IL NUOVO CIMENTO Vol. 25 C, N. 5-6 Settembre-Dicembre 2002

The atmospheres of penumbral fine-structure(*)(**)

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(ricevuto il 10 Giugno 2002; approvato il 7 Agosto 2002)

Summary. — High spatial resolution observations recorded with the Swedish Vacuum Solar Telescope are used to study the atmospheric structure of the penumbra of sunspots. Spectra in the wing of the Ca II K line are inverted to derive the temperature distribution of fine-scale structures in the penumbra. Weak line blends in the Ca II K wing probe the Evershed effect at different heights in the atmosphere.

PACS 96.60.Qc – Sunspots, faculae, plages.
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

Theoretical models of the penumbra of sunspots are often based on atmosphere models with mean penumbral properties or based on observations with low spatial resolution. In this work, high spatial resolution spectra of the Ca II K line observed with the Swedish Vacuum Solar Telescope (SVST) are used to derive semi-empirical atmosphere models of penumbral fine structure. The extensive damping wings of the Ca II K line are formed over a broad range in height and is used to probe the temperature distribution of the penumbral atmosphere. Measurements of the Doppler shift of different weak line blends in the Ca II K wing map the Evershed effect at different heights. Figure 1 illustrates how we can probe different atmosphere layers using the Ca II K wing and weak line blends. Two competing theoretical models of the Evershed effect, the siphon flow model by Montesinos and Thomas [1] and the dynamical model by Schlichenmaier *et al.* [2], argue that the Evershed flow is confined in elevated channels. This was first observed by Rimmele [3]. In this work, the height dependence of such Evershed channels is investigated.

(*) Paper presented at the International Meeting on THEMIS and the New Frontiers of Solar Atmosphere Dynamics, Rome, Italy, March 19-21, 2001.
(**) Based on observations made with the Swedish Vacuum Solar Telescope operated on the island of La Palma by the Royal Swedish Academy of Sciences in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias.
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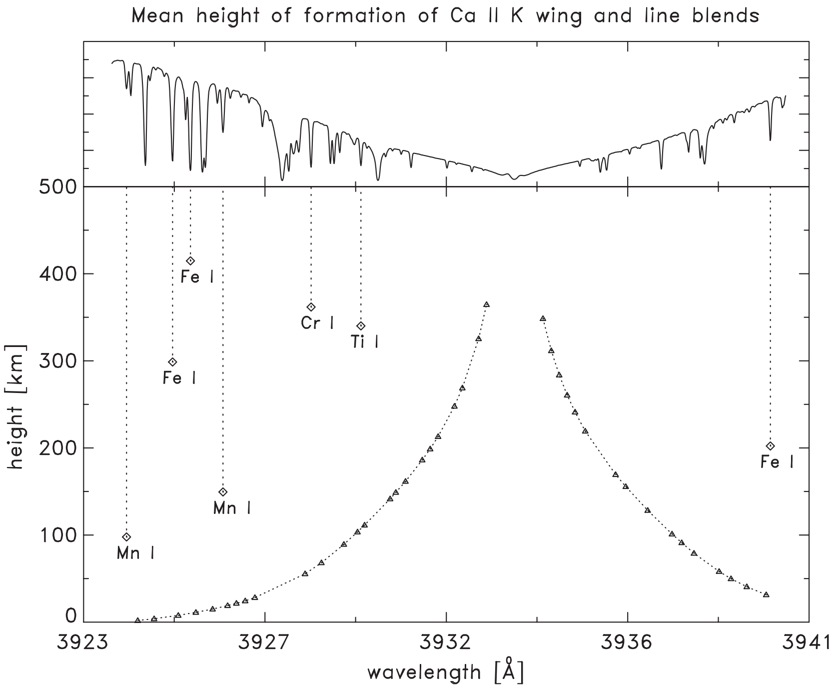

Fig. 1. – The top panel shows a solar atlas spectrum of the Ca II K line. The wavelength range is the same as the observations. In the bottom panel the mean height of formation of the Ca II K wing (triangles) and the cores of weak line blends (diamonds) are plotted. The heights of formation result from LTE calculations of synthetic line spectra in the Holweger-Müller model atmosphere for the quiet Sun.

