Multi–line Zeeman Analysis

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Abstract: I present preliminary results of a multi–line Zeeman analysis of the active star ξ Boo A and the inactive star τ Cet. High S/N echelle spectra are compared with LTE model line profiles for 25 Fe I lines to deduce surface magnetic fields.

1. Introduction

Magnetic field strengths on cool stars are typically measured by searching for Zeeman broadening of a single magnetically sensitive spectral line (Robinson, 1980; Marcy, 1984). The accuracy of such measurements is limited not by the precision of the data, but by uncertainties in analysis. Numerical radiative transfer is required to properly interpret line shapes (Basri and Marcy, 1988), so accurate model atmospheres are imperative. Previous analyses have usually been based on single spectral lines (Saar, 1988; Marcy and Basri, 1989) and hence are subject to uncertainty. By analyzing many lines formed at a variety of atmospheric depths, the accuracy of inferred model atmospheres and resultant magnetic field determinations can be ascertained. Multi–line analysis also permits the study of multi–component atmospheres and vertical field gradients.

2. Data

Multi–line studies of magnetic fields require high S/N, high resolution spectra covering a large wavelength range. Using the Hamilton echelle spectrograph at Lick Observatory, I obtained spectra with S/N of 500/1, resolution of 40,000, and wavelength coverage of 2380 Å in the range 4929–8917 Å. The spectra were corrected for scattered light, fringing, and instrumental profile effects, and the correction procedures were tested by comparing Hamilton day sky spectra with the NSO solar flux atlas (Kurucz *et al.*, 1984). In the lines the disagreement exceeded the noise by 0.7%, due to a poorly determined instrumental profile.

https://doi.org/10.1017/S0252921100080027 Published online by Cambridge University Press

Since the Hamilton has substantially poorer resolution than is typically used in magnetic field work, it is necessary to establish the Hamilton's ability to detect magnetic fields. Solar plage provide a good test case, as they are believed to have magnetic properties similar to those of active cool dwarfs as a whole. I obtained solar intensity spectra of quiet and plage regions, which should have weak and strong magnetic fields respectively. The low Landé g, magnetically insensitive 7583.8 Å line profiles for the two regions agree to 0.3%; whereas, the high Landé g, magnetically sensitive 8468.4 Å line profiles differ systematically by as much as 4%. The plage profile is broader as expected. Thus echelle spectrographs such as the Hamilton are good instruments with which to study magnetic fields, as they sample many spectral lines while maintaining the required accuracy.

3. Models

I modeled each Stokes component in a fully depth dependent scaled solar atmosphere (Holweger and Müller, 1974) under the assumption of local thermodynamic equilibrium. Line profiles based on laboratory oscillator strengths (Fuhr *et al.*, 1988) disagreed with the NSO solar flux atlas by as much as 2%, so I used the atlas to determine empirical oscillator strengths. These empirical oscillator strengths are close to Holweger's (1967), but diverge systematically from laboratory values, disagreeing by almost an order of magnitude for the strongest lines, indicating a potential problem with the Holweger–Müller atmosphere. The collisional broadening term C_6 also had to be enhanced by a factor of six above its nominal value. Stars other than the Sun were modeled by two components with identical temperature structures, one with no magnetic field and the other with a possibly nonzero, uniform, vertical magnetic field.

I generated synthetic line profiles for 25 Fe I lines present in spectra of the inactive star τ Cet and the active star ξ Boo A, for a coarse grid of iron abundances, magnetic field strength, $|B|$, surface covering factors, f, macroturbulent velocities, and $v \sin i$. The models represented in the grid were ranked according to how well they agree with observations of *all 25 lines considered simultaneously*. For τ Cet the zero field case is best; whereas, for ξ Boo A a 2 kilogauss field covering 20% of the star is best. Other models with similar unsigned magnetic fluxes, $|B|f$, are nearly as good. The best fitting model inferred from each individual line sometimes differs significantly from the best global model, demonstrating that atmospheric parameters and therefore magnetic fields should be based on the analysis of many spectral lines.

Residuals of the best model fits to observed line profiles have an average magnitude of 1.4% for τ Cet and 1.5% for ξ Boo A, which is large compared to the expected photon noise of 0.2%. These large residuals are primarily due to use of a coarse parameter grid of limited extent, an inaccurate temperature structure, and a poorly determined instrumental profile. The results are also affected to a lesser extent by small blends, unaccounted for magneto-optical effects, and a crude treatment of macroturbulence. Despite these shortcomings, the results of this analysis are similar to those of other investigators. More study is needed to determine whether this is indicative of the robustness of multi–line analyses or simply coincidence.

4. Conclusion

A preliminary multi–line Zeeman analysis of the active star ξ Boo A gives a magnetic field strength of 2 kilogauss covering 20% of the star's surface; whereas, analysis of the inactive star τ Cet gives a null field result. Although more study is required, it seems that the use of many lines compensated for the various shortcomings of this analysis. Once these shortcoming are overcome, multi–line analyses will be a useful method for determining magnetic fields along with other properties of active stellar atmospheres.

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