1st Advances in Solar Physics Euroconference
Advances in the Physics of Sunspots
ASP Conference Series, Vol. 118, 1997
B. Schmieder, J.C. del Toro Iniesta, M. Vázquez, eds.

Umbral Polarimetric Measurements Using the Ti I Multiplet at 2.2 μm

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Abstract. We present the first measurements of sunspot magnetic fields using the lines of the Ti I multiplet at 2.2 μm. These lines are most sensitive to the plasma in the umbra. The observed line profiles suggest that the temperature gradient in mid-photospheric layers of a sunspot umbra is steeper than that of the standard sunspot models of Maltby et al. (1986).

1. Introduction

The observation of umbral magnetic field strengths is, on the one hand, simple since the strong umbral magnetic field completely splits many spectral lines. On the other hand, such measurements are hampered by a number of factors. For example, the low umbral temperature leads to a strengthening of the line profiles, i.e. to their saturation and hence broadening which can result in large uncertainties in the measured field strengths. Another problem lies in stray-light contamination from the surrounding penumbra and plages which can corrupt even polarized line profiles and lead errors in the deduced magnetic field strength inclination.

The lines of the Ti I multiplet at 2.2 μm are not affected by both of these problems and are therefore ideal candidates for stray-light free measurements of umbral magnetic fields. Up to now, these lines have not been used for the investigation of solar magnetic structures although they have previously been observed in sunspots (Hall 1974, Wallace & Livingston 1992, Rüedi et al. 1995) and have been employed to probe the magnetic field of late-type stars (Saar & Linsky 1985, Saar 1996a, b). In this paper we report on the first measurements of umbral magnetic fields using these lines, as well as the first numerical transfer calculations of these lines.

[1]Operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science foundation.

2. Spectral Lines and Modelling

The Ti I lines treated in this paper all belong to the same multiplet. Their wavelengths, transitions, effective Landé factors, $g_{\rm eff}$, excitation potentials, χ_e, and loggf values (Biémont 1976) are listed in Table 1.

Table 1. Titanium Multiplet

Ion	λ [Å]	Transition	$g_{\rm eff}$	χ_e [eV]	loggf
Ti I	22310.61	$a\,^5P_1 - z\,^5D^\circ_0$	2.500	1.73	-2.21
Ti I	22211.22	$a\,^5P_1 - z\,^5D^\circ_1$	2.000	1.73	-1.85
Ti I	22232.91	$a\,^5P_2 - z\,^5D^\circ_2$	1.667	1.74	-1.74
Ti I	22274.07	$a\,^5P_3 - z\,^5D^\circ_3$	1.583	1.75	-1.84
Ti I	21897.38	$a\,^5P_2 - z\,^5D^\circ_3$	1.167	1.74	-1.53

The combination of long wavelengths and large Landé factors (of some of these lines) makes them extremely sensitive to magnetic fields. In particular, the Zeeman splitting of λ 22319 Å can on its own give precise field strength values in umbrae and the combination of two of these lines, having different Landé factors, gives an additional diagnostic on magnetic field strength distributions.

Due to the combination of their excitation potentials and their oscillator strengths, as well as to the low solar titanium abundance, these lines are not saturated in the umbra. In addition, due to the ionization potential of neutral titanium (6.82 eV) they are very sensitive to temperatures above umbral values and show a significant strength only in cool features such as sunspot umbrae. At umbral temperatures a portion of the Ti atoms is bound into molecules, so that the strength of atomic Ti I lines is reduced. Therefore, we incorporated the molecular dissociation equilibrium into the employed radiative transfer code (Solanki 1987, Solanki et al. 1992a).

Line profile and contribution function computation showed that, at typical umbral temperatures, the Ti I lines are almost unaffected by the formation of TiO molecules, although these are abundant. The reason for this peculiar effect is that the height range at which the Ti I lines are formed has almost no overlap with the higher atmospheric layers at which significant amounts of TiO molecules exist.

The temperature sensitivity of these lines is one of their great assets. Since they are only prominent in cool features, they are unaffected by polarized stray light from the surrounding plages or quiet sun regions where the lines disappear. However, contamination from colder parts of the penumbra into the umbra and vice versa cannot be excluded.

