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Oscillations and waves in sunspot umbrae

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Abstract. Sunspots show oscillations of velocity, of intensity (that is of thermodynamic quantities), and possibly of the magnetic field. The oscillations are observed in different period bands (in particular around 2–3 min, 5 min, and > 20 min), at all height levels of the sunspot atmosphere, and with different spatial distributions and characteristic phase relations. In the present invited talk some basic properties of the observed umbral oscillations are shortly reviewed, and different approaches to the modeling and interpretation are discussed.

Key words: sunspots, oscillations, hydromagnetic waves

1 Introduction

A sunspot is a unique laboratory to investigate the structure and dynamics of the magnetized stellar atmosphere and of magneto-atmospheric waves in particular. Hydromagnetic waves are possibly candidates for energy transport and heating in stellar atmospheres, and up-to-date observational techniques make it possible to resolve many details of such periodic disturbances and of the atmospheric fine structure as well. In this way models of both the waves and the atmosphere can be tested. The observed data provide the base of a seismological sounding not only of the subphotosphere, but also of the atmospheric layers, thus completing customary spectroscopic diagnostics.

Sunspots show oscillations of velocity u (Doppler shifts), of intensity I (that is, of thermodynamic quantities), and of geometric displacements of the line or the continuum forming layers, if the sunspot is observed close to the limb. The time series often display sharp power peaks which are closely packed and concentrated in period bands around 2–3 min, 5 min, and >20 min, the oscillations of which are likely produced by different physical mechanisms. Periods around 2–3 min are found mainly in the umbral chromosphere and transition region and are probably a resonant oscillation of the spot itself, but periods at ≈5 min and >20 min are present rather at photospheric levels and seem to represent the passive response to the forcing of the spot by the p-modes in the surrounding convective zone and oscillatory convection, respectively.

Observations of sunspot oscillations are known for almost 4 decades. Only an incomplete list with some examples of the historical development can be given here, some further references are given in the subsequent sections. At the beginning the dramatic phenomena of umbral flashes in the Ca II H and K lines were discovered by Beckers and Tallant (1969) and Wittmann (1969). Only three years later Zirin and Stein (1972) and Giovanelli (1972) detected the running penumbral waves in Hα, and in the umbral photosphere oscillations with periods of 5 min (Bhatnagar et al. 1972) as well as of 3 min

(Giovanelli 1972; Bhatnagar et al. 1972; Beckers and Schultz 1972) were found as well as penumbral oscillations (Musman et al. 1966); the umbral 3-min oscillations show larger amplitudes at higher, chromospheric umbral levels (see Fig. 1). In the umbral chromosphere-coronal transition region (CCTR) first oscillations were observed by Gurman et al. (1982) and Henze et al. (1984). The interpretation of observations in the corona above umbrae were contradictory because many observations of oscillations were related to flares. For quiet conditions 3-min microwave oscillations have been measured in the higher umbral atmosphere by Gelfreikh et al. (1999) and Shibasaki et al. (2001). The results of attempts to measure oscillations of the umbral magnetic field were contradictory for many years; they are discussed in Section 2.2.

During the past 16 years several reviews on various aspects of observations and modeling of sunspot oscillations have been published, e. g., by Kneer (1990), Staude (1991, 1992, 1994, 1999), Bogdan (1992), Chitre (1992), Lites (1992), Roberts (1992), Thomas and Weiss (1992), Bogdan (2000), Brynildsen et al. (2002), and Bogdan and Judge (2006), and about sunspots in general by Solanki (2003). In the present review I shall mainly focus on oscillations in the sunspot umbra and lay emphasis on the discussion of results from my today's personal point of view, that means, it is an individual selection determined by ideas and interests of the author. I am responsible for possibly misquoted results from other authors. The references are incomplete and only provide some examples, more complete lists can be found in the reviews listed above.

