Abstract. Magnetic fields play a central role in the atmospheric properties and variability of active M dwarfs. Information on the strength and structure of magnetic fields in these objects is vital for understanding dynamo mechanisms and magnetically-driven activity of low-mass stars, and for constraining theories of star formation and evolution. We have initiated the first systematic high-resolution survey of magnetically sensitive infrared spectral lines in M dwarf stars using the CRIRES instrument at the ESO VLT. We have completed observations for a sample of 35 active and inactive M dwarfs. Here we report first results of our project, demonstrating a clear detection of magnetic splitting of lines in the spectra of several M dwarfs. We assess diagnostic potential of different Zeeman-sensitive lines in the observed spectral region and apply spectrum synthesis modelling to infer magnetic field properties of selected M dwarfs.

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INTRODUCