MODELS OF THE SOLAR ATMOSPHERE ABOVE SUNSPOTS

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ABSTRACT. During the last five years common efforts have been made within the KAPG cooperation to derive the spatial structure of the atmosphere above the umbra of a typical large sunspot from subphotospheric layers up to the lower corona, using complex observed data from soft X-ray, EUV, optical, and microwave emissions. The main results from this work will be summarized in the present paper.

The "Wroclaw-Ondřejov sunspot model" proved able to explain most of the existing observations by a unified working model and to provide a good basis for further investigations. Recent improvements include a two-component structure consisting of a main component (cold at photospheric levels, deep-set and thin chromosphere-corona transition region) and a secondary component (filling factor 5-10 percent, hot in the photosphere, extended transition region).

A model of a chromospheric resonator for slow-mode magneto-atmospheric waves, together with the sunspot models mentioned above, proved able to explain velocity and intensity oscillations observed in lines which are formed at different heights of the umbral atmosphere.

МОДЕЛИ СОЛНЕЧНОЙ АТМОСФЕРЫ НАД ПЯТНАМИ: В течение прошлых пяти лет в рамках сотрудничества КАПГ совместные усилия были направлены на разработку модели пространственной структуры фотосферы над тенью типического большого солнечного пятна с подфотосферных слоев до нижней короны. Для моделирования используются комплексные наблюдения в рентгеновском, крайнем ультрафиолетовом, оптическом и микроволновом диапазонах. Главные итоги этой работы подводятся в настоящей статье.

Оказалось, что "Вроцлав-Ондржейовская модель солнечного пятна" способна объяснить большинство современных наблюдений и заложить полезную основу дальнейших исследований. Недавние уточнения включают двухкомпонентную структуру, состоящую из главной компоненты (холодная фотосфера, узкий переходный слой

между хромосферой и короной) и вторичной компоненты (0.05 - 0.10 доли объема, горячая фотосфера, обширный переходный слой).

Модель хромосферного резонатора для замедленных магнито-атмосферных волн и вышеуказанные модели солнечных пятен способны объяснить колебания скоростей и интенсивностей, наблюдаемых в линиях, которые образуются на различных высотах атмосферы тени.

MODELY SLNEČNEJ ATMOSFÉRY NAD ŠKVRNAMI: V rámci mnohostrannej spolupráce AV SK KAPG boli za posledných päť rokov rozpracované modely priestorovej štruktúry nad typickym jadrom veľkej slnečnej škvrny a to od podfotosférických vrstiev až do dolnej koróny. Pre modelovanie sú použité komplexné pozorovania v röntgenovej, ultrafialovej, optickej a mikrovlnnej časti spektra. Hlavné výsledky tejto práce sú nasledovné:

"Wroclawsko-ondřejovský model slnečnej škvrny" umožňuje vysvetliť väčšinu súčasných pozorovaní a tvorí užitočnú základňu pre ďalšie výskumy. Nedávne spresnenia obsahujú dvojzložkovú štruktúru, ktorú tvorí hlavná zložka (studená fotosféra, úzka a nízko sa nachádzajúca prechodová vrstva medzi chromosférou a korónou) a sekundárnej zložky (0.05 - 0.10 objemu škvrny, horúca fotosféra, rozsiahla prechodová vrstva).

Model chromosférického rezonátora pre spomalené magneto-atmosferické vlny, spolu s vyššie uvedenými modelmi slnečných škvŕn, môžu vysvetliť oscilácie rýchlostí a intenzít, ktoré sú pozorované v spektrálnych čiarach, vznikajúcich v rôznych výškach umbrálnej atmosféry.

1. INTRODUCTION

Sunspots are the strongest concentrations of magnetic flux in the solar atmosphere and the kernels of solar active regions. Their investigations is of basic importance for our understanding of physical processes in solar active regions or, generally speaking, in magnetically determined stellar atmospheres. Many reviews (e.g. Obridko and Teplitskaya, 1978; Maltby, 1981) as well as complete conferences (Zwaan, 1981; Cram and Thomas, 1981) were focused on the sunspot phenomena, and a comprehensive survey has been given in the recently published book by Obridko (1985).