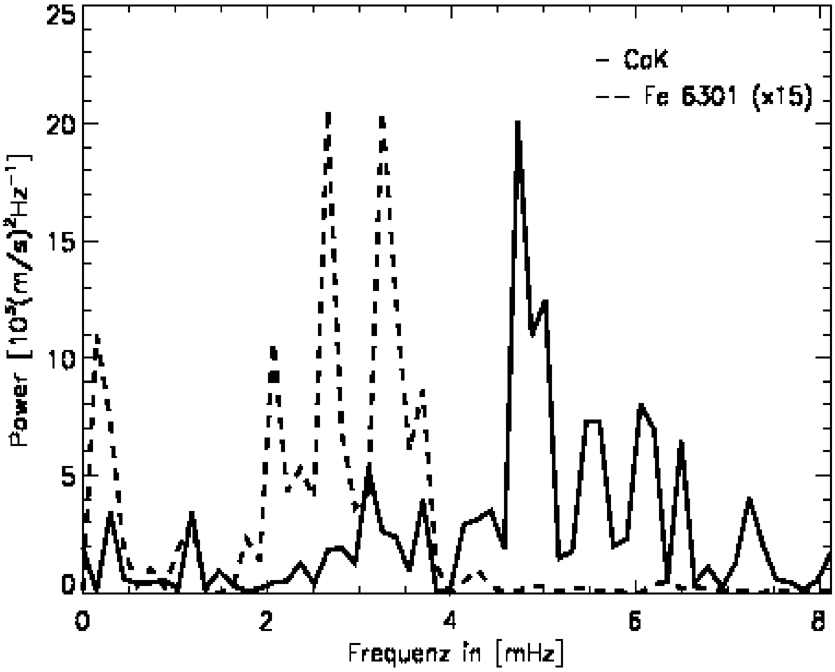

Fig. 1. Velocity oscillations in the photosphere (dashed) and in the chromosphere (full curve) at an umbra-penumbra boundary, observed with the Advanced Stokes Polarimeter at the Sacramento Peak Observatory, USA, June 15, 2000, by Settele et al. (2002b)

2 Observations

2.1 Umbral velocity and intensity oscillations

2.1.1 3-min band

There are oscillations with periods P of $100 \leq P \leq 200$ s which are mainly observed in the chromosphere and transition region above umbrae, with a dominant peak at $P \approx 3$ min or $\nu \approx 5.5$ mHz (frequency). At photospheric levels the amplitudes of these oscillations are much lower, the typical rms velocities are $u \leq 50$ m s^{-1}, and they are not always discovered. The amplitudes become larger with increasing height z. Measurements of amplitudes in the lower umbral chromosphere relative to those in the upper chromosphere show a decrease with increasing frequency ν. In the chromosphere u is an order of magnitude larger, but the kinetic energy may be smaller than in the photosphere due to the strong decrease of mass density with height. The z dependence of the phase difference between velocity and intensity oscillations shows at upward propagating waves.

There are hints at a non-linear character of the oscillations in the chromosphere: sawtooth waveforms are sometimes observed. However, most observations refer to time series of optically thick chromospheric lines, the interpretation of which is not straightforward.

Most observers assume that the closely packed peaks are cospatial modes, but it cannot be excluded that they are the result of the finite duration (20–40 min) of the wavetrains. There is a strong correlation with the photospheric 3-min oscillations, showing coherence from the photosphere up to the transition region. The horizontal extent of an oscillating element is still a matter of debate: some authors found coherence over the whole umbra or a subdivision of an umbra into a few (2–4) oscillating elements, others measured diameters of ≤3″–5″ (that is smaller than for 5-min. oscillations in the photosphere), followed by rapid quasi-circular expansion with the shape of 'chevrons', also in the photosphere (Kobanov and Makarchik 2004; Kobanov, et al. 2006). The horizontal phase velocity reaches 60–70 km/s.

Measured phase differences between u and I oscillations and their height dependence are of particular importance for any comparison with theory. There are hints at upward propagating waves in the chromosphere, but rather standing waves in the photosphere. Unfortunately, simultaneous measurements in lines formed at different heights of the umbra from the lower photosphere up to the transition region are rare. Observations of the center-to-limb variation show longitudinal oscillations in the 3-min band and in the 5-min band as well, that means, the displacements are longitudinal, that is aligned to the vertical magnetic field.

UV line observations of oscillations in the umbral upper chromosphere and corona obtained onboard the SOHO satellite have been presented by several groups, e. g., in a series of papers by Brynildsen et al. (2002, 2003) and by Rendtel et al. (2003). A wavelet analysis of the longer time series obtained by the latter authors show a strongly non-stationary behavior of the upper chromosphere and CCTR above umbrae.

