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Magnetoacoustic waves in a stratified magnetic atmosphere(*)

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Summary. — Observed variations of magnetic field in sunspots comprise intrinsic oscillations contaminated by "false" oscillations due to time-dependent opacity effects. We present a preliminary model intended for the separation of these components. We develop a mathematical formalism based on the analytical solution of the MHD equations including gravity, inclination of the magnetic field and effects of non-adiabaticity. The theoretical results are compared with observations in the near infrared at 1.56 μm using TIP (Tenerife Infrared Polarimeter). It is shown that a part of the detected magnetic-field variations can be intrinsic magnetic-field oscillations caused by magnetoacoustic waves.

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1. – Introduction

The 5 min oscillations of velocity and intensity are observed in sunspots with nearly the same spectra as in the quiet sun, but with reduced amplitudes (*e.g.*, [1,2], reviews [3,4] and references therein). It is not clear whether these oscillations are a response forced by global p-modes, eigenmodes of sunspot itself or quiet-sun acoustic waves transformed into magnetoacoustic ones in the magnetized atmosphere of a sunspot. Measurements of magnetic-field oscillations are very important to answer this question. For that reason, a large amount of observational and theoretical work was dedicated to study such oscillations during the last decades (*e.g.*, [5-8], observational, and [9, 10], theoretical papers). However, the detection of intrinsic magnetic-field oscillations is still a matter of debate. Theory predicts the amplitudes of oscillations to be very low, of about a few G [6], which is at the level of observational noise.

The observed amplitudes of magnetic-field oscillations vary from one measurement to another. Lites *et al.* [6] reported that an upper limit of the observed amplitude of

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oscillations is 4 G. Balthasar [11] later found substantially larger amplitudes, up to 50 G, in individual patches of enhanced oscillations. Even less is known about phases of the velocity and magnetic-field oscillations. Most observations give values about 90 degrees with upward velocity leading magnetic field [11, 7, 12, 8].

The presence of magnetic-field gradients in sunspots makes the detection of intrinsic magnetic-field oscillations more complicated. Any compressible wave passing through the atmosphere will produce oscillations of the line-forming region and, thus, an apparent fluctuation in the observed magnetic-field strength. As was pointed out in the paper by Rüedi *et al.* [13], the observed amplitudes and phases of magnetic-field oscillations are similar to those produced by this opacity effect.

Thus, there are several questions to be answered. Do we observe intrinsic magnetic-field oscillations? How important is the effect of temporal variations of opacity? Which types of waves can explain the observed magnetic-field variations?

We address these questions in this contribution, which is the continuation of the work by Bellot Rubio *et al.* [7]. We complement the analysis with a theoretical modeling of oscillations applying a method which has not been used before to study magnetoacoustic waves and was used initially for acoustic-gravity waves in the quiet-sun stratified atmosphere (see, *e.g.*, [14-17]). Finally, we make a direct comparison of the observed and modeled magnetic-field oscillations in a sunspot.

2. – Observations and inversion

We use spectropolarimetric observations of the full Stokes vector obtained with the Tenerife Infrared Polarimeter (VTT, Teide Observatory) on November 1998 [18, 7]. The two Fe I spectral lines at 15648 Å ($g_{\rm eff} = 3$) and 15653 Å ($g_{\rm eff} = 1.6$) were observed; the slit was placed across the center of a sunspot located at about 27 degrees off the disc center; a time series of 22 minutes was taken.

The analysis was restricted to 6 pixels spanning the region between the umbra center and the umbra-penumbra boundary. The time series of Stokes profiles coming from these pixels were inverted with the SIR [19] inversion code. The inversion retrieves the temperature, macroscopic velocity, microturbulent velocity, magnetic-field strength, inclination and azimuth stratifications along the line of sight (see [7] for a detailed discussion).

The results of the inversion can be summarized as follows: both velocity and magnetic field show oscillatory behavior and are coherent in the different spatial points. The magnetic-field oscillations decrease in amplitude toward the umbra/penumbra boundary.

In contrast, the amplitude of velocity oscillations increases toward the umbra/penumbra boundary (in accordance with Lites *et al.* [6]). The maximum power of oscillations of both magnetic field and velocity is at 3.75 mHz. The velocity leads magnetic field by $105° \pm 30°$ with the convention that positive velocities are downflows. Apart from magnetic field and velocity, no significant variations were found in other atmospheric parameters such as temperature, and inclination of magnetic field.