The present paper does not intend to repeat such complete reviews. Instead of it we plan to summarize the main results from common efforts within the frame of the KAPG cooperation, theme "Modelling of the atmosphere above sunspots and faculae", made for the most part during the past five years. This work was centred on the derivation of the spatial structure of the atmosphere, that is, the distribution of thermodynamic quantities, in the umbra of a typical large sunspot from subphotospheric layers up to the lower corona, using complex observations from soft X-ray, EUV, and optical emissions up to microwaves. The elaboration of such a semi-empirical model provides the first step in any attempt to investigate basic physical processes and structures such as mechanical and energy balances, stability, waves and oscillations in sunspots. Of course, each sunspot is an individuum with its own structure and dynamics, and ideally a model should be derived for a particular sunspot in a fixed phase of its development. Unfortunately, not all of the necessary data are available for such a situation, and we are forced to work up observed data from different sunspots into a model of a typical large sunspot umbra in a stable phase of its development. Such a working model should be based on uniform and self-consistent physical assumptions for the whole range of heights, it should be able to explain the majority of existing observations at various wavelengths, and it should be improved if new and better data become available. Moreover, a reference model of the mean quiet solar atmosphere and a plage model should be derived for comparison using the same physical assumptions and procedures which are also applied in modelling the umbra.

In the following sections the basic features of the existing models will be outlined at photospheric and chromospheric levels (Section 2) as well as in the transition region and lower corona (Section 3). An application of the umbral model to the interpretation of umbral oscillations within a chromospheric resonator model will be discussed in Section 4, and finally some conclusion and suggestions for further work will be given in Section 5.

2. PHOTOSPHERE AND CHROMOSPHERE

The modelling of subphotospheric sunspot layers will not be described in detail. An earlier approach to the calculation of heat flux below the umbral photosphere was based on a generalized version of Öpik's mixing length theory of cellular convection (Staude, 1976, 1978) and could in principle explain the observations of umbral granulation (Bumba et al., 1975; Bumba and Suda, 1980). For the quiet sun the procedure yields results in agreement with standard models of the solar convective zone. For the umbra, however, there remains some ambiguity. We probably fail to understand the basic processes of convection in a strong magnetic field; some kind of oscillatory convection (Obridko, 1979a; Knobloch and Weiss, 1984) is likely to act here.

At photospheric levels umbral models seem to be well established due to many observations in the visible and infrared spectral regions. This remark relates to horizontally averaged models which disregard fine structures such as umbral bright dots. Only six years ago the situation was not so clear at chromospheric heights. Empiric models of the lower umbral chromosphere had been derived by Baranovsky (1974 a,b), Teplitskaya et al. (1977, 1978) and Kneer and Matting (1978), using line profiles of CaII H and K, H_α , and some mediumstrong lines. Figure 1 shows the strong differences between the temperature distributions T(z) of these models; due to different assumptions concerning the densities these differences are evident even between the models from the same authors.

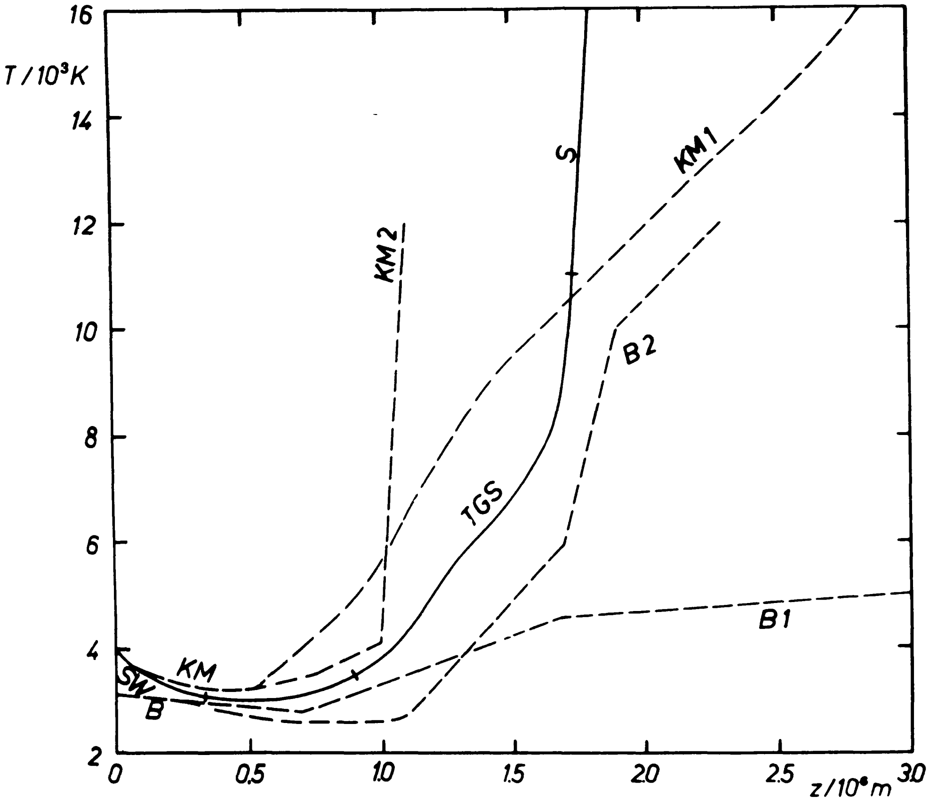

Fig. 1: Temperature T versus geometrical height z in the photosphere and lower chromosphere of several sunspot models. Full line - model proposed by Staude (1981), where the letters indicate the original data for separate heights levels: SW - Stellmacher and Wiehr (1975), TGS - - Teplitskaya et al. (1978), S - the extension by Staude (1981). Dashed curves: B1 and B2 - Baranovsky (1974 a,b), KM1 and KM2 - Kneer and Matting (1978), 'thick' and 'thin' models, respectively.

