Improving Transmission Spectroscopy with Limb Darkening derived from 3D Models

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3D hydrodynamical stellar model atmospheres

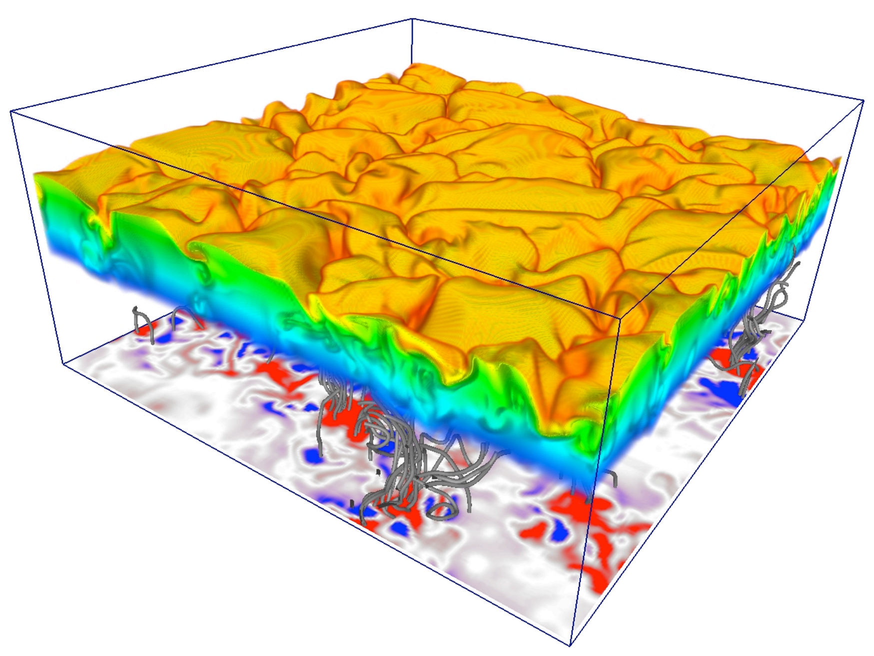

Figure 1: Temperatures and velocities in a 3D model atmosphere

3D hydrodynamical simulations of stellar surface convection provide a realistic description of the atmospheres of late-type stars. The stellar surface is represented in a 3D box (Fig. 1), which covers the photosphere and the top of the underlying convection zone. Hot plasma is free to enter and leave the box at the top and at the bottom boundaries, while the horizontal boundaries are periodic.

Convective motions form bright granules and dark intergranular lanes, which influence the atmospheric temperature stratification and emitted radiation (e.g., Stein & Nordlund, 1998).

Transiting exoplanets

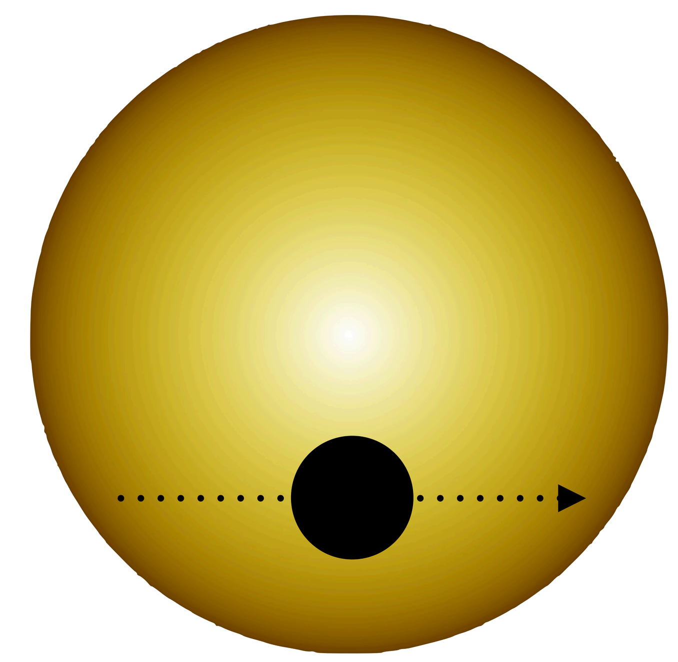

Figure 3: Limb-darkened star and transiting exoplanet

A transiting exoplanet eclipses the stellar disk and samples its surface brightness distribution during the transit. The limb darkening effect causes intensity to reach a maximum in the disk center and decrease outward. The more accurately the brightness distribution is known, the more precisely can the transit light curve be analyzed: less free parameters need to be included in the fit, and fixing limb darkening breaks a degeneracy with transit depth (Sing et al., 2011).

At the same time, an observed transit light curve constrains the atmospheric temperature structure that gives rise to the surface brightness distribution. The observations can therefore be used to test the accuracy of stellar model atmospheres.

