MAGNETIC FIELD MEASUREMENTS ON LATE-TYPE STARS: A NEW TECHNIQUE

Geoffrey W. Marcy
San Francisco State University

Gibor Basri
Univ. of California, Berkeley

ABSTRACT. A new technique for detecting and measuring magnetic fields on cool stars is presented, incorporating both an improved observational approach and a rigorous LTE theoretical treatment. We have identified two lines in the near infrared, one of which is very sensitive to Zeeman broadening and the other relatively insensitive, that are easily accessible to CCD and Reticon detectors. The lines are modelled by solving numerically the equations of transfer for the Stokes parameters in a full model atmosphere, permitting computation of all relevant depth-dependent physics such as polarized line opacities and broadening sources. We have obtained high resolution, high S/N spectroscopic observations of several G and K dwarfs and have synthesized the two lines using two free parameters, namely, the average field strength, B, and the fraction, f, of the surface covered by fields. For the chromospherically active stars ϵ Eridani and Xi Boo A, we find B=1000, f=35% and B=1200, f=40%, respectively. A careful study has been made of various sources of broadening to determine their ability to mimic Zeeman broadening, and none is capable of doing so.

1. INTRODUCTION

It has become increasingly clear during the past decade that a variety of characteristics of cool stars, including spots, chromospheres, flares, and coronae, are qualitatively similar to corresponding solar phenomena that are spatially associated with magnetic fields. (For a review see Hartmann and Noyes, 1987.) Thus, several attempts have been made to detect the Zeeman effect in stellar spectra, notably, Robinson et al.(1980), Marcy (1984), Gray (1985), and Saar (1988). Generally, these workers have tried to detect the tiny extra broadening in line profiles due to the Zeeman effect. The effort therefore requires predicting, with extreme accuracy, the magnitude of all other sources of broadening in a line profile and then properly extracting the residual Zeeman signal.

However, these past attempts have all involved various assumptions about the line formation. The most sophisticated effort (Saar, 1988)

G. Cayrel de Strobel and M. Spite (eds.), The Impact of Very High S/N Spectroscopy on Stellar Physics, 301–307.

https://doi.org/10.1017/S007418090003518X Published online by Cambridge University Press

includes the transfer of the Stokes parameters through an artificial atmosphere that has a linear source function with optical depth and a constant ratio of line to continuous opacity. This work, and the previous efforts, have all yielded field-strength estimates on late-type dwarfs of between 1000G and 2000G, similar to those on the solar surface. But, the fraction of the stellar surface covered by fields is often found to be remarkably high, typically 30% to 50% for the more chromospherically active stars.

Here we present a Zeeman analysis which treats the line transfer of the Zeeman effect in a realistic model atmosphere, and we include all depth-dependent physics, with special attention given to the mechanisms that broaden the profiles. Observationally, we adopt two lines in the near infrared: λ8468.41 (FeI) having a Landé-g value of 2.5 and λ7748.28 (FeI) having a Landé-g value of 1.1 . The former line is considerably more sensitive to the Zeeman effect than optical lines since Zeeman splitting increases as the square of the wavelength.

2. THE THEORETICAL CALCULATION

The differential equations of transfer for the Stokes parameters through an atmosphere containing Zeeman-split transitions were developed by Unno (1956) and were shown to be analytically solvable under the assumption of a linear source function (taken to be the Planck function) and a constant ratio, η, of line to continuous opacity. Clearly, this analytical approach will not yield profiles that are directly comparable to real stellar flux profiles within the required accuracy of about 1%. Saar (1988) has addressed this difficulty by estimating effective fixed values for η and the line-broadening parameters through the use of observed Zeeman-insensitive lines. This approach (along with several other important improvements) has apparently confirmed the existence of magnetic fields covering substantial fractions of the surfaces of active stars. However, since no two lines are formed in the same way, the estimated effective stellar and line parameters represent good approximations at best, and, as we have found, moderate errors will result from even the best choices for those parameters.

A significant improvement is possible by solving numerically the Unno equations of transfer in a realistic atmosphere, in which all depth-dependent quantities are included. The three coupled transfer equations for I, Q, and V can be integrated upward through the atmosphere, starting with the boundary conditions at the base, namely, I = Planck function, and Q = V = 0. A second-order Runge-Kutta scheme is employed and is found to be stable and accurate as long as the step sizes in optical depth are no more than about one third of one optical depth. To meet this requirement, all physical quantities are interpolated onto a dynamic depth grid, resulting in between 100 and 350 depth points, depending on the angle of the line-of-sight to the surface normal. A Gaussian quadrature method is used to construct a flux profile from intensity profiles at three points on the stellar

https://doi.org/10.1017/S007418090003518X Published online by Cambridge University Press

surface. The splitting and relative intensities of the Zeeman components of the lines of interest were computed assuming LS coupling (Condon and Shortely, 1970).

