Magnetic fields in M-dwarfs: quantitative results from detailed spectral synthesis in FeH lines

Shulyak, D.\textsuperscript{1}, Reiners, A.\textsuperscript{1}, Wende, S.\textsuperscript{1}, Kochukhov, O.\textsuperscript{2}, Piskunov, N.\textsuperscript{2}, Seifahrt, A.\textsuperscript{3}

\textsuperscript{1}Universität Göttingen, Institut für Astrophysik, Friedrich-Hund-Platz 1, D-37077 Göttingen, Germany
\textsuperscript{2}Department of Physics and Astronomy, Uppsala University, Box 516, 751 20, Uppsala, Sweden
\textsuperscript{3}Department of Physics, University of California, One Shields Avenue, Davis, CA 95616, USA

Abstract. Strong surface magnetic fields are ubiquitously found in M-dwarfs with mean intensities on the order of few thousand Gauss – three orders of magnitude higher than the mean surface magnetic field of the Sun. These fields and their interaction with photospheric convection are the main source of stellar activity, which is of big interest to study links between parent stars and their planets. Moreover, the understanding of stellar magnetism, as well as the role of different dynamo-actions in particular, is impossible without explaining magnetic fields in M-dwarfs. Measuring magnetic field intensities and geometries in such cool objects, however, is strongly limited to our ability to simulate the Zeeman effect in molecular lines. In this work, we present quantitative results of modelling and analysis of the magnetic fields in selected M-dwarfs in FeH Wing-Ford lines and strong atomic lines. Some particular FeH lines are found to be the excellent probes of the magnetic field.

1. Introduction

Magnetic fields in non-degenerate stars are found all across the Hertzsprung-Russell diagram, from hot high-luminous stars down to cool and ultra-cool dwarfs (see, for example, the review by Donati & Landstreet 2009, and references therein). The characterization of the magnetic fields in cool low-mass M-stars is of high interest because a) these stars contribute up to 70\% by number of the total stellar population of our galaxy; b) these stars often show dynamo-generated activity in their atmospheres similar to that of the Sun (i.e. with flares seen as strong emission in X-ray, H\alpha, Ca II H & K lines, see Berdyugina (2005)), however, objects later than M3.5 (\textit{T}_{\text{eff}} \approx 3400K, \textit{M}<0.35\text{M}_\odot) are believed to become fully convective, therefore different dynamo mechanisms need to be involved to explain their fields; c) these stars are promising targets to search for Earth-size planets inside their habitable zones, and thus knowledge of the magnetic activity of a parent star is potentially important for the climate modelling of these distant earth’s. In this paper we will present first quantitative and independent estimates of the surface magnetic fields in selected M-dwarfs based on synthetic spectra modeling in FeH lines of the Wing-Ford $F^4\Delta - X^4\Delta$ transitions.
2. What is known about magnetic fields of M-dwarf up to now?

Measurements of the magnetic fields in cool stars rely on polarimetric observations and analysis of Zeeman broadening of spectral lines. Utilizing the Zeeman Doppler Imaging (ZDI) and Least Square Deconvolution (LSD) techniques as applied to Stokes V spectra, Donati et al. (2008) and Morin et al. (2008) carried out a systematic characterization of the magnetic field topologies in a sample of M-dwarfs. Authors found a clear transition in the magnetic field topologies between partly and fully convective stars, with later tend to host strong, poloidal, mostly axisymmetric fields contrary to much weaker, non-axisymmetric fields with strong toroidal component for the former. In contrast, most recent investigation revealed a presence of M-dwarfs with strong toroidal non-axisymmetric fields among fully convective objects, and thus no clear transition between these two groups of M-stars seem to exist any more (Morin et al. 2010). These results must be taken with certain caution, since using LSD technique and limiting only to Stokes V may result in missing an important information about the true magnetic field geometry and total magnetic flux, as discussed in the talk of A. Reiners (this meeting) and recent study by Kochukhov et al. (2010).

