Modeling Convection in Slowly-Rotating Stars

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Abstract:

The behavior of solar-type stars is heavily influenced by their rotation, which slowly decreases over their main-sequence lifetimes. Recent observational results have shown that stars older than our Sun behave differently than younger stars. The behavior of sun-like stars and their changes in rotation rate are determined by the convection in their outer layers. Using the Rayleigh code to create 3D global simulations of stellar convection, we seek to model how rotation rate influences the convection realized in stars at varying ages. These simulations will produce petabyte-scale datasets, which will require specialized numerical tools to analyze and visualize. Here we present the development and initial results of a suite of computational tools to analyze the convection and differential rotation of a sample simulation.

Background:

As a star ages, it's rotation rate slows down. Astronomers have observed that the sun also rotates differentially, meaning that the poles spin slower than the equator. However, as a star ages, this differential rotation slows down. When a star gets slightly older than our Sun, this differential rotation reverses, meaning that the axis will rotate faster than the equator. Using Rayleigh, a code designed to model solar rotation, we hope to build a model of solar rotation that matches our observations and find out the cause of this differential rotation shift. As of today, our simulation is that of a sun-like star with no magnetic field. We would need a significantly more computing power to run a full simulation.

Parameters:

Our model has our dynamo starting its rotation from rest. While this initial condition is not reflective of true solar rotation (the sun does not start from rest), it averages out over enough time iterations such that it is indistinguishable from an initial-rotating star. This parameter also allows us to run the simulation without the need of a supercomputer. We modeled the convection for a sun-like convection zone, from 500 Mm to the solar surface, which is 672 Mm. We were able to model the convection for 265000 1000-second time-steps, which is approximately 8.2 years.

Future Research:

Given more computing power, we would like to model our simulation as more of a dynamo, which is a star with a magnetic field. Further, we would like to alter our rotation rate to simulate that of an older star so that we could model differential rotation like what we have observed in sun-like dynamos.

References:

Featherstone, N.A. & Hindman, B.W., 2016, "The spectral amplitude of stellar convection and its scaling in the high-Rayleigh-number regime," Astrophys. J., 818, 32 {presents anelastic benchmarking results for Rayleigh} DOI: 10.3847/0004-637X/818/1/32

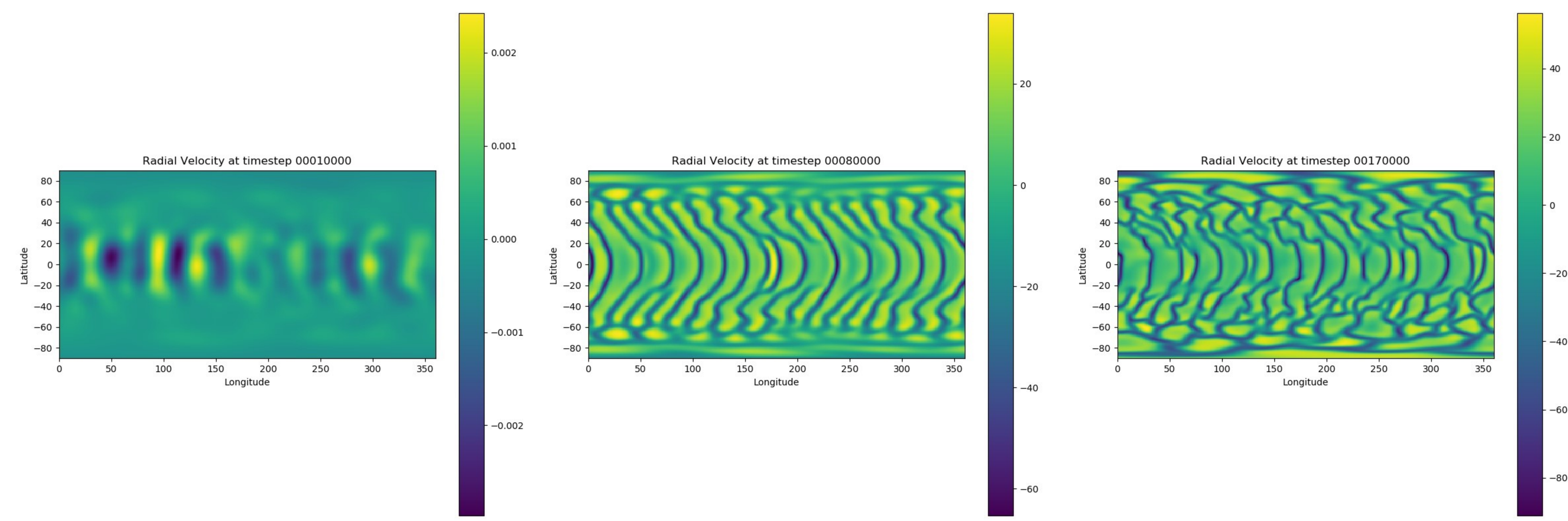
Matsui, H. et al., including Featherstone, N.A., 2016, "Performance benchmarks for a next generation numerical dynamo model," Geochem., Geophys., Geosys., 17,1586 {presents initial performance data from Rayleigh as measured on Intel Sandybridge processors}
DOI: 10.1002/2015GC006159

