRCPC National Supercomputing Center in Wuxi, China</td>
<td>10,649,600</td>
<td>93,014.6</td>
<td>125,435.9</td>
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<td>4</td>
<td>Sunlight - TH-IVB-PEP Cluster, Intel Xeon E5-2690v4 2.2GHz, TH Express-2, Matrix-2000, NVIDIA / IBM National Super Computer Center in Guangzhou, China</td>
<td>4,981,760</td>
<td>81,444.5</td>
<td>100,578.7</td>
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<td>5</td>
<td>Piz Daint - Cray XC50, Xeon E5-2695v3 2.6GHz, Aries interconnect, NVIDIA Tesla P100, Cray Inc. Swiss National Supercomputing Centre (SCS) Switzerland</td>
<td>387,872</td>
<td>21,230.0</td>
<td>27,154.3</td>
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<td>Triniti - Cray XE64, Xeon EP 2698 16C 2.3GHz, Intel Xeon Phi 7250 68C 1.4GHz, Aries interconnect, Cray Inc. DOE/NASA/LANL/SK United States</td>
<td>979,072</td>
<td>20,158.0</td>
<td>41,451.2</td>
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<td>7</td>
<td>AIBridging - Cloud Infrastructure (ABC) - PRIMERGY CX2570 M4, Xeon Gold 6136 20C 2.4GHz, NVIDIA Tesla V100 SXM2, Infiniband EDR, Fujitsu National Institute of Advanced Industrial Science and Technology (AIST) Japan</td>
<td>391,680</td>
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<td>305,856</td>
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<td>Titan - Cray XK7, Opteron 6274 16C 2.20GHz, Cray Gemini interconnect, NVIDIA K20x, Cray Inc. DOE/SC/Oak Ridge National Laboratory United States</td>
<td>560,840</td>
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<td>Sequoia - BlueGene/Q, Power BQC 16C 1.60 GHz, Custom, IBM DOE/NNSA/LLNL United States</td>
<td>1,572,864</td>
<td>17,173.2</td>
<td>20,132.7</td>
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</tbody>
</table>
The original numerical methods

\[ \frac{\partial}{\partial t} \begin{pmatrix} \rho \\ \rho \vec{v} \\ \rho E \end{pmatrix} + \nabla \cdot \begin{pmatrix} \rho \cdot \vec{v} \\ \rho \vec{v} \cdot \vec{v} \\ \rho E \cdot \vec{v} \end{pmatrix} = \begin{pmatrix} 0 \\ -\nabla p \\ -\nabla \cdot (p \vec{v}) \end{pmatrix} \]

\[ \frac{\vec{u}^{n+1}_k - \vec{u}^n_k}{\tau} + \frac{F_{k+\frac{1}{2}} - F_{k-\frac{1}{2}}}{h_i} = 0 \]

Vectors

\[ F = \frac{F(-\lambda \tau) + F(\lambda \tau)}{2} + \frac{c + \| \vec{u} \|}{2} (U(-\lambda \tau) - U(\lambda \tau)) \]

The piecewise-parabolic functions
The Parallel Implementation

Domain Decomposition

Geometry Decomposition
(MPI + FFTW)

Threads Decomposition
(OpenMP)

Vectorization
(AVX 512)

* _mm512_set1_pd_
  set value for a vector

* _mm512_load_pd_
  load a vector from main memory

* _mm512_mul_pd_
  vector multiply

* _mm512_add_pd_
  vector summation

* _mm512_sub_pd_
  vector substitution

* _mm512_store_pd_
  store a vector to main memory

Main advantages is 302 GFLOPS
on Intel Xeon Phi KNL

Main disadvantages – formation of the
8-double elements vector for computing

Pitfalls: associative of cache memory, align of
memory, schedule distribution, data dependency
The Sedov explosion
The Evrard collapse

![Graph showing the evolution of different energy components over time. The graph plots energy (y-axis) against time (x-axis). There are curves for kinetic energy (E_{kin}), internal energy (E_{int}), gravitational energy (E_{grav}), and total energy (E_{total}). The graph indicates the collapse dynamics and the interplay between these energy components.]
From subgrid to “subreal” models

Supernovae explosion

Star formation

Protoplanetary disks and planet formation
From subgrid to “subreal” models

CPU
From subgrid to “subreal” models

CPU

Many CPU
From subgrid to “subreal” models

- CPU
- Many CPU
- SMP
The Base/Satellite Computing

The Base Computing

- Base & Nested meshes
  - MPI_Spawn
  - Resolution $1 : 10^7$

The Satellite Computing

- Satellite regular mesh

Shared Memory
- Core 0
- Core 1
- Core N
- Memory
- Intel Optane

Massive Parallel Supercomputer
- CPU 0
- Memory
- GPU/IXP

- CPU N
- Memory
- GPU/IXP
The organization of Base Computing
The variables

- The root mesh
- Hydrodynamics
- Gravity (FFT)

- The nested mesh
- Hydrodynamics
- Gravity (SOR)
- Riemann
The adjacent for Riemann problem
The mesh reconstruction
The Carbon burning
(The Satellite Computing)
The asymmetric explosion of white dwarf (The Base Computing)
Conclusion

- A new numerical model of Supernovae Ia type explosion is created.
- The Base/Satellite computing concept is described.
- The scenarios of a non-central SNIa is modeled.
- The SNIa is non standard problem!!!

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All of You for Your attention!