# Exploring the Science of Supernovae with Three-Dimensional Computer Simulations

MSCOPE

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## Executive Summary

The proposed MSCOPE project will result in a set of three educational modules for the Adler Planetarium and Astronomy Museum that covers the areas of physics fundamental to supernovae: gravity, fluid dynamics and instabilities, and nuclear reactions and nucleosynthesis. Each module will include visual content from computer simulations for presentation in theaters capable of three-dimensional projection. Where possible, these visualizations will be complemented with two- and three-dimensional images from laboratory experiments and other terrestrial environments. Occassions for optional live demonstrations of fluid dynamics and combustion are also planned.

While each module will be constructed as a separate (and separable) unit, they will be unified in the context of a thermonuclear supernova explosion. This common thread will be based upon the Gravitationally Confined Detonation (GCD) model for supernovae developed by the ASC/Alliances Center for Astrophysical Thermonuclear Flashes (the "Flash Center") at the University of Chicago. The simulations produced by the Flash Center tell a story about the processes leading up to the explosion.

The target audience for these modules is of high school age and older, with some understanding of elements, matter, energy, and forces being desirable.

## 1 Introduction

Some of the most interesting and dramatic events observed by astronomers are thermonuclear supernovae – typically classified as Type Ia ("one-A") – in which a compact white dwarf star experiences a runaway thermonuclear reaction. These dramatic explosions of stars can outshine entire galaxies, and have thus become the fundamental tools for measuring cosmological distances. Furthermore, these stars are recognized as the primary sources of iron and other elements important for life. They are therefore worthy of public understanding, as are the basic physical processes that contribute to them; specifically, these are gravity, fluid dynamics, and nuclear reactions.

In this project, we plan to develop a set of presentation components for the 3D GeoWall display at the Adler Planetarium & Astronomy Museum – with possible extension to the new 3D auditorium – that utilize visualizations of supernova simulations to motivate discussions of each of these processes. We will also include videos of terrestrial experiments from high-speed 3D cameras, additional simulations, and suggestions for live demonstrations of fluid dynamics or explosions.

## 2 Educational Components

In this section, we present possible topics of discussion for each of the modules in this program. While the specific topics and presentation methods chosen will depend on evaluations with museum visitors, and the specific audience involved, the goal is to provide a set of materials that

- ▷ Are highly visual, interesting, and clear
- ▷ Make connections to terrestrial phenomena and experiments
- ▷ Follow the stages leading up to the supernova explosion
- ▷ Increase visitors' familiarity with interpreting visualizations of data
- ▷ Are "seamless," minimizing transitions between 3D and non-3D visuals

### 2.1 Gravity

The gravitational force is, perhaps, the simplest of the physical processes at work in supernova. Gravity holds the white dwarf together, maintaining the high mass densities, and giving buoyancy to the hot material that is produced. Since the standard model of a Type Ia supernova involves an interaction with a neighboring star, gravity is also at work in determining the orbits and tidal distortion of both objects.

This section will lean primarily on astrophysical simulations to provide visual material (orbital dynamics, Roche-lobe overflow, etc.). However, the concepts of hydrostatic equilibrium, buoyancy, and tidal forces have clear associations with phenomena that visitors experience on Earth, and can be incorporated, as well.

- ▷ Atmospheric pressure variations with altitude
- ▷ Bubbles rising in liquids
- ▷ Ocean tides

### 2.2 Fluid Dynamics

Responding to gravity and producing the conditions necessary for detonation, fluid dynamics (and, particularly, fluid instabilities) play a central role in triggering thermonuclear supernovae. Because fluid flows in the supernova behave in a manner similar to that of terrestrial fluids, the visual materials for this module will be balanced between simulation results and videos of experiments.

In addition to the supernova simulations themselves, simulations that isolate different aspects of the fluid flows (e.g., shock waves or Rayleigh-Taylor instabilities) are also available. We will also make use of high-speed stereographic cameras to record fluid flow experiments, which may include shock waves and instability growth. We will also investigate the possibility of live demonstrations of fluid dynamics.

### 2.3 Explosions and Nuclear Reactions

Nuclear reactions are produce the energy that is released during a Type Ia supernova. They are also responsible for synthesizing heavier elements (e.g., iron and nickel) from the carbon and oxygen that compose the pre-explosion white dwarf.

The nuclear reactions occur along a thin surface called a “flame front.” In this regard, the nuclear flame is similar to chemical flames in normal combustion. We will make use of this analogy by including explosions recorded by the high-speed cameras; the feasibility of live demonstrations of combustion (i.e., a hydrogen balloon explosion).

Nucleosynthesis will be described with visual materials that show the progression of element creation from the nuclear reactions.

## 3 Necessary Resources

The supernova simulations have been constructed by the Flash Center, which will provide assistance for the production of three-dimensional visuals. Access to the high-speed cameras will be provided by the Chicago Materials Research Center at the University of Chicago.