Howe, R. Living Rev. Sol. Phys. (2009) 6: 1. https://doi.org/10.12942/lrsp-2009-1

Shell Averages:

These plots show the average of all shell slices, and shows how our velocity changes as our radius increases. As expected, our radial velocity maintains a constant velocity when compared to the average. However, it is interesting how our equatorial velocity and our polar velocity changes with respect to radius.

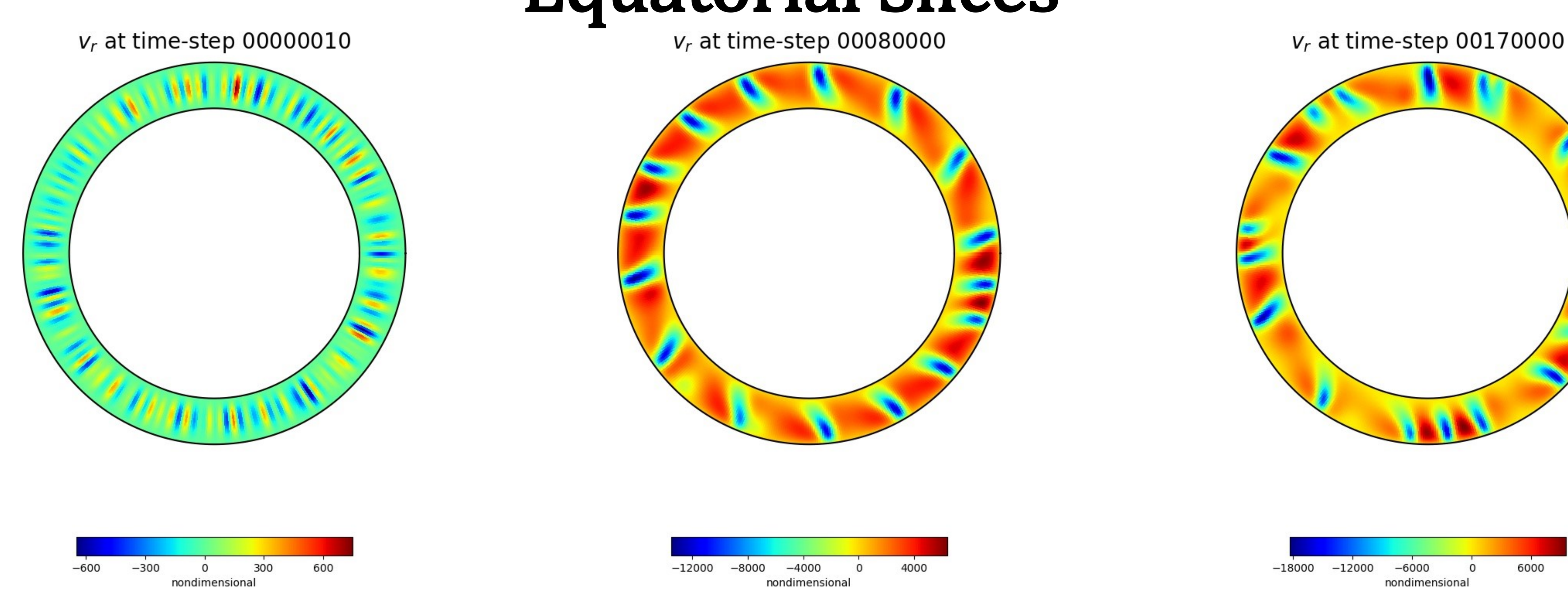
Shell Slices



Shell Slices:

These plots show the radial velocity of the surface of the sun at a given time step. We can see how the convection starts from rest, as we stated in our initial conditions, and goes on to form a more convective rotation.

