INTERIOR DYNAMICS OF YOUNG STARS REVEALED BY 3D HYDRODYNAMIC SIMULATIONS

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EXECUTIVE SUMMARY

Our current understanding of the evolution of stars is drawn from one-dimensional calculations based on simple phenomenological approaches and fitted observational data. To interpret the data produced from the recent space missions CoRoT, Kepler, and GAIA, as well as to understand new high-quality data from the upcoming missions TESS and PLATO, it is necessary to study realistic stellar conditions using three-dimensional hydrodynamic simulations.

Toward the center of a star, plasma becomes progressively hotter and more dense; convective plumes characterize some layers, while others contain a variety of waves. Mixing of chemically different material and heat between these layers, and the mixing due to the different dynamics within these layers, are basic ingredients needed to predict the course of stellar evolution. This work involves large and physically complex 3D simulations that address the multiscale dynamics of the entirety of the stellar interior, a problem for which Blue Waters is ideally suited.

RESEARCH CHALLENGE

Through simulations of a young, low-mass star, the research team studied convection in a large convective envelope, as well as convective penetration, rotation, and internal gravity waves. The main challenge for the simulations was to design them to be realistic to the stellar interior. The team set up the simulations using a realistic stratification produced with the MESA stellar evolution code and used a realistic tabulated equation of state and opacity in the calculations. To produce realistic simulation results, the group also needed sufficient spatial resolution to accurately reproduce the multiscale flows in the large convection zone and lower radiative zone. They then needed to run these simulations for a long period of simulation time to capture a full range of the dynamics. This is, therefore, a project of large computational scale that requires Blue Waters' unique capabilities.

METHODS & CODES

This project used the MUltidimensional Stellar Implicit Code (MUSIC), a code that has been designed and developed under a European Research Council Advanced Grant over the last six years. MUSIC solves fully compressible fluid equations in a spherical geometry using a second-order finite volume method and MPI–FORTRAN. MUSIC also uses fully implicit time integration in order to cover long windows of stellar dynamics. The time integration algorithm is second-order and centers on a Jacobian–Free Newton–Krylov method using physics-based preconditioning. Each aspect of the design of MUSIC has been chosen to seamlessly extend one-dimensional stellar evolution calculations into three dimensions.

Figure 1: Visualization of radial velocity in 3D simulation of a young sun. Red indicates outward flows while grey indicates inward flows. Simulation performed with the MUSIC code.

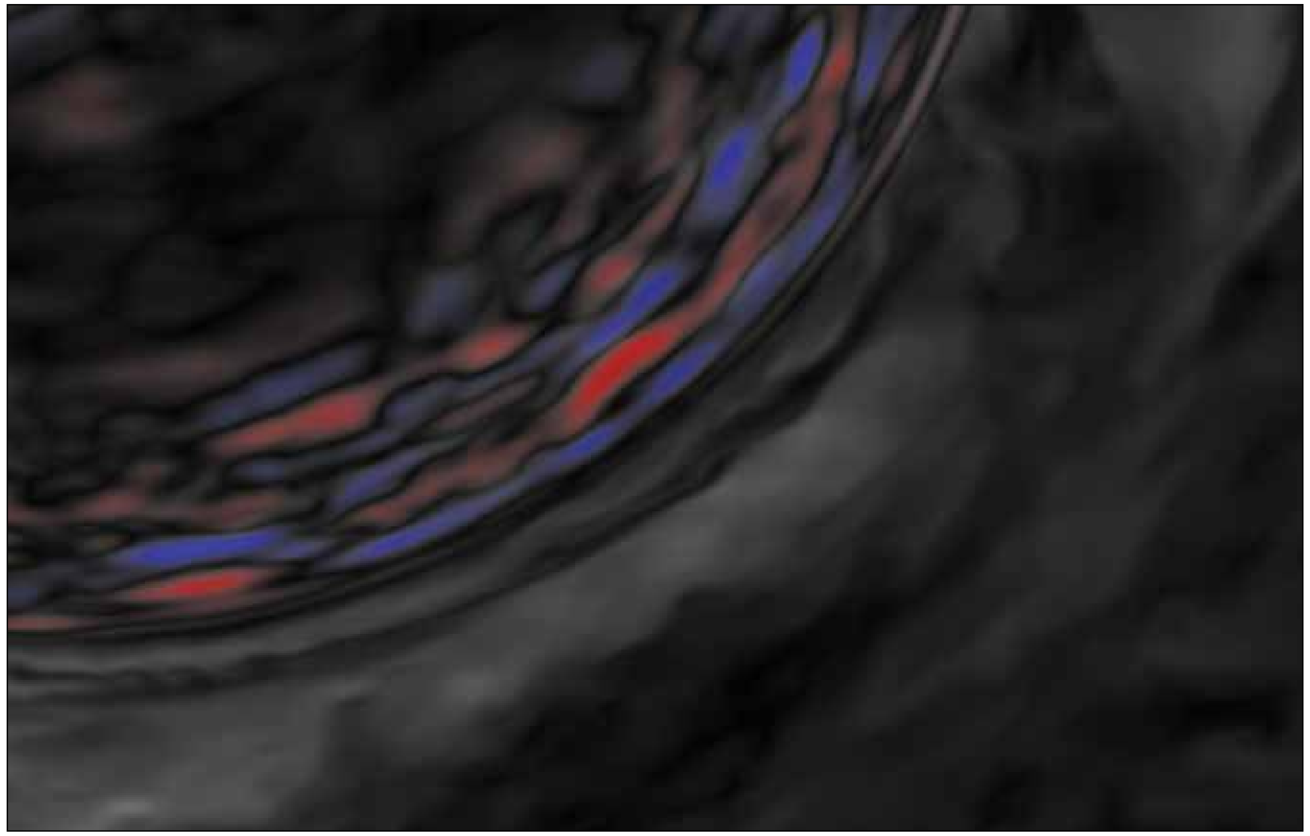

Figure 2: Visualization of large thermal fluctuations, zoomed in around the bottom of the convection zone and the top of the radiative zone of the young sun. Blue indicates large negative thermal fluctuations while red indicates large positive thermal fluctuations. Greyscale shows the velocity magnitude in this region.

RESULTS & IMPACT

Early results from a simulation performed on Blue Waters are shown in Figs. 1 and 2. In Fig. 1, radial velocities are shown in a spherical wedge that fills 80% of the star's radius. Smaller-scale convective flows are visible near the surface, while the extent of these radial flows is larger, deep in the stellar interior.

Although these flows are of a length scale similar to the stellar radius, they also clearly have small-scale features that are important for diffusion and chemical mixing. The research team is currently producing a long time-sequence of data in order to perform a complete statistical analysis of these convective flows and the consequences for mixing when they overshoot the convection zone.

One of the consequences of convective plumes overshooting into the radiative zone is the mixing of colder fluid into a hotter layer, potentially changing the temperature gradients within the stellar interior. Fig. 2 shows that heat becomes trapped in waves that are excited in the overshooting layer. A full study of this phenomenon is underway and will be completed using the simulations currently running on Blue Waters.

This work is expected to result in improved models for stellar evolution, which the researchers expect to be included in open-source code such as MESA. As a result of this project, stellar physicists will be better able to understand how a young star such as that in this project's simulations can evolve into a sun.

WHY BLUE WATERS

The research team has carried out its simulations on Blue Waters because of the large grid size and large number of timesteps necessary for simulations of a star. Simulations of this size would be expected to run continuously for several years on a university-size system and can be completed on Blue Waters in less than a year. Blue Waters' staff played an essential role in the success of this project by installing the Trilinos library, used by MUSIC.