## Appendix

### Example Data and Visualizations

Figure 1 shows the progression of the deflagration (subsonic combustion) phases of the Gravitationally Confined Detonation supernova model. Here, nuclear flame begins as a bubble near the center of the star; buoyancy causes the bubble to rise, and continued burning expands the volume enclosed by it. Rayleigh-Taylor instabilities cause the bubble to take on a mushroom-like shape before it breaks the surface. After breaking through the surface, unburned material is pushed along the surface ahead of the flame front, resulting bands of hot, compressed fuel. This material eventually converges at the opposite side of the star, where high temperatures and densities trigger the detonation (supersonic combustion) wave, and hence, the supernova explosion.

Figure 2 shows an example image of fluid dynamics captured by a Phantom high speed video camera like those used by the Chicago Materials Research Center at the University of Chicago. Multiple cameras can be synchronized to produce stereoscopic images of fluid dynamics experiments. In addition to fluid flows and instabilities, these cameras will also be used to record combustion experiments.

### Required Background

To fully and efficiently appreciate the concepts presented with this material, the audience should have some familiarity with physical phenomena at the beginning high school level or greater. The desired background corresponds to Chapter 4 of the American Association for the Advancement of Science educational benchmarks; the following benchmark

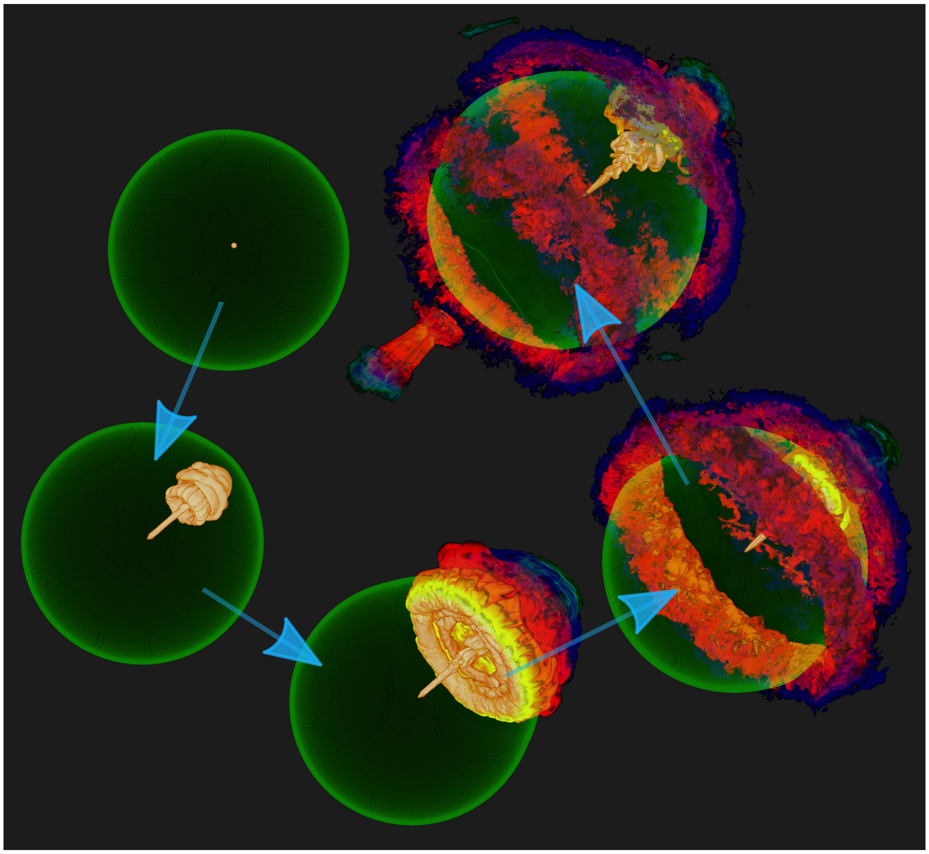

Figure 1: Simulation images from the deflagration phase of the GCD model. (Time progresses counter-clockwise from the upper left.) The surface of the white dwarf star is shown as a green spheroid, and the flame surface (nuclear burning front) is shown in orange and bright yellow. Beginning with the bottom image, red and violet colors are used to show hot material pushed along the surface of the star after the flame breaks through the surface.

sections – taught during grades 6 through 8 – apply:

D. Structure of Matter
   - ▷ Matter is composed of atoms
   - ▷ Chemical elements

E. Energy Transformations
   - ▷ Mass–energy conservation
   - ▷ Different forms of energy

F. Motion
   - ▷ Unbalanced forces acting on matter

G. Forces of Nature
   - ▷ Gravitational forces

Figure 2: Example image of water droplet taken with Vision Research Phantom Camera, similar to those used by the Chicago Materials Research Center.