The Zeeman effect is sensitive to the surface averaged magnetic field modulus and thus naturally gives information about the true magnetic field flux. Strong fields up to $\approx 4$ kG were then reported for some M-dwarfs based on the relative analysis of magnetically sensitive Fe I line at $\lambda = 8467$Å (Johns-Krull & Valenti 1996, 2000). For dwarfs cooler than mid - M, molecular lines of FeH Wing-Ford $F^4 \Delta - X^4 \Delta$ transitions around 0.99 $\mu$m are usually utilized (Valenti et al. 2001; Reiners & Basri 2006). Some of these lines do show strong magnetic sensitivity, as seen, for instance, in the sunspot spectra (Wallace et al. 1998).

3. Landé g-factors of FeH: roots of the problem

Unfortunately, most lines of FeH are formed in the intermediate Hund’s case, which theoretical description is based on certain approximations. The main problem is connected with the Born-Oppenheimer approximation, which assumes a clear separation between the electronic and the nuclear motion in terms of energies. This approximation fails for FeH, and no satisfactory description of Landé g-factors exist so far. Among recent improvements in understanding the Zeeman splitting in diatomic molecules one should mention papers by Berdyugina & Solanki (2002) and Asensio Ramos & Trujillo Bueno (2006). However, theoretical g-factors still cannot describe correctly the broadening of great majority of FeH lines.

An alternative solution was then suggested by Reiners & Basri (2006, 2007), who estimated the $|B|f$ values ($f$–filling factor) in a number of M-dwarfs by simple linear interpolation between the spectral features of two reference stars, one with zero field and another one with the magnetic field known from Johns-Krull & Valenti (1996), but the error bars of such an analysis stays high ($\approx 1$ kG).

First semi-empirical fit to FeH lines in a sunspot spectra was presented in Afram et al. (2008). The authors succeeded to obtained a very good agreement with observations for selected FeH lines and presented best-fitted polynomial g-factors of upper and lower levels of corresponding transitions. A little earlier, Harrison & Brown (2008) presented measured g-factors for a number of FeH lines, but were limited to low magnetic $J$-numbers only. As an example, Fig. 1 illustrates a comparison between experimental
Magnetic fields in M-dwarfs: quantitative results from detailed spectral synthesis in FeH lines

4. Methods

The line list of FeH transitions and molecular constants were taken from Dulick et al. (2003) and corrected as described in Wende et al. (2010). The VALD (Vienna Atomic Line Database) was used as a source of atomic transitions (Piskunov et al. 1995; Kupka et al. 1999). Magnetic spectra synthesis is performed using the SYNNAST code (Kochukhov 2007). The code represents an improved version of the SYNMAG code described by Piskunov (1999). The model atmospheres are from the recent MARCS grid (Gustafsson et al. 2008). To compute g-factors in different Hund’s cases, we implemented numerical libraries from the MZL (Molecular Zeeman Library) package originally written by B. Leroy (Leroy 2004), and adopted for the particular case of FeH.

5. Results

A sunspot spectrum is probably the only trustworthy data source to test the predicted Zeeman patterns of FeH lines because a) the temperature inside a spot is still hot enough to see strong unblended atomic and FeH lines and b) very high-resolution and S/N observations are available. We thus made use of an umbra spectrum from Wallace et al. (1998). They also derived the magnetic field intensity $|B| = 2.7 \text{ kG}$. Our fit to the atomic

1 http://bernath.uwaterloo.ca/FeH/
2 http://marcs.astro.uu.se
lines (mostly Fe, Ti, and Cr) in the range 9800 – 10 800 Å also suggests a field intensity $|B| = 2.7$ kG (model atmosphere with $T_{\text{eff}} = 4000$ K).