2. – Observations and analysis

The sunspot in NOAA Active Region 8704 was observed on 20 September 1999 (S19.2°, E31.5°, $\mu = 0.77$) and 22 September 1999 (S20.0°, E4.0°, $\mu = 0.88$) with the SVST and Dutch Open Telescope (DOT) at La Palma. The observations comprise spectra of the Ca II K (3933.66 Å) line, slit-jaw images recorded with a narrow filter (FWHM 3 Å) centered on the Ca II K line core and reference images recorded with a wide filter (FWHM 10 Å) centered on the G-band (4305 Å). The top two images in fig. 2 show a G-band and a Ca II K slit-jaw image. The sunspot was scanned by moving the spectrograph slit perpendicular to the slit direction thereby creating a 3-dimensional data cube with 1 spectral and 2 spatial dimensions. The bottom two images in fig. 2 are examples of images constructed from such scan: an intensity image in the far Ca II K wing on the left, on the right a line core intensity image in the Mn I 3926.48 Å line.

The method to derive models of the upper photospheric regions from the damping wings of the Ca II resonance lines was first described by Shine and Linsky [4]. For the formation of the wings of the Ca II K line a number of reasonable assumptions are made: all calcium atoms are in the Ca II ground state, LTE is valid (non-LTE effects are only important within ~ 1 Å from the line core) and the Eddington-Barbier relation couples the observed outgoing intensity to the source function at $\tau = \mu$, which equals the local Planck function using LTE. With the assumption of hydrostatic equilibrium