The entire calculation is carried out in LTE with all atomic physics computed at each depth point. We used scaled solar models based on the HSRA such that the temperature structure is scaled as the effective temperature and all particle densities are recomputed to satisfy the equation of hydrostatic equilibrium and the Saha equation. Both thermal and collisional broadening are computed at each depth and we have carefully considered different values of the collisional broadening coefficient, C6, in an effort to examine its ability to mimic Zeeman broadening. The final flux profiles were broadened to simulate macroturbulence (an exponential form was used), rotation, and the instrumental effects. As a final check, profiles were synthesized assuming a linear source function and constant ratio of line-to-continuous opacity. The resulting profiles agreed well with the analytic solutions of Unno.

It is worth noting that for field strengths of about 1000G, the theoretical intensity profiles often exhibit central reversals and odd bends in the shape of the line profile. These are also seen in the exact analytic solutions for certain values of η and are due to the presence or absence of overlap between the displaced Zeeman components, each having different intensities and polarizations. These abnormalities disappear upon broadening.

Finally, we have included one line blend in the theoretical calculation, namely that due to Ti I, that is 0.05A longward of line center of λ8468.41 . We have taken the gf value from Kurucz and Peytremann (1975) which yields a feature of equivalent width 16 mA, in the absence of the principal line.

3. OBSERVATIONS

Spectroscopic observations were made of λ8468.41 and λ7748.28 at the coudé focus of the 3-m telescope at Lick Observatory using a CCD detector. The resolution was about 130,000 and S/N ratio per pixel was typically 200. A small stellar sample was initially chosen consisting of the Sun (daytime sky), Xi Boo A, ε Eridani, and HD 166620, the last being a chromospherically inactive K2 dwarf. Two weak blends, due to MgI and terrestrial water, in the red wing of 8468.41 were carefully removed using neighboring similar lines.

To apply the theoretical calculations, a number of atomic and stellar parameters must be determined. The gf values for both lines were taken from Kurucz and Peytremann (1975) and we chose to augment the value of the collisional damping constant, C6, by a factor of seven as this yielded excellent fits to solar profiles. We explored extensively the role played by C6 in the detection of residual Zeeman broadening in the observed profiles. In short, as collisional broadening acts primarily on the wings, one can easily determine upper limits to C6 and its broadening effect cannot mimic that due to the

https://doi.org/10.1017/S007418090003518X Published online by Cambridge University Press

Zeeman effect. The abundance of Fe was determined for each star by matching the equivalent width of the Zeeman-insensitive line, λ7748, and the shape of that line was also used to determine the macroturbulence. Values for rotational broadening were derived from the literature (Soderblom 1981, Noyes et al. 1984) and all macro-broadening was accomplished by standard convolution (Gray 1976, but see Bruning 1984).

The observed solar profiles are fit well, within one percent, by assuming that there is no magnetic field on the surface. For the chromospherically inactive K2 dwarf, HD166620, the Zeeman-insensitive line, λ7748, is also fit well, as seen in Fig.1. Note that no scaling has been done to any of the profiles. The observed Zeeman-sensitive line for HD166620 appears slightly broader than that calculated, assuming B=0. This appears to be weak evidence for Zeeman broadening in that inactive star. A similar synthesis of the two lines of ϵ Eridani is also shown in Fig.1. Here, the observed Zeeman-sensitive line appears significantly broadened relative to the theoretical line computed with B=0, though the Zeeman-insensitive line is well fit. We consider this strong evidence that Zeeman broadening is playing a significant role in the line formation on ϵ Eri. Similarly, the Zeeman-sensitive line from Xi Boo A is considerably broader than that computed with B=0 (Fig.1).

For the three stars mentioned above, theoretical profiles were computed for a variety of assumed magnetic field strengths. These profiles were added with various weights to those constructed with no magnetic field to simulate the flux profiles from a stellar surface having a fraction, f, covered by fields. The final theoretical profiles providing a best fit are shown in the right column of Fig.1. There is a clear indication that the red wing of λ8468 is still contaminated by some blend, especially at K2. However, the blue wing is fit well in all cases. The resulting magnetic field parameters are, Xi Boo A: B=1200G, f=40% ; ϵ Eri: B=1000G, f=35%; HD166620: B=1500G, f=15%.