Unpolarized stray light (from the quiet-sun continuum) can also affect our data, but only the temperature and the filling factor. We stress that it can in no way falsify the values of the magnetic parameters obtained in the analysis. Stray-light contamination reduces the strength of the Ti I lines. Consequently, the influence of the stray light can be mistaken for too high a temperature or too low a filling factor. If the stray light is unpolarized it only affects Stokes I directly, but enters into Stokes V via the continuum intensity with which we normalize both Stokes I and V.

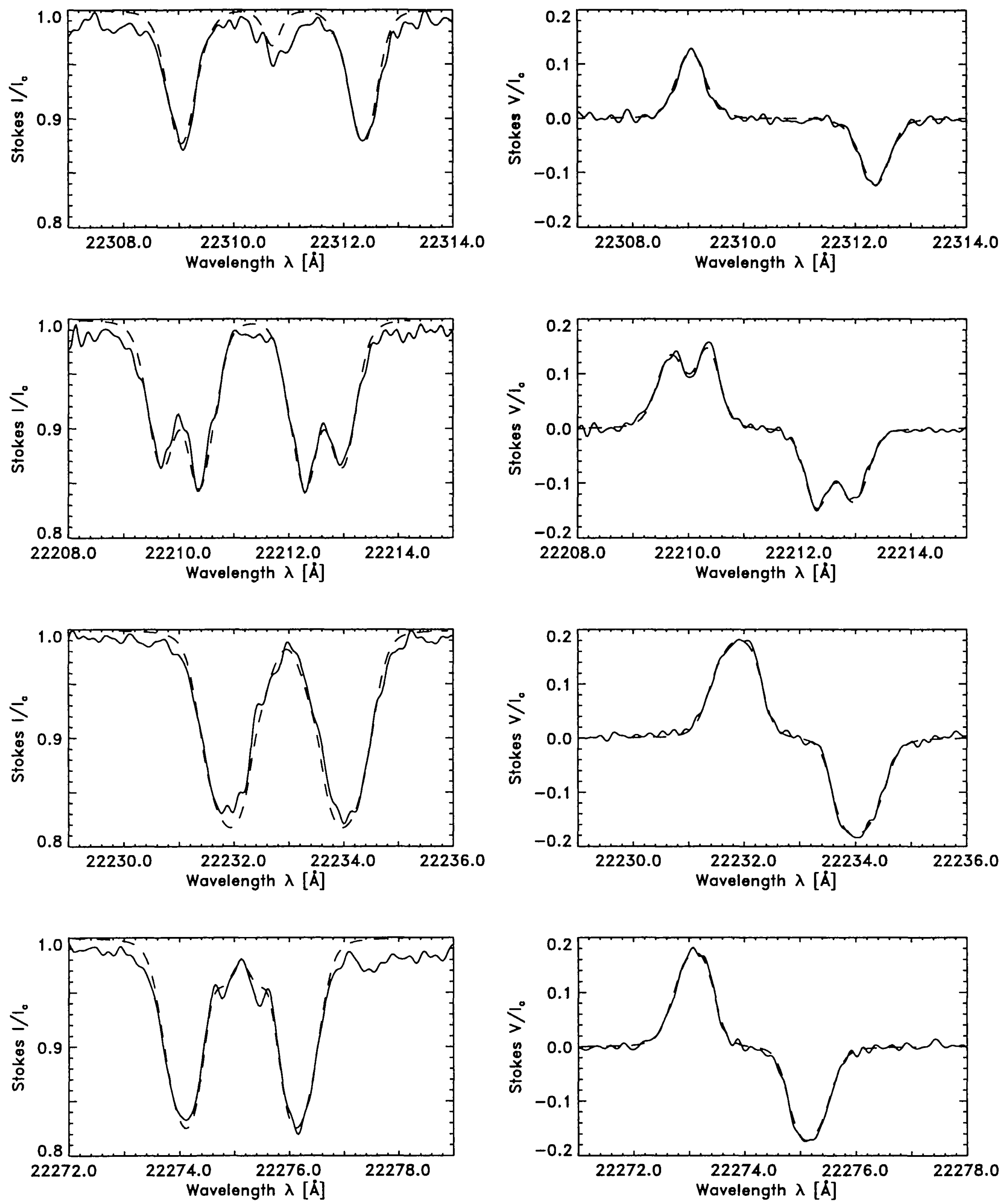

Figure 1. Stokes I (left) and V (right) FTS spectra of the four Ti I lines which are unblended by solar lines. The recordings were made in a large sunspot umbra (after telluric blend correction). The solid curves represent the observations, the dashed curves the best fit obtained using the Kurucz models.

