SEMI-EMPIRICAL MODELS OF SUNSPOTS IN VARIOUS PHASES OF EVOLUTION

M. Sobotka
Astronomical Institute, Czechoslovak Academy of Sciences,
251 65 Ondřejov, Czechoslovakia

ABSTRACT The characteristics of 10 semi-empirical models of umbrae of different sizes and in various phases of evolution are studied, namely: 1) The spectral distribution of the umbra/photosphere continuum intensity ratio 2) the dependence of the integral umbra/photosphere intensity ratio on the umbral radius, 3) the variations of the integral contrast of umbrae from the disk center to the limb. This study and earlier ones indicate that the characteristics of the model depend mainly on the umbral radius (for $r_u <$ 3.5"- 4") and do not depend on the phase of evolution, but there are substantial differences caused by specific qualities of each individual sunspot.

ПОЛУЭМПИРИЧЕСКИЕ МОДЕЛИ СОЛНЕЧНЫХ ПЯТЕН НА РАЗНЫХ СТАДИЯХ РАЗВИТИЯ
В работе изучаются характеристики 10-ти полуэмпирических моделей теней разного размера и на разных стадиях развития, именно: 1) Спектральное распределение относительной интенсивности тени в непрерывном спектре, 2) зависимость интегральной относительной интенсивности тени от радиуса тени, 3) изменение интегральной относительной интенсивности тени в зависимости от положения пятна на диске. Из этого исследования и также из предыдущих работ вытекает, что свойства модели зависят прежде всего от радиуса тени (для $r_u <$ 3,5"- 4") и не зависят от фазы развития. Однако, важную роль играют отклонения, вызываемые индивидуальными свойствами отдельных пятен.

SEMIEMPIRICKÉ MODELY SLUNEČNÍCH SKVRN V RŮZNÝCH STADIÍCH VÝVOJE
V práci jsou studovány charakteristiky 10 semiempirických modelů umber různých rozměrů a v různých fázích vývoje, jmenovitě: 1) Spektrální rozdělení relativní intenzity kontinua umbry vzhledem k fotosféře, 2) závislost integrální relativní intenzity umbry na poloměru umbry, 3) změny integrální relativní intenzity umbry směrem od středu disku k jeho okraji. Z této a předcházejících prací vyplývá, že vlastnosti modelu závisejí především na poloměru umbry (pro $r_u <$ < 3,5"- 4") a nejsou závislé na vývojovém stadiu. Nicméně, projevují se zde

podstatné odchylky způsobené individuálními vlastnostmi jednotlivých skvrn.

Recent umbral models (e.g. Avrett, 1981; Staude et al, 1983; Maltby et al, 1985) chiefly describe large, well-developed umbrae, which allow reliable observations of good quality to be obtained. Nevertheless, for the study of the birth and evolution of sunspots one must have an idea of the models of umbrae differing in size and phase of evolution.

In the preceding papers (Sobotka, 1985a, 1985b - hereinafter referred to as Paper I and II, respectively) we constructed 12 semi-empirical models of photospheric layers in young, stable and decaying umbrae with radii r_u from 2" to 8". The models are based on spectroscopic observations performed with the horizontal telescope-spectrograph HSFA 2 of the Ondřejov Observatory in the years 1982 - 1983. Unlike the models mentioned at the beginning of this paper, which are usually based on continuum observations, we used the profiles of the lines Mg I b_1 518.4 nm, Fe I 543.5 nm and Na I D_2 589.0 nm. Thus our models are less sensitive to stray light. As we are confined to photospheric levels, we may assume that LTE, hydrostatic equilibrium and temperature-versus-height distribution in the form $T(z) = T_1 (z+c)^b / (50+c)^b$, where z is the geometric height and T_1, b, c are parameters (see Paper I), apply.

The models obtained can be divided into three groups: "hot", "medium" and "cool". The first group includes models of small ($r_u \sim 2$") spots without penumbrae. The models of the well-developed, stable sunspots belong to the last group. By studying the principal parameters of the models (Wilson depression, temperature and density at unity optical depth), we are able to draw the following conclusions (see Paper II): 1) For the umbral radius $r_u < 3.5$"- 4" the model is strongly dependent on r_u; for larger values of r_u the dependence does not occur. 2) For a fixed umbral radius there are no differences between the models of umbrae in various evolutionary phases.