2.1.2 5-min band

The 5-min oscillations $200 \leq P \leq 400$ s are predominantly a photospheric phenomenon. The amplitudes decrease with increasing z, they can hardly be detected in the upper chromosphere and transition region. Their appearance in the umbral photosphere is similar to that of the p-modes in the quiet Sun, but the amplitudes in the umbra are strongly reduced (by a factor between 2 and 3; e. g., Balthasar et al. 1987; Braun et al. 1987). Diagnostic ν–k_h diagrams (k_h is the horizontal wavenumber) have been obtained only a few times: the observations of Abdelatif et al. (1986) show significant power only for small ν and k_h but strong attenuation to the right-hand side of a line corresponding to a phase velocity of 25 km/s which is close to the Alfvén speed c_A in the umbral photosphere. Penn and

LaBonte (1993) found consistency with the ridge structure of the global *p*-mode power outside the spot.

Coherently oscillating elements cover a large part of the umbra; this property seems to support a monolithic, single flux tube model of the umbra. The closely packed power peaks, however, very probably result from the interference of many modes, similar to the quiet Sun.

There is no place here to discuss the interesting topics of local helioseismology, for example the acoustic subsurface imaging of sunspots by applying the time-distance relationship. However, there are excellent reviews by Kosovichev (1999, 2006), giving examples of such approaches, together with some references to more detailed descriptions.

Attempts to measure oscillations of the umbral magnetic field are considered in Section 2.2.

2.1.3 Long-period band

Several observers found significant power of oscillations with $P \approx 20$ min (Soltau and Wiehr 1984; Balthasar et al. 1987; Federspiel and Mattig 1993). Torsional oscillations of the whole spot with $P \approx 40$ min have been discovered by Gopasyuk (1985), Berton and Rayrole (1985), and Druzhinin et al. (1993). The relation between both phenomena is not yet clear. However, the periods of such oscillations are close to the observed lifetimes of umbral dots and to the periods of oscillatory convection models in a strong magnetic field, thus indicating possible connections.

2.2 Magnetic field oscillations

The results of earlier attempts to measure oscillations of the magnetic field at photospheric levels of sunspots were contradictory. There are a few papers reporting oscillatory power of magnetic field components in the 3-min and 5-min period bands (Mogilevskij et al. 1972, 1973; Milovanov 1980; Gurman and House 1981, Efremov and Parfinenko 1996), without a clear correlation with other oscillatory phenomena in some cases. Potsdam observers found that apparent variations of the magnetic field were introduced by seeing fluctuations (Bachmann 1983; Landgraf 1997). The latest one-dimensional data obtained by Lites et al. (1998) with the Advanced Stokes Polarimeter only found an upper limit of 4 G (rms) of the magnetic field oscillations. The authors argue that the 4 G are due to seeing influences. They also tried to explain such a limit for the amplitudes by a model of eigenmodes due to magneto-atmospheric waves in a homogeneous, vertical magnetic field.

The situation has changed recently when two-dimensional data of high quality became available: Observations with a Fabry-Perot interferometer (FPI) at the Vacuum Tower Telescope (VTT) on Tenerife (Horn et al. 1997; Balthasar 1999a,b) and with the Michelson Doppler Imager (MDI) onboard SOHO (Rűedi et al. 1998; Norton et al. 1998, 1999) have shown that significant signals of magnetic field oscillations exist, but they are limited to much smaller regions inside the spots than the well known velocity oscillations which cover large parts of a sunspot: the magnetic power is concentrated in isolated small flux bundles (pores) outside of larger umbrae and in small features piling up at the boundary between umbra and penumbra of larger spots.

The interpretation of such measurements requires a careful consideration of spurious magnetic oscillation signals (Staude 2002), in particular if the magnetic power seems to be concentrated in regions with large gradients of I and B in the image plane. It has already been mentioned that seeing variations can result in spurious fluctuations of the magnetic signal (Bachmann, 1983; Landgraf, 1997). Rűedi et al. (1999) have shown that also crosstalks from temperature and density oscillations of a magneto-acoustic wave could produce apparent magnetic signals and simulate wrong phase differences, if not all the details of the observing equipment, e. g. the filter profiles of the MDI-magnetograph, are correctly taken into account. Such warnings should be taken seriously in future work, but there exist observations which obviously cannot be explained by such models. For example, this mechanism cannot explain why the observed magnetic and velocity oscillations have sometimes different periods at one place. Spurious magnetic signals can also be produced by a crosstalk from velocity oscillations, when the line profile is scanned in the VTT-FPI or the MDI and the time scale of the profile recording is of an order similar to the period of velocity oscillation (Settele et al., 2002a). However, often the phase differences between magnetic and velocity oscillations predicted for such crosstalks are different from the measured phase shifts.

