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# DYNAMICS AND STRUCTURE OF MAIN-SEQUENCE STARS WITH SHALLOW CONVECTION ZONES

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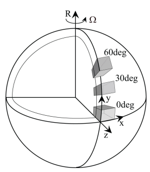
A dramatic increase in observational data from NASA's Kepler, K2, and TESS missions and supporting ground-based observatories has opened new opportunities to investigate the internal structure, dynamics, and evolution of stars and their atmospheres. We present 3D radiative MHD simulations for several main-sequence stars with masses from 1.4 to 1.5 $M_{sun}$. The simulations are performed using the "StellarBox" code developed for modeling stellar turbulent convection and atmospheres with a high degree of realism. This presentation discusses similarities and differences between 3D realistic-type and 1D mixing-length models with regard to structural, thermodynamic, and turbulent property variations from the radiative zone to the convection zone and photosphere.

## 'StellarBox' code (Wray et al., 2018)

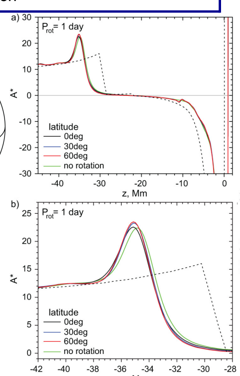
- 3D rectangular geometry
- Fully conservative, Fully compressible
- Fully coupled radiation solver:
- LTE using 4 opacity-distribution-function bins
- Ray-tracing transport by Feautrier method
- 18 ray angular quadrature
- Non-ideal (tabular) EOS
- 4th order Padé spatial discretization
- 4th order Runge-Kutta time integration
- Turbulence models:

- Compressible Smagorinsky model
- Compressible Dynamic Smagorinsky model (Germano et al., 1991; Moin et al., 1991)
- MHD subgrid models (Theobald et al., 1994; Balarac et al., 2010)

- Stellar rotation
- Metallicity effects
- MPI parallelization

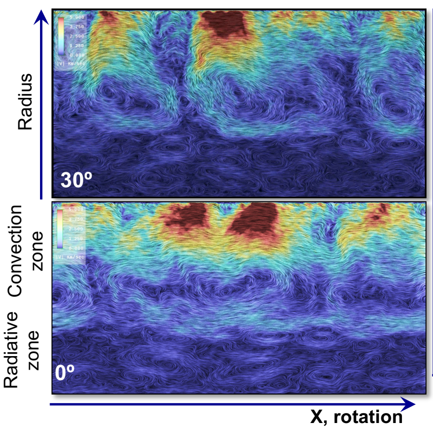



Schematic representation of the stellar models' location relative to the rotation axis of a star.

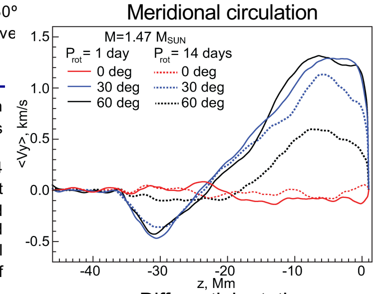


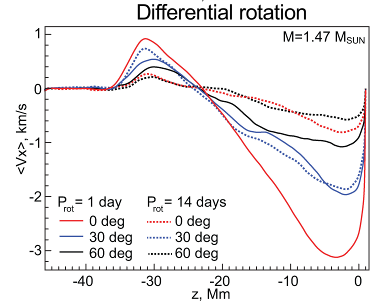

Temperature gradient profiles at three latitudes: 0º (equator, black curves), 30º (blue), and 60º (red) for period of rotation 1 day. The green curve corresponds to the non-rotating case. Thin black dashed curves correspond to the temperature gradient from a 1D mixing-length model.

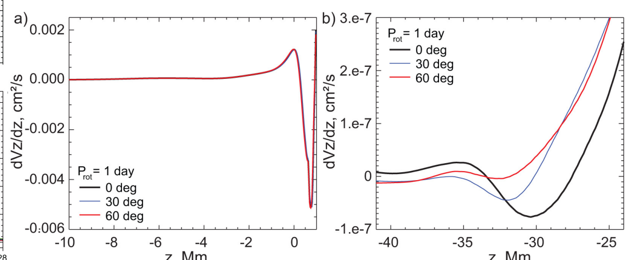
Comparison of the convection zone with period of rotation of 1 day at two latitudes: 30º (upper panel), and 0º (equator, bottom panel). The dynamical structure of the convective patterns is visualized by a particle tracing method.