The situation greatly improved when space-borne data with high spatial resolution from Skylab, HRTS, and OSO-8 became available, including profiles of H Ly-α, SiIII, and molecular lines in the ultraviolet. Such data have been used to select the best model of the lower umbral chromosphere: it became evident that only the model by Teplitskaya et al. (1978) was compatible with the new information. This model has then been extended to the upper chromosphere at $T = 4 \times 10^4$ K to get a unified umbral working model up to a height of about 2000 km above the umbral photosphere (Staude, 1981; the optical depth in the umbral continuum at 5000 Å, $\tau_0 = 1$, has been fixed at z=0). A similar model has been derived by Lites and Skumanich (1982); both models

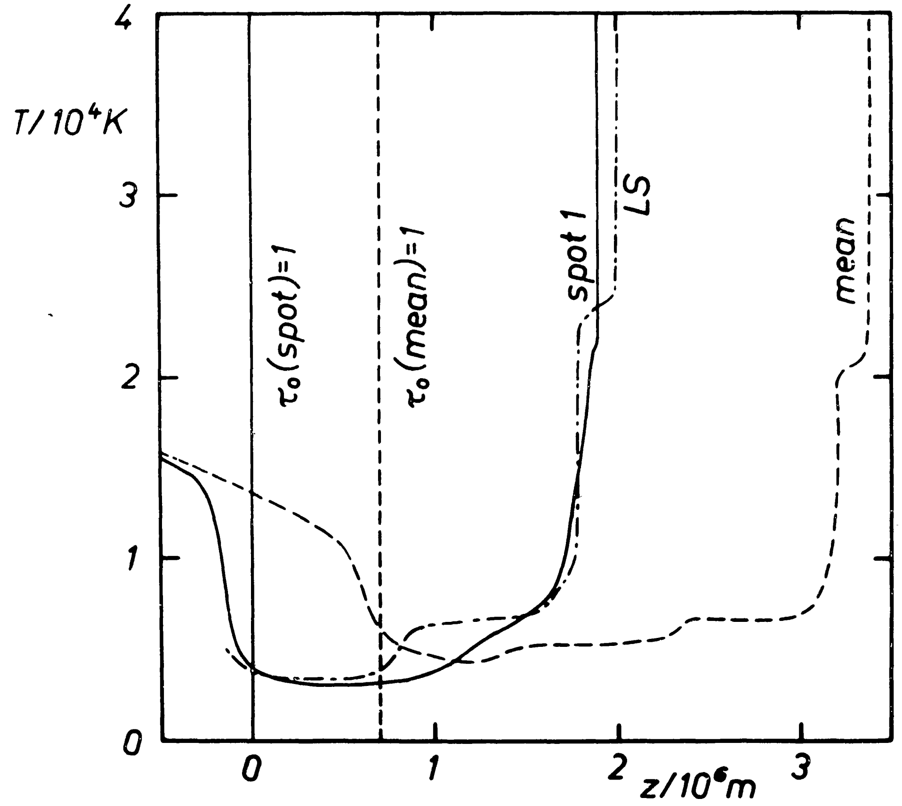

Fig. 2: T(z) for the umbral model of Staude (1981; full line), the umbral model of Lites and Skumanich (1982; dashdot), and the mean quiet atmosphere (dashed) for comparison.

are shown in Figure 2, where also a model for mean quiet atmosphere is included for comparison. The model of Lites and Skumanich was based on new observed data which were not available to Staude (1981); both models differ from each other by the assumption of two plateaus of temperature at $T \approx 7000$ K and 23 000 K in the Lites-Skumanich model, while a steady gradient of T(z) has been proposed by Staude. Either of the two types of models has some advantages in explaining special observed spectral features, but a unique decision in favour of one of these models is not yet possible. The model of Staude (1981) has been adopted by our KAPG sunspot modelling group to form the lower part of the more extended "Wroclaw-Ondřejov sunspot model" (hereafter, WOSM), which will be described in more detail in the following section. The procedures for calculating the described models, that means, for solving the equations of state, of hydrostatic equilibrium, of radiative transfer including deviations from LTE, the conversion of different height scales, etc., have