Temperature structure of 3D models and 1D models

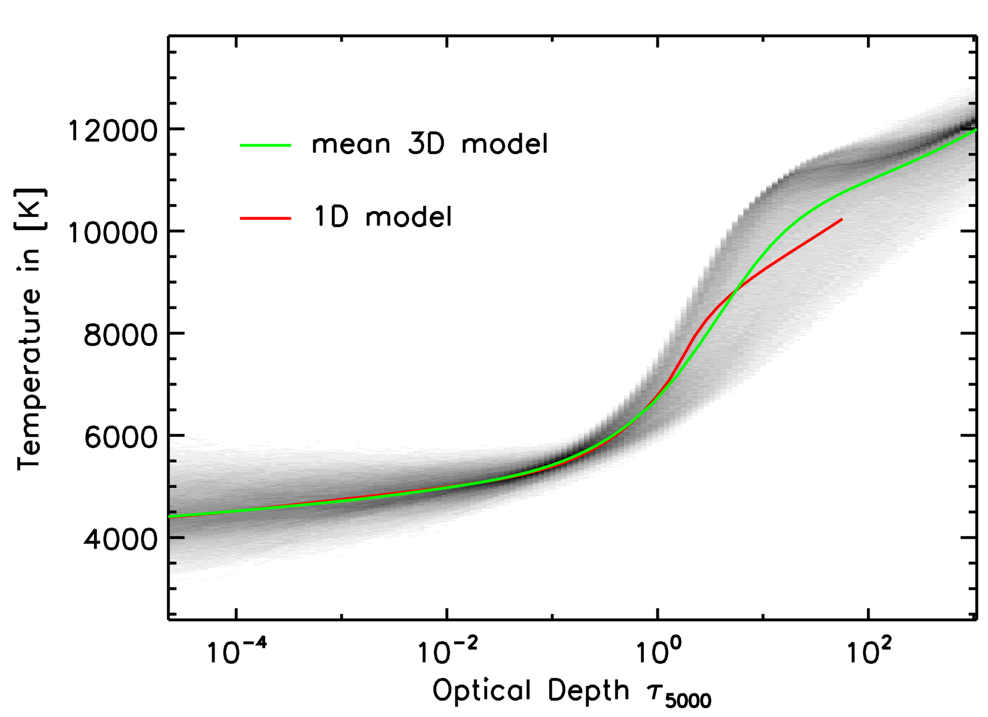

Figure 2: Temperature stratifications of a 3D model atmosphere and a 1D MARCS model

The 3D model contains a distribution of temperatures, which exhibits steeper gradients with optical depth in granules and shallower gradients in intergranular lanes (gray shades in Fig. 2). Averaging over surfaces with constant optical depth and over time yields a mean gradient (green line) that is shallower around the optical surface at τ_{5000}=1 than the gradient of a 1D MARCS model with the same stellar parameters (red line).

3D models reproduce the solar temperature structure with better accuracy than 1D models (Asplund et al., 2009, and references therein).

HST transit observations of HD 209458b

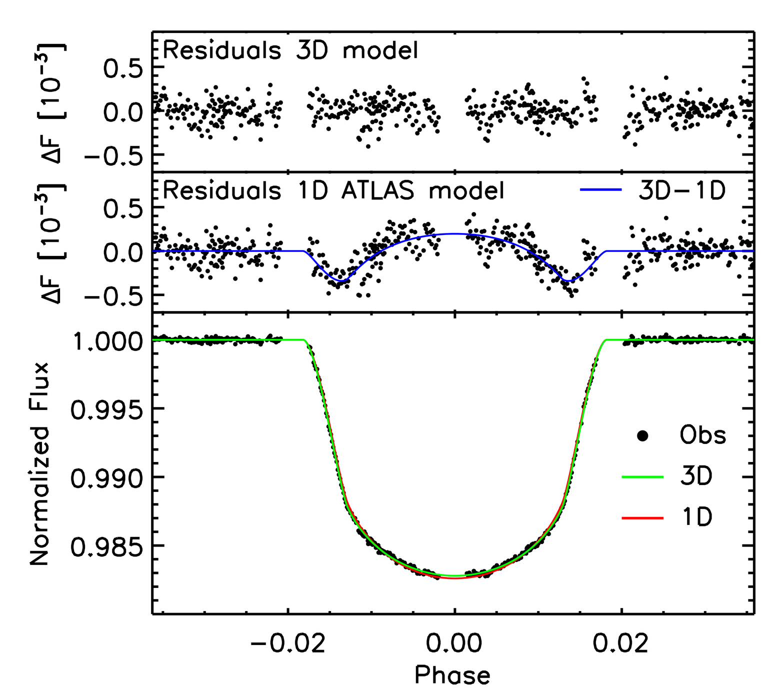

Figure 4: HST transit light curve (Knutson et al., 2007) and fits

The very high S/N light curves that can be observed with the HST (Fig. 4) provide an excellent tool to analyze exoplanetary atmospheres and test the temperature structure of stellar model atmospheres. The 3D model produces a much better fit (green line) than the 1D ATLAS model (red line), exhibiting no systematics in the residuals (upper panel). The characteristic deformation of residuals in the 1D prediction (center panel; see also Knutson et al., 2007) matches the deviation between the models (blue line).

Light curve fits with 3D limb darkening predictions reach the same quality as a direct fit of limb darkening, but with fewer free parameters (Sing et al., 2011).

Conclusions

Limb darkening predictions from 3D hydrodynamical models of stellar atmospheres lead to light curve fits that rival the quality of direct fits of the limb darkening coefficients, but with fewer free parameters. This breaks the degeneracy between limb darkening and transit depth, leading to more accurate transmission spectra and thus improving our understanding of the structure of exoplanetary atmospheres (Sing et al., 2011).

A comparison with the predictions of 1D models reveals that 3D models produce a more realistic temperature stratification, following the success of similar tests with solar observations (Asplund et al., 2009).

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References

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