Figure 2. Comparison between observed and theoretical sunspot spectra in selected regions of FeH transitions. Blue dashed line – best-fitted g-factor from Afram et al. (2008), red solid line – calculations with MZL library; both with a purely radial field of $B = (2.7, 0, 0)$ kG. Red dash-dotted line – synthetic spectra accounted for the horizontal field component $B = (2.5, 1, 0)$ kG (hardly seen in the figure, coincides with red solid line), brown dotted line – zero-field spectrum. Labels over lines indicate their central wavelengths, omegas of lower and upper states (in brackets), branch, and the $J$-number of the lower state (in brackets). Wavelengths are in vacuum.

Using the MZL library and sunspot spectra we find that the intermediate Hund’s case (with its present treatment in MZL) is a good approximation if ($l –$ lower, $u$ – upper states)

1. $\Omega_l = 0.5$

2. $\Omega_l$ or $u \leq 2.5$ and $3Y > J(J + 1)$ for the P and Q branches

3. $\Omega_l$ and $u = 2.5$ and $5Y > J(J + 1)$ for the R branch.

For the rest of transitions the assumption of Hund’s case (a) for the upper level and Hund’s case (b) for lower level provide reasonable results.
Magnetic fields in M-dwarfs: quantitative results from detailed spectral synthesis in FeH lines

Figure 2 illustrates a comparison between best-fitted g-factor from Afram et al. (2008) and our calculation for some selected lines in the 9900 – 10 000 Å region. Note that apart from the figures shown in Afram et al. (2008), we did not make an attempt of correcting the theoretical spectra, i.e. no filling factors were applied. The model atmosphere and field intensity are the same as determined previously from the metallic line spectra. Still, the discrepancy is found for low omega R-branch lines like FeH 9945 Å, 9962 Å, etc., which indeed show splitting closer to pure Hund’s cases. Even though we succeeded well enough to fit the width of the observed lines with the same field of $|B| = 2.7$ kG derived previously from atomic lines, this cannot be judged to be more physical though until new improvements in the theoretical description of the intermediate case will become available.

Having fixed g-factors for important FeH transitions, we used them to derive the magnetic field strength in selected M-dwarfs. As an example, here we compare model predictions for active M-dwarfs AD Leo and YZ Cmi, for which previous attempts to measure its magnetic field resulted in $(|B|/f) = 2.9$ kG and $(|B|/f) > 3.9$ kG respectively (Reiners & Basri 2007). Theoretical fit to FeH lines is shown in the Fig. 3 together with the predictions for the non-active M4.5 star GJ 1002. In particular, magnetically sensitive lines such as FeH 9905 Å, 9906 Å, 9942 Å, and 9959 Å clearly point to the lower field modulus. That the widths of these lines are well reproduced in the sunspot spectra (see Fig. 2) allows us to consider them as important indicators of the mean field intensity. In particular, increasing $|B|$ results in the appearance of the characteristic feature owing to the crossed $\sigma$-components of the two FeH lines at 9906 Å. Overlaid, these components give rise to the absorption feature which is not seen in the observed spectra. Consequently, weaker fields are needed to keep these lines separated.

Table 1. Atmospheric parameters of investigated M-dwarfs.

| Name   | Spectral type | Teff (K) | $\upsilon \sin i$ (km/s) | $|B|_{\text{m}}$ (kG) | $(|B|/f)$ (kG) |
|--------|---------------|----------|--------------------------|------------------------|----------------|
| Sunspot| –             | 4000     | 0.0                      | 2.7                    | 2.7            |
| GJ 1002| M5.5          | 3100     | 2.5                      | 0                      | 0              |
| GJ 1224| M4.5          | 3200     | 3.0                      | $\approx 2$            | 1.7 – 2        |
| YZ Cmi | M4.5          | 3300     | 5.0                      | 3 – 4                  | 3 – 3.5        |
| EV Lac | M3.5          | 3400     | 1.0                      | 3 – 4                  | 3 – 3.5        |
| AD Leo | M3.5          | 3400     | 3.0                      | 2 – 3                  | 2 – 2.5        |