We can further investigate the characteristics of the models. Assuming LTE, Holweger's (1967) model of the quiet photosphere and opacity sources H, H^-, Mg, Si, H_2^+, we computed the spectral distribution of the umbra/photosphere continuum intensity ratio $(I_u/I_{ph})_\lambda$ for models Nos 12 (hot), 13 (cool) and 22 (medium), published in Paper II. The results are presented in Fig. 1. For comparison, the observed values for a typical large umbra, taken from Albregtsen and Maltby (1981) and Maltby et al (1985), are shown. We can see that the hotter the model, the greater the gradient of $(I_u/I_{ph})_\lambda$.

In case of small sunspots, a horizontal transfer of radiation from the surrounding photosphere may take place (Obridko, 1985). For the study of its influence on the physical structure of the umbra it is useful to know the dependence of the integral umbra/photosphere intensity ratio I_u/I_{ph} on the umbral radius. We computed the values of I_u/I_{ph} for 10 umbral models, integrating the intensities I_u, I_{ph} over the region λ 390 - 800 nm. The models of all three groups were used (hot models No 12 and 61, medium models Nos 21, 22, 53, 63 and cool models Nos 13, 33, 43 and 72). The results are shown in Fig. 2.

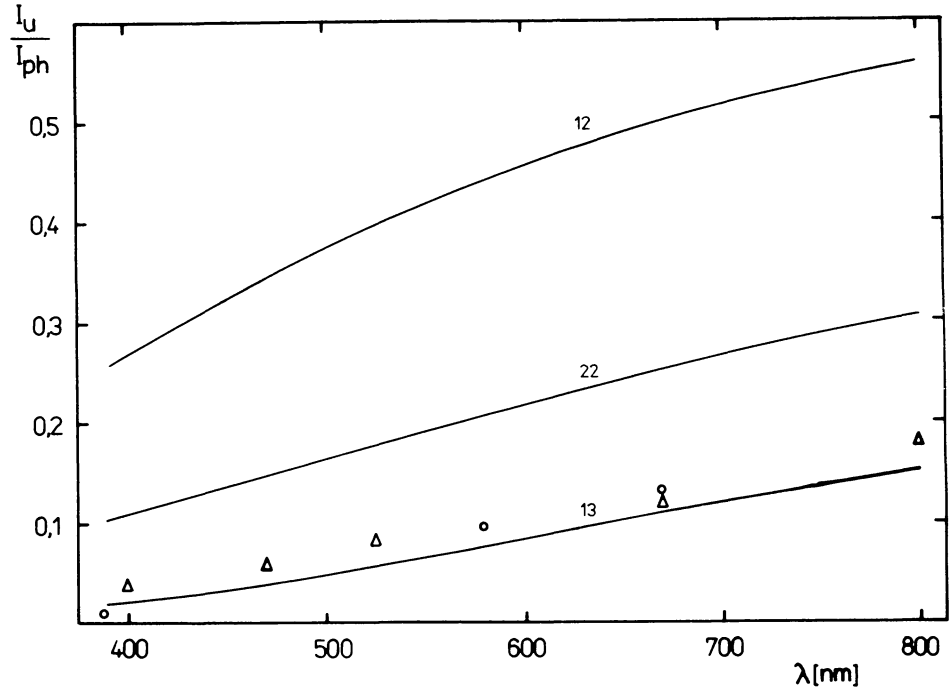

Fig. 1: Spectral distribution of the umbra/photosphere continuum intensity ratio for models Nos 12, 13 and 22.