An estimate of the uncertainties can be gained qualitatively by varying the input magnetic parameters until the fit of the theoretical profile becomes unacceptable. Such tests indicate that the uncertainties in the magnetic field strength are about 250G and those in the covering factor are about 1/5 of the measured value. However, the true uncertainties are greater owing to our poor knowledge of the atmosphere in the magnetic regions. Indeed the large covering fractions derived here imply that all determinations of surface parameters, such as gravity and effective temperature, represent rough averages over the inhomogeneous surface.

4. DISCUSSION

The important question is whether or not the Zeeman broadening implied here for the three late-type stars is real. We have carried out an exhaustive search for alternative mechanisms that could provide differential broadening of the Zeeman-sensitive line over the insensitive line. In particular, we considered the effects of varying

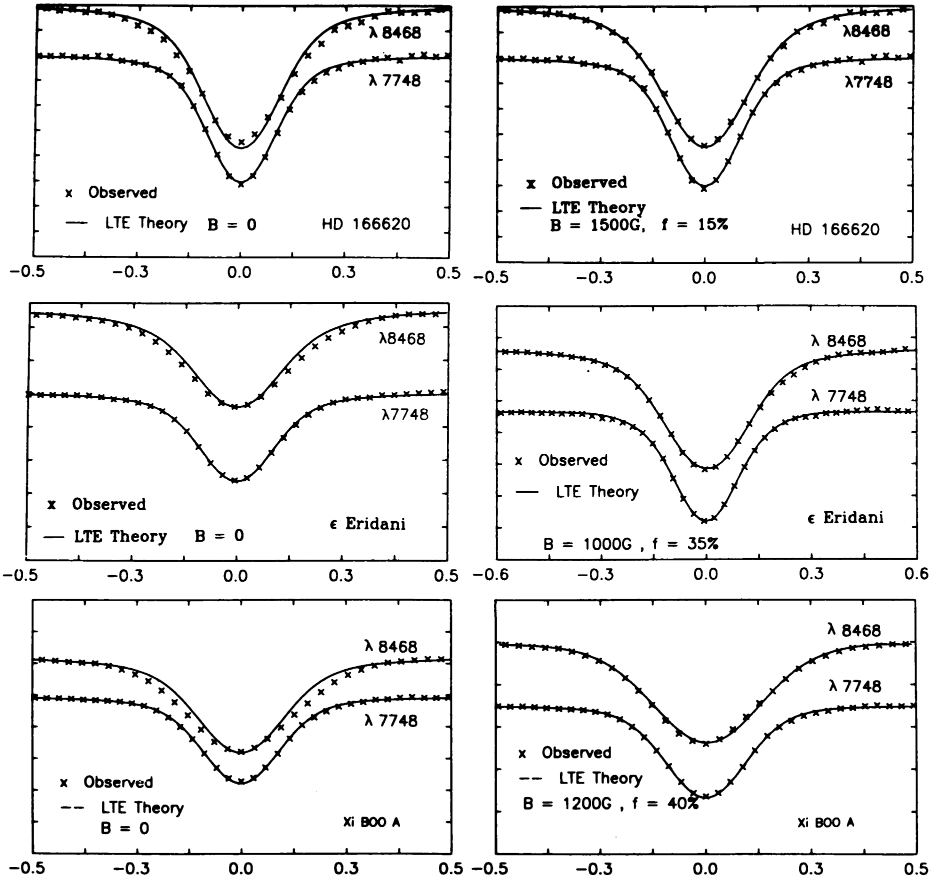

Figure 1. Comparison of the observed profiles to those computed theoretically for λ8468 (Zeeman-sensitive) and λ7748 (Zeeman-insensitive). The three panels on the left show theoretical profiles constructed with no magnetic field. Note that the observed profile λ8468 is apparently broadened due to the Zeeman effect in all three cases. The right panels show the fit obtained when a magnetic field is included in the synthetic profiles. B is the average field strength assumed, and f is the fraction of the stellar surface covered by the fields.

a number of input parameters to the line synthesis, including gf, C6, the atmospheric structure, Fe abundance, and macro-broadening. While some variation in these parameters can be shown to be consistent with the observed profiles, they can, in no way, account for the observed excess broadening of the Zeeman-sensitive line. We conclude that the observed broadening is indeed due to the Zeeman effect.

