Magnetic Fields throughout Stellar Evolution
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Magnetic fields in M-dwarfs from high-resolution infrared spectroscopy

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Abstract. Accurate spectroscopic measurements of magnetic fields in low mass stars remain challenging because of their cool temperatures, strong line blending, and often fast rotation. This is why previous estimates were based either on the analysis of only a few lines or made use of some indirect techniques. This frequently led to noticeable scatter in obtained results. In this talk I will present and discuss new results on the determination of the intensity and geometry of the magnetic fields in M-dwarfs using IR observations obtained with CRIRES@VLT. The instrument provides unprecedented data of high resolution ($R = 100\,000$) which is crucial for resolving individual magnetically broadened molecular and atomic lines. Such an in-depth analysis based on direct magnetic spectral synthesis opens a possibility to deduce both field intensity and geometry avoiding most of the limitation and assumptions made in previous studies.

Keywords. stars: atmospheres – stars: low-mass – stars: magnetic field

1. Introduction

Low-mass stars of spectral type M often show high level of activity accompanied by strong X-ray fluxes, appearance of emission lines, and global magnetic fields of the order of a few kilogauss detected in many stars, and the scales of these fields are comparable to the size of the stars themselves (see, e.g., Morin *et al.* 2010).

Stellar evolution predicts that stars of spectral types later than M3.5 become fully convective and do not host an interface layer of strong differential rotation. Both partially and fully convective stars can host magnetic fields of similar intensities but likely with different dynamo mechanisms operating in their interiors, and this asks for observational confirmations or otherwise.

There have been a number of attempts to measure magnetic fields in M-dwarfs and more information can be found in the review by Reiners (2012). Because in stars cooler than mid - M atomic line intensity decay rapidly, the molecular lines of FeH Wing-Ford $F^4\,\Delta - X^4\,\Delta$ transitions around 0.99 μm were proposed as alternative magnetic field indicators (Valenti *et al.* 2001; Reiners & Basri 2006).

Unfortunately, theoretical attempts to compute Zeeman patterns of FeH lines have not achieved much success. This is because the Born-Oppenheimer approximation, which is usually used in theoretical descriptions of level splitting, fails for the FeH molecule (for more details see Asensio Ramos & Trujillo Bueno (2006), Berdyugina & Solanki (2002), and poster #28 by P. Crozet at al., this meeting). As a consequence, empirical (Afram *et al.* 2008) and experimental (Harrison & Brown 2008; Crozet *et al.* 2012) attempts were carried out to estimate the Landé g-factor of FeH lines.

In this work we make use of very high resolution infrared spectra of M-dwarfs obtained with CRIRES@VLT to measure the complexity of their surface magnetic fields by studying individual line profiles. We attempt to derive distributions of filling factors of local magnetic field components that provide a best agreement between observed and theoretical spectra and to address the question whether there are any differences between fully and partially convective stars solely from spectroscopic analysis.

2. Fitting methods

The approach to compute g-factors was described in Shulyak *et al.* (2010), and is based on numerical libraries from the MZL (Molecular Zeeman Library) package originally written by B. Leroy (Leroy 2004), and adopted by us for the particular case of FeH.

Using Stokes I spectra we measure the intensity and complexity of surface magnetic fields, i.e. the minimum number of magnetic field components required to fit the observed line profiles.

For each spectrum we apply a chi-square Levenberg-Marquardt minimization algorithm with filling factors f_i as fit parameters. We consider 21 filling factors which correspond to the magnetic fields ranging from 0 kG to 10 kG in steps of 0.5 kG. The whole procedure is applied for different sets of atmospheric parameters: $T_{\rm eff}$, α(Fe), and $\upsilon \sin i$.

3. Results

Figure 1 illustrates examples of theoretical fits to a few selected FeH features in four M dwarfs GJ 388, GJ 729, GJ 285, and GJ 406, as well as recovered distribution of magnetic fields. The computations presented on the figure were carried out assuming magnetic field model with the dominating radial component of the magnetic field. Results for alternative configuration, as well as more detailed explanations will be given in Shulyak *et al.* (2013).

The values of the mean sufrace magnetic field $\langle B_{\rm s} \rangle$ derived in our study are, in general, consistent with the measurements taken at different times and considering the substantial uncertainties reported by all authors and the different spectral indicators used (see Saar & Linsky 1985; Johns-Krull & Valenti 1996, 2000; Kochukhov *et al.* 2009; Reiners & Basri 2007).

All four stars show three distinct groups of different magnetic field strength. We did not find solutions with homogeneous field distributions ($f = 1$ for the component that equals the average field), and we did not find solutions in which different field strengths are equally represented on the stellar surfaces ($f = const$ for all values of B up to $B_{\rm max}$). This is an interesting result because the *average* fields on the four stars are on the order of the *maximum* field strength we observe in sunspots, while the local magnetic flux densities occur to be much larger than those found in sunspots, and they co-exist with groups of much lower flux densities.