Bellot Rubio et al. (2000) have shown that magnetic field oscillations can be measured if the fluctuations of opacity due to a wave move up and down the region where the spectral line of the diagnostics is formed, if there exists a gradient of $B(z)$. The action of both effects – opacity and intrinsic magnetic field oscillations – on the observed magnetic oscillations in sunspot umbrae has been investigated by Khomenko et al. (2003). It is shown that in the umbral center the observed oscillations is produced mainly by opacity fluctuations, while the part of intrinsic magnetic field oscillations is increasing towards the umbral boundary, in agreement with our earlier results of both measurements and modeling (Zhugzhda et al. 2000; see Section 3.3).

3 Theory and modeling

3.1 MAG waves

A discussion of the wave modes in a stratified, compressible atmosphere permeated by a magnetic field vector **B** of arbitrary direction requires the simultaneous consideration of the three restoring forces due to magnetic pressure and tension (without the other forces this would result in Alfvén waves), gas pressure (alone → sound waves), and buoyancy (alone → gravity waves). The resulting MAG (magneto-acoustic-gravity) waves or magneto-atmospheric waves form a complicated system of oscillations which so far has been studied for simplifying special cases only. The wave equations and dispersion relations of MAG waves in a vertically stratified atmosphere permeated by a constant vertical magnetic field (parallel to the direction of gravity **g**) have been derived by Ferraro and Plumpton (1958), assuming additionally constant values of the turbulent pressure P_{turb} and of the adiabatic coefficient γ with depth z. A generalization to depth-dependent values of P_{turb} and γ, which can significantly modify the quantitative results in realistic umbral model atmospheres, has been given by Settele et al. (1999, 2001).

A first analytic approach to an inclined magnetic field has been published by Zhugzhda and Dzhalilov (1984a, b), detailed numerical simulations by Rosenthal et al. (2002) and Bogdan et al. (2003), demonstrating the bewildering complexity of wave patterns even in a rather simple **B** structure. A direct numerical comparison of these theoretical results with observations is difficult due to the simplifying, restrictive assumptions even in these rather general approaches:

1) Two-dimensional structuring of the atmosphere and of **B**, that is to say any variation perpendicular to the plane containing the directions of gravity and **B** is neglected. In this case the pure Alfvén waves are completely decoupled from the other waves, the fast- and slow-mode MAG modes, and are no longer considered.

2) Isothermal atmosphere, in this case effects of a resonant transmission of MAG waves due to a temperature stratification are excluded. Such effects have been studied for sunspot umbrae assuming a vertical **B,** e. g., by Žugžda et al. (1983, 1987), Gurman and Leibacher (1984), and Settele et al. (1999, 2001), see the following Subsection 3.2.

For very strong magnetic fields B we have $\beta \ll 1$, for very weak B follows $\beta \gg 1$ (the plasma $\beta = 8\pi P_{gas}/B^2$), and in both limiting cases the slow mode and the fast mode are decoupled from each other. Mode transformations (conversions) or reflections occur at a level $\xi = \omega H/c_A \approx 1$, where $\omega = 2\pi\nu$ is the wave frequency, $H = c_0^2/(\gamma g)$ is the atmospheric scale height, c_0 is the adiabatic sound speed, $c_A = B^2/(4\pi)$ is the Alfvén speed, and ρ is the mass density. $\xi \sim \omega B^{-1} \rho^{1/2}$. In a first approximation $\xi \approx 1$ is close to $\beta \approx 1$ and in an umbra close to $\tau_0 = 1$, where τ_0 is the continuum optical depth at $\lambda = 500$ nm. Having in mind the other uncertainties of the modeling it seems justified to look for the corrugated layers of mode conversion and reflection at $\beta \approx 1$, which is called 'magnetic canopy' by Bogdan et al. (2003). Such an approach has been applied to the interpretation of oscillations around sunspots by Muglach et al. (2005).

