Advancing Astrophysics Science

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Summary

Petascale simulations of the deaths of massive stars are important to the understanding of the origin of the diversity of elements within the universe. The data sets from these petascale simulations are becoming larger due to increases in spatial and temporal resolution as well as large increases in data model complexity. The SciDAC Visualization and Analytics Center for Enabling Technology (VACET) has developed new techniques that enable rapid scientific knowledge discovery from these data sets. These techniques leverage the parallel data analysis platforms at DOE's supercomputing centers to provide "turn key" visualization and analysis for DOE's astrophysics research programs.

Astrophysics researchers from Oak Ridge National Laboratory, Florida Atlantic University, and North Carolina State University are working, through DOE's INCITE program, to develop petascale simulation codes with the capability of modeling the complex physics of core-collapse supernovae. Such phenomena are arguably the most important links in our chain of origin from the Big Bang to the present day. They are the dominant source of elements in the periodic table between oxygen and iron and are responsible for producing half of the elements heavier than iron. Ascertaining the explosion mechanism for core-collapse supernovae is one of the most important unsolved problems in astrophysics.

INCITE researchers are developing a fully coupled, extensible radiation hydrodynamic code, CHIMERA, that implements scalable multi-dimensional hydrodynamics and magnetohydrodynamics solvers and neutrino radiation transport solvers, along with nuclear kinetics solvers and gravitational solvers for both Newtonian and general relativistic gravity.

A core-collapse supernova is initiated by the collapse of the core of a massive star. The core rebounds at high density, launching a shock wave into the star that will ultimately disrupt it. The shock stalls in the core, however, losing energy as it plows through the still infalling stellar matter. Exactly how the shock is revived is still unknown. This is the central question in core-collapse supernova theory today. Core-collapse supernovae are in part radiatively driven. After core bounce, 10^{53} ergs of energy in the form of neutrinos of all

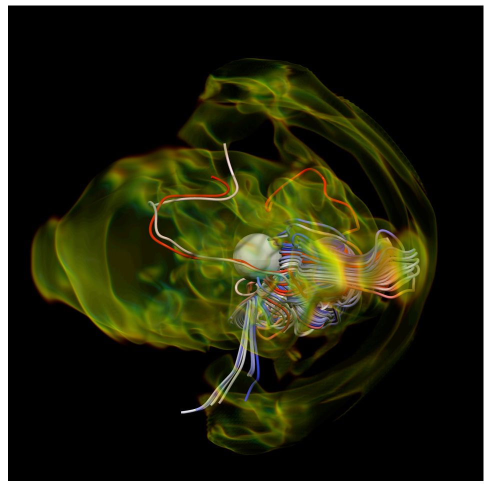

Figure 1. The collapse of massive star's core results in the formation of an outgoing spherical shock wave that eventually disrupts the entire star, giving rise to a supernova. Along the way the shock temporarily stalls and experiences the "stationary accretion shock instability" (SASI), which causes large deviations from spherical symmetry. This appears to be important to the supernova explosion mechanism, and may be responsible for spinning up the collapsed core – a nascent neutron star – into a pulsar. This image shows an exploratory view of a simulation run to ascertain the extent to which the SASI may generate magnetic fields: a volume rendering shows the fluid speed, and a sampling of fluid streamlines is colored by magnetic field strength. The simulation was run on Jaguar at NCCS with *GenASiS*, a multi-physics code under development for the simulation of astrophysical systems involving nuclear matter. Image credit: Visualization: Dave Pugmire (Oak Ridge National Laboratory). Simulation: Eirik Endeve, Christian Cardall, and Reuben Budiardja (Oak Ridge National Laboratory and University of Tennessee, Knoxville)

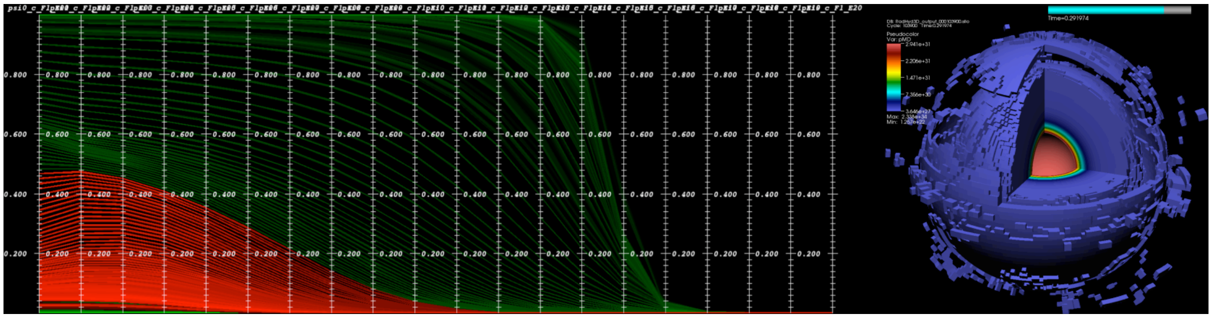

Figure 2. Multidimensional parallel coordinates exploration of the 20-energy group neutrino radiation field in a large supernova simulation. Increasing neutrino occupation highlighted in red. The multidimensional analysis on the left is directly linked to a traditional spatial visualization on the right. Visualization: Sean Ahern (Oak Ridge National Laboratory). Simulation: Steve Bruenn (FAU), Bronson Messer, Tony Mezzacappa, Raph Hix (Oak Ridge National Laboratory)

three "flavors" (electron, mu, and tau) is released from the "proto-neutron star (PNS)" at the center of the explosion. The supernova explosion energy is 10^{51} ergs, one hundred times smaller. Energy in the form of neutrinos emerging from the PNS will be deposited behind the shock and will help revive it. This "neutrino reheating'" is central to the core-collapse supernova mechanism. However, while a prodigious amount of neutrino energy emerges from the PNS, the neutrino heating is very sensitive to the distribution of neutrinos in energy (i.e., their spectra) and direction of propagation (i.e., their angular distributions) at any given spatial point behind the shock. Given that different neutrino flavors have different spectra, mixing between flavors may be crucial. Thus, multi-angle, multi-frequency neutrino transport is ultimately required to accurately compute the neutrino distributions in the heating region.

All of this complexity renders the core-collapse supernova problem a truly multidimensional, petascale problem, and it demands analysis and visualization tools that can be brought to bear in taming such complexity. The CHIMERA team has turned to the SciDAC Visualization and Analytics Center for Enabling Technology (VACET) for assistance and has increasingly relied upon VACET's VisIt parallel analysis and visualization tool for understanding their petascale datasets.

Specifically, the capabilities for large-scale data parallelism in the generation of images and analyses for exploring pressure, density, and entropy fields have been deployed into the hands of scientists.

In the past two years, VACET staff members have added multi-dimensional analysis techniques that allow for scientists to directly explore the complex data models inherent in their files. These techniques have, for the first time, allowed the researchers to directly see the energy distribution and propagation direction of neutrino radiation in their simulations. In addition, these multi-dimensional visualizations are linked to traditional spatial visualizations, allowing for focused analysis of features of interest.

These new capabilities are implemented in production-quality, parallel-capable visual data exploration software that runs on virtually all modern platforms, ranging from DOE's largest petascale computer systems down to laptop-class machines.

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