It is remarkable that very similar magnetic field distributions are found in all analized stars. Spectropolarimetric observations of stars in this spectral range indicate the existence of two distinct magnetic field geometries (with a few exceptions, see, e.g., Morin *et al.* (2010)): partially convective objects seem to harbor non-axisymmetric, toroidal fields, while fully convective objects prefer axisymmetric, poloidal fields. However, if such a dichotomy of geometries exists, we would expect it affecting the distribution of magnetic field components among our sample stars. The pattern of the magnetic field distributions we find show no evidence for such a transition at the convection boundary (where GJ 388 and GJ 729 are partially convective and GJ 285 and GJ 406 are fully convective, see Fig. 1). We therefore conclude that our Stokes I measurements of the entire magnetic field cannot confirm a difference in magnetic field geometries between partially and fully convective stars.

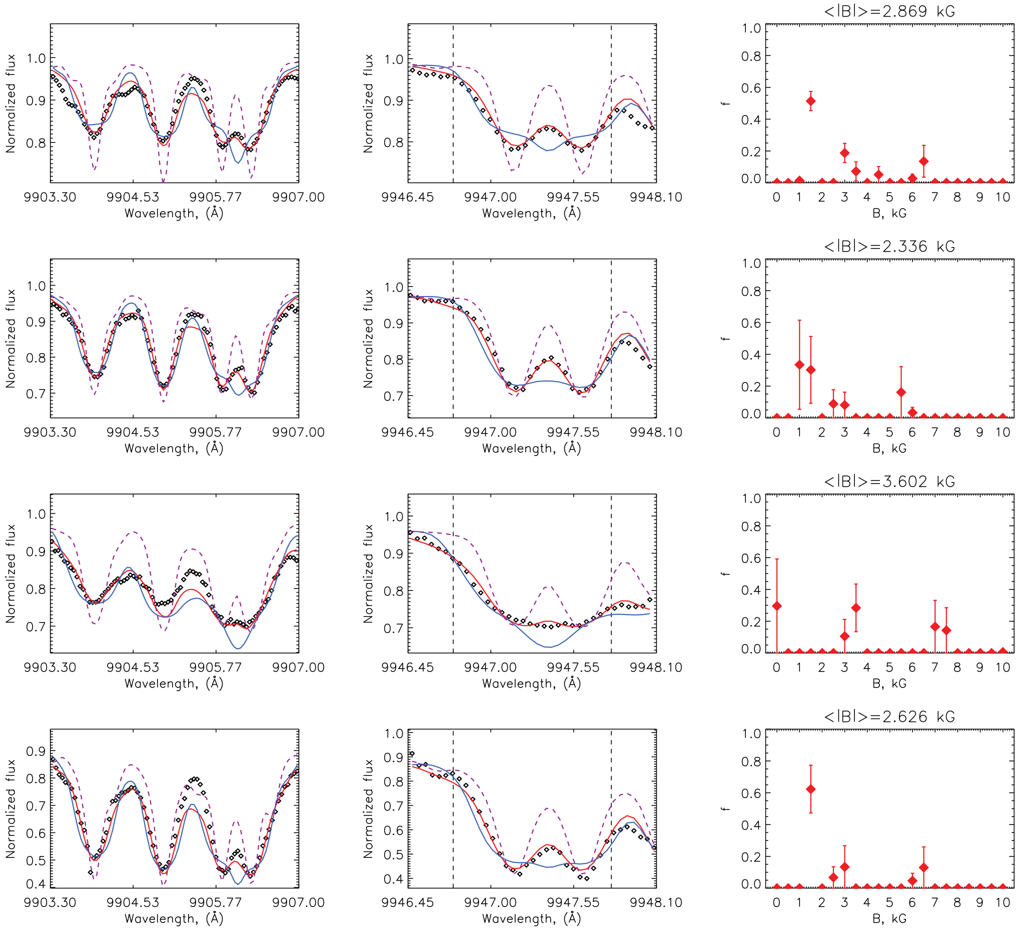

Figure 1. Examples of theoretical fit to selected FeH lines and resulting distributions of filling factors for (from top row to bottom) GJ 388 ($T_{\rm eff}$ = 3400 K, $v \sin i$ = 3 km/s), GJ 729 ($T_{\rm eff}$ = 3400 K, $v \sin i$ = 4 km/s), GJ 285 ($T_{\rm eff}$ = 3300 K, $v \sin i$ = 6 km/s), and GJ 406 ($T_{\rm eff}$ = 3100 K, $v \sin i$ = 3 km/s). Violet dashed line – computation with zero magnetic field, red line – computation with multi-component magnetic field shown on the right bottom plot, blue line – computations with homogeneous magnetic field (i.e. $f = 1$) of the same intensity as multi-component magnetic field. The strength of the resulting surface magnetic field is given on top of each plot of field distributions.

In our sample, the maximum field strength correlates with (projected) rotation rate. While the average field strength saturates at Rossby numbers $Ro \sim 0.1$ and $B \approx 4\,$kG (Reiners *et al.* 2009), the local field strength found in the present work does not saturate.

The detection of localized field components with the strength of up to 7.5 kG (GJ 285) suggests that if these structures are stable over long time intervals they must be in equipartition with the surrounding plasma. The equipartition field at the level of photosphere of a mid-M dwarf is of the order of only $4 - 5$ kG. That means that, similar to sunspots, the high localized field strength can be in equipartition with the surrounding plasma if the regions of strong magnetic fields have cooler temperatures compared to the rest of the atmosphere. Unfortunately, no accurate estimate of the temperature contrast is available for M-dwarfs because their surfaces remain unresolved, and high quality time series of spectroscopic observations in Stokes I are not yet available. This is a very interesting problem to be addressed in future research.

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