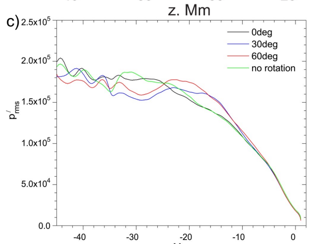



Effect of stellar rotation on the mean velocity profiles for rotation periods of 1 day (solid curves) and 14 days (dotted curves) at three latitudes: 0º (red curves), 30º (blue), and 60º (black). Bottom panel shows radial profiles of the azimuthal velocity, showing differential rotation. Top panel shows radial profiles of the mean velocity field corresponding to the meridional circulation at different latitudes.

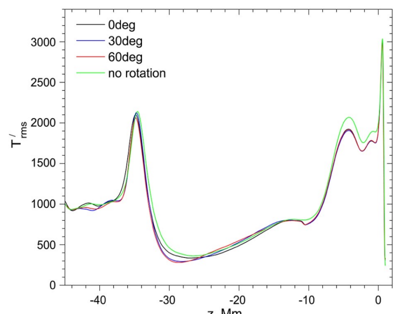


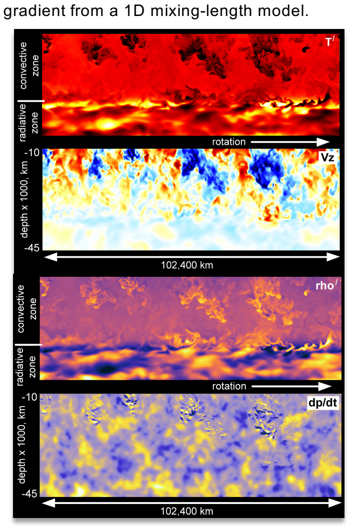




Radial profiles of the time-derivative of the mean vertical velocity, $dV_z/dz$, for the whole computational domain (panel a) and near the tachocline layer (b); gas pressure fluctuations (panel c).




Radial profiles of rms temperature fluctuations for rotating and non-rotating stars.




Vertical snapshots of the bottom part of the computational domain showing (from top to bottom): temperature fluctuations, radial velocity, density perturbations, and time-derivative of the gas pressure.

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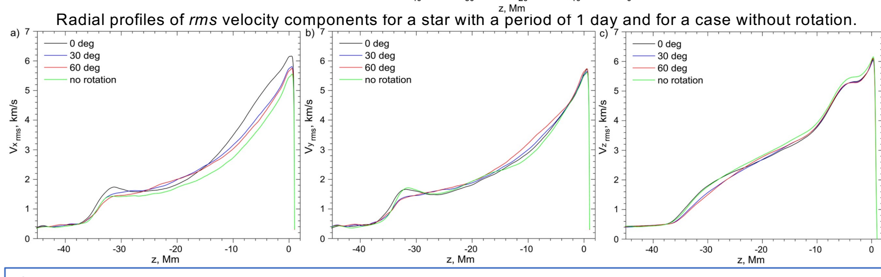
Radial profiles of *rms* velocity components for a star with a period of 1 day and for a case without rotation.




## References

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## Conclusions

- Despite the availability of advanced observational data from modern space and ground instruments, investigation of the dynamics and structure of the surface and subsurface layers of stars is quite challenging. We performed a series of 3D radiative hydrodynamic simulations of an F-type star with mass 1.47$M_{sun}$ in which the entire convection zone and the upper layers of the radiative zone were included in the computational domain.
- The simulation results reveal the formation of an overshoot layer and also multi-scale populations and clustering of the surface granulation. High-speed convective downdrafts of 20 - 25km/s penetrate through the convection zone, form an overshoot layer, and contribute to excitation of internal gravity waves (*g*-modes). These waves are identified near the overshoot layer. At the stellar photosphere, these modes are hidden among strong turbulent convective flows, and only *f*- and *p*-modes are clearly displayed in the simulated power spectra.
- Simulating of effects of stellar rotation, for rotational periods of 1 and 14 days at different latitudes, allowed us to identify the formation of a subsurface shear flow and roll-like convective patterns in the deep layers of the convection zone. The radial profiles of the differential rotation indicate that it is of anti-solar type. The subsurface shear-flow velocity peaks closer to the photosphere at higher latitudes. The meridional circulation profiles do not show a significant difference between 30º and 60º latitudes. The simulation results show that the tachocline layer is located deeper and is less prominent at higher latitudes.