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SIMULATIONS OF THE SOLAR ATMOSPHERE AND SOLAR LIMBS

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Abstract. We perform simulations of the solar atmosphere either using the 1D hydrostatic code Atlas12 or the 3D (magneto)hydrodynamic code Stagger. The former numerical tool relies on a phenomenology of convection whereas the later one addresses the surface convection directly and accounts for its dynamical effects. Once the average atmosphere stratification is obtained it is used to perform radiative transfer at speficic wavelengths in order to compute the solar limb darkening. We report a ≈ 60 mas shift between inflection point positions of limb profiles computed from 1D and 3D models. This is due to turbulent support present in 3D simulations but not 1D. We further report a slight decrease of the turbulent support when a moderate magnetic field is included in the simulation which suggests that the solar radius should be anti-correlated with the solar activity cycle.

Keywords: Solar atmosphere, Magnetic activity, Simulation, Limb darkening.

1 Introduction

In the few thousands kilometers around the solar surface, temperature and density vary by many orders of magnitude, the medium goes from optically thick to optically thin and from mostly ionized to mostly neutral (Stein & Nordlund 1998). The convective flow is compressible and affected by magnetic activity. All these phenomena make the solar surface difficult to model and to understand. Yet solar and stellar surfaces are important for numerous reasons. Some are related to the interior of the star: surface physics sets the boundary conditions to the stellar structure and evolution. It affects absolute oscillation frequencies (Turck-Chièze, et al. 1997) in a way that remains to investigate (Rosenthal et al. 1999). Some are related to the environment of the star: the dynamics of surface physics has a direct impact on planets atmospheres and likely on their climates.

The work we present here explores the effects of the solar surface dynamics from the point of view of 3D simulations and 1D modelling. We focus on the limb darkening at the edge of the solar disk and at the wavelengths of observation of the SODISM instrument aboard the Picard satellite (215, 393, 535, 607 and 782 nm) and the HMI instrument (617 nm) aboard the SDO satellite. Picard (Thuillier et al. 2006) and SDO (Pesnell et al. 2011) spacecrafts have been launched on June 15 2010 and February 11 2010 respectively to address the solar surface dynamics. For the sake of brievity results only on a few of these wavelengths are reported here. After describing our simulations and method in the next section, we show the effect of turbulent support on limb profiles as deduced from 3D and 1D simulations of the solar atmosphere. Then we show the effect of a moderate horizontal magnetic field entering the simulation domain before concluding.

2 Method

We proceed in two steps. First, we perform a 1D or 3D solar atmosphere calculations adopting the recent Asplund et al. (2009) composition. This provides temperature, mass density, and electron density average stratifications. Subsequently these structures are used to perform radiative transfer for the wavelengths of interest: the wavelengths of current observation by the SODISM instrument aboard Picard satellite and the

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HMI instrument aboard SDO satellite. In both 1D and 3D atmospheres cases the simulation domain starts nearly 1 Mm above Rosseland optical depth τ_{Ross} unity where $\rho \approx 10^{-10}$g.cm^{-3} and $\tau_{\mathrm{Ross}} \approx 10^{-7}$. The 1D simulation region extends down to $\tau_{\mathrm{Ross}} = 100$ whereas the 3D simulation extends deeper below the atmosphere at $\tau_{\mathrm{Ross}} \approx 2\,10^7$.

The 1D atmosphere calculation is made with the `Atlas12` code (Castelli 2005). The version of the code we use relies on the (Canuto, Goldman & Mazzitelli 1996) phenomenology for surface convection where we consider that the characteristic length scale for convection is a fraction of H_p the pressure scale height. We chose $\Lambda = 0.5H_p$ as a characteristic convection length. Atlas12 does not account for the dynamical effects of convection such as turbulent pressure. It also ignores the magnetic field and its consequences.

The 3D atmosphere calculations are made with the Stagger code (Stein & Nordlund 1998). Stagger accounts directly for surface convection dynamics and optionally solves the equation of magnetic induction. The simulation domain corresponds to a box of 6 by 6 Mm horizontally and 4 Mm vertically that straddles the solar surface. We solve explicitly the equations of compressible hydrodynamics over 240^3 meshes. The average stratification of a quantity is obtained from a series of 3D snapshots. For a snapshot we consider the horizontal average of the quantity. The vertical profiles that are obtained this way for different snapshots in time are then averaged.