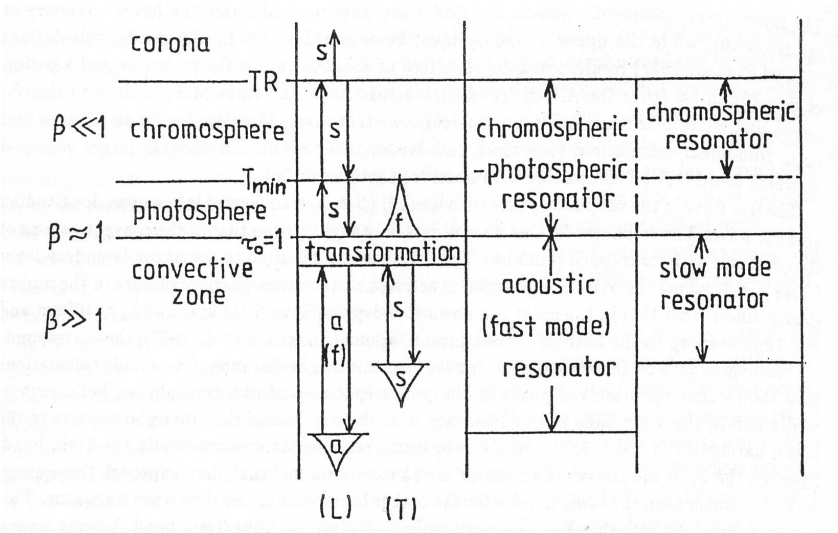

Fig. 2. An interpretation of the results of a resonant transmission modeling: scheme of the system of coupled resonators for MAG waves in an umbral model. Letters *s, a*, and *f* indicate slow, acoustic, and fast mode waves, respectively. (L) means quasi-longitudinal waves, (T) quasi-transverse waves. TR is the CCTR; other symbols are defined in the text. Vertical arrows show the direction of wave propagation, triangles (tips) mean evanescent waves (Staude, 1991, 1992)

3.2 Sunspot filter theory (resonant transmission model)

The most realistic description of the umbral atmosphere is provided by semi-empirical models based on spectroscopic diagnostics. Multi-wavelengths data from X-rays up to radio emission have been used earlier to derive umbral models from the lower corona down to the deep photosphere (see, e. g., Staude 1981; Obridko and Staude 1988), and the subphotospheric layers are modeled by a mixing length formalism. Such models describe the basic state which is subsequently subjected to periodic disturbances by MAG waves. In a series of papers starting with Zhugzhda et al. (1983) such an approach has been used to investigate umbral oscillations (see the reviews by Zhugzhda et al. 1987; Staude et al. 1987; Staude 1992; but also the paper by Gurman and Leibacher 1984, and the more recent papers by Settele et al. 1999, 2001).

In order to simplify the calculations the analysis has been restricted to a vertical **B** and $k_h / k_z \ll 1$, where $k_z = \omega/c_0$ is the vertical wave number. That means, we consider 'longitudinal' waves, whose displacements are directed along **B**. Assuming a period of 3 min we obtain $k_z \approx 7 \times 10^{-8}$ cm^{-1} in the umbral photosphere, consequently, our approximation is valid for horizontal wavelengths $\lambda_h \gg 10^3$ km of the MAG waves. Interactions between these longitudinal and the transverse modes are investigated in a supplementary analysis applying the formulae for mutual wave conversion given by Zhugzhda and Dzhalilov (1984a, b).

The behavior of the longitudinal waves in such a model is investigated by calculating the coefficient D of the transmission of a broad-band flux of wave energy from the deep layers of the convective zone up to the corona above the umbra, taking into account the partial reflections at all intermediate heights. The resonance frequencies are given by the maxima of D *(ω)*. Moreover, the calculation provide information on the real positions of the reflecting boundaries, without imposing artificial boundary conditions, and makes understandable the system of coupled resonators for MAG waves acting in the umbral atmosphere (see Fig. 2). The quality of each resonator and the height dependence of amplitudes and phases of the oscillations of velocity, of vertical plasma displacements, and of thermodynamic quantities result from the computations as well. Our conclusions about the atmospheric cavities and the longitudinal character of the motion along the magnetic field lines has been supported by Wood (1997) in an evaluation of the normal modes of MAG waves, taking into account the coupling of both longitudinal and transverse oscillations.