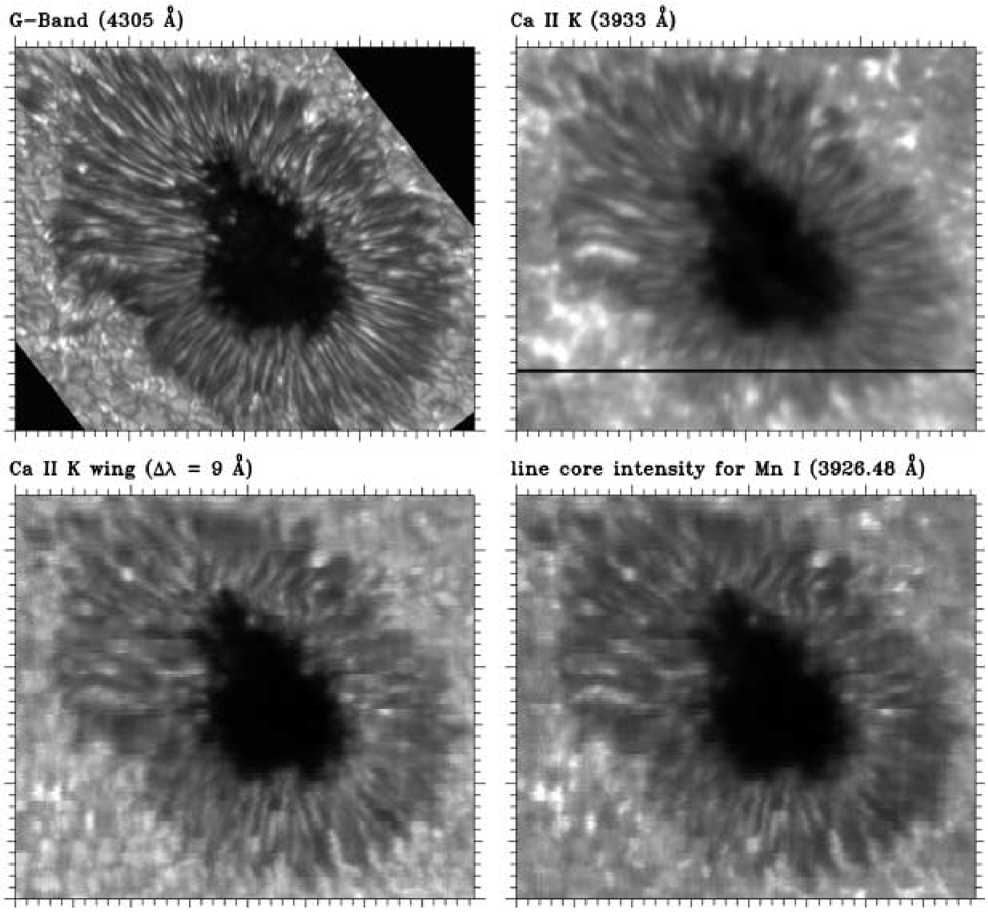

Fig. 2. – Sunspot in AR 8704 observed on 20 September 1999 by the SVST and the DOT at La Palma. The two images at the top are filtergrams: left is a speckle-reconstructed G-band image recorded by the DOT. The right image was recorded with a Ca II K filter and served as slit-jaw image to locate the spectrograph slit on the Sun. Note the dark slit crossing the penumbra. The two images at the bottom are constructed from a sunspot scan consisting of 150 spectrograms. The left image is an intensitygram in the far wing of the Ca II K line, near 3924 Å, 9 Å from the Ca II K line core, this part of the wing is formed in the bottom of the photosphere (see fig. 1). The right image is an intensitygram in the line core of Mn I at 3926.48 Å, a weak line blend in the wing of the Ca K line, the core is formed around 100 km above the continuum in the quiet Sun (see fig. 1). Tick marks in seconds of arc.

we can obtain the temperature as a function of column density. To derive radiation temperatures from the observed Ca II K wing spectra, the mean spectrum outside the sunspot, excluding bright plage, was calibrated to a synthetic Ca II K spectrum from the Holweger-Müller model atmosphere [5].

From the sample of observed weak line blends in the wing of the Ca II K line a subset of lines was selected to probe material velocities at different heights in the penumbral atmosphere. Atomic data was obtained from the VALD data base [6-8] and for each line a synthetic line spectrum was calculated and compared to an atlas spectrum [9]. For

