New Insights into Thermonuclear-Powered Supernovae from Large-Scale Simulations

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FLASH is a multi-physics finite-volume Eulerian code and framework whose capabilities include:

- Adaptive mesh refinement (AMR) on a block-structured mesh
- Multiple state-of-the-art hydrodynamic solvers
- State-of-the-art magnetohydrodynamics
- Implicit solvers for diffusion using the HYPRE library (currently being used to model thermal conduction, radiation diffusion, and viscosity)
- Many physics modules relevant to astrophysics and cosmology, including gravity and nuclear burning
- Generic, highly scalable parallel particles framework (currently used for PIC simulations, laser ray tracing, dark matter, tracer particles)

FLASH contains 1.25 M lines of code of which > 1 M are executable.
FLASH scales to well over a hundred thousand processors. FLASH uses a variety of parallelization techniques including domain decomposition, mesh replication, and threading to best utilize hardware resources.

FLASH is extremely portable and can run on a variety of platforms from laptops to supercomputing systems such as the IBM BG/P and BG/Q.

FLASH is composed of interoperable units/modules; particular modules are combined to run individual simulations. Thus only the code relevant to a particular problem is included when FLASH is compiled. This also allows for important compile-time optimizations that improve performance.

FLASH is professionally managed software with daily, automated regression testing on a variety of platforms, version control, coding standards, extensive documentation, user support, and integration of code contributions from external users.

Nearly 1200 scientists around the world have now used FLASH, and more than 800 papers have been published that directly use it.
What are Type Ia supernovae?
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Peak luminosities of most Type Ia SNe are similar – making them excellent “cosmic yardsticks”
Calibration using empirical correlation between peak brightness and duration

Peak brightnesses of Type Ia SNe vary by roughly 1 mag = factor 3

Using empirical correlation between peak brightness and duration, variation can be reduced to about 15%

Goal of the Flash Center SN Ia Project is to understand these events better and by doing so, help observers make them more accurate "standard candles"
Type Ia supernovae are an important tool for determining the properties of dark energy.
Flash Center uses the world’s most powerful computers to do simulations with FLASH

- IBM Blue Gene/Q *Mira* supercomputer at Argonne Leadership Computing Facility has 768 K processors yielding 10 Petaflops
- FLASH capstone simulations of thermonuclear-powered (Type Ia) supernovae and of buoyancy-driven nuclear combustion – a key physical process in such supernovae – use a significant fraction of the machine
Computational demands of large-scale 3D Type Ia supernova simulations

- FLASH was an informal acceptance test for the IBM BG/L and was a formal acceptance test for BG/P and BG/Q
- FLASH has been fully threaded, which enables it to compute at scale on the BG/Q
- Capstone 3D simulations of the explosion phase of Type Ia supernovae require 300-800 K CPU-hrs; the radiation transfer phase requires more computational resources
- Each capstone simulation generates ~ 20-100 TB of data
- Each of the past three years we used ~ 80 M CPU-hrs on Intrepid at ANL under DOE Office of Science INCITE program; this year we will use 150 M CPU-hrs on Mira for Early Science plus 20 M CPU-hrs on Intrepid and 80 M CPU-hrs on Mira under INCITE
- We generated ~ 3 PB of data last year and we expect to generate more this year; in-line analysis and intelligent triaging of data is therefore essential
Physics of Type Ia supernovae

Accretion
- Stellar binary in which main sequence star transfers mass onto white dwarf

Smoldering
- Subsonic convection in core of white dwarf
- Heat transport is by electron conduction

Flame
- Nuclear burning initially due to laminar flame
- Buoyancy—driven turbulence increases nuclear burning rate
- Transition from deflagration to detonation occurs, causing the star to explode

Lightcurve
- Free expansion of star
- Radioactive decay of $^{56}\text{Ni}$ heats expanding gas and makes explosion visible
- This causes the ejecta to glow, which makes the supernova visible

Ignition
- $\sim 10^4 \text{ yr}$

$10^8 \text{ yr}$

$\sim \text{seconds}$
Buoyancy-driven turbulent nuclear burning

- The nuclear flame is initially ~ 1 mm thick while the resolution of our best simulations is 1 km – a factor of $10^8$ larger!
- A model of the nuclear flame is therefore essential
- The burning rate during the deflagration phase and the physical conditions at which a DDT might occur depend on the model
- The correct model to use is controversial
- We have done extensive simulations to better understand this key physical process

Zhang et al. (2007); Townsley et al. (2008, 2010) Jordan et al. (2011)
Large-scale simulations of buoyancy-driven turbulent nuclear combustion
Simulation of Buoyancy-Driven Turbulent Nuclear Burning for a Froude Number of 0.010

This work was supported in part at the University of Chicago by the DOE NNSA ASC ASAP and by the NSF. This work also used computational resources at LBNL NERSC awarded under the INCITE program, which is supported by the DOE Office of Science.
Conclusions from extensive verification simulations of buoyancy-driven turbulent nuclear burning

- Buoyancy-driven turbulent nuclear combustion produces a much lower burning rate than nuclear combustion in the presence of fully developed turbulence.
- One length scale determines the rate of burning: $\lambda_c$, the “flame polishing length”.
- Variations in the rate of burning are due to variations in the area of the flame surface at large length scales.
- We are using the results to develop a better model of such burning for use in our whole-star simulations of Type Ia supernovae.
Simulation of the Deflagration and Detonation Phases of a Type Ia Supernovae

Ignition occurs 40 km from the center of the star. Hot material is shown in color and stellar surface in green.

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Discovery of an entirely new explosion mechanism for Type Ia supernovae

Calder et al. (2003); Plewa, Calder and Lamb (2004); Townsley et al. (2007); Jordan et al. (2008); Meakin et al. (2009)

Discovery of GCD model
• Illustrates importance of 3D whole-star simulations
• Exemplifies scientific discovery through advanced computation
Impact of pre-expansion on nucleosynthetic products of supernova

Products of nuclear burning depend only on density at which burning occurs: iron-peak nuclei are formed at high densities, intermediate mass nuclei are formed at lower densities.
Failed GCD model may explain peculiar underluminous Type Ia supernovae.

- Failed GCD model produces only $\sim 0.05 - 0.1 M_{\text{sun}}$ of Nickel compared to $0.5 - 0.7 M_{\text{sun}}$ for normal Type Ia supernovae.
- Consequently, these events are underluminous by a factor $\sim 10 - 100$.
- The core of the white dwarf survives and gets a $\sim 300$ km s$^{-1}$ kick which may allow it to escape from the binary in some cases.
Partnership with SDSS-II Supernova Survey and Dark Energy Survey to validate Type Ia supernova models

SDSS Supernova Project has spectroscopically identified more than 500 Type Ia supernovae, and obtained high-quality light curves and spectra for many of them (Holtzman et al. 2009, Kessler et al. 2009)
Validation of GCD model using light curves of individual Type Ia supernovae

Comparison of U, V, B, R light curves predicted by GCD model and obs. of Type Ia Supernova SN 2001el

Kasen and Plewa (2006)

Comparison of spectra predicted by GCD model and obs. of Type Ia supernova SN 1994D

Light curves and spectra resemble the observations
Validation of Type Ia supernova models using light curve properties of an ensemble of observed supernovae

Underluminous pure deflagration models

Normal luminosity DDT models

Diemer et al. (2013)
Conclusions

- The Flash Center has extensively simulated two key processes in Type Ia supernovae that are not fully understood:
  - Buoyancy-driven turbulent nuclear combustion, and
  - Transition to distributed nuclear combustion

- The Center is using the results of these simulations to develop a better model of buoyancy-driven turbulent nuclear combustion for use in its whole-star simulations of Type Ia supernovae

- While surely not the final story, the GCD model discovered by the Center reproduces several key observed properties of “Branch normal” Type Ia supernovae, and is therefore a promising model of these explosions

- The Center has done extensive large-scale, 3D simulations of all current Chandrasekhar-mass Type Ia supernovae models

- The Center has begun a rigorous, systematic validation of these models using high-quality data from the SDSS-II Supernova Survey and the Dark Energy Survey, and their collaborators