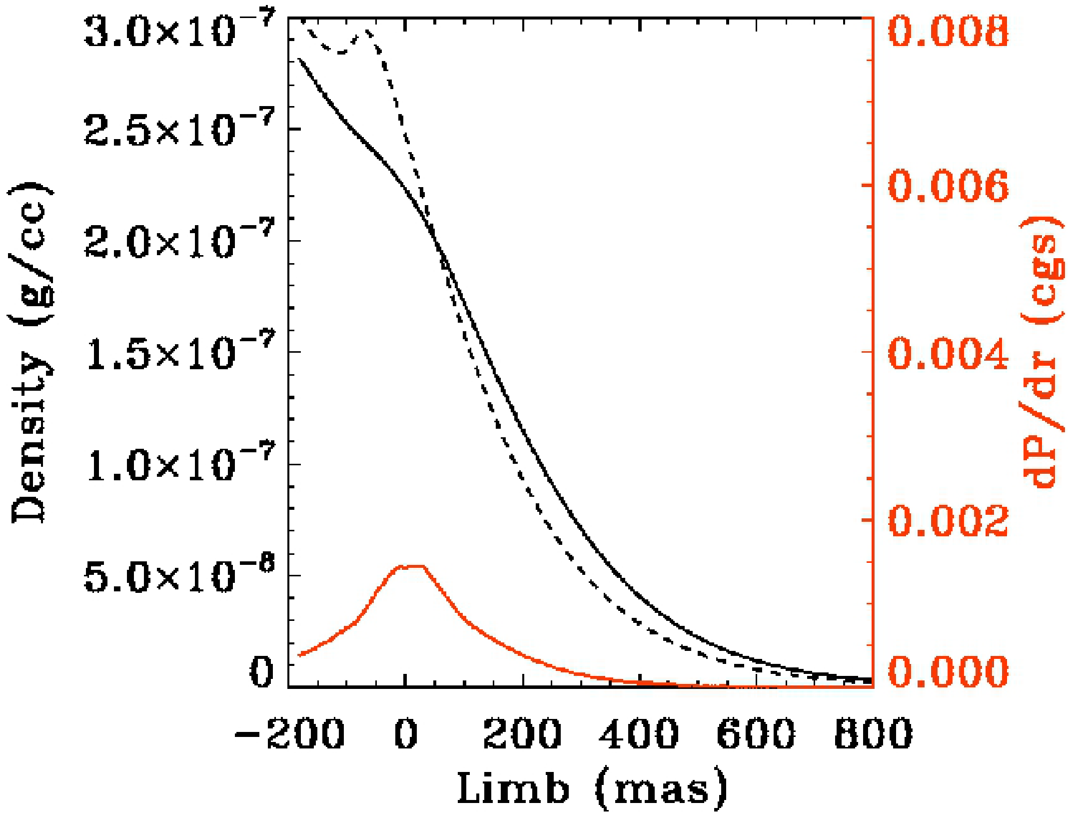

Fig. 1. Density as a function of the distance on the solar limb in milli arcseconds. Solid line: average from 3D simulations. Dashed line: density of the 1D Atlas12 model. Red line: turbulent pressure gradient as a function of the distance on the limb.

3 Limbs and turbulence

Figure 1 compares the vertical density profile computed from averages of 3D Stagger simulations to the 1D density profile obtained with Atlas12. The density is given as a function of the angular distance in milliarc second at the edge of the solar disk. The 3D density is above the 1D density in the higher solar atmosphere because the 3D simulations account for the turbulent pressure whose gradient is also shown on Figure 1 . The