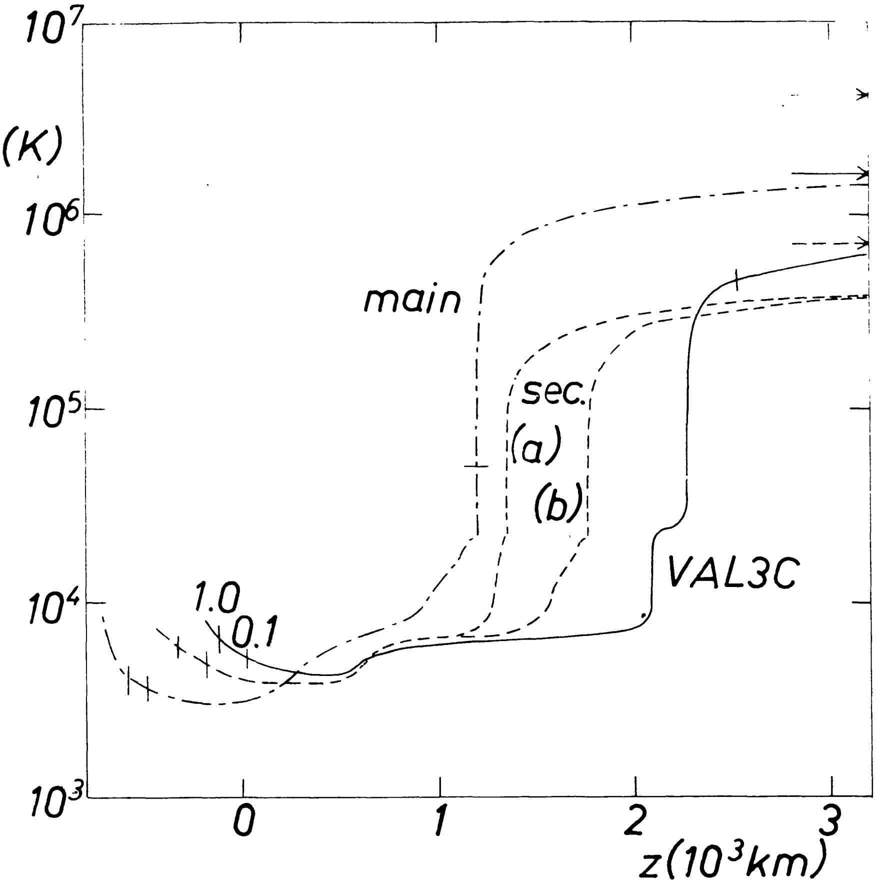

Fig. 3: T(z) of the two-component umbral model by Obridko and Staude (1986): Main component (dash-dot), 'thin' (b) and 'thick' (a) secondary component (dashed), and then mean quiet sun model VAL3C (Full curve). Arrows on the right-hand side indicate the coronal values T_c which are asymptotically approached at $z \to \infty$.

been described in a special report by Staude (1982).

Hitherto only a few attempts have been to consider the inhomogeneous structure at photospheric levels of the umbra, which is evident in the umbral bright dots or in the umbral granulation mentioned above. Years ago Makita (1963) and Mogilevsky et al. (1968) suggested already empiric and theoretical approaches to model the discrete fine structure of the plasma in sunspot. Detailed two-component models of the umbral photosphere have been proposed by Obridko (1974, 1985; Obridko and Teplitskaya, 1978) and by Adjabshirzahdeh and Koutchmy (1981). Both models assume a cold main component of the umbra, similar to the existing homogeneous models which were usually derived from