3. – Model

The observed oscillations are a possible signature of magnetoacoustic waves propagating in the sunspot atmosphere. The self-consistent solution of magnetoacoustic waves propagation in a stratified medium is a complicated mathematical problem. The system of MHD equations is linearized and can be reduced to a single 6th-order differential equation. In the general case, the Fourier transform of this equation can be done in the horizontal direction ($\partial/\partial x \equiv ik_x x$) where the medium is assumed to be homogeneous, but not in vertical direction, where it is stratified.

One of the simplifying approximations used in the past is the local dispersion equation method [20]. It implies that the vertical wavelength of the perturbation is much smaller than the characteristic scale height. This allows to neglect the vertical stratification of the atmosphere parameters and to reduce the differential equation to an algebraic one. The solution of this equation gives k_z either purely real or purely imaginary and does not predict correctly the amplitude variation with height of a vertically propagating wave.

An exact solution of this system of equations exists for the case of constant oblique magnetic field. It was obtained for the first time by Zhugzhda and Dzhalilov [10] in the terms of Meijer functions and was generalized later for the case of non-adiabatic oscillations by Babaev *et al.* [21]. This theory can be used in the case of any wavelength of oscillations and should give a correct height variation of the oscillatory amplitude in the atmosphere with a constant magnetic field. The application of this method leads to extensive mathematical computations.

Yet another possibility is to apply the method of horizontal slabs used originally in the paper on gravity waves by Mihalas and Toomre [17]. The method consists in splitting the atmosphere into a series of horizontal slabs with constant temperature and scale height. The set of algebraic equations is solved separately in each slab and the height variation of the oscillatory amplitude is obtained. Mihalas and Toomre tested the slab method for accuracy in the particular case of adiabatic waves and linear temperature gradient and found that it reproduces almost perfectly the exact solution.

We apply this method to solve the system of linearized MHD equations:

$$\frac{\partial \rho_1}{\partial t} + \vec{v_1}\vec{\nabla}\rho_0 + \rho_0\vec{\nabla}\vec{v_1} = 0\,, \tag{1}$$

$$\rho_0\frac{\partial \vec{v_1}}{\partial t} + \vec{\nabla}P_1 - \vec{g}\rho_1 + \frac{1}{4\pi}[\vec{\nabla}(\vec{B_0}\vec{B_1}) - (\vec{B_0}\vec{\nabla})\vec{B_1}] = 0\,, \tag{2}$$

$$\rho_0 c_v\frac{\partial T_1}{\partial t} + P_0(\vec{\nabla}\vec{v_1}) = -\frac{1}{\tau_R}\rho_0 c_v T_1\,, \tag{3}$$

$$\frac{\partial \vec{B_1}}{\partial t} - (\vec{B_0}\vec{\nabla})\vec{v_1} + \vec{B_0}(\vec{\nabla}\vec{v_1}) = 0\,, \tag{4}$$

where the variables have the usual meaning. The atmosphere was divided into 102 layers of about 5 km thick. We considered the problem in two dimensions and, thus, excluded Alfvén waves. Those waves produce mainly oscillations of inclination of magnetic field and we did not see these oscillations in observations. We took into account radiative losses of oscillations under the Newtonian cooling approximation. The radiative losses can be important in deep layers where the oscillations were observed. The oscillations in density, pressure and magnetic field were found from polarization relations, which give these quantities in terms of the velocity perturbation.

The equations were solved for a discrete set of frequencies ω in the range 2–8 mHz and the variations obtained were summed. The zeroth-order conditions were the time-averaged model atmosphere at each pixel. The initial values of the velocity amplitudes and phases were taken from observations and we considered propagation of waves along the observational LOS (about 27 degrees to the vertical). In addition, waves propagating at different angles with respect to the LOS were taken into account.

