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HOW ACCURATE ARE STELLAR MAGNETIC FIELD MEASUREMENTS?

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ABSTRACT We study the accuracy of two magnetic analysis methods by applying them to a large grid of lines computed using detailed 1.5–D radiative transfer (RT) calculations in a variety of stellar atmospheres embedded with fluxtubes. We find errors of $\leq \pm 20\%$ when using the more realistic analysis method if the fluxtube and external quiet atmospheres are similar; errors can increase substantially if this condition is relaxed.

Keywords: stellar magnetic fields; stellar atmospheres; stars – late-type

1. INTRODUCTION AND MODEL CALCULATIONS

Analyses of the magnetic field strengths (B) and filling factors (f) of active regions on cool stars typically fit unpolarized absorption lines (F) with a two component model: $F = fF_m(B) + (1-f)\ F_q(0)$. Here, F_m is the profile in magnetic regions – assumed to uniformly cover a fraction f of the surface – and F_q is the quiet region profile ($B = 0$). Further simplifying assumptions used include taking the F_m and F_q atmospheres as identical, and $\nabla\ B = 0$ in F_m. Neither of these assumptions is accurate for the Sun (*e.g.*, Schüssler 1990), and much of the disagreement between fB values for some stars can be explained by a non-zero $\nabla\ B$ combined with differences in the height of the formation of the lines used (Grossmann-Doerth & Solanki, 1990). Since significant errors, especially in f, can result from these assumptions (Saar 1988; Basri *et al.* 1990), their effects on f and B determinations need to be thoroughly studied. The best work to date (Basri *et al.* 1990) has explored the effects of various atmospheres on field determinations using two Fe I lines (7748 and 8468 Å), but assuming no geometric changes with height and (usually) $\nabla\ B = 0$.

Here we expand this work, studying ten lines (5 pairs with $g_{eff} = 1.0$ and 2.5) with various f and excitation potentials (χ_L) at several wavelengths, all generated using self-consistent fluxtube models (see also Saar 1991). Moderately strong (40–250 mÅ), simple triplet Fe I lines are computed in each case. The fluxtube models (Steiner & Pizzo 1989) take into account the expansion of the field with height, as dictated by vertical and horizontal pressure balance. Several atmospheres are used to simulate F_q and F_m (see Table 1). For each atmosphere combination a grid of models with different f and B values have been calculated, summing along a number of parallel rays through the fluxtubes (1.5–D RT). Since stellar spectra are dominated by regions near disk-center, we here concentrate on models at $\mu = 1$. In spot atmospheres, we set $dB/dz = 0$ but allowed B and the angle it makes with the vertical to vary across the spot.

2. ANALYSIS AND DISCUSSION

We have applied two simple analyses to our line models (treating them as data): an Unno (1956) type code and a Milne-Eddington atmosphere (Saar 1988) and the Fourier ratio method (Robinson 1980). We adopted the following procedure for the Unno fits, since in practice, Fe/H, the oscillator strengths (log gf) and the collisional broadening must usually be adjusted. First, the low g_{eff} line was fit (minimizing χ^2) with the line opacity (η_0), source function slope, and collisional broadening (Voigt a) as free parameters. These values then became initial guesses in a fit of the high g_{eff} line with η_0, f and B free. A final fit was then made to both lines simultaneously, with η_0, a, f, and B free. Sample results (f_U and B_U) are given in Table 1, for the case of $f \approx 0.30$ at $z = 0$. The "actual" B at the level of line formation in the model has been estimated using the center-of-gravity approach (B_C; Rees & Semel 1979). For the Robinson fits, the ratio of the Fourier transforms of high and low g_{eff} lines was modeled with an equivalent width ratio, f_R and B_R as free parameters; the fits were limited to frequencies short of the first saturation zero.