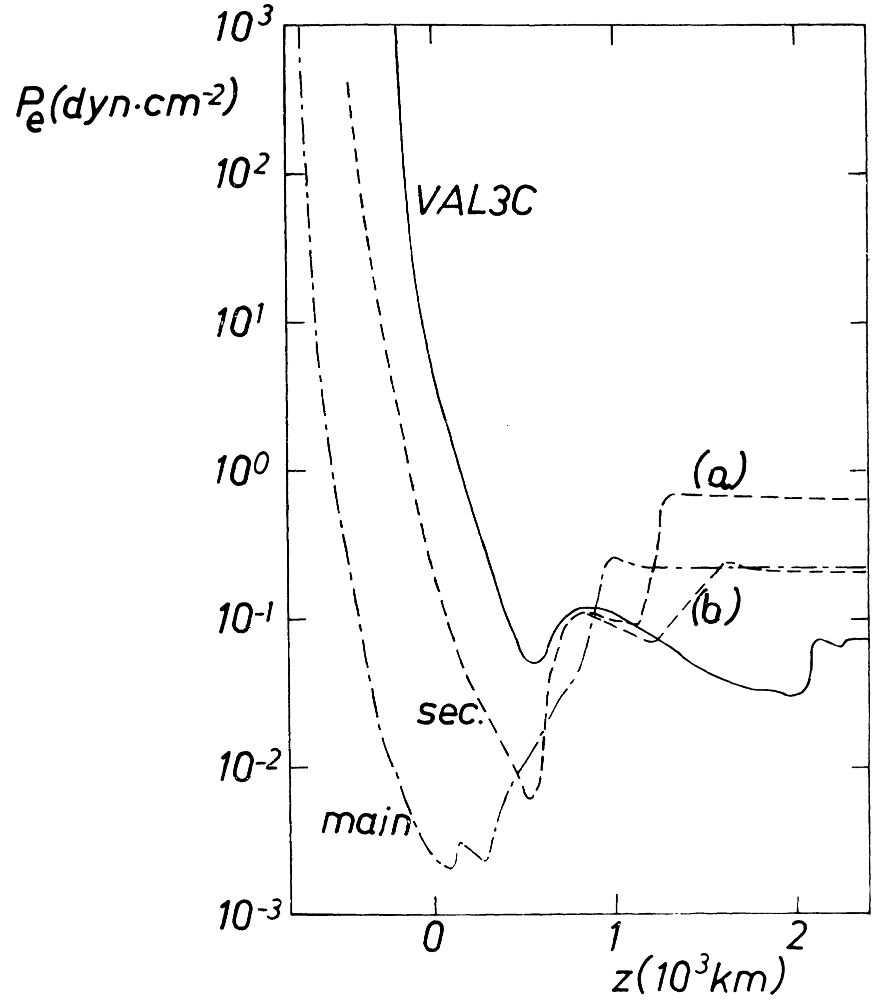

Fig. 4: Electron pressure P_e (z) for the same models as in Figure 3.

the darkest umbral cores, and a hot secondary component with a volume filling factor of $\beta \approx 0.05$ to 0.10. While the earlier of the two-component models proposed a secondary component with a temperature below that of the undisturbed photosphere, T is even hotter than the quiest photosphere in the latter model. Recently an attempt has been made to improve our WOSM by considering the inhomogeneous structure of the umbral atmosphere also at photospheric and chromospheric levels in a two-component model (Obridko and Staude, 1986). While the main component of the model is close to the earlier model by Staude (1981) or to the WOSM, the secondary component has been constructed starting from Obridko's model. Two variants of the secondary component have been derived: in variant (b) the pressure in the upper chromosphere is close to that

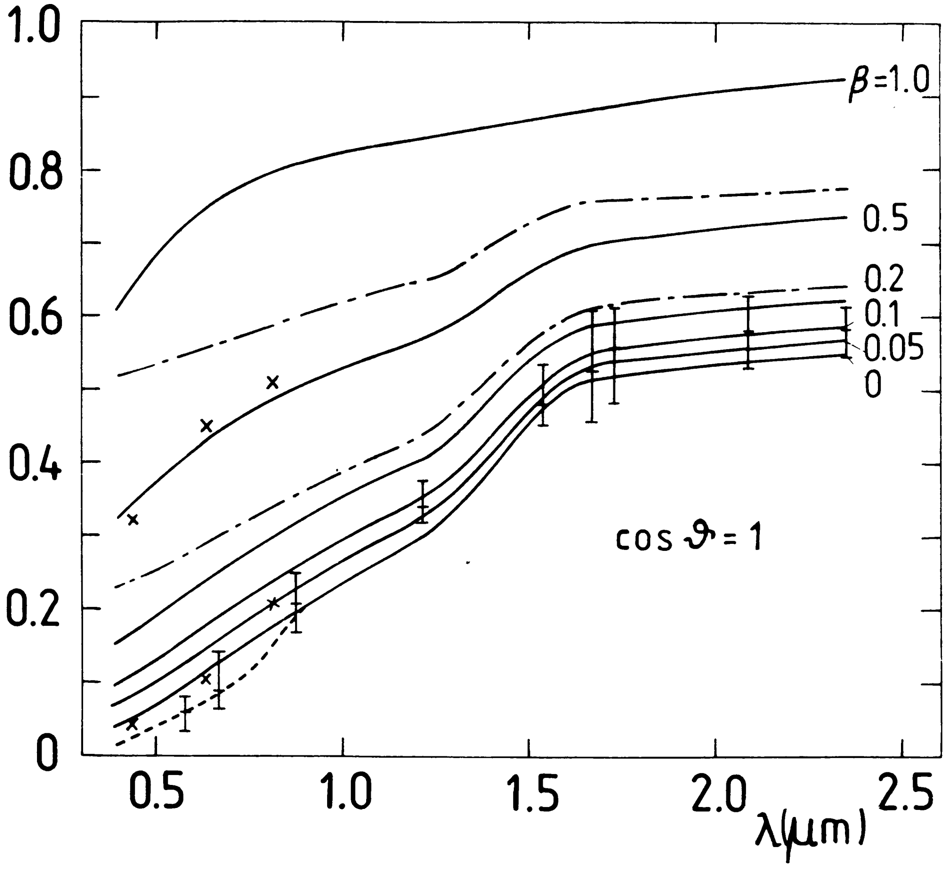

Fig. 5: Predicted continuum intensity ratios φ_λ between spot and quiet sun versus wavelength λ for different filling factors β of the secondary component (full curves). Dashed curves: modified variant using the VAL3C model for the secondary component (only for β = 0.2 and 0.5). Crosses and vertical bars: observations by Wiehr and Stelmacher (1985) and Albregtsen and Maltby (1981), respectively.

