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LINES IN THE WAVELENGTH RANGE $\lambda\lambda$ 4300–6700 Å WITH LARGE STOKES V AMPLITUDES OUTSIDE SUNSPOTS

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Abstract. A list of solar spectral lines in the wavelength $\lambda\lambda$ 4300–6700 Å exhibiting large Stokes V amplitudes in observed spectra of active region plages and the quiet network is presented.

1. Introduction

Lists of spectral lines with large Zeeman splitting have been published by von Klüber (1947) and Harvey (1973). These lists are useful for magnetic field measurements in sunspots, since in the strong fields found there such lines may be completely split. However, in the small fluxtubes, which contain most of the photospheric magnetic flux outside sunspots, lines in the visible part of the spectrum are far from being completely split, and for most of them the weak field approximation provides a better description. This approximation is valid when the Zeeman splitting is small as compared with the Doppler width of the line, i.e. $\Delta\lambda_H \ll \Delta\lambda_D$. If this condition is fulfilled, we can write

$$V(\lambda) \approx \cos\gamma\, \Delta\lambda_H \frac{\partial I_{\mathrm{M}}}{\partial\lambda} \sim \cos\gamma \langle B \rangle\, g_{\mathrm{eff}} \lambda^2 \delta \frac{\partial I_{\mathrm{NM}}}{\partial\lambda} \,. \tag{1}$$

Here I_{M} is the Stokes I profile inside the fluxtube, I_{NM} represents the Stokes I profile in the non-magnetic photosphere, and δ is a factor which crudely describes the weakening of the I profile in the magnetic region (mainly due to the higher temperature in the fluxtube). g_{eff} is the effective Landé factor, γ the angle between the magnetic field and the line-of-sight, and $\langle B \rangle$ the magnetic field strength averaged over the resolution element.

For observations of fluxtubes a large signal to noise ratio in Stokes V is desired. In the weak field approximation it follows from Equation (1) that it is not sufficient for the observed lines to have a large Zeeman splitting. Instead, lines with a combination of reasonably large Zeeman splitting, little thermal weakening, and a deep and narrow Stokes I profile in the non-magnetic atmosphere are needed. No list of lines which fulfill these criteria, i.e., lines most suitable for the observation of small magnetic fluxtubes, is available in the literature.