$|B|_{\text{m}}$ – mean surface magnetic field
$(|B|/f)$ – results of previous investigations

(1) – Wallace et al. (1998)
(2) – Reiners & Basri (2007), scaled from (3)
(3) – Johns-Krull & Valenti (1996)

Table 1 gathers the main results of the present study including several other M-dwarfs which were analyzed applying the same approach. An average surface magnetic field resulting from the analysis of atomic and FeH lines are shown separately. For GJ 1224, the measurements of the magnetic field from atoms were based on Ti I lines located in the region 10 400 – 10 800 Å, while for AD Leo, YZ CMi, and EV Lac results are from the Fe I 8468 Å line (the same way as presented in Johns-Krull & Valenti (1996)). A large scatter resulting from the analysis of the Fe I 8468 Å line is
Figure 3. Comparison between observed and theoretical spectra of selected M-dwarfs. **Upper panel:** non-active star GJ 1002, red solid line—assuming $\epsilon_{\text{Fe}} = -4.37$, blue dashed line—$\epsilon_{\text{Fe}} = -4.59$. **Middle panel:** active star AD Leo, green dashed $- \mathbf{B} = (1.7, 1.7, 0)$ kG, blue dash-dotted $- \mathbf{B} = (2, 0, 0)$ kG, brawn dotted $- \mathbf{B} = (2.5, 0, 0)$ kG, red solid $- \mathbf{B} = (2.9, 0, 0)$ kG. **Bottom panel:** active star YZ CMi, green dashed $- \mathbf{B} = (0, 4, 0)$ kG, blue dash-dotted $- \mathbf{B} = (2.5, 2.5, 0)$ kG, red solid $- \mathbf{B} = (4, 0, 0)$ kG, dotted $- \mathbf{B} = (3, 0, 0)$ kG.
due to the uncertainties of fitting blue and red wings of this line, which seem to require different $|B|$. The low quality of the data (low resolution and signal-to-noise ratio) can also introduce uncertainties in the fitting procedure, and thus it is difficult to draw strict conclusions without further more accurate analysis. In addition, fitting the spectra of magnetic stars we assumed the magnetic field to be homogeneous everywhere on the stellar surface (corresponding filling factor $f = 1$), while previous studies assumed the stellar surface to consist of combinations of magnetic ($f < 1$) and non-magnetic ($f = 0$) regions, but with the former being represented by radial magnetic field only, i.e ignoring possible horizontal vector components of the magnetic field. We refer the interested reader to the work of Shulyak et al. (2010) for more details.

6. Summary

In this study we developed an approach of modelling the Zeeman splitting in FeH lines of Wing-Ford $F^4 \Delta - X^4 \Delta$ band which then applied to measure magnetic fields in selected M-dwarfs. The main result of this study is that the magnetic field strengths derived from FeH lines are 15 – 30% lower than results presented in Reiners & Basri (2007), which are based on atomic line analysis scaled from Johns-Krull & Valenti (2000). The estimates of the magnetic field modulus from the Fe I 8468 Å line seem to be systematically higher than those from FeH lines. This needs further more extensive investigation.

Acknowledgments. We thank Dr. Bernard Leroy for his kind advice and help with the MZL routines.

This work was supported by the following grants: Deutsche Forschungsgemeinschaft (DFG) Research Grant RE1664/7-1 to DS and Deutsche Forschungsgemeinschaft under DFG RE 1664/4-1 and NSF grant AST07-08074 to AS. SW acknowledges financial support from the DFG Research Training Group GrK - 1351 "Extrasolar Planets and their host stars". OK is a Royal Swedish Academy of Sciences Research Fellow supported by grants from the Knut and Alice Wallenberg Foundation and the Swedish Research Council. We also acknowledge the use of electronic databases (VALD, SIMBAD, NASA's ADS). This research has made use of the Molecular Zeeman Library (Leroy, 2004).