in the main component, in variant (a) this pressure is three times larger. In order to test our procedures and for comparison with the umbral components the often used model VAL3C of the mean quiet atmosphere (Vernazza et al., 1981) has been recalculated, starting only from the given T(z) relation. All models are assumed to be in hydrostatic equilibrium in vertical direction, taking into account a turbulent pressure calculated from the given turbulent velocity $v_{tu}(z)$. The T(z) structures of all model components are shown in Figure 3, while Figure 4 gives the corresponding electron pressures. The model has been tested by comparing predictions of the continuum intensity ratios φ_λ = I(spot)/I(VAL3C) with observations at different wavelenths λ. Figure 5 shows that the agreement is good: our two-component model with a filling factor of $\beta \approx 0.05$ to 0.10 fits the broad-band data of Albregtsen and Maltby (1981; vertical bars in the figure) if we additionally consider a lowering of the violet continuum by lines. The lower dashed curve indicates that effect for $\beta = 0$. The small-band, high-resolution data of Wiehr and Stellmacher (1985; crosses in Figure 5) could be explained as well: the lowest intensities would correspond to $\beta \lesssim 0.05$, while the highest intensities are close to a model with $\beta \approx 0.50$. A secondary component with quiet sun temperatures (dash-dot curves for $\beta = 0.2$ and 0.5) or even higher values of T cannot explain the existing observations.

The point z = 0 has been arbitrarily fixed at $\tau_0 = 0.1$ in the umbral main component in figures 2 and 3; the heights where $\tau_0 = 0.1$ and 1.0 are indicated in the T(z) curves for each model. A Wilson depression of 500 km has been assumed between the $\tau_0 = 0.1$ levels in the quiet sun and the umbral main component, while the depression is 200 km for the secondary component. These values are compatible with the assumption of magnetohydrostatic equilibrium in horizontal direction using known values of magnetic field strengths.

3. TRANSITION REGION AND LOWER CORONA

20 years ago Lifshits et al. (1966) proposed a model of the upper atmosphere above sunspots which has been further elaborated by Gelfreikh and Lubyshev (1979), when high-resolution radio data become available: the model assumes a thin chromosphere-corona transition region starting at a height of z = 2000 km above the umbral photosphere. Such a model could explain the observed microwave emission (spectrum, brightness temperatures of $T_b \approx 1.8 \times 10^6$ K, and strong polarization) from sunspots due to gyromagnetic emission as main contribution to the S-component in strong magnetic fields. The picture became more complicated by high-resolution data obtained in the EUV (bright emission at transition region temperatures) and in X-ray lines (very weak emission from sunspot umbrae-contrary to the appearance of the surrounding plage regions). These data cannot be explained simultaneously in the frame of a homogeneous model with plane-parallel stratification. Therefore, Obridko (1979 b) suggested a two-component model consisting of cold and hot elements (loops) where the fraction of cold elements decreases with height. Lately published observed data of high quality, however, raised some objections even to this scheme of a model.

In this situation our KAPG sunspot modelling group started its activity during a workshop held at the Astronomical Institute of the University of Wroclaw, Poland; the work was continued during a working session held at the Astronomical Observatoty Ondřejov, Czechoslovakia. Some preliminary results from these efforts have been presented at two meetings (Bromboszcz et al., 1981 a,b) while the finally resulting "Wroclaw-Ondřejov sunspot model" (WOSM) has been published afterwards by Staude et al. (1983, 1984). At photospheric and chromospheric levels the WOSM incorporated the homogeneous umbral model by Staude (1981) which has been descibed in the preceeding section. At higher levels two components have been assumed: The hot main component with a volume filling factor of $1-\beta \approx 0.9$ has a shallow transition region and coronal values of $T \approx 1.8 \times 10^6$ K and electron density $n_e \approx 10^9 \mathrm{cm}^{-3}$ already at $z \approx 3000$ to 4000 km. Such values are consistent with both the weak X-ray flux above large umbrae and the strong and polarized microwave emission from the same place. The hot matter encloses the feet of cold filaments (loops) which start in a bundle from the umbra; this secondary component has an amply extended transition region and emits the majority of the observed strong EUV emission lines. In the corona of the main component and in the transition region of the secondary component the z-dependence of all physical quantities and of the filling factor β as well may be considered as being small over distances of several 10^3 km. However, strong gradients of T and P_e may exist in horizontal direction, i.e. perpendicularly to the strong magnetic field all transport mechanisms are strongly reduced. Along the loops T slowly increases. Those loops reaching greater distances tend to become more horizontal and hotter corresponding to the occurrence of hot X-ray loops at distances and heights of several 10^4 km above the plage region.