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TABLE I

Lines with strong Stokes V signals outside sunspots

Ion	Wavelength	Multiplet	Transition	$g_{\mathrm{eff}_{\mathrm{LS}}}$	Blends	$\frac{a_b(\lambda_0)}{a_b(5250)}$	$\frac{a_r(\lambda_0)}{a_r(5250)}$	Notes
Fe I	4352.743	71	$a\,^5P_1 - z\,^5S_2^0$	1.750	3*r*	1.041	0.772	
Fe I	4408.425	68	$a\,^5P_2 - x\,^5D_1^0$	2.000	3*r*	1.101	0.610	
Fe I	4430.6205	68	$a\,^5P_1 - x\,^5D_0^0$	2.500	2*rb*	1.261	0.994	1
Fe I	4447.728	68	$a\,^5P_1 - x\,^5D_1^0$	2.000	3*r*	0.995	0.673	
Fe I	4461.6582	2	$a\,^5D_2 - z\,^7F_3^0$	1.500	2*rb*	0.999	0.722	
Fe I	4482.174	2	$a\,^5D_1 - z\,^7F_2^0$	1.500	3*r*	1.013	0.536	
Cr I	4626.182	21	$a\,^5D_1 - y\,^5P_1^0$	2.000	1*b*	1.034	0.779	
Fe I	4654.504	39	$a\,^3F_3 - y\,^5F_4^0$	1.750	3*r*	1.034	0.565	
Mn I	4783.424	16	$z\,^4P_{7/2}^0 - e\,^8S_{7/2}$	1.968	1*rb*	0.978	0.865	
Fe I	4872.144	318	$z\,^7F_1^0 - e\,^7D_1$	2.250	3*b*	0.925	0.860	
Fe I	4878.2161	318	$z\,^7F_0^0 - e\,^7D_1$	3.000	3*b*	0.436	1.231	1
Fe I	4938.8209	318	$z\,^7F_2^0 - e\,^7D_3$	2.000	1*rb*	1.081	0.963	
Fe I	4939,6931	16	$a\,^5F_5 - z\,^5F_4^0$	1.500	1*rb*	1.048	0.909	
Fe I	4985.5530	318	$z\,^7F_3^0 - e\,^7D_4$	1.875	2*rb*	1.037	0.921	
Fe I	4994.1364	16	$a\,^5F_4 - z\,^5F_3^0$	1.500	1*b*	1.110	0.927	
Fe I	5012.0768	16	$a\,^5F_5 - z\,^5F_5^0$	1.400	3*r*	1.036	0.470	
Fe I	5068.7727	383	$z\,^7P_4^0 - e\,^7D_3$	1.750	1*rb*	1.001	0.890	
Fe I	5079.7462	16	$a\,^5F_2 - z\,^5F_1^0$	1.500	1*r*	1.008	0.895	
Fe I	5083.3450	16	$a\,^5F_3 - z\,^5F_3^0$	1.250	1*b*	1.016	0.830	
Fe I	5110.4168	1	$a\,^5D_4 - z\,^7D_4^0$	1.575	1*rb*	0.725	0.968	
Fe I	5127.3655	16	$a\,^5F_4 - z\,^5F_5^0$	1.500	1*rb*	1.104	0.944	
Fe I	5131.4748	66	$a\,^5P_1 - y\,^5P_1^0$	2.500	2*rb*	1.176	1.085	1
Fe I	5139.2600	383	$z\,^7P_3^0 - e\,^7D_2$	1.833	3*r*	0.994	0.811	
Fe I	5150.8465	16	$a\,^5F_2 - z\,^5F_3^0$	1.500	2*r*	1.131	0.751	
Fe I	5166.2867	1	$a\,^5D_4 - z\,^7D_5^0$	1.800	2*rb*	0.857	1.039	
Fe I	5168.9051	1	$a\,^5D_3 - z\,^7D_3^0$	1.625	3*rb*	1.017	0.614	
Fe I	5191.4631	383	$z\,^7P_2^0 - e\,^7D_1$	2.000	2*r*	1.063	0.993	
Fe I	5198.7171	66	$a\,^5P_1 - y\,^5P_2^0$	1.500	1*r*	1.020	0.885	
Fe I	5202.3395	66	$a\,^5P_3 - y\,^5P_3^0$	1.667	3*b*	0.690	0.970	
Cr I	5204.5233	7	$a\,^5S_2 - z\,^5P_1^0$	1.750	3*r*	1.096	0.944	
Cr I	5206.0461	7	$a\,^5S_2 - z\,^5P_2^0$	1.917	3*rb*	1.074	0.994	
Fe I	5226.8714	383	$z\,^7P_2^0 - e\,^7D_2$	2.167	3*rb*	1.058	0.960	
Cr I	5247.5737	18	$a\,^5D_0 - z\,^5P_1^0$	2.500	0	1.165	1.098	1
Fe I	5250.2171	1	$a\,^5D_0 - z\,^7D_1^0$	3.000	1*b*	1.000	1.000	1
Fe I	5250.6527	66	$a\,^5P_2 - y\,^5P_3^0$	1.500	1*r*	1.068	0.919	
Cr I	5254.9587	201	$a\,^5D_1 - z\,^7D_2^0$	2.250	2*r*	0.708	0.965	
Cr I	5264.1659	18	$a\,^5D_1 - z\,^5P_1^0$	2.000	3*r*	1.153	0.725	
Cr I	5298.2797	18	$a\,^5D_2 - z\,^5P_2^0$	1.667	3*rb*	1.068	0.942	
Fe I	5332.9062	36	$a\,^3F_3 - z\,^3F_4^0$	1.500	1*rb*	1.044	0.910	
Cr I	5348.3231	18	$a\,^5D_3 - z\,^5P_3^0$	1.583	1*rb*	1.044	0.885	
Fe I	5476.5718	1062	$y\,^5D_4^0 - g\,^5D_4$	1.500	2*rb*	0.934	0.841	
Fe I	5497.5224	15	$a\,^5F_1 - z\,^5D_2^0$	2.250	1*b*	1.215	1.277	
Fe I	5501.4715	15	$a\,^5F_3 - z\,^5D_4^0$	1.875	1*r*	1.370	1.182	
Fe I	5506.7864	15	$a\,^5F_2 - z\,^5D_3^0$	2.000	1*rb*	1.423	1.257	
Ca I	5588.7594	21	$3\,^3D_3 - 3d4p\,^3D_3^0$	1.333	2*r*	1.019	0.930	
Ca I	6102.7323	3	$4\,^3P_0^0 - 5\,^3S_1$	2.000	1*rb*	1.240	1.224	
Ca I	6122.2247	3	$4\,^3P_0^1 - 5\,^3S_1$	1.750	1*r*	1.118	1.122	
Ba II	6141.7259	2	$5\,^2D_{5/2} - 6\,^2P_{3/2}^0$	1.100	1*r*	1.167	1.054	
Fe I	6213.4375	62	$a\,^5P_1 - y\,^5D_1^0$	2.000	0	1.101	1.047	
Fe I	6219.2886	62	$a\,^5P_2 - y\,^5D_2^0$	1.667	1*r*	1.099	1.024	
Fe I	6230.7342	207	$b\,^3F_4 - y\,^3F_4^0$	1.250	1*r*	1.013	0.854	