Such calculations are carried out for various models of the umbral atmosphere, after that the model predictions are compared with observations. In this way we looked for possibilities to use observations of umbral oscillations for sounding the atmospheric as well as the subphotospheric structure by helioseismology. For example, the model calculations suggest the following methods for sounding the umbral atmosphere:

– the extent of the chromosphere between the temperature minimum, T_{min}, and the transition region determines the spectrum of resonance frequencies in the 3-min band, thus providing a method to determine the chromospheric gradient of $T(z)$ (see Fig. 3);

– the values of T_{min} in umbral fine structures can be estimated from the spectrum and the quality of the resonator (Locāns et al. 1988);

– measurements in UV lines provide information on the umbral transition region, where the observed oscillations seem to be concentrated in cold fine structure elements which occupy only a few percent of the volume (Staude et al. 1985).

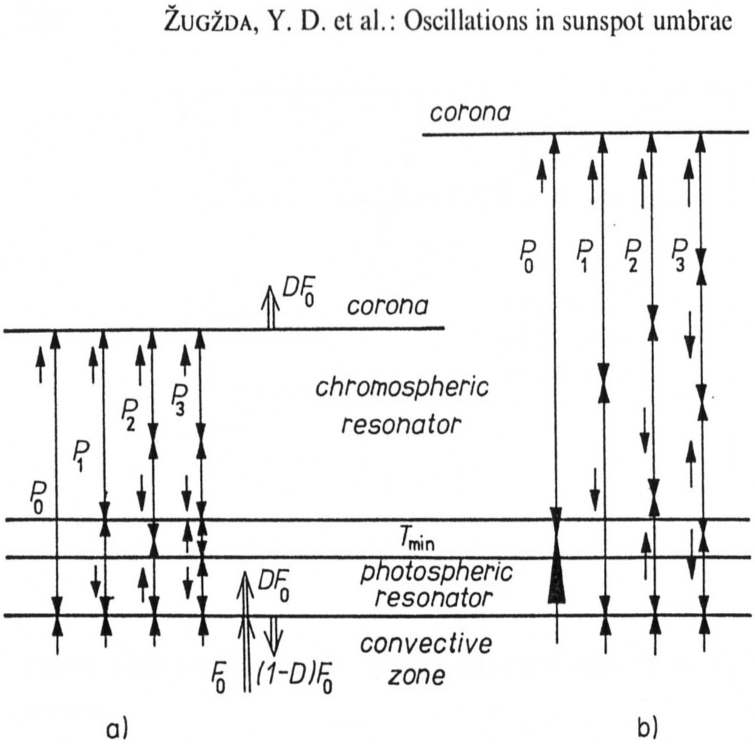

Fig. 3. Helioseismic diagnostics of the chromospheric extent: scheme of the coupled photospheric-chromospheric resonators in 2 different models of the umbral atmosphere: a) thin (shallow) chromosphere, b) 'thick' (extended) chromosphere. Short arrows indicate the direction of velocity in a given phase for each mode P_i (the extent between 2 arrows is a measure of period length), encounters of arrows represent modes, double arrows describe the energy flux (Žugžda et al. 1987; Staude, 1991)

Recently, Chaouche and Abdelatif (2005) have discussed analytically some special effects (trapping, resonant properties, leakage of waves) in a simple 2-layer model of the umbral atmosphere.

According to Brynildsen et al. (2002, 2003) their observations seem to contradict the predictions of our sunspot filter theory (resonant transmission model) as described above. Their observations show one dominant oscillation frequency while there are several power peaks almost equally spaced in frequency in the transmission curve calculated for the higher sunspot atmosphere. However, such a comparison has to consider the assumptions of the modeling: the theoretical transmission coefficient is valid for an incoming wave flux which is constant over all frequencies (a ‘white flux’). Any other frequency structure in the wave flux incoming from below – for example due to subphotospheric resonators – will modify the picture because the transmission coefficient has to be weighted with this frequency distribution to predict the oscillations at higher levels of the sunspot atmosphere. Further objections against the filter theory have been discussed and disproved in more detail by Zhugzhda (2002).