For both components of the WOSM hydrostatic equilibrium and a constant conductive heat flux F_c for $T > 5 \times 10^4$ K were assumed (cf. Alissandrakis et al., 1980), resulting in well defined model atmospheres, if the pressure P_o at the base of the transition region is prescribed.

The WOSM proved able to explain simultaneously many different sunspot observations. For comparison of model predictions with observed data detailed emission models have been developed. The procedures for calculating non-LTE emission in optical and UV lines and continua have been described in the papers mentioned above (Staude, 1981, 1982). X-ray line emission has been analysed using a modified Withbroe iteration procedure for deriving the differential emission measure (Sylwester et al., 1980). The emission model of the S-component of solar microwave emission has been described by Krüger et al. (1982, 1985); it has been successfully applied to the interpretation of high-resolution radio data using the WOSM together with analytic sunspot magnetic field models in cylindric symmetry (e.g., Urpo et al., 1982; Akhmedov et al., 1983; Krüger et al., 1983), but also with more realistic magnetic field data using measured magnetograms and a force-free field extrapolation procedure (Seehafer et al., 1983; Hildebrandt et al., 1984). The WOSM has also been used and discussed by other authors, among them Chiuderi-Drago et al. (1982), Lang and Willson (1982), Lang et al. (1983), Gurman (1984), Gurman and Leibacher (1984), and Doyle et al. (1985). Applications of the WOSM to studies of umbral oscillations and waves will be discussed in the next section.

During a recent workshop held by our KAPG sunspot modelling group in October 1984 at the Central Institute for Astrophysicsin Potsdam, G.D.R., latest ground-based and space-borne high-resolution sunspot observations have been discussed. We tried to test the ability of the WOSM to explain the various new data, but also to discover shortcommings which could suggest improvements of the model (Staude, 1984). Mainly two modifications have been planned and subsequently worked out. Obridko (1985) suggested a general two-component structure of the umbra going through photosphere, chromosphere, transition region, and corona with a fixed filling factor of the secondary component, $\beta \approx 0.05$ to 0.10. This new model is now available (Obridko and Staude, 1986) and shown in the Figures 3 and 4. The photospheric and chromospheric part has already been described in the preceding section. The analytic expressions for the transition region and lower corona have been modified: F_c = constant has now been replaced by the more realistic assumption of a constant coronal temperature T_c which is asymptotically approached at large heights, $z \rightarrow \infty$. Within the transition region the new formulation practically agrees with the earlier version, but at larger heights the differences become clearly visible (Staude, 1985). Two variants of the secondary component have been derived: The 'thin' variant (b) has a value of P_0 close to that of the main component or the WOSM, while in the 'thick' variant (a) P_0 is three times larger. Variant (a) is typical for sunspots with strong EUV plumes and light bridges at lower levels. In such 'active phases' of the spot's development also β may increase. Recent EUV data from sunspots are well explained by the new model (Staude, 1985; Obridko and Staude, 1986).

4. UMBRAL OSCILLATIONS

Velocity and, often, intensity oscillations have been observed in spectral lines formed at different heights of the umbral atmosphere. In the chromosphere and transition region the power spectra of these oscillations often show closely packed narrow peaks at periods between 100 s and 200 s. Contrary to these features oscillations at photospheric level occur in a much broader range of periods between 2 and 8 min. A clear correlation among the parameters period, amplitudes, umbral area, and magnetic field strength does not exist for the chromospheric oscillations.

These oscillations can be attributed to the resonant transmission of slow-mode magneto-atmospheric waves which are semi-trapped in a chromospheric cavity. Detailed calculations for such a model, together with the semi-empiric models of the umbral atmosphere described above, have shown that the basic features of the observed oscillations can be explained in this way (Zhugzhda et al., 1983, 1984, 1985; Staude et al., 1985). The spectrum of resonance periods depends on the structure of the umbral atmosphere (the extent of the chromosphere or the gradient of T), therefore the interpretation of the oscillations provides some kind of 'sunspot seismology', that means valuable information on the atmospheric fine structure can be derived. There is good agreement between the spectrum of resonance periods predicted for the WOSM model and the observed spectrum. Also the predicted differences between the phases of velocity and intensity oscillations and their dependences on height z and on period coincide well with the observed values, thus further corroborating the assumed models of the chromospheric resonator and of the atmospheric structure. The oscillations observed in UV lines are concentrated in the cold fine structure elements of the umbral transition region, that is in the secondary component.