A more detailed analysis is left to a future paper (which will also study center-to-limb effects and include more sophisticated analyses). Here, we briefly note: (1) The Robinson fits are almost always less accurate, especially in the K dwarfs, probably due to neglect of RT effects. (2) f is the most poorly determined parameter. B_U is typically determined to better than $\pm$ 250 G, except in the spot (H/S) models (see [6]). fB_U is usually better determined than f_U or B_U, as errors in f and B partially cancel out (cf. Gray 1984; Saar 1988; Basri *et al.* 1990). (3) Errors for Unno fits to "same"-atmosphere models (H/H and K/K) were generally $\leq$ 20%. Underestimation of fB in H/H seems to be due to an overestimation of a; overestimation for K/K arises from the inaccuracy of the simple Unno RT in the stronger K2V lines. (4) We obtain underestimates of f and fB similar to (and somewhat larger than) Basri *et al.* in the case of the solar + network model ($\approx$ 50%). Here, line weakening more than counteracts the small increase in continuum brightness in F_m. Overestimates ($\leq$ 35%) of fB in the K/H model are due the opposite effect: here, the continuum brightness of F_m dominates. These results confirm trends predicted from changes in line strengths (Solanki 1991, these proceedings). (5) For a given model, fB at 600 nm increases with χ_L, consistent with a stronger contribution to the line from F_m for lines of higher χ_L (see Grossmann-Doerth & Solanki 1990). (6) Fits were poorer for the infrared models, where the effects of ∇B on the Zeeman σ components were evident. The broad σ components led to a greatly underestimated f values (at high B), made still worse by overestimates of a due to the broad wings.

In summary, our models suggest that current Unno-based methods of stellar fB measurements are accurate only at the $\pm$ 20% level, and *then* only when differences between F_m and F_q do not change the emergent F substantially. Methods ignoring RT (*e.g.*, Robinson 1980) fare even worse. Careful estimates of a, especially in the IR, are also important for improved f_U and B_U. More realistic models applied to data on lines spanning a range of strengths, λ, and χ_L will likely be needed to disentangle the "true" f and B for cool stars.

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Table 1: Line Model Parameters ($f_{z=0} \approx 30\%$) and Results of the Fits

F_q/F_m atm.*	λ (nm)	$\log gf$	χ_L (eV)	B_C (G)	f_C[1] (%)	fB (G)	B_U (G)	f_U (%)	$\Delta\Phi_U$[2] (%)	B_R (G)	f_R (%)	$\Delta\Phi_R$[2] (%)
H/N	600	-5.58	0	1034	45	465	1240	13	-66	1270	12	-67
H/N	600	-3.54	2	1217	38	465	1360	15	-56	1290	15	-59
H/N	600	-1.60	4	1394	33	465	1450	18	-44	1280	18	-50
H/N	1600	0.07	6	1523	31	465	1380	17	-49	1690	16	-42
H/N	2200	-0.70	5	1333	35	465	1170	15	-58	1470	18	-42
H/H	600	-5.58	0	1248	37	464	1460	24	-26	1390	25	-26
H/H	600	-3.54	2	1409	33	464	1510	25	-20	1350	25	-28
H/H	600	-1.60	4	1551	30	464	1530	25	-18	1260	26	-30
H/H	1600	0.07	6	1671	28	464	1520	30	-1	1810	31	19
H/H	2200	-0.70	5	1518	31	464	1350	31	-11	1600	37	29
H/S	600	-5.58	0	1770[3]	30	531	...[4]	...[4]	...[4]	3120	2.8	-83
H/S	600	-3.54	2	1770[3]	30	531	2960	1.4	-92	2960	3.0	-83
H/S	600	-1.60	4	1770[3]	30	531	2730	2.0	-90	2900	2.2	-88
H/S	1600	0.07	6	1770[3]	30	531	2500	2.9	-86	2970	2.6	-86
H/S	2200	-0.70	5	1770[3]	30	531	2070	5.3	-79	2900	5.2	-72
K/H	600	-5.58	0	2159	27	591	1950	34	11	2230	37	40
K/H	600	-3.54	2	2438	24	591	2240	32	21	1560	37	-1
K/H	600	-1.60	4	2689	22	591	2480	32	35	2900	34	68
K/H	1600	0.07	6	2941	20	591	2650	29	29	3070	32	65
K/H	2200	-0.70	5	2648	22	591	2420	27	13	2740	37	72
K/K	600	-5.58	0	1915	31	585	2100	27	-3	890	26	-61
K/K	600	-3.54	2	2198	27	585	2070	33	16	1590	25	-31
K/K	600	-1.60	4	2439	24	585	2210	31	18	1540	28	-26
K/K	1600	0.07	6	2700	22	585	2500	28	20	1890	22	-28
K/K	2200	-0.70	5	2485	24	585	2240	31	17	1600	28	-23

*References: H = Harvard–Smithsonian Ref. Atm.; N = network model (Solanki 1986); K = K2 dwarf model (Basri & Marcy 1988); S = sunspot model (Maltby *et al.* 1986)

Notes: [1] $f_C \equiv (fB)/B_C$; [2] $\Delta\Phi \equiv (fB_{\rm fit} - fB)/fB$; [3] $\overline{B}$ over spot ($dB/dz = 0$); [4] Did not converge