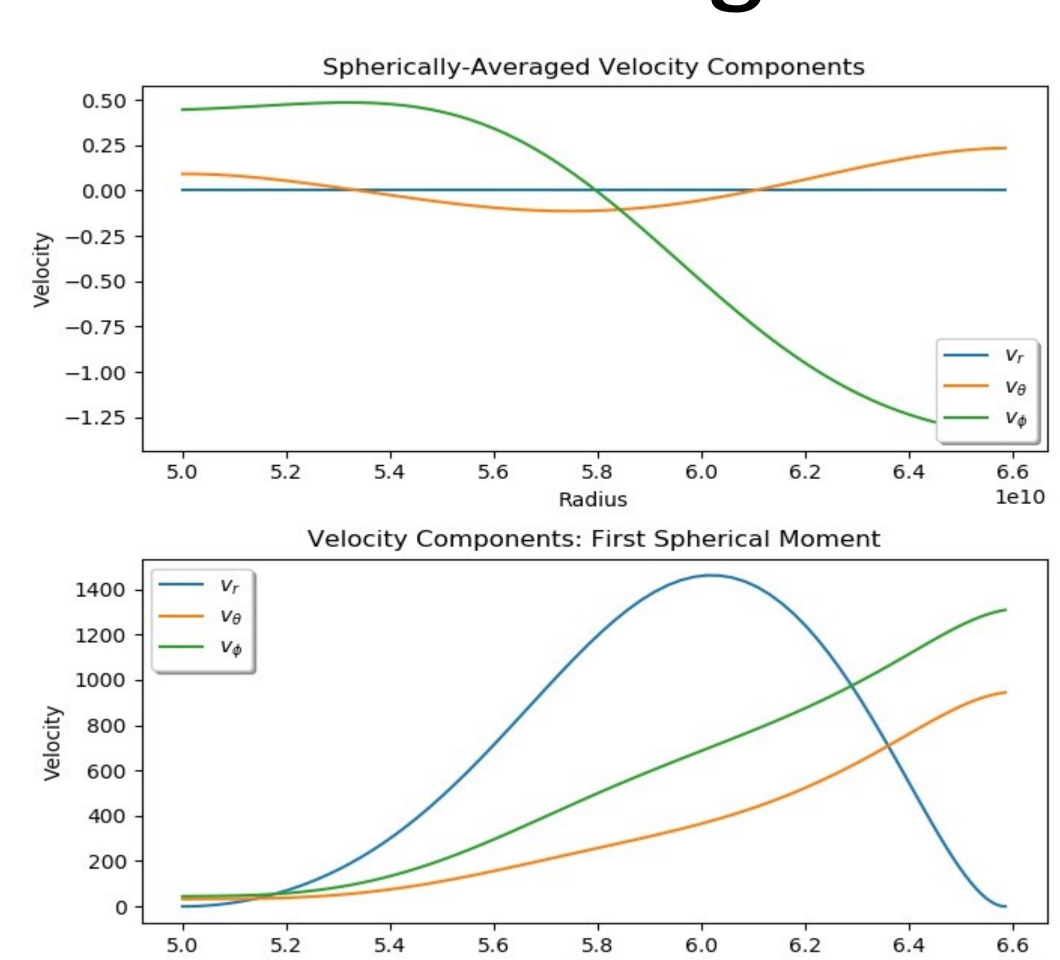
Equatorial Slices



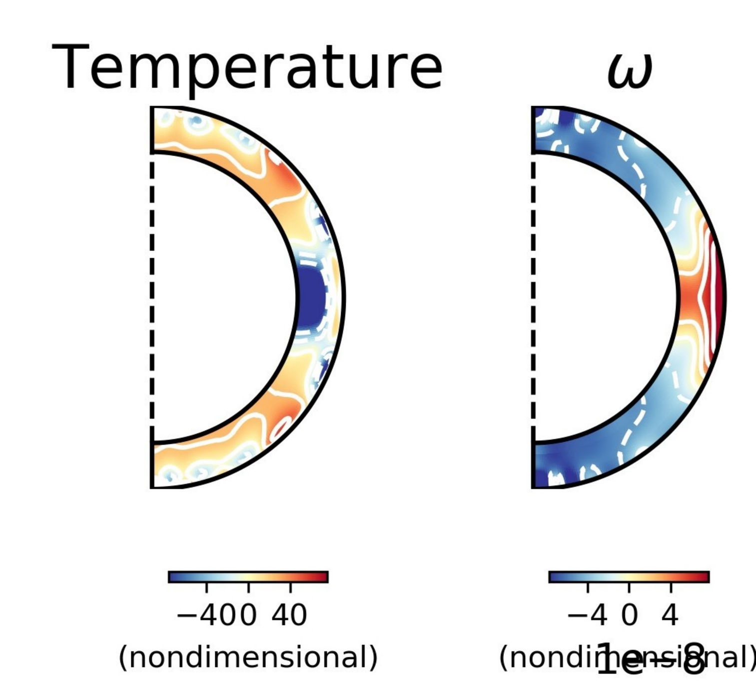
Equatorial Slices:

These plots show the average radial velocity around the equator of the sun. These three graphs show the difference between each data point and the average. Each graph shows this at a separate data time step, which allows us to see what these averages looked like 10000 seconds after starting from rest versus 170 000 000 seconds after starting from rest.

Shell Averages



Azimuthal Averages



Azimuthal Averages:

These plots show the angular momentum and temperature averages between each axis of rotation. We expected this angular momentum averages as it confirms our idea of differential rotation. The blue spot on the temperature average is curious and would require further research to analyze.