Other resonator models have also been discussed in the literature, e.g. Thomas (1984) argued in favour of a model of a photospheric resonator for fast-mode waves. In our opinion, such a resonator could be excited as well and coupled with the chromospheric resonator within a more complex system of sunspot resonators (Zhugzhda, 1984). For the closely packed peaks of resonance periods in the umbral chromosphere and transition region only the chromospheric resonator model is able to explain all existing observed data (cf. Gurman and Leibacher, 1984; Zhugzhda et al., 1985).

5. CONCLUSIONS

Great progress has been made during the past five years in our knowledge of physical processes and structures in sunspots. Owing to the publication of new high-resolution observations at various wavelengths from X-ray, UV, and optical emissions up to microwaves semi-empiric models of the spatial fine structure of the sunspot atmosphere could be substantially improved and applied to the investigation of basic physical processes such as umbral oscillations. Our KAPG sunspot modelling groups participated in this progress. The 'Wroclaw-Ondřejov sunspot model', together with its recent improvements, provides a unified working model based on self-consistent physical assumptions for a large of heights from the deepest photospheric levels up to the lower corona. Using the WOSM together with emission models developed for the various wavelength regions, the theoretically predicted emissions have been beautifully checked by comparison with the new observed data mentioned above. Also dynamic processes such as umbral oscillations could be explained by a combined model consisting of the WOSM and a chromospheric resonator model for slow-mode magneto-atmospheric waves.

Of course, a lot of work remains to be done. Future work should consider the dependence of the atmospheric structure on the development of the sunspots which is indicated, e.g., in the work of Pap (1985) and Sobotka (1985). The latter work pointed out that differences in the photospheric structures of sunspots are small for large and stable spots, thus confirming to some extent our approach to derive a model for a 'typical'large spot. It would be highly desirable, however, to get more complete observed data of a single sunspot with high spatial and spectral resolutions which should be obtained simultaneously at many different wavelengths, but also in different phases of the spot's development and with high time resolution to record dynamic processes such as oscillations and mass motions at different height levels. The emission models should be improved in various points (e.g., more exact non-LTE calculations, three-dimensional radiative transfer in fine structure elements) and also applied to features outside the umbra (penumbra, plage, active region loops) to get better models also for these important structures of active regions. In order to investigate the role of waves in the energetics of sunspots the theory of oscillations should include nonlinear and nonadiabatic processes (e.g., radiative dissipation). Some of such activities are being prepared. In this way improved information on plasma parameters could be placed at disposal which is necessary for a further investigation of physical processes in magnetized atmospheres such as solar active regions in general or sunspot umbrae in particular.

ACKNOWLEDGEMENTS

The author would like to thank all collaborators of our KAPG sunspot modelling group for their active participation in our common work. I must apologize for all shortcomings and incompleteness in this review.

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Discussion

M.A. Mogilevsky:
Допускает-ли Ваша статическая модель пятна обобщение на случаи учета динамических процессов? Например, возможность использовать метод ак. В.В. Соболева для решения уравнения переноса с учетом движения?

J. Staude:
In its present state, our semi-empirical umbral model atmospheres only provide information on the spatial distribution of thermodynamic parameters (T, n_e, etc.) in some basic state. In our study of umbral chromospheric oscillations small deviations from this basic state have been considered. In the future, dynamic processes should be taken into account, by solving simultaneously the non-LTE equations of radiative transfer and of hydromagnetics, but this can only be done for special purposes admitting simplifying assumptions in the complicated system of equations.

Ye.Ya. Zlotnik:
You have no 20000°K plateau at the height 2000 km in your sunspot model. Does it consist with observations?

J. Staude:
Considering models which try to explain Ly-alpha profiles in different solar features (see e.g. Basri et al., 1979) it is obvious that the extent of T = 20000°K plateau decreases with increasing gradient of T in the chromosphere, that means with increasing density in hydrostatic models. Sunspot umbrae belong to the high-density models (close to plages) which do not require an extended plateau of T. There is, however, some ambiguity in determing the detailed T/z/ run, and better observations are required to exclude such uncertainties.

G.B. Gelfreikh:
Radio observation made with the RATAN-600 have shown that the strength of magnetic field in CCTR above a sunspot is very high and are nearly two-fold higher than the magnetic field strength found for the same sunspot from SMM observation in CIV line. Can your model explain this contradiction?

J. Staude:
Yes, this is indeed possible within the frame of our two-component model: The microwave emission is formed in the umbral main component, where coronal temperatures of about 2×10^6 K exist at relatively small heights above the umbral photosphere (a few 10^3 km, where the magnetic field is still large). UV lines such as the CIV line are formed mainly in the secondary component with its largely extended transition region, that means at much larger heigth, where the magnetic field strength is smaller.