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Toward the analysis of waves in the solar atmosphere based on NLTE spectral synthesis from 3D MHD simulations

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Abstract. From the analysis of Dopplergrams in the K I 7699 Å and Na I 5890 Å spectral lines observed with the Magneto-Optical filter at Two Heights (MOTH) experiment during the austral summer in 2002–03 we find upward traveling waves in magnetic regions. Our analysis shows that the dispersion relation of these waves strongly depends on whether the wave is detected in the low-beta or high-beta regime. Moreover, the observed dispersion relation does not show the expected decrease of the acoustic cut-off frequency for the field guided slow magnetic wave. Instead, we detected an increase of the travel times below the acoustic cut-off frequency and at the same time a decrease of the travel time above it. To study the formation height of the spectral lines employed by MOTH in greater detail we are currently in the process of employing 3D MHD simulations carried out with CO^{5}BOLD to perform NLTE spectral synthesis.

Key words. MHD – magnetic fields – Line: profiles – waves – Sun: activity – Sun: chromosphere – Sun: faculae, plages – Sun: oscillations

1. Introduction

The physics of the chromosphere and corona is most important for an understanding of the formation and variability of the solar UV/EUV radiation. However, the heating mechanism that causes the rising temperature profile of the upper chromosphere is not fully understood. In particular, the reason why the Sun shows a rising temperature profile over all phases of the solar cycle is still an open question.

A number of potential heating mechanisms of the solar chromosphere and corona are, e.g., low-frequency magnetoacoustic gravity (MAG) waves (Jefferies et al., 2006; McIntosh & Jefferies, 2006), the Farley-Bune-

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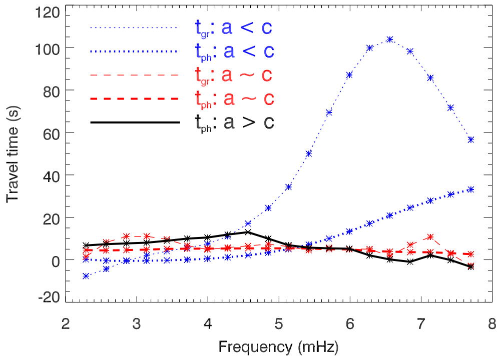

Fig. 1. Observed dispersion relations from the analysis of the Doppler signal observed with MOTH. The thin lines denote the phase travel time and the thick lines the group travel times. The different line styles denote whether the travel time was derived from a magnetic or non-magnetic region, i.e., the dotted line corresponds to areas on the solar disk where $a < c$, the dashed lines where $a \sim c$, and the solid line where $a > c$. For details see Haberreiter & Finsterle (2010).

man instability (Fontenla et al., 2008), coronal heating from Alfvén waves (Cranmer et al., 2007), nanoflares (Patsourakos & Klimchuk, 2009), and heating processes of the corona that are rooted in the chromosphere (De Pontieu et al., 2009).

The ultimate aim of this work is to study the energy provided by MAG waves. Theory predicts that different types of MAG waves exist in the solar atmosphere (Schunker & Cally, 2006; Cally, 2007). They can couple at the height where the magnetic pressure equals the gas pressure, exchange energy, and thereby convert into a different wave type. Moreover, because of partial mode conversion, theory predicts that more than one wave type is likely to exist on both sides of the conversion layer. These processes are already well understood from a theoretical point of view, however mode conversion has not yet been unambiguously identified in observations.

The unambiguous identification of the different wave types from the observations is however a challenging task. To clearly disentangle the various wave types it is crucial to determine the observational heights of the instrument with respect to the magnetic canopy, as has been pointed out by Bogdan et al. (2003). From the Magneto-Optical Filter at Two Heights experiment (Finsterle et al., 2004, MOTH) and the Michelson Doppler Imager observations (Scherrer, 1998, MDI) onboard the NASA/ESA Solar and Heliospheric Observatory (SOHO), Haberreiter & Finsterle (2010) determined the group and phase travel times of the observed MAG waves depending on the $a = c$-layer, i.e., the layer where the sound speed equals the Alfvèn speed, with respect to the observational height of the K I 7699 Å and Na I 5890 Å lines. Figure 1 gives the dispersion relation for the cases where $a > c$, $a \sim c$, and $a < c$; for details see Haberreiter & Finsterle (2010).