References

Afram, N., Berdyugina, S. V., Fluri, D. M., Solanki, S. K., & Lagg, A. 2008, A&A, 482, 387
Asensio Ramos, A., & Trujillo Bueno, J. 2006, ApJ, 636, 548
Berdyugina, S. V. 2005, Living Reviews in Solar Physics, 2, 8
Berdyugina, S. V., & Solanki, S. K. 2002, A&A, 385, 701
Donati, J., & Landstreet, J. D. 2009, ARA&A, 47, 333
Donati, J., Morin, J., Petit, P., Delfosse, X., Forveille, T., Aurière, M., Cabanac, R., Dintrans, B., Fares, R., Gastine, T., Jardine, M. M., Lignières, F., Paletou, F., Velez, J. C. R., & Théado, S. 2008, MNRAS, 390, 545
Dulick, M., Bauschlicher, C. W., Jr., Burrows, A., Sharp, C. M., Ram, R. S., & Bernath, P. 2003, ApJ, 594, 651
Gustafsson, B., Edvardsson, B., Eriksson, K., Jørgensen, U. G., Nordlund, Å., & Plez, B. 2008, A&A, 486, 951
Harrison, J. J., & Brown, J. M. 2008, ApJ, 686, 1426
Johns-Krull, C. M., & Valenti, J. A. 1996, ApJ, 459, L95
Ansgar Reiners

— 2000, in Stellar Clusters and Associations: Convection, Rotation, and Dynamos, edited by R. Pallavicini, G. Micela, & S. Sciortino, vol. 198 of Astronomical Society of the Pacific Conference Series, 371
Kochukhov, O., Makaganiuk, V., & Piskunov, N. 2010, A&A, 524, A5
Kochukhov, O. P. 2007, in Physics of Magnetic Stars, 109
Kupka, F., Piskunov, N., Ryabchikova, T. A., Stempels, H. C., & Weiss, W. W. 1999, A&AS, 138, 119
Leroy, B. 2004, in Molecular Zeeman Library Reference Manual (avaialble on-line at http://bass2000.obspm.fr/mzl/download/mzl-ref.pdf)
Morin, J., Donati, J., Petit, P., Delfosse, X., Forveille, T., Albert, L., Auricère, M., Cabanac, R., Dintrans, B., Fares, R., Gastine, T., Jardine, M. M., Lignières, F., Paletou, F., Ramirez Velez, J. C., & Théado, S. 2008, MNRAS, 390, 567
Morin, J., Donati, J., Petit, P., Delfosse, X., Forveille, T., & Jardine, M. M. 2010, MNRAS, 407, 2269
Piskunov, N. 1999, in Polarization, edited by K. N. Nagendra & J. O. Stenflo, vol. 243 of Astrophysics and Space Science Library, 515
Piskunov, N. E., Kupka, F., Ryabchikova, T. A., Weiss, W. W., & Jeffery, C. S. 1995, A&AS, 112, 525
Reiners, A., & Basri, G. 2006, ApJ, 644, 497
— 2007, ApJ, 656, 1121
Shulyak, D., Reiners, A., Wende, S., Kochukhov, O., Piskunov, N., & Seifahrt, A. 2010, A&A, 523, A37
Valenti, J. A., Johns-Krull, C. M., & Piskunov, N. E. 2001, in 11th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, edited by R. J. Garcia Lopez, R. Rebolo, & M. R. Zapaterio Osorio, vol. 223 of Astronomical Society of the Pacific Conference Series, 1579
Wallace, L., Livingston, W. C., Bernath, P. F., & Ram, R. S. 1998, in An Atlas of the Sunspot Umbral Spectrum in the Red and Infrared from 8900 to 10 050 cm\(^{-1}\) (6642 to 11 230Å), NOAO
Wende, S., Reiners, A., Seifahrt, A., & Bernath, P. F. 2010, A&A, 523, A58