3D MHD modelling of a chromosphere above the sun's convective zone

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Abstract

We report on the extension of the ASH 3D anelastic MHD stellar model to include an atmospheric stable layer (*i.e* not convective). This layer is meant to model the sun's chromosphere within the anelastic approximation limits while coping with the wide range of densities, time and spatial scales between $r = 0.7\ R_\odot$ and $r = 1.05\ R_\odot$. With this approach we will not impose boundary conditions at the photosphere. This is a necessary condition to correctly capture the dynamics of the transition between the CZ and the chromosphere. In particular, we aim at: 1) studying flux emergence phenomena either at the scale of a fluxtube and at the global scale; 2) investigate the magnetic flux transport processes in a *full MHD* atmospheric environment (*i.e* unlike in pressureless and potential magnetic field models). Convective overshoot into the stable atmospheric layer is observed in a region $\sim 0.01\ R_\odot$ thick . Convective "blobs" excite waves at the top of the CZ, which propagate upwards into the atmosphere.

1. Introduction

Subject:

- flux emergence
- photospheric/chromospheric shearing
- sub-photospheric forcing of magnetic loops
- feedback from the sheared loops onto the photosphere

Reputedly a hard problem to study;
The CZ→chromosphere transition is characterised by
- a very strong stratification
- very different length scales
- very different dynamical time scales

Connections between both media are still poorly understood.

Atmospheric and sub-photospheric phenomena are usually studied separately

Atmosphere:
- Coronal loops
- Jets, plumes
- CME triggering
- Numerically, photosphere as a lower boundary condition (see Grappin et al., 2008; Pinto et al., 2010, for a discussion)

Below the photosphere:
- Dynamo models
- Flux rope generation and emergence
- Sunspot formation and evolution
- photosphere as an upper boundary condition

In between:
- Some models address specifically the CZ/atmosphere transition, but on small scales (*i.e* few tens of Mm)
- **No large-scale studies**

∴ **Need to move away from the "photosphere as an interface/impenetrable wall" paradigm**

2. Background profile

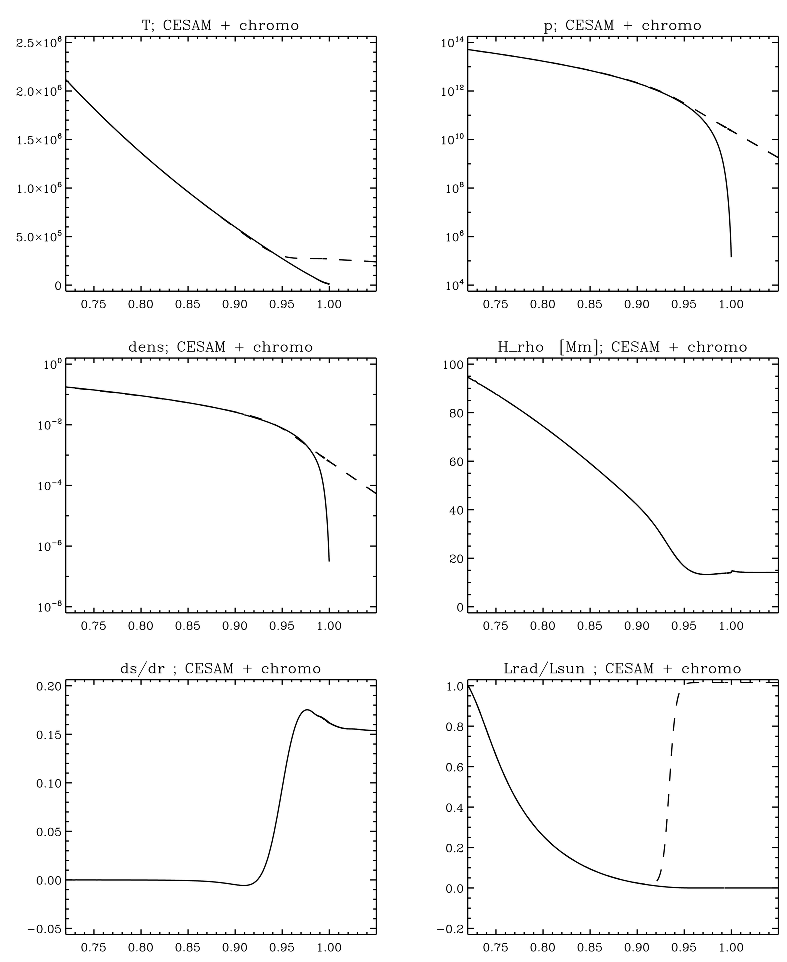

Figure 1: Background hydrostatic radial profiles. A CESAM solar profile is extended up to 1.05 $R_\odot$ assuming an idealised isothermal chromosphere. The radiative flux is defined accordingly. The continuous line shows the original CESAM profiles, and the dashed line shows the extended profile (the exceptions are the H_ρ and dS/dr profiles, for which only the extended profiles are shown).