From this analysis it is clear that the conversion layer changes the type of wave that is observed. The main question that needs to be answered is to what extent is the wave converted from a slow acoustic mode to a fast magnetic mode (Cally, 2007). The observed dispersion relation has the potential to shed light on this matter. However, the dispersion relations derived from the observations can only be fully understood through the analysis of wave propagation from numerical simulations. We will use 3-dimensional (3D) MHD simulations carried out with CO^{5}BOLD (Freytag et al., 2002; Wedemeyer et al., 2004; Schaffenberger et al., 2006; Steiner et al., 2007).

In this paper we report on continuing efforts to provide synthetic data that might allow us to understand the observed dispersion relations of these waves.

2. Ongoing spectral synthesis from 3D MHD simulations

Figure 2 shows the temperature profiles of a snapshot of a vertical slice through the simulation carried out with CO^{5}BOLD. We are currently in the process of calculating the NLTE level populations of hydrogen, sodium, and potassium, and the most important elements to synthesize the solar line profiles for each of the grid points and snapshots. This will allow us to study in detail the formation height of these lines, which is essential for an understanding

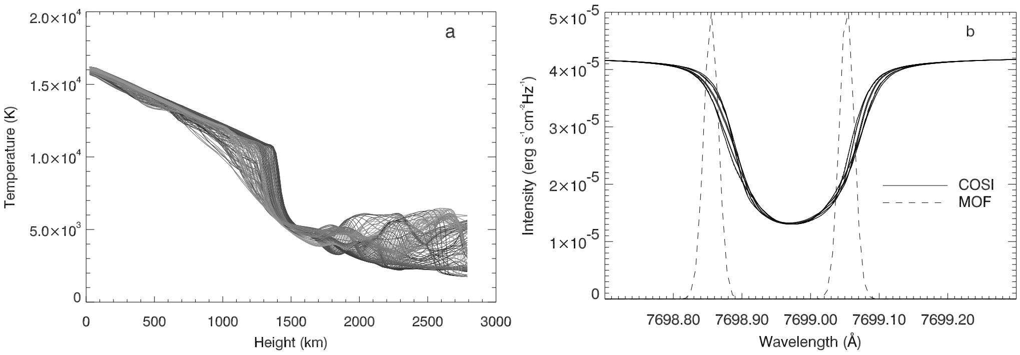

Fig. 2. *Panel (a):* Shown are the temperature structures of a snapshot of the simulation carried out with CO^5BOLD. *Panel (b):* Shown is the modulation of the K I 7699 Å line calculated with COSI based on the Doppler signal of a vertically propagating wave with $\nu = 14$ mHz in a 1D atmosphere structure. The dashed line indicates the narrow band MOF filters employed with the MOTH instrument; for details see Haberreiter et al. (2007).

of the phase lag between the different observational layers in the solar atmosphere.

3. Results from 1D model

For testing purposes we have already modeled the K I 7699 Å line profile being modulated with the Doppler velocity signal corresponding to waves with various frequencies. The line profiles have been calculated with the COde for Solar Irradiance (Haberreiter et al., 2008, COSI). Figure 2b shows the line profiles for waves with 14 mHz. It is clear that the spectral line does not show a pure Doppler shift, but rather a change in the overall line profile, i.e., the C-shape of the line. The reason is that the core of the line is formed higher in the solar atmosphere than the wings of the line. Therefore, the line center and the wings of the line are not modulated simultaneously by the Doppler signal but experience a time lag. If the spatial wavelength of the acoustic wave is of the order of the extent of the contribution function of the spectral line, then the line profile is modulated, as shown in Fig. 2b. This poses a challenge for the exact determination of the Doppler signal of high frequency waves from this kind of observations; for details see Haberreiter et al. (2007).

Detailed modeling of the wave excitation as carried out by Steiner et al. (2007) and C. Nutto (priv. communication) will allow us to disentangle the effect of the wavelength of the acoustic wave on the line profile.

4. Synergy of 1D and 3D models

Semi-empirical 1D models are very successful for modeling the solar spectrum from the UV/EUV to the IR (Fontenla et al., 2009; Haberreiter et al., 2008; Shapiro et al., 2010). Of course, 1D models do not represent any dynamics of the solar atmosphere, but are a temporal and spatial mean of the solar atmosphere. However, as they can reproduce a broad wavelength range and also detailed line profiles, they are a powerful means to study realistic radiative losses of different layers in the solar atmosphere, in particular the chromosphere, for the quiet Sun as well as active regions.

