The Infrared Ca II lines in Sunspot Umbrae

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ABSTRACT

Aims. We present an empirical working model for sunspot umbrae which equally describes observed continuum intensities and line profiles.

Methods. The wings of the infrared Ca II lines depend sensitively on the temperature gradient at \(-0.6 < \log T_{\odot} < +0.3\) but not essentially on the absolute value of \(T\). These lines are observed to remain almost unchanged from photosphere to umbra and are thus insensitive to parasitic light. It is also shown that the infrared K I 7699 Å line is suitable for umbra spectroscopy since it is not seriously blended, its continuum is well defined and it is less influenced by parasitic light as compared to lines in the visible spectrum, due to the smaller umbal contrast.

Results. Calculations show that the umbal gradient \(dT/d\tau\), required to fit the Ca II triplet lines, strongly conflicts with the observed profiles of K I 7699, Na D₂ and Fe I 5434 \((g=0)\), even when assuming vanishing Fe II lines for a maximum correction of parasitic light. It is shown that the discrepancy from the different line profiles may be removed by adopting an opacity enhancement as introduced by Zwaan (1974) from a discussion of continuum contrasts alone. The finally proposed umbal working model is very close to a scaled model of the quiet Sun with \(T_{\text{eff}} = 4000\)K thus resembling a M0 rather than a K5 stellar atmosphere.

Key words. Sunspot umbra - line profiles - empirical model - effective temperature

1. Introduction

A sensitive method for the determination of the empirical model atmospheric of a sunspot umbra is the investigating line profiles. The infrared Ca II triplet lines (at 8498, 8542, and 8662 Å) have so far not been considered. Calculations show that the wings of these lines are very sensitive to the temperature gradient at \(-0.6 < \log T_{\odot} < +0.3\) but much less sensitive to the absolute value of the temperature. Cursory inspection of umbral spectra shows that these triplet lines are largely unchanged when compared to the spectrum of the neighboring photosphere. This implies an almost negligible influence of parasitic light, which anyway is reduced with respect to the visible region due to the smaller continuum contrast. In addition, the wavelength region around 8500 Å seems not seriously perturbed by purely umbral lines.

2. Observations

We investigated the infrared Ca II lines from several sunspot spectra observed in summer 1967, 1968, and 1979 at the Locarno solar station of the Göttingen observatory with the plane grating spectrograph (Czerny-Turner type) at high dispersion (0.2 Å/mm) and also with the concave grating spectrograph (Pasche-Rungen mounting) at low dispersion (2.5 Å/mm). Microphotometry of the infrared Ca II lines in these umbral spectra consistently shows no significant difference with the simultaneously observed line profiles in the neighboring photosphere. For further confirmation of this interesting result we recorded photoelectrically the line-to-continuum ratio of these Ca II lines in a spot near the disc center on July 7, 1979, and obtain the same result.

Those of our observed Ca II IR lines which occasionally show emission cores, always yield symmetric ones for Ca II 8542 but asymmetric ones for 8Ca II 498 and Ca II 8662 with opposite sign: Ca II 8498 has a steeper blue, Ca II 8662 a steeper red flank of its core emission.

In addition to these lines, spectra of the strong K I 7699 line were investigated in the same manner. In contrast to the Ca II lines, this K I line is not unchanged and therefore strongly affected by parasitic light. A maximum correction has been applied by assuming Fe II 7711 to vanish in umbrae (cf. Stellmacher and Wiehr, 1970). A first photoelectric recording of this K I line was obtained in the July 7, 1979, spot with particular care for parasitic light correction, which typically consists of 5% penumbral blurring and <1% photospheric scattering (in units of the photospheric continuum intensity).

Figure 1 shows calculated profiles of Ca II 8542, K I 7699, NaD₂ and Fe I 5434 \((g = 0)\) using different empirical models. It can be seen that the strong criterion of the unchanged Ca II lines is only reproduced by Zwaan’s (1974) umbral model. Closer inspection shows that this agreement is essentially due to the high temperature gradient in the region \(-0.6 < \log T_{\odot} < +0.3\), where the line wings are formed. On the other hand, it was shown by Stellmacher and Wiehr (1975) that Zwaan’s (1974) model does not reproduce the wings of NaD₂ and Fe I 5434 within the observational limits given by vanishing and, respectively, maximum correction
Fig. 1. Observed lines profiles in sunspots: vertical bars give raw and maximum straylight-corrected values. Comparison with calculated profiles using the models by Kjeldseth-Moe & Maltby dark (d) and bright (b), Stellmacher & Wiehr (+), Henoux (H), Kneer (K), Zwaan with \( q(\lambda) = 1.05 \) (O), and model M4 of this paper with \( q=1.0 \) (full line). The four panels give: [a] Ca II 8542; [b] K 7699 with Zeeman splitting = 3000 G and \( q=1.3 \); [c] Fe I 5434 with \( q=1.62 \); [d] Na D2 (only blue wing) with \( q=1.57 \). For comparison the photospheric (dashes) and penumbral (dash-points) profiles are shown.