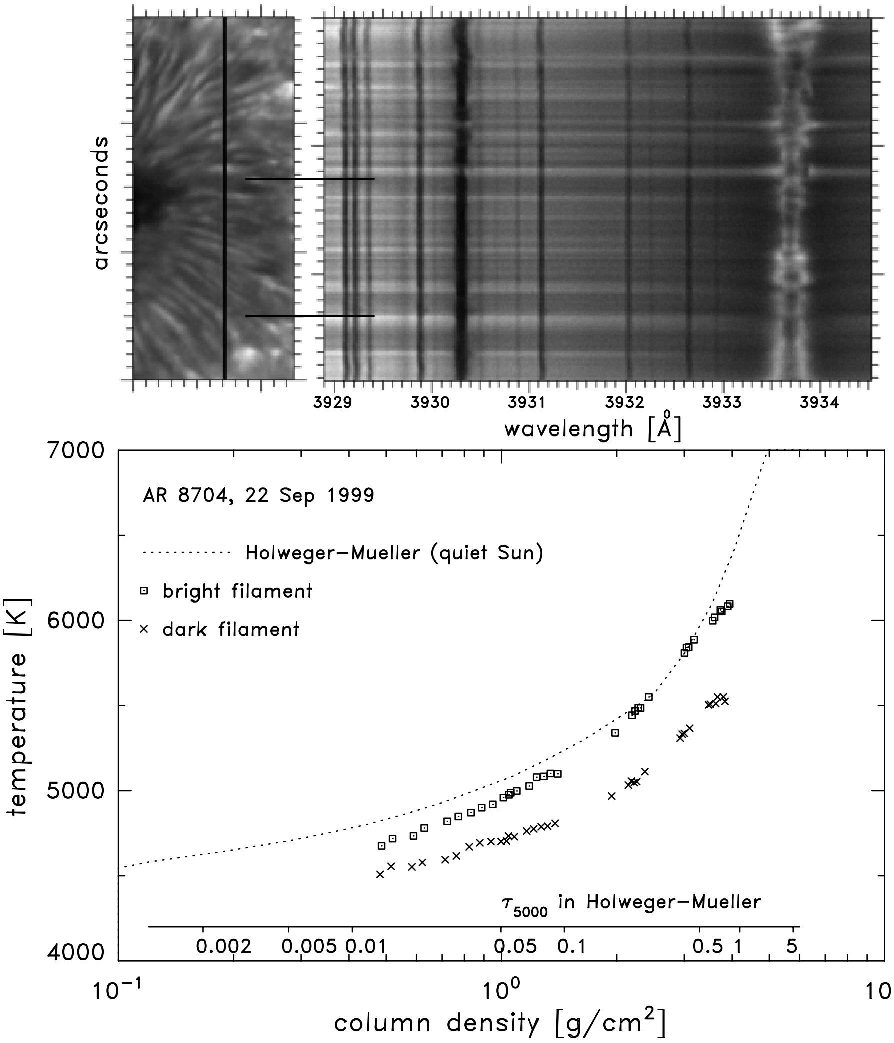

Fig. 3. – The two top panels show a spectrogram and a corresponding slit-jaw image. The spectral range covers the Ca II K core and a small portion of the observed blue wing. Note that the slit crosses the "inversion" line for the Evershed effect; the Evershed flow is directed perpendicular to the line of sight for this part of the penumbra and the line blends are not Doppler shifted. Two black bars mark a dark and a bright filament in the slit-jaw image and the corresponding spectra in the spectrogram. For these spectra, the temperature distributions of the atmospheres derived from the inversion are shown in the bottom graph. These two temperature distributions are the extrema for this slit position, all other temperature distributions lay between these two.

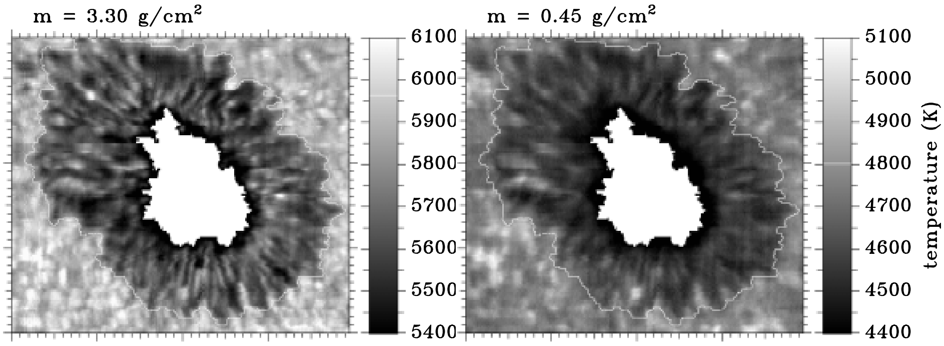

Fig. 4. – Temperature maps for two different values of column density (m). The umbra is excluded from the inversions because of large uncertainties due to scattered light. Each map has an individual color-coding temperature scaling box on the right.

the radiative transfer LTE was assumed to hold and the Holweger-Müller atmosphere was used as model atmosphere. Given the uncertainty in the atomic data, the $\log(gf)$ values were altered for the line core depression to fit the atlas spectrum. The lines were selected on the basis of the quality of the atomic data, their applicability for Doppler shift measurements, *i.e.* well isolated, not contaminated by other lines and relatively strong, and their uniqueness of line-core height of formation, so that the ensemble of lines probes material velocities at different heights. The diamonds in fig. 1 mark the mean height of formation for the selected line blends.

More details about the observations and analysis can be found in [10].

3. – Results and discussion

The bottom graph in fig. 3 shows the result of the inversion for two locations along the slit. The temperature distributions of a dark and a bright filament are plotted.

