Kinetic Simulation of the Magnetosphere
Simulation data from Homa Karimabadi, et al, University of California at San Diego

Advanced Visualization Lab (AVL), NCSA, University of Illinois
Donna Cox, Bob Patterson, Stuart Levy, AJ Christensen, Kalina Borkiewicz, Jeff Carpenter

The AVL worked with astrophysics data scientists to create a narrative journey through the dynamic processes of the sun in a digital fulldome production titled “Solar Superstorms”, narrated by Benedict Cumberbatch, as part of the CADENS NSF ACI-1445176 grant. This visualization represents a part of the story of the dynamic processes of our sun, and how they affect life on Earth.

Homa Karimabadi’s science team conducted the most detailed 2D and 3D global hybrid simulations of the interaction between solar wind and the magnetosphere. These simulations focus on how ion kinetic processes at the bow shock, a standing shock wave in front of the magnetosphere, drive turbulence in a region behind the shock called the magnetosheath. Massive electromagnetic storms on the Sun can reach the Earth, wreaking havoc on our technological systems. Homa’s team simulated their data using a particle-in-cell method to produce rectangular multigrid data on the Blue Waters supercomputer.

The team faced a unique challenge in representing the scientists’ data as thoroughly as possible while working within the constraints of limited data output. The scientists were able to output hundreds of timesteps of 2D slices from the volume data, but only a few dozen full 3D descriptions of the volume, all sampled from an early part of the simulation evolution. Because of the nature of the compute-expensive simulation, the scientists could not afford to re-run the simulation to output intermediate data. After testing several techniques, the team chose a hybrid 3D and 2D approach. The sequence begins with a slow step-dissolving treatment of the 3D data, rendered from the perspective of a continuously moving camera. Then it fades into a treatment of the 2D data, played at the correct relative cadence to match it with the 3D data, and smoothly interpolated across every frame using an image-based technique called “motion flow” that is a feature of commercial compositing software package Nuke. Finally, the team used a supercomputation data analysis and visualization software package called “yt” to trace magnetic field lines through the 3D data. This line data was cycled through the shot’s duration to visually associate the 3D and 2D data, and to give a sense of environment once the 3D volume data had disappeared.

To create interactive previews of scientific datasets, the AVL uses an original open-source software tool called Partiview, which was primarily authored by AVL programmer Stuart Levy. Partiview is able to render particles, lines, triangle meshes, and star-like data and interactively update their visual attributes based on data attributes. To flexibly navigate through these Partiview environments, explore 3D data topology, and develop complex camera choreography in an immersive stereoscopic 4K environment, the team links Partiview with another original software tool called Virtual Director, authored by past AVL programmer Matt Hall and Marcus Thiebaux. Virtual Director is a remotely collaborative camera control and design tool capable of performing or keyframing path splines and editing them during interactive data playback.

Previsualization of this scene focused on the 2D data which had incredible detail, so the Partiview scene was optimized for playback on an image plane representing the 2D data. Geometric magnetic field lines, and the Earth and sun were added as well. This allowed the team to choreograph a camera path that started by facing the lit side of the Earth, and then turning to simultaneously reveal the sun and reveal the turbulence in the magnetosphere that the sun was causing.

The team faced a challenge in rendering the 3D data with embedded geometric features. After attempting a pipeline utilizing Z-buffered occlusion maps in yt that had aliasing limitations, it was discovered the 3D data did not have highly resolved features from its early stage in the simulation, and so it did not look visually different when its volume resolution was reduced. Therefore, the team used a commercial visual effects tool called Houdini to integrate all of the data assets that had been created together. The 3D data was downsampled from the raw data on the Blue Waters supercomputer into a compressed Houdini-native data format using a custom Python script. The magnetic field lines were filtered for artifacts and then splatted into sparse VDB volumes to create an integrated volumetric appearance. The 2D data was rendered on a plane and augmented with a color transfer function and falloff mattes to make it appear to be an organic flying 2D bow shock, removing artifacts that suggested it was a 2D slice from a rectangular grid. The sun was constructed from a glare image oriented toward the camera. The Earth was textured with night and day photography on opposite sides, oriented to show the camera as much human civilization as possible, and an atmosphere was added.

The 3D data and line data were step-dissolved in Nuke using two full render passes with the datasteps updating every second, one with the datasteps offset by one step. These two layers with matching camera positions allowed the team to cross-fade each adjacent pair of datasteps slowly over the course of a full second. Other image layers including the 2D data, sun, Earth, and background starfield were then included in the final composite.