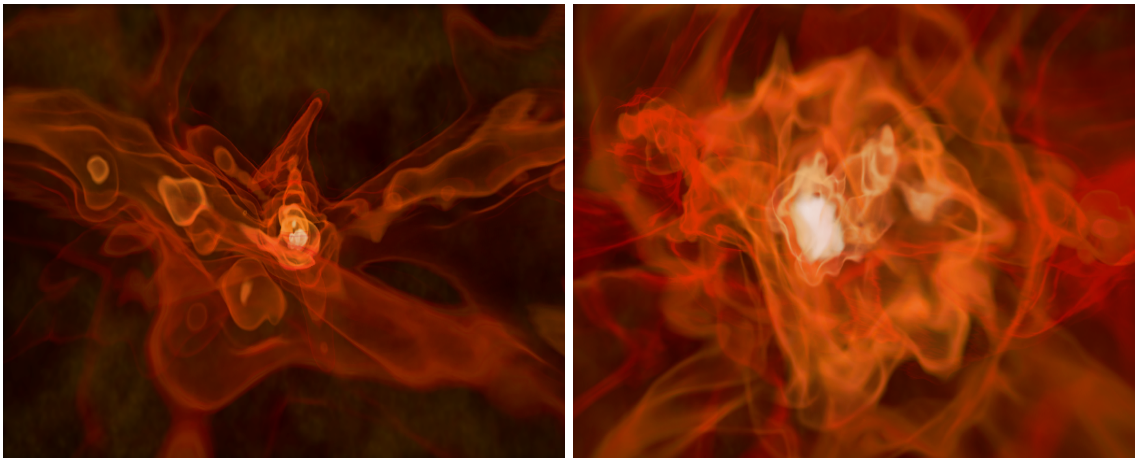

Figure 5.27: Two out of the $1,350$ time steps from the first simulation: the formation of the star out of primordial dark matter and gas (mainly hydrogen and helium). The depth of the hierarchy raised from 4 levels of refinement (and several hundred grids) after some hundred time steps, up to 10 levels (and $2,500$ grids) for the later time steps. The resolution of the root grid was $128 \times 128 \times 128$ cells. *(dataset courtesy of T. Abel, Stanford University)*

5.7 Rendering the First Star in the Universe - A Case Study

The remainder of this section reports on the application of the texture-based volume rendering algorithm in a collaboration with physicists, to render a time-dependent AMR simulation of the evolution of the first stars in the universe, starting with its formation out of gaseous interstellar matter up to its death in a supernova explosion. Parts of the data contained up to 27 levels of refinement, resolving an initial coarse computational domain of several thousand light years down to the region the newborn protostar. The volume renderer was applied to display the 3D density distribution of the interstellar gas. The voice and gesture controlled CAVE application VIRTUAL DIRECTOR [85] was utilized to define camera paths following the interesting features in the data domain. Background images were created from another cosmological simulation, with the STAR RENDERER, developed at PIXAR ANIMATION STUDIOS. Parts of the resulting renderings were broadcasted on the DISCOVERY CHANNEL program “The unfolding Universe”, aired in summer 2002.

5.7.1 The Simulation

The first star datasets [2] were computed with the AMR code Enzo [17, 65], designed for high-resolution cosmological structure formation simulations. The simulations follow the hydrodynamics, gravity of the gas and the dark matter, the chemical rate equations