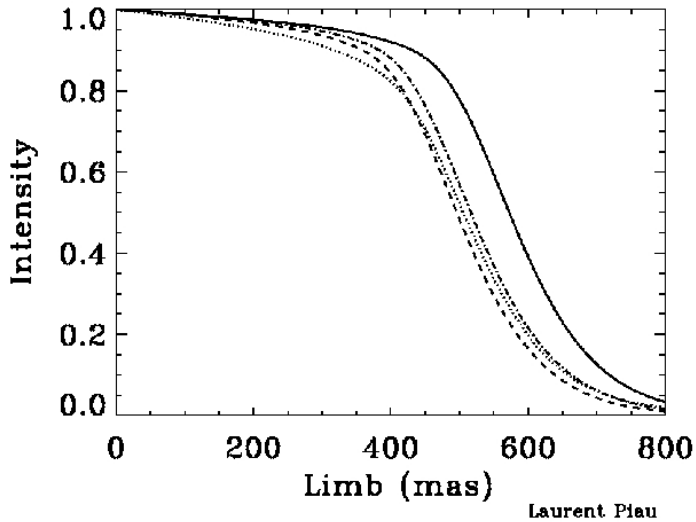

Fig. 2. Light intensity profiles estimated at 782.4 nm from various atmosphere models. The X-axis is the distance on the limb in milli arcseconds. The differents tracks correspond to different models and the intensity is normalized to unity at the origin of the X-axis. The solid line comes from our 3D Stagger simulations. The dot-dashed line comes from our 1D Atlas12 model. The other lines are from other 1D atmosphere calculations.

turbulent pressure is given by:

$$P_{turb} = \rho(\overline{v_z^2} - \bar{v}_z^2) \tag{3.1}$$

with ρ, the density and v_z, the vertical velocity. The gradient of turbulent pressure lifts the atmosphere simulated in 3D but is absent from 1D models which by nature do not include the 3D convective movements.

The 1D/3D shift is to be found again in the Figure 2. There, the darkening profile based on the 3D calculations is pushed away from the limb with respect to the 1D calculations. The 1D based profiles were either computed by us or adapted from the previous work by Thuillier et al. (2011). The origin of the horizontal axis of Figure 2 corresponds to the optical depth unity at 500 nm. The luminosity intensity profiles of the various models have been normalized to one at this origin. The 1D/3D angular shift is about 60 mas at the inflection point of the limb which represents 40 km at the distance of the Sun. These limb profiles illustrate how accurate the limb darkening profiles could constrain the surface turbulent pressure provided one is able to establish the precise direction of optical depth unity at or near 500 nm. This last point clearly is an observational challenge. Besides the shift from 1D to 3D atmosphere models the limb profiles have very similar shapes. In particular we checked that the full width at half maximum of the derivative of a limb profile (the width of the limb) does not depend on the atmosphere model whatever the wavelength that is considered.

4 Magnetic effect

The Stagger code version we use can take into account the magnetic field in the following manner: the plasma injected in the simulation box from below carries a magnetic field of given density and direction. Then the equation of induction is solved over the simulation domain. We report here on the first configuration of magnetic field injected in the domain we have explored. For this configuration, the incoming field is horizontal and 0.25 kiloGauss in intensity. The left panel of Figure 3 shows how the turbulent support changes between the purely hydrodynamical 3D simulation and the magnetohydrodynamical 3D simulation. The peak of gradient of turbulent pressure decreases by 20 percent with respect to the non magnetic simulation. This has the consequence of diminishing the turbulent support to the atmosphere and the right panel of Figure 3 shows how the limb darkening profile changes. We predict that when solar surface magnetism is stronger the solar radius should be smaller by a few tens of milliarcseconds. This conclusion however supposes that the solar activity does not affect the solar radius in regions deeper than the region we simulate and upon which our simulation provide no indications.