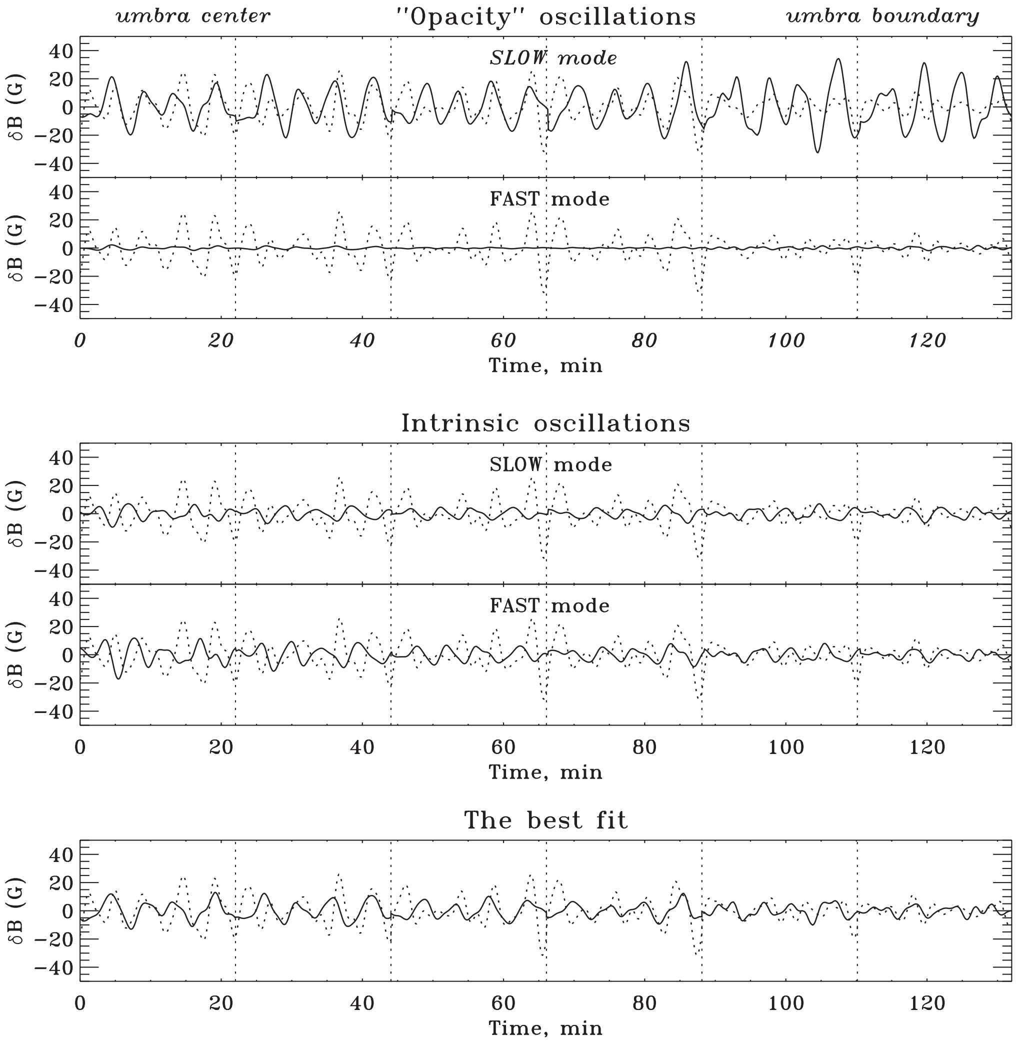

Fig. 1. – Top panel: dotted curves—observed variations of magnetic field at $\log \tau_5 = -1$. Oscillations are filtered in the frequency range 2–8 mHz. Solid curves—variations of magnetic field produced by time variations of opacity due to the SLOW (upper plot) and FAST (lower plot) magnetoacoustic modes. Individual 22 min time series from 6 adjacent pixels are put together to make the oscillations more visible. The farther from the left, the larger the distance to the umbra center. Middle panel: the same for intrinsic variations of magnetic field. Bottom panel: dotted curve—observations. Solid line—the best least-square fit to observations from the "opacity" and intrinsic parts of δB variations of both modes.

The resulting oscillations of density and pressure were introduced into the average model atmosphere for each of the 6 positions in the spot and oscillations of magnetic field due to opacity changes were calculated at the level $\log \tau_5 = -1$.