Numerical Model
We use the ASH 3D stellar code (references...).
- Anelastic MHD
- 3D, parallel, high resolution spherical grid (Clune et al., 1999; Miesch et al., 2000)

Initial Conditions
- Fit to a CESAM solar profile in the CZ
- Transition to a nearly isothermal chromosphere

We explicitly set the chromospheric temperature to $\sim 4\times$ the standard 6000 K for numerical stability. We don't include a coronal *Transition Region*, but rather extend our chromosphere up to 1.05 $R_\odot$.

The 1D background reference state is calculated this way:
1. Fix a given density profile $\rho(r)$ (see fig. 1)
2. Use the temperature profile $T(r)$ in fig. 1 (top left panel) as an initial guess
3. Assume hydrostatic equilibrium and, using the relation

$$\frac{1}{T}\frac{dT}{dr} + \frac{1}{\rho}\frac{d\rho}{dr} = -\frac{g}{R_c T}$$

refine $T(r)$ using the Newton-Raphson iterative method.

3. Radial energy flux balance

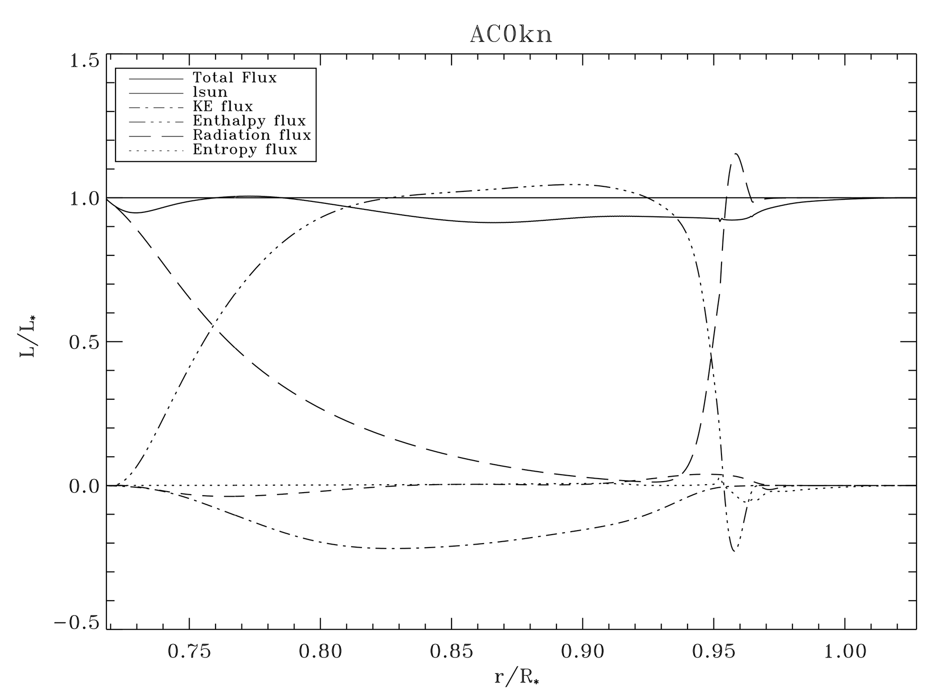

Figure 2: Energy flux balance in the radial direction in "units of solar luminosity". Note the layer of negative enthalpy flux ($0.95 - 0.96\ R_\odot$), which indicates convective overshoot into the photosphere. Note also that the all the star's luminosity is transported radiatively at the top.