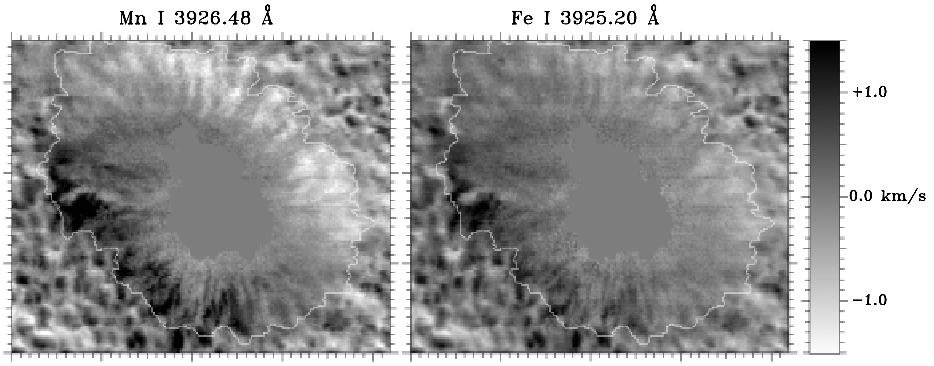

Fig. 5. – Doppler maps for two line blends in the Ca II K wing. Blue shift is dark (positive). The umbra is masked out. The deeper formed Mn I line shows a stronger Evershed signal than the higher formed Fe I line. Compare the Mn I Doppler map with the line core intensity map in fig. 2.

The bright filament (squares) has similar temperatures as the Holweger-Müller model atmosphere (dotted line) at low heights. Higher in the atmosphere, the bright filament is significantly cooler and the temperature comes closer to the dark filament temperatures. Note that the temperature contrast in the lower atmospheric layers of the penumbra is larger than in the higher layers. This is also illustrated by the temperature maps in fig. 4. On the left the deepest observed atmospheric level is shown: at $m = 3.3$ g/cm^2. This corresponds to a spectral distance in the Ca II K wing of about 9.8 Å from the line center. On the right a map for higher atmospheric levels is shown: $m = 0.45$ g/cm^2, corresponding to $\Delta\lambda \approx 1.3$ Å. The temperature contrast in the left (deep) map is much higher than in the right (high) map. The photon mean free path increases with height, giving higher parts of the atmosphere an intrinsic "fuzzy" character.

Figure 5 shows Doppler maps for two line blends: Mn I 3926.48 Å formed at an height of around 150 km and Fe I 3925.20 Å formed around 280 km. Line core position of the mean umbral line profile is used as reference wavelength. The Evershed effect is clearly present in both maps: a blue shift at the disk center side of the penumbra and a red shift at the limb side. At several locations the material flow is confined in flow channels. These flow channels cover a large fraction of the penumbra. For both lines the Evershed effect is increasing with increasing distance from the umbra. The lower formed Mn I line shows a stronger Evershed effect than the higher formed Fe I line. Analysis of the Doppler shift of the other line blends shows a general trend of stronger Evershed effect for the deepest formed lines. For the deepest formed line, Mn I 3924 Å formed around 100 km, the Evershed signal (*i.e.* Doppler shift) is strongest. This supports the idea that the Evershed effect could flow through channels that are elevated at moderate heights as proposed in the Schlichenmaier model. In the siphon flow model of Montesinos, Evershed channels reach heights over 300 km above the continuum. Such channels would result in different Doppler signals than was observed: the lower formed Mn I lines would be formed below the channels and show a smaller Doppler shift than the lines that are formed at higher layers. For each location in the penumbra detailed information about the atmospheric structure is known from the inversion of the Ca II K wing. It is planned to perform detailed line formation calculations for the line blends to investigate the effect on height of formation due to penumbral atmospheric structure to be able to draw firm conclusions about height dependence of the Evershed effect.

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The author wishes to thank the SVST staff for support during the observations. Dr. P. SÜTTERLIN is thanked for the high-resolution G-band image of AR8704. The author is very grateful to Dr. D. KISELMAN for helpful discussions and suggestions.

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