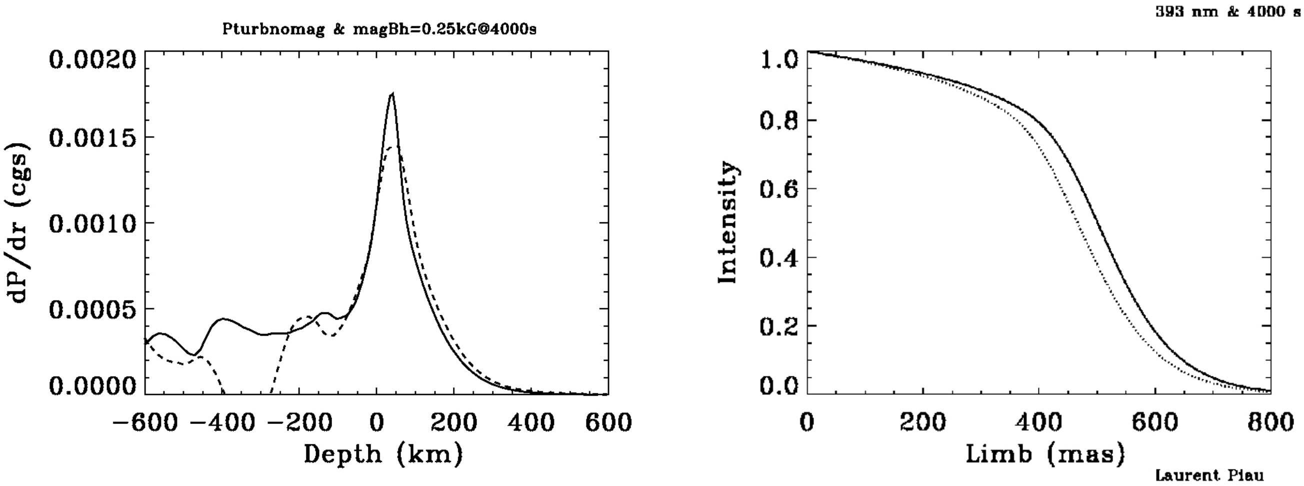

Fig. 3. Left: Turbulent support as a function of altitude in the solar atmosphere. Solid line: no magnetic field, Dashed-line: horizontal incoming magnetic field of 0.25 kG at the bottom of the simulation domain i.e. 3 Mm below Rosseland optical depth unity. **Right:** Light intensity profiles estimated at 393 nm from two Stagger atmosphere 3D models. The X-axis is the distance on the limb in milli arc seconds. The solid line corresponds to the non magnetic simulation. The dotted line corresponds to the magnetic simulation with a 0.25 kG incoming field.

5 Conclusion

We compute 1D hydrostatic and 3D hydrodynamic solar atmosphere models and use these models to compute the average limb profile at specific wavelengths. We then compare the 1D and 3D calculations. While our 1D calculation is in agreement with limb profiles estimated from previous 1D atmospheres, the limb profile estimated from the 3D simulations shows a significant shift with respect to those based on 1D. The shift is due to the turbulent pressure support of the atmosphere and reaches approximately 60 mas at the inflection point position of the limb profile (Figure 2). This suggests that accurate measurements of the limb darkening profile can constrain the dynamics in surface and subsurface solar layers. Further we performed a magnetohydrodynamical simulation. The turbulent support decreases when a moderate horizontal magnetic field of 0.25 kG is caried by the plasma entering the simulation at 3 Mm below the surface (Figure 3). The direct effect is that the atmosphere extension diminishes. Provided the solar radius is estimated from the inflection point position of the limb profile and that activity does not affect the radial mass distribution deeper than 3Mm below the surface, we anticipate a decrease of the solar radius the order of a few 10 of mas when the star goes from the minimum to the maximum of surface activity.

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References

Asplund, M., Grevesse, N. Sauval, A. J. Scott, P., 2009, ARA&A 47, 481

Canuto, V. M., Goldman, I., Mazzitelli, I., 1996, ApJ, 473, 550

Castelli, F., 2005, MSAIt, 8, 25

Pesnell, W. D., B. T. Thompson, and P. C. Chamberlin, 2011, Solar Phys., submitted

Rosenthal, C. S., Christensen-Dalsgaard, J., Nordlund, A., Stein, R. F., Trampedach, R., 1999, A&A, 351, 689

Stein, R. F., Nordlund, A, 1998, ApJ, 499, 914

Thuillier, G., Claudel, J., Djafer, D., Haberreiter, M., Mein, N., Melo, S. M. L., et al., Solar Phys. 268, 125

Thuillier, G., Dewitte, S., Schmutz, W., 2006, Adv. Space Res. 38, 1792

Turck-Chièze, et al., 1997, Solar Phys. 175, 247