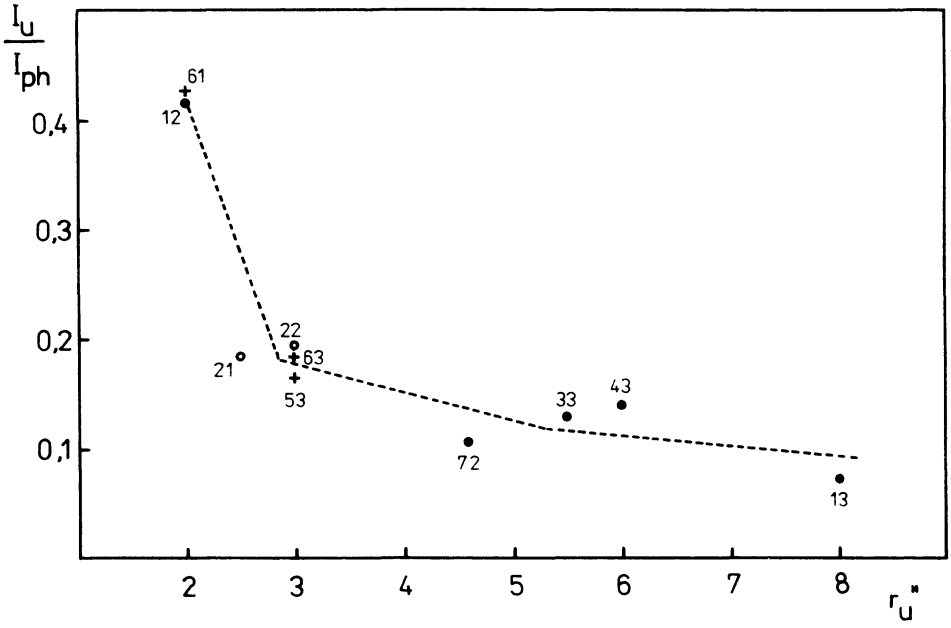

Fig. 2: Integral umbra/photosphere intensity ratio (region 390 - 800 nm, μ=1) versus umbral radius.

The mean dependence of integral I_u/I_{ph} on the umbral radius is roughly approximated by the broken line. With decreasing r_u it rises slowly from 0.1 (cool models) to 0.2 (medium models, $r_u \sim$ 2.5"- 3") and then very quickly to about 0.4 (hot models, $r_u \sim$ 2"). We marked the sunspots in early phases of evolution by circles, those in maximum by dots and the old, decaying spots by crosses, to intercept the evolutionary effects. It is clearly seen (in accordance with the results of Paper II) that the phase of evolution has no significance.

All the computations mentioned above were performed for the position of the sunspot in the disk center, i.e. for $\mu = \cos\vartheta = 1$. Besides, the integral intensity ratio I_u/I_{ph} was also computed for μ = 0.8, 0.6 and 0.4. In general, it was found that it rises with decreasing μ, but the behaviour of this dependence was very individual. For example, in case of models Nos 13, 21 and 63 the integral intensity ratio increased from μ = 1 to 0.4 by a factor of 1.3 - - 1.5 and, on the contrary, for No 22 did not change at all. This is in contradiction to another semi-empirical models (e.g. Albregtsen and Maltby, 1981; Avrett, 1981), which predict a decrease of I_u/I_{ph} towards the limb.

Summarizing the results, we can say that the conclusions deduced in Paper II have been confirmed. The characteristics of the models depend mainly on the umbral radius. However, this dependence is influenced substantially by the **specific qualities of each individual sunspot.**

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DISCUSSION

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DISCUSSION

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V. Bumba

По Вашим графикам и из Вашего материяля вытекает что самые малые пятна являются самыми холодными. Нет ли исключения по Вашим наблюдениям из этого правила?

M. Sobotka:

Из этого правила, кроме одного пятна наблюдаемого вблизи края диска, нет исключения. Даже индивидуальные отклонения в распределениях температуры отдельных пятен не имеют существенного влияния.

M.A. Mogilevsky:

Вы рассматриваете модели изолированных (одиночных) пятен. Как правило пятно находится в группе (даже самой простой-биполярной). Зависит ли модель от того изолировано ли оно или в группе?

M. Sobotka:

При наблюдениях подбирались более менее изолированные пятна и зависимость модели от того, является ли пятно членом группы или нет не изучалась.