3.3 Multi-mode oscillations

So far theoretical models of sunspot oscillation have treated the sunspot as an axi-symmetric, vertical tube with a constant magnetic field. Main emphasis was placed on the stratification and on the upper and lower boundary conditions, while the effect of the surrounding atmosphere on the oscillations was ignored to a great extent. In order to explore the observed 2-D distribution of magnetic power we have considered a model of an intense flux tube with a uniform, vertical magnetic field embedded in a plasma with a weaker external field B_e ($B_e = 0$ will be assumed in the further discussion). We ignore the effect of stratification, but we take into account the effect of the surroundings. The temperature T of the plasma outside the tube is higher than inside: The effective T_{eff} differ by 2000 K, but due to the Wilson effect the real difference of T at equal geometrical heights z is much higher – at $T = 3600$ K, a typical value in the umbral line-forming layer, we have $T \geq 12000$ K outside in the surrounding convective zone. The slow body mode provides an explanation of the appearance of magnetic oscillations in small sunspots, if the azimuthal wave number $m = 0$, but also of the small features of magnetic power piling up in rings around the umbrae of large sunspots can be explained: in the latter model the magnetic oscillations are the signature of the slow body mode with $m \gg 1$, which bears a resemblance to the well-known whispering gallery mode in acoustics (Zhugzhda et al. 2000).

4 Discussion and conclusion

In their latest interesting review on sunspot oscillations Bogdan & Judge (2006) have mentioned two puzzles. Here they will be shortly discussed in terms of our terminology:

Puzzle #1: ‘5-min versus 3-min oscillations. “A tale of two frequencies?”

The interpretation given by Bogdan and Judge (2006) completely agrees with our earlier ‘resonant filter theory’ as outlined in Section 3.2 above. Photospheric and chromospheric umbral oscillations are compressible acoustic modes moving along vertical **B** in a low-β plasma, that means slow MAG waves. The 3-min oscillations are the ‘high-frequency tail’ of the 5-min oscillations, the related waves are transmitted through T_{min} when $\omega > \omega_{ac}= c/2H_\rho$ to the transition region (and partly trapped there); the predicted power is in agreement with observations. $\omega_{ac} = \gamma g/(2c_0)$ is the acoustic cutoff frequency.

Puzzle #2 : “Where are the 3-min oscillations at $T \geq 10^6$ K?”

In the *corona* the interpretation by Bogdan & Judge (2006) is convincing: we have an increased scale height H_T of T, $H_T \gg \lambda_z$ is valid, and optically thin lines get contributions from an extended region and a cancellation of contributions from wave compressions and rarefactions.

In the *chromosphere-corona transition region* we have to consider another effect (Žugžda et al. 1984; Staude et al. 1985): an optically thin line is formed here in a narrow range of T, $T_L \pm \delta T$, where the considered ion exists. Taking into account the z-displacement of this range by the wave but also the difference between this displacement and the Lagrangian displacement due to the wave we get the following relation for the intensity fluctuation I' normalized to the mean intensity I_0 ($P'_{gas}/P_{0\,gas}$ is the relative fluctuation of gas pressure):

$$|I'/I_0| \approx |P'_{gas} / P_{0\,gas}|\ (5 - 3\gamma) / (2\gamma).$$

For almost adiabatic oscillations, $\gamma \to 5/3$, we have $|I'/I_0| \to 0$, that is a lack of significant power in intensity fluctuations. For isothermal waves (perhaps due to radiative energy losses), however, we would have $\gamma \approx 1$ and clearly observable intensity oscillations.

To get a deeper physical insight into the MAG waves in sunspots better observations are required. They should include infrared measurements (larger Zeeman splitting), an application of adaptive optics, polarization measurements, and a compensation of instrumental polarization. Moreover, the data should achieve higher resolution and larger ranges in space, in time and in the spectrum (more lines). The interpretation should be based on realistic Stokes profile inversion, including the derivation of the atmospheric structure and dynamics. Moreover, the number of the degrees of freedom should be reduced by imposing reasonable physical conditions.

Future steps in theory and modeling should simultaneously consider the atmospheric stratification (→resonant filtering) and the multi-mode structure (← lateral boundary conditions) of the magnetic flux-tube oscillations, that is a linear superposition of the eigenmodes of a stratified umbral atmosphere. Moreover, the divergence of the umbral flux-tube with height and its filamentary structure (‘spaghetti model’) should be taken into account. Non-adiabatic processes such as the interaction with radiation, non-LTE behavior and non-linear effects (umbral flashes) should be included in the modeling. Special emphasis should be given to the diagnostics of phase differences between oscillations of velocity, magnetic field, and thermodynamic quantities and at different heights as well, both from the point of view of observations and of modeling.

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