In the near future we plan to synthesize detailed line profiles as well as the spectrum over broad wavelength ranges based on 3D MHD simulations. Hopefully, 1D and 3D models can provide complementary insight to achieve this goal. For example, detailed radiative losses calculated from 1D models might prove valuable for a comparison with the values used in 3D MHD simulations.

5. Discussion and conclusions

From the analysis of Dopplergrams in the K I 7699 Å and Na I 5890 Å spectral lines observed with the MOTH experiment during the austral summer in 2002–03 we find upward traveling waves in magnetic regions. Our analysis shows that the dispersion relation of these waves strongly depends on whether the wave is detected in the low-β or high-β regime. Moreover, the observed dispersion relation does not show the expected decrease of the acoustic cut-off frequency for the field guided slow magnetic wave. Instead, we detect an increase of the travel times below the acoustic cut-off frequency and at the same time a decrease of the travel time above it. To study the formation height of the spectral lines employed by MOTH in greater detail, we use 3D MHD simulations carried out with CO^{5}BOLD to carry out NLTE spectral synthesis.

Total and spectral solar irradiance changes are understood to be linked to the Sun's magnetic cycle; see e.g., Haberreiter (2010). With increasing magnetic activity more radiation is emitted, in particular in the UV and EUV. However, the physical processes that provide the enhanced heating in magnetic regions are not yet fully understood. Waves *leaking* through magnetic regions are considered one of the drivers. A detailed spectral synthesis based on different scenarios of magnetic field strengths representing different phases during the solar cycle might help to understand the contribution of MAG waves in the heating process.

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References

Bogdan, T. J., Carlsson, M., Hansteen, V. H., et al. 2003, ApJ, 599, 626
Cally, P. S. 2007, Astron. Nachr., 328, 286
Cranmer, S. R., van Ballegooijen, A. A., & Edgar, R. J. 2007, ApJS, 171, 520
De Pontieu, B., McIntosh, S. W., Hansteen, V. H., & Schrijver, C. J. 2009, ApJ, 701, L1
Finsterle, W., Jefferies, S. M., Cacciani, A., et al. 2004, Sol. Phys., 220, 317
Fontenla, J. M., Curdt, W., Haberreiter, M., & Harder, J. 2009, ApJ, 707, 482
Fontenla, J. M., Peterson, W. K., & Harder, J. 2008, A&A, 480, 839
Freytag, B., Steffen, M., & Dorch, B. 2002, Astron. Nachr., 323, 213
Haberreiter, M. 2010, in Solar and Stellar Variability – Impact on Earth and Planets, ed. A. G. Kosovichev, A. H. Andrei, & J.-P. Rozelot (Cambridge Univ. Press, Cambridge), IAU Symp., 264, 231
Haberreiter, M. & Finsterle, W. 2010, Sol. Phys., accepted
Haberreiter, M., Finsterle, W., & Jefferies, S. M. 2007, Astron. Nachr., 328, 211
Haberreiter, M., Schmutz, W., & Hubeny, I. 2008, A&A, 492, 833
Jefferies, S. M., McIntosh, S. W., Armstrong, J. D., et al. 2006, ApJ, 648, L151
McIntosh, S. W. & Jefferies, S. M. 2006, ApJ, 647, L77
Patsourakos, S. & Klimchuk, J. A. 2009, ApJ, 696, 760
Schaffenberger, W., Wedemeyer-Böhm, S., Steiner, O., & Freytag, B. 2006, in Solar MHD Theory and Observations: A High Spatial Resolution Perspective, ed. J. Leibacher, R. F. Stein, & H. Uitenbroek, ASPCS, 354, 345
Scherrer, P. H. 1998, in Dynamics of the Interior of the Sun and Sun-like Stars, ed. S. Korzennik, ESA Special Publication, 418, 15
Schunker, H. & Cally, P. S. 2006, MNRAS, 372, 551
Shapiro, A. I., Schmutz, W., Schöll, M., Haberreiter, M., & Rozanov, E. 2010, A&A, submitted
Steiner, O., Vigeesh, G., Krieger, L., et al. 2007, Astron. Nachr., 328, 323
Wedemeyer, S., Freytag, B., Steffen, M., Ludwig, H., & Holweger, H. 2004, A&A, 414, 1121