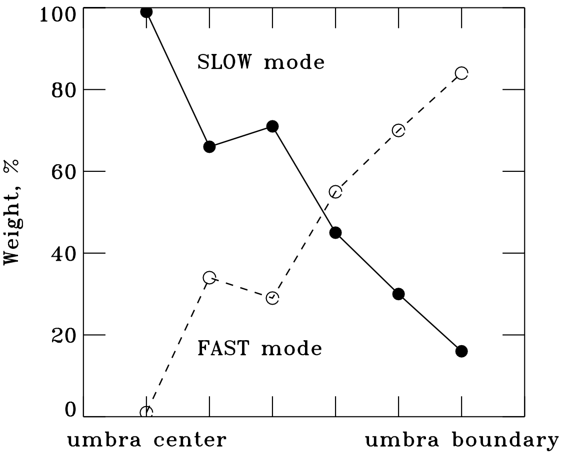

Fig. 2. – Weights of the SLOW and FAST modes in the observed δB variations.

4. – Results and discussion

The results of the computations of magnetic-field oscillations are presented in fig. 1 together with the observations. The system of eqs. (1)-(4) has 4 solutions: two fast and slow magnetoacoustic modes, each propagating up and down. In the upper layers, with plasma $\beta \ll 1$, and for high frequencies, one mode has a phase speed close to the Alfven speed, and the other close to the sound speed. We call the first one "fast" mode and the second one "slow" mode, and keep this convention for the layers with log $\tau_5 = -1$ and periods around 5 minutes despite that the relations between the phase speed of both modes change. Here we show the results for the two upward-propagating solutions.

The oscillations of magnetic field due to opacity variations are displayed in the top panel of fig. 1. The two modes behave quite differently. The slow mode is affected more by radiative losses and behaves similar to an acoustic wave. It is compressible and, thus, produces significant variations of density and opacity. At the umbra center, the amplitude and phase of this mode looks quite similarly to the observational data. At the umbra-penumbra boundary, the amplitude is much larger and the calculated curve does not describe the observations. Since we have performed a linear analysis, the amplitudes of density oscillations are proportional to the initial velocity amplitudes, which are larger at the umbra-penumbra boundary. This causes an increase of magnetic-field oscillations due to opacity variations at the corresponding pixels. The average phase shift between velocity and "opacity" magnetic-field oscillations due to the slow mode is about 90°. The fast mode produces negligible opacity variations and is less affected by radiative losses.

The intrinsic magnetic-field oscillations are shown in the middle panel of fig. 1. Their behavior differs strongly from those due to the opacity effects. The amplitudes of the intrinsic δB oscillations produced by both modes are similar. They decrease toward the umbra boundary in the same way as in the observations. This decrease is the consequence of the geometry of the sunspot magnetic field which is more inclined in the penumbra, and the location of the sunspot off the disc center. The intrinsic δB oscillations are in antiphase with the observations, which is in agreement with the results of Rüedi *et al.* [13]. It is worth noting that the amplitudes of "opacity" δB oscillations are larger than those of intrinsic ones. The comparison of the top and middle panels of fig. 1 leads us to the conclusion that the contribution of the fast and slow modes to the resulting δB variation is different and depends on the position in the sunspot umbra. We found the best least-square fit to the observations from the weighted sum of "opacity" and intrinsic parts of both modes. We performed the fit separately for each of the 6 pixels, keeping the weight constant for all the frequencies. The result of the fits is displayed in the bottom panel of fig. 1. The weights of both modes obtained from this fit are given in fig. 2.

At the umbra center, the slow mode dominates and thus, most of the observed δB variations are due to opacity changes. At the umbra-penumbra boundary the weight of the fast mode increases. Since this mode does not produce opacity variations, most of the observed δB there are intrinsic oscillations produced by the fast mode.

5. – Conclusions

The analysis of polarimetric observations of infrared Fe I lines allowed us to detect oscillations of magnetic-field strength with amplitudes of about 10 G. The analytical model describing the propagation of magnetoacoustic waves in a sunspot atmosphere leads us to the conclusion that at the umbra center most of the observed δB is due to time-dependent opacity effects produced by the slow magnetoacoustic mode. The intrinsic magnetic-field oscillations in our model decrease their amplitude toward the sunspot penumbra, which is in qualitative agreement with observations. At the umbra-penumbra boundary, most of the observed magnetic-field variations are intrinsic.

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