Table I (*continued*)

Ion	Wavelength	Multiplet	Transition	$g_{\mathrm{eff}_{\mathrm{LS}}}$	Blends	$\frac{a_b(\lambda_0)}{a_b(5250)}$	$\frac{a_r(\lambda_0)}{a_r(5250)}$	Notes
Fe I	6246.3271	816	$z\,^5P_3^0 - e\,^5D_3$	1.583	0	1.006	0.939	
Fe I	6265.1412	62	$a\,^5P_3 - y\,^5D_3^0$	1.583	0	1.056	0.985	
Fe I	6301.5091	816	$z\,^5P_2^0 - e\,^5D_2$	1.667	1*r*	1.039	0.976	
Fe I	6302.5017	816	$z\,^5P_1^0 - e\,^5D_0$	2.500	1*r*	1.084	1.089	1
Fe I	6336.8328	816	$z\,^5P_1^0 - e\,^5D_1$	2.000	1*b*	1.051	1.007	
Fe I	6421.3591	111	$a\,^3P_2 - z\,^3P_2^0$	1.500	2*r*	1.229	1.060	
Fe I	6430.8538	62	$a\,^5P_3 - y\,^5D_4^0$	1.250	0	1.074	0.948	
Ca I	6439.0851	18	$3\,^3D_3 - 3d4p\,^3F_4^0$	1.125	1*b*	1.031	0.956	
Ba II	6496.9095	2	$5\,^2D_{3/2} - 6\,^2P_{1/2}^0$	0.833	1*b*	1.059	0.962	

2. List of Lines

A list of lines with strong Stokes V signals outside sunspots is presented. It was obtained by searching for the Stokes V profiles with the largest amplitudes (determined by fitting a quadratic function through the three points around each peak), in spectra obtained in active region plages and the quiet network with the Kitt Peak McMath telescope and the 1 m Fourier transform spectrometer (FTS) used as a polarimeter. A total of five spectra in the visible have been obtained near disk centre, two in strong active region plages with $\mu = \cos\theta \approx 0.92$ (θ is the heliocentric angle), and three in enhanced network regions at μ values between 0.98 and 1.00. The combined wavelength interval covered by the spectra extends from 4104 to 6907 Å. For more details concerning the observations and the data we refer to Stenflo *et al.* (1984).

The criterion chosen for selecting a line with wavelength λ_0 is that its absolute blue or red amplitude, $a_b(\lambda_0)$ or $a_r(\lambda_0)$, must be larger than $0.92a_b(5250)$ or $0.92a_r(5250)$, respectively, where 5250 refers to the well known Fe I 5250.2 Å line. The lines with wavelengths between 4300 and 6700 Å which fulfill this criterion for both plage and network regions are listed in Table I. We have restricted ourselves to this somewhat smaller wavelength range, in order not to be influenced by noise, which increases rapidly near the edges of each spectrum. In the first, second and third columns of Table I the ion, the solar wavelength and the multiplet number of the line, as listed by Pierce and Breckinridge (1973), are given. For the few lines not listed by these authors, the data have been taken from Moore *et al.* (1966) The fourth column contains the atomic transition, taken from Moore (1972). In column 5 the effective Landé factor of the line as calculated in LS coupling is given (Beckers, 1969). A more or less subjective index of the amount of blending in each line is listed in column 6. The scale has been matched to the one used by Harvey (1973) by visual inspection of the lines in his list which are also present in our spectra. The blending is parameterised by the following four values: 0 = no detectable blend, 1 = minor blending, 2 = significant blending, 3 = severe blending, and the letters *r* and *b*, which mark whether the red or blue (or both) wings are blended. Lines with blending index 1 can be considered unblended for most applications;