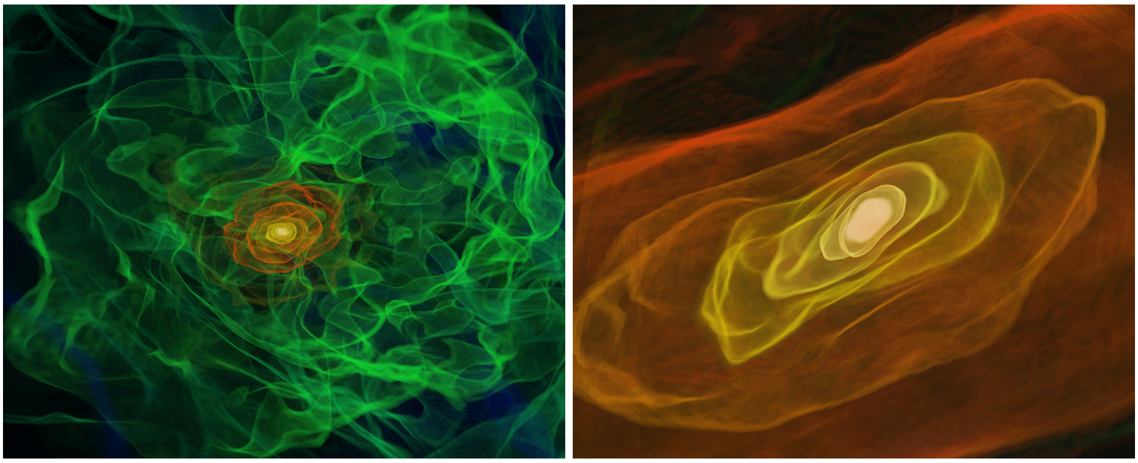

Figure 5.28: The second dataset: A time step of the most complex AMR simulation ever carried out. The root grid with $64 \times 64 \times 64$ cells was refined by $5,500$ grids on 27 levels of resolution, resolving down to the region of the newly formed proto-star. The pictures show two different camera positions, inside level 10, 16, and 22 respectively. *(dataset courtesy of T. Abel, Stanford University)*

following the non-equilibrium chemistry of the formation of ions and molecules, as well as all relevant radiative processes. It represents and ab initio calculation of the formation of the first star in the universe. It has no free variables. The simulation starts at about 400,000 years after the big bang and evolves it for approximately 200 million years. We use frames typically spaced by hundreds of thousands years in the dynamic sequence.

The initial coarse grid, representing the root node of the hierarchical data structure, covered a computational domain of about $18,000$ light years.

To visualize the formation of the first star we zoom into the static data set of an equal but further evolved simulation of the same type. The simulations find that a single massive star is formed per proto–galactic object of $\sim 10^6\, M_{\odot}$. Consequently, it is known that it will die in a supernova. To follow the explosion the simulation ejects the typical energy of a supernova explosion in ten solar masses of material at a scale of approximately a thousand times the distance between earth and the sun. As this simulations evolves a dense shell is formed and expands very rapidly. The typical timescales between frames is now less than thousands of years as compared to the hundreds of thousands of years for the first sequence. Look at Figures 5.27 to 5.30 for more details about the three different parts of the simulation.

5.7.2 VR Environment

To analyze the AMR data and create camera paths to highlight the interesting aspects for the wide-screen visualization, the team used VIRTUAL DIRECTOR [85] in a room sized CAVE immersive VR environment. VIRTUAL DIRECTOR is a voice and wand gesture

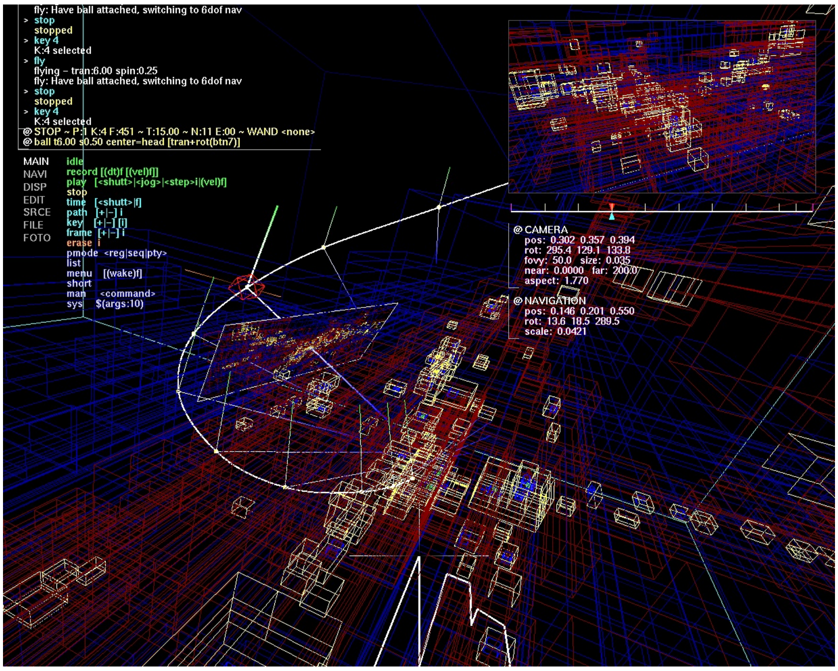

Figure 5.29: The graphical interface of the VIRTUAL DIRECTOR software [85] as seen in the CAVE. It shows the AMR grids bounding boxes and the edited camera path. Use of image with kind permission of Donna Cox, NCSA

controlled application for navigation and camera choreography, compare Figure 5.29.