3. Discussion

A reasonable fit to all observed lines and continuum data (see Fig. 2) could be achieved when introducing the opacity enhancement \( q(\lambda) \) for \( \lambda < 8500\AA \) as suggested by Zwaan (1974). Several alterations of the \( q(\lambda) \) dependence did not improve this fit. The concept of an opacity enhancement for sunspot umbrae had been proposed since the wavelength variation of umbral continuum intensities at \( 0.5\mu < \lambda < 1.7\mu \) cannot be reproduced by a model even when assuming a maximum temperature gradient from a radiative equilibrium stratification.

On the other hand, Stellmacher and Wiehr (1975) argue that the range of observed umbral continuum data and the uncertainties of the photospheric reference intensities still allow a radiative equilibrium stratification without introducing an opacity enhancement. In that case, their model M3 gives the 0.5\( \mu \) intensity at its upper and the 1.7\( \mu \) intensity at its lower observational limits (Stellmacher and Wiehr, 1975, cf. Fig. 1). On the other hand, model M3 nicely describes the observed Fe I 5434 and Na D2 line wings.
The consideration of observed infrared Ca II lines in addition that of Fe 5434, Na D2, K 7699 and the corresponding continuum data gives further support to the existence of an enhanced opacity, which originally had been proposed by Zwaan (1974) for a good representation of umbral continuum contrasts alone.

Our present observations do not allow to essentially refine the \( q(\lambda) \) given by Zwaan. In particular, we can not verify whether \( q(\lambda) \) further increases at \( \lambda < 5000 \text{Å} \), which might give some hint to the still unknown physical nature of the opacity enhancement. A possible explanation is line haze produced by atomic and molecular lines (Zwaan, 1974; Gaur et al., 1979) and/or unknown continuum absorbers (as e.g. proposed by Oinas, 1974, 1977, for cool stars).

### 3.1. Umbral model

Our improved model 'M4', is given in Fig. 3 together with our former model M3 and with Zwaan’s (1974) model. The new model M4, listed in the table, differs from M3 only for the layers \( -0.6 < \log \tau_{0.5} < +0.3 \) in order to fit to the observed infrared Ca II lines discussed in this paper. For the outer layers \( \log \tau_{0.5} < -0.6 \) M4 is identical with M3 to preserve the description of observed non-magnetic lines as discussed by Stellmacher and Wiehr (1970 and 1972). Also the deep layers \( \log \tau_{0.5} > 0.6 \) of M4 agree with M3 in order to meet the radiative equilibrium stratification, which is required for \( \log \tau_{0.5} > 0.8 \) to fit the infrared Ca I lines discussed by Stellmacher and Wiehr (1975).

The final umbral model M4 then optimally describes the whole range of continuum and line profile observations. It can thus be considered as an empirical working model with wide validity for dark umbral cores. Its temperature stratification is close to a scaled model of the undisturbed Sun with a scaling factor of \( T_{\text{eff}}^{\text{umbra}} = 4000 \text{K} \) and thus to a M0 rather than a K5 stellar atmosphere.

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**References**

- Brault, J.: 1976 (private communication)
- Ekmann, G., Maltby, P.: 1974, Solar Phys. 35, 317
- Gaur, V. P., Pande, M. C, Sah, M.: 1979, Solar Phys. 62, 83
- Henoux, J. C.: 1969, Astron. Astrophys. 2, 288
- Kjeldseth-Moe, K. O., Maltby, P.: 1974, Solar Phys. 36, 109
- Kneer, F.: 1972, Astron. Astrophys. 18, 39
- Oinas, V.: 1974, Astrophys. J. Suppl. 27, 405
- Oinas, V.: 1977, Astron. Astrophys. 61, 17
- Schleicher, H.: 1977, Thesis Göttingen
- Shine, R. A., Linsky, J. L.: 1972, Solar Phys. 25, 357
- Stellmacher, G., Wiehr, E.: 1970, Astron. Astrophys. 7, 432
- Stellmacher, G., Wiehr, E.: 1972, Astron. Astrophys. 19, 293
- Stellmacher, G., Wiehr, E.: 1975, Astron. Astrophys. 45, 69
- Zwaan, C.: 1974, Solar Phys. 37, 99