an example is Fe I 5250.2 Å). Columns 7 and 8 list the blue and red amplitudes normalised to the corresponding amplitude of the Fe I 5250.2 Å line, i.e., $a_b(\lambda_0)/a_b(5250)$ and $a_r(\lambda_0)/a_r(5250)$. For $\lambda > 4680$ Å these values have been taken from plage spectra, due to their better signal-to-noise ratio. Below this wavelength no plage spectrum was available, so that a network spectrum was used. Finally, the lines marked by a '1' in column 9 are also present in the list of Harvey (1973). The overlap between the two lists is small, demonstrating the importance of other parameters besides g_{eff} for a large value of Stokes V.

The application of the criterion of choosing the line ($a > 0.92\, a(5250)$) is straightforward for the spectra which contain Fe I 5250.2 Å. However, these cover only a fraction of the complete observed spectral range. In order to apply it to other spectra, the filling factors of the corresponding solar regions must be known relative to the filling factor of the region for which a spectrum containing Fe I 5250.2 Å is available. The filling factors were determined using the technique described by Solanki and Stenflo (1984, 1985). For relative filling factors this technique should be accurate to within approximately 5%. The accuracy is limited by the scatter in the data and the uncertainty in the temperature differences between fluxtubes in different regions. As an additional check, lines within the range of wavelength overlap of two spectra were also compared.

We have also studied how representative Table I may be for different regions on the Sun, by comparing the lists of lines with strong Stokes V signals obtained from plage and network spectra with each other. Due to the higher temperature in network fluxtubes (Solanki and Stenflo, 1984; Solanki, 1986), the Stokes V amplitudes of lines of lower excitation potential (in particular of our reference line, Fe I 5250.2 Å with $\chi_e = 0.12$ eV) are decreased more in the network than the amplitudes of higher excitation lines. As a result we find that all the lines in Table I are also present in a corresponding list obtained from the network data. In addition a number of lines which do not fulfill the criterion in plages fulfill it in the network. However, the strongest Stokes V profiles in the network also show strong Stokes V signals in plages. For example, the 20 lines with the largest a_b value in the network in the wavelength range 4800–5400 Å are all present in Table I. We, therefore, conclude that the list of lines given in Table I should be universally applicable for Stokes V observations of small fluxtubes, which require a good signal-to-noise ratio. However, the actual values of $a(\lambda_0)/a(5250)$ may vary considerably from one region to another.

TABLE II

Unblended Fe II lines with strong Stokes V signals outside sunspots

Ion	Wavelength	Multiplet	Transition	$g_{\text{eff}_{\text{LS}}}$	Blends	$\frac{a_b(\lambda_0)}{a_b(5250)}$	$\frac{a_r(\lambda_0)}{a_r(5250)}$
Fe II	4520.2258	37	$b\,^4F_{9/2} - z\,^4F^0_{7/2}$	1.500	1*rb*	0.852	0.568
Fe II	4555.8937	37	$b\,^4F_{7/2} - z\,^4F^0_{7/2}$	1.238	1*r*	0.795	0.517
Fe II	4923.9299	42	$a\,^6S_{5/2} - z\,^6P^0_{3/2}$	1.700	1*rb*	0.884	0.810
Fe II	6456.3878	74	$b\,^4D_{7/2} - z\,^4P^0_{5/2}$	1.214	1*r*	0.831	0.788

It may be noticed that except for two Ba II lines in Table I, all the lines belong to neutral elements. However, for some purposes it is an advantage to observe lines of an ionised element (e.g., for the determination of filling factors). In Table II we, therefore, list the four unblended Fe II lines with the largest Stokes *V* amplitudes among the unblended Fe II lines selected by Dravins *et al.* (1986). Table II is structured in the same way as Table I.

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