Finally, one wonders whether the large covering fractions derived for active stars are real. We have assumed that the observed profile is accurately represented by the weighted sum of profiles from magnetic and non-magnetic regions. We cannot account, however, for the relative continuum brightness of the two types of regions, nor have we compensated for the different line strengths from the two regions. Thus the true covering factors may be considerably different from those derived here. One may ask whether the magnetic regions on active stars are crudely similar to solar spot umbrae, penumbrae, or faculae. To resolve this, future stellar magnetic work should include simultaneous photometric and spectroscopic observations to search for rotationally modulated diagnostics of analogous solar magnetic regions.

We would like to acknowledge helpful discussions with L. Hartmann, D.Bruning, and S.Saar. This research was supported in part by NSF grant AST 86-03979.

REFERENCES

Bruning, D.H. 1984, Ap.J.,281,830.
Condon,E.U. and Shortley,G.H. 1970, The Theory of Atomic Spectra Cambridge Univ. Press, London.
Gray, D.F., 1976, The Observation and Analysis of Stellar Photopheres, Wiley and Sons, NY, p394.
Hartmann,L.W. and Noyes,R.W. 1987, 'Rotation and Magnetic Activity in Main Sequence Stars', to appear in Annual Reviews of Astronomy and Astrophysics, Vol.25.
Kurucz,R.L. and Peytremann,E. 1975, Smithsonian Astroph. Obs. Special Report 362.
Marcy,G.W. 1984, Ap.J.,276,286.
Noyes,R.W., Hartmann,L.W., Baliunas,S.L., Duncan,D.K., Vaughan,A.H. 1984, Ap.J.,279,763.
Robinson,R.D., Worden,S.P., and Harvey,J.W. 1980, Ap.J. Letters, 236,L155.
Saar, S.H. 1988 preprint.
Soderblom,D.R. 1981, Ap.J.,263,239.

DISCUSSION

LANDSTREET You have gone to some trouble to obtain accurate local line profiles. Another important aspect of the problem is the assumed magnetic geometry, which one would expect to have substantial effect on the resulting profiles. Could you describe your assumed magnetic geometry, and tell us how much your results depend on that geometry ?

MARCY (As I understood it) The magnetic geometry assumed is an average of radial magnetic fields at three different values of μ. Other magnetic geometries should be explored.

LINSKY It is important to recall that the analyses by Marcy and Saar both assume that the model atmospheres and broadening parameters for magnetic and nonmagnetic regions are the same. This is unlikely to be true if the Sun may be considered a useful guide. For example, if the continuum brightness is larger in magnetic, than nonmagnetic regions then the filling factor will be smaller than derived by assuming no difference. Also if the broadening parameters are different in the magnetic and nonmagnetic regions, then the derived magnetic parameters may be quite uncertain.

MARCY This is an important point. Not only are the atmospheres different in and out of magnetic regions, but the velocity fields may well be different. A two-components stellar atmosphere, perhaps based on solar faculae, should be considered for future work.

SNEDEN How do you set your continuum and how does it affect the accuracies of your results ?

MARCY The continuum is set by using the highest points in the 80 angstroms of spectrum that we obtain. Tests show that misplacement of the continuum can indeed affect the derived fields. The percent error in the field is approximately equal to the error in continuum placement divided by the amount of enhancement of the line wing due to the Zeeman effect.

HOLWEGER You mentioned the strange line profiles you have got in your model atmosphere calculations, and you have given an explanation in terms of an interplay of different Zeeman components. I suggest that these emission cores are due to the use of a model with a chromosphere, and assuming LTE. An emission core is easily generated with the HSRA in this manner.

MARCY We tested your concern by a trial in which the source function decreased linearly with optical depth. The oddly shaped profiles persist. They can be understod entirely by considering the LTE line transfer of both linearly -and circularly- polarized radiation, in the presence of Zeeman absorption components.

BASRI A remark following Holwegger's question: as an old fan of chromospheric activity, it immediately occured to me that your point might be the case. We re-ran the computation with the chromosphere removed, with the result that all features of the profile remained, including the "central reversal". Examination of the contribution functions showed the line is really fully formed below the temperature minimum.

https://doi.org/10.1017/S007418090003518X Published online by Cambridge University Press