4. Convection pattern

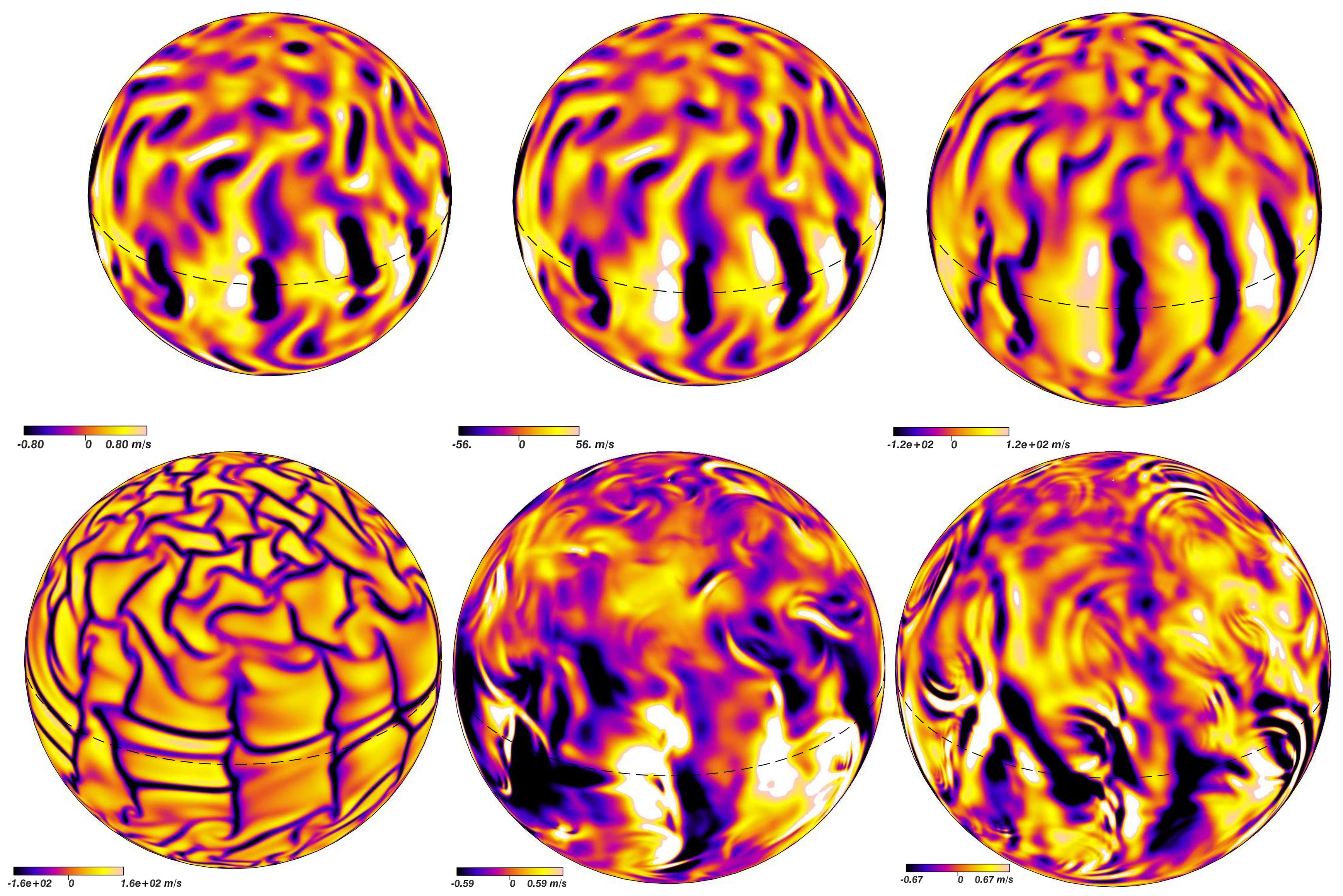

Figure 3: Radial velocity V_r at spherical surfaces with different radii. From left to right, top to bottom: $r = 0.72,\ 0.75,\ 0.83,\ 0.93,\ 0.99,\ 1.03\ R_\odot$.

Convection

The fig. 3 shows the radial velocity V_r at different radii between the bottom of the convection zone and the top of the chromosphere. The atmospheric layers are represented in the last two images. *Cf.* fig. 2, which shows the enthalpy radial flux as a function of r.

Note the granular pattern showing wide upflows and thin downflows at the top of the CZ. Propagating wavefronts can be identified in the upper non-convective layers, while any traces of the underlying granular motions fade away.