For smooth VR interaction, we needed a lightweight subset of the AMR data. Since the AMR computation naturally creates refined grids in dense regions, a time-dependent animation of the bounding boxes of the grid domains provided a very good guide to visually interesting areas for the star-formation scenes, where opacity was derived from gas density, as shown in Figure 5.27. Display toggles for each level of grids helped in reducing visual clutter. In the supernova scene, compare Figure 5.30, the temperature field was the visually appropriate one; but it was poorly correlated with density, and AMR grid placement was less helpful. Temperature-colored particles from a subset of grid cells served as an interactive guide.

Due to the dramatic range of scale inherent in the data, controlling the user's scale is crucial. VIRTUAL DIRECTOR allows the user to shrink down to a very small virtual size, enabling controlled flight around the tiny newly born protostar, or to become large enough to reach across the 18,000 light year dataset. The proper scale enables the user to make sense of the data when immersed within the nested domains.

A background provides motion cues and enhances the perception of depth in visualization. It is particularly desirable when artistically crafting visualizations for large, general audiences. We chose a background to suit the first-star theme: a simulation of dark matter formation over a 100^3 Mpc volume of the early universe, by Norman, Bryan, and O'Shea, also computed with the AMR code ENZO, but as a pure N-body gravitational calculation.

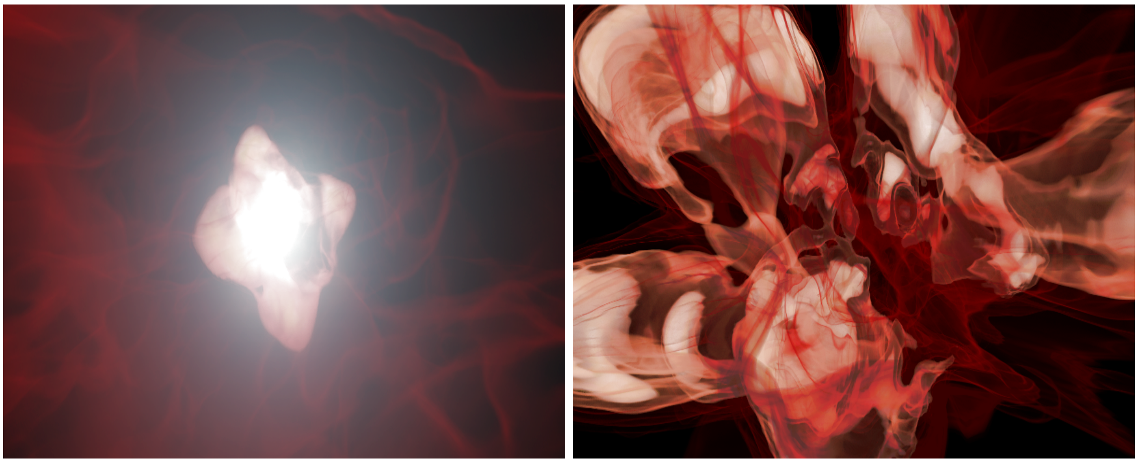

Figure 5.30: The images are renderings of the third dataset for two different time steps and camera positions. The simulation describes the supernova explosion of the star, and consists of 760 time steps with between 6 and 10 levels of refinement and about $1,350$ to $2,500$ grids per time step. *(dataset courtesy of T. Abel, Stanford University)*

Its periodic boundary conditions allowed tiling many copies of the data to cover the sky smoothly. If is most clearly visible in the background of the right image in Figure 5.27.

The dark matter was given in particle form; images were created with the STAR RENDERER, a fast Gaussian-spot particle renderer from PIXAR ANIMATION STUDIOS. Particle velocity, a proxy for mass density, determined the choice of color from a palette of black-body radiation colors.

5.7.3 Results

The volume rendering was carried out on a SGI ONYX2 INFINITEREALITY2 with two RM7 raster managers with 64 MBytes of texture memory. Information about the separate datasets and their rendering times (for a viewport size of 864×486 pixels) is given in the captions of Figures 5.27 to 5.30.

We learned from this project that hardware supported, texture-based volume rendering can be used for broadcast quality rendering of even highly resolved AMR simulations. The VR environment proved to be extremely helpful for defining smooth camera paths deep inside the computational domains on very diverse spatial scales.