3. Observations

The observations analysed in this paper have been obtained using the McMath-Pierce telescope at Kitt Peak and the Fourier transform spectrometer (FTS). Stokes I and V spectra of all 5 lines of the multiplet were recorded simultaneously on 31st January 1991 in a sunspot umbra (NOAA 6469). These observations have been described in detail by Rüedi et al. (1995) and have been corrected for telluric line blending according to the procedure discussed in that paper.

4. Results

Simultaneous fits to the four lines of the multiplet which are unblended by other solar lines were performed with the inversion code described by Solanki et al. (1992b, 1994), now modified to take into account TiO dissociation equilibrium, and different atmospheric models. Figure 1 shows the result of such an inversion. It has been obtained using the radiative equilibrium atmospheric models of Kurucz (1991), with a height-dependent field strength. On the whole the profile shapes and strengths are very well reproduced. Therefore, we see no need to use $\log gf$ values different from the literature values used for this fit, which are listed in Table 1. The slightly too strong Stokes I profile obtained for Ti I 22232.9 Å is probably due to a difficulty in determining the true continuum level. The code returns a field strength of 2820 G at the height of line formation. A horizontal or vertical distribution of field strength (corresponding to a vertical gradient of 4 G/km, if no horizontal distribution of the field is present) is required to reproduce the data

Due to possible contamination by stray light these spectral lines cannot be used to determine the absolute temperature in the umbra. They are, nevertheless sensitive to the temperature gradient.

Inversions were carried out using different atmospheric models. Figure 2 shows the temperature structure of typical representatives of the two groups of models we used: the non-grey radiative equilibrium models of Kurucz (1991) and the empirical models of Maltby et al. (1986).

The results obtained using the Maltby et al. models were far less satisfactory than those obtained with the Kurucz models for the following reasons. Firstly, the strengths of all lines could not be simultaneously reproduced using a unique set of fit parameters. Secondly, the relative strength of the inner and outer peaks of the Ti I 22210 Å line (the second line from the top in Fig. 1) were never reproduced properly in both Stokes I and V. This result suggests that the temperature structure of the Maltby models deviates significantly from the temperature structure of the observed umbra. The Kurucz models, which have a much larger temperature gradient at the height of formation of these lines, appear to be more appropriate. This is in agreement with the conclusions of Severino et al. (1994) obtained using completely different spectral lines.

Acknowledgments. This work was partly supported by the Swiss National Science Foundation, grant No. 20-37323.93, which is gratefully acknowledged.

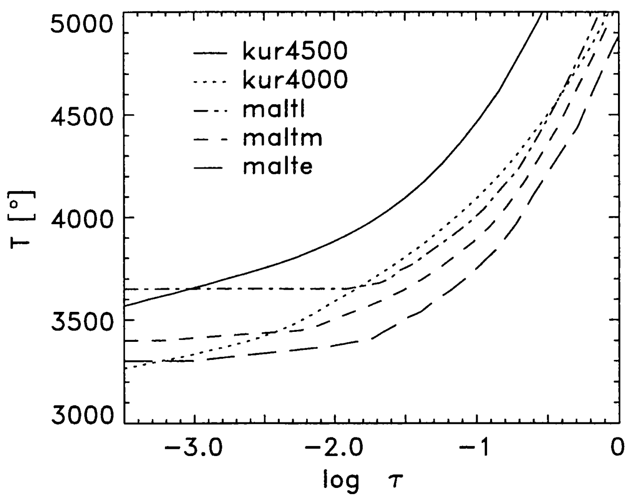

Figure 2. Temperature of the atmospheric models of Kurucz and Maltby as a function of logarithmic continuum optical depth (logτ) at 2.2μm.

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