5. Differential rotation

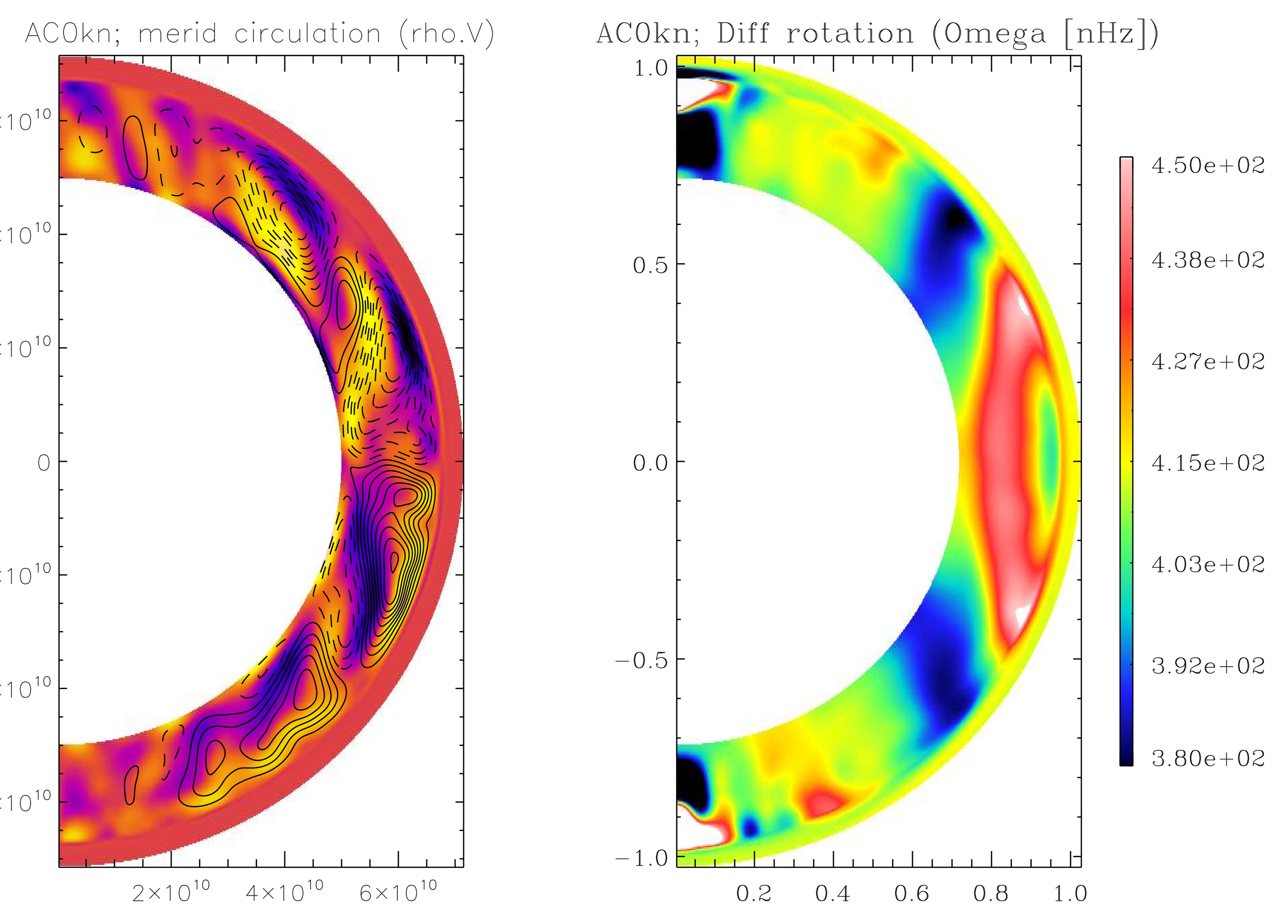

Figure 4: Time-averaged meridional circulation (left) and differential rotation (right). Distance units are cm on the left plot, and $R_\odot$ on the right plot. The colourscale on the left plot represent ρV_θ (normalised to unity) and the black contours are streamlines of $\rho \mathbf{V}_{\mathbf{poloidal}}$. On the right plot, the colourscale represents the azimuthal rotation rate in nHz.

6. Conclusions

- We extended the ASH stellar numerical model in order to include a atmospheric layer above the solar convection zone. The photosphere now lies within the numerical domain, and isn't treated as a boundary surface.
- This atmospheric layer models the sun's chromosphere (but one spanning a wider radial domain – the coronal *Transition Region* isn't included). Radiation dominates the energy transport in the chromosphere, which is stable in respect to convection.
- Convection *overshoots* into the chromosphere. Waves are excited there and then propagate upwards.
- The atmospheric layer shows some prograde differential rotation, but not with the same profile as the CZ/photosphere. It rotates slower and more uniformly.
- Work in progress: Study flux tube emergence into the chromospheric layer; interaction of the dynamo-generated magnetic fields with the atmosphere.

7. References

Clune, T. C., Elliott, J. R., Miesch, M. S., Toomre, J., & Glatzmaier, G. A. 1999, Parallel Computing, 25, 361
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