Investigation of Turbulence in the Early Stages of a High Resolution Supernova Simulation

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Abstract

Cosmologists have used the light curves of Type Ia supernovae (SN Ia) as tools for surveying vast distances. Previous simulations have used coarse resolution and artificial initial conditions that substantially influenced their outcome. Here, we have the unique advantage of being able to import the results from previous simulations of convection leading to ignition from our low Mach number code, MAESTRO, directly into our compressible code, CASTRO. These initial conditions include the location of ignition and the turbulence on the grid. In this video, we show the turbulence within the early "bubble" of a supernova via renderings of the magnitude of the vorticity within the simulation. We then focus on the highest values of the magnitude of vorticity to observe the formation of "vortex tubes."

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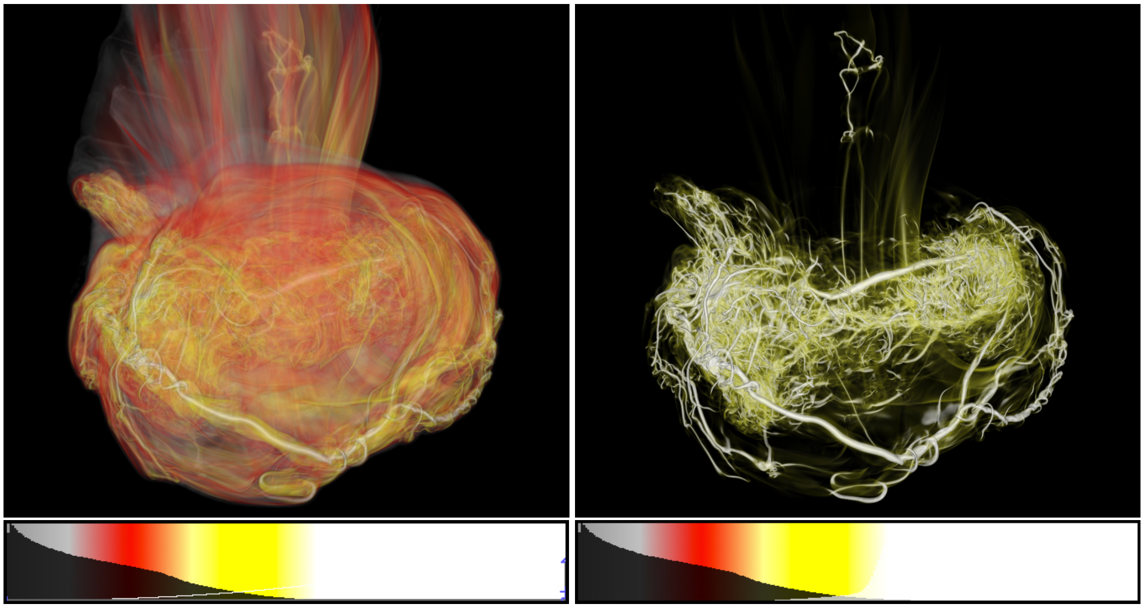
1 The Data

Cosmologists have used the light curves of Type Ia supernovae (SN Ia) as tools for surveying vast distances. However, great uncertainty still exists regarding the underlying physics of a SN Ia explosion. While it is generally accepted that the exploding star is a white dwarf driven to thermonuclear runaway by the accretion of mass from a binary companion, the nature of the progenitor star and how it ignites and burns are debated. Previous simulations have used coarse resolution and artificial initial conditions that substantially influenced their outcome. Here, we have the unique advantage of being able to import the results from previous simulations of convection leading to ignition from our low Mach number code, MAESTRO [4, 6], directly into our compressible code, CASTRO [1, 5]. These initial conditions include the location of ignition and the turbulence on the grid. CASTRO is a finite-volume, adaptive mesh refinement (AMR) code. We are using multiple levels of grid refinement to capture the early post-ignition dynamics at unprecedented resolution, revealing the essential character of the burning.

In our CASTRO simulation, we divide up the entire star into 10,000 to 20,000 grids. Each grid contains between 10,000 to 100,000 computational zones, each carrying information about the fluid velocity, density, temperature, pressure, composition, etc., in that particular zone. The finest grid resolution is ~ 130 m zone^{-1}, whereas the full size of the star is $\sim 2,500$ km. The grid structure dynamically changes over time to ensure that we are tracking the flame front using zones at the highest resolution. The data used to create this video was a result of running this simulation on the Blue Waters Early Science System (48 Cray XE6 Cabinets). On the Blue Waters machine, we are able to distribute these grids among 65,536 cores for efficient parallelization. Blue Waters is also able to handle the complex communication patterns between grids of different sizes containing zones at different spatial resolution. At peak, about 2 billion computational zones were used in the simulation up to the point shown in the movie.

2 The Visualization

With the exception of two image tween effects and the credits slides, the data visualizations were created using VisIt [7, 2] on Blue Waters systems. VisIt has been show to scale extremely well on similar architectures [3]. For this video,



(a) (b)

Figure 1: Representative video screens with their respective transfer functions.

VisIt's engine was run on both the Blue Waters Early Science System as well as the Test and Development System, with different frames and effects generated on engines running anywhere between 256 to 1024 cores of those systems. There are a total of 76 time steps of data, with the most complex (the later ones) having five levels of refinement, and taking up approximately 150G of space on disk. VisIt's ray caster was used to generate the frames and Figure 1 shows the two transfer functions used in volume rendering of the vorticity field and what features of the data are consequently highlighted.

For Figure 1(a) a gaussian selection was used on VisIt's transfer function widget. The area to the right of where the gaussian (white line) intersects the data distribution (black area) represents the values of the data that are fully opaque (the white and some yellow values). For Figure 1(b) the selection has been shifted so that all but only the highest values are fully transparent.

3 The Science

The movie follows the first ~ 0.37 seconds of evolution of the hot ignition point as it buoyantly rises towards the stellar surface. In this time, the bubble has risen 250 km — about 10% of the way to the surface — and expanded from its initial size of about 2 km to over 120 km across, and taken on a mushroom shape. The bubble's rise and expansion will continue at an accelerated rate, and it will reach the stellar surface in another ~ 0.6 seconds.

As seen in the movie and in Figure 1, the fluid flow in the "cap" of the mushroom is highly vortical. We study the vorticity as a tracer of turbulence, and the vortex tubes highlighted in the Figure are signatures of high Reynolds number turbulence. One side effect of the turbulence is to warp and wrinkle the flame surface, effectively increasing its area and boosting the bulk rate at which the fuel is converted to ash via nuclear reactions. The details of how this happens are uncertain and depend on the resolution of the simulation. One consequence of this increased nuclear burning is a change in the amount and the composition of the ash products, which then has an effect on the overall spectrum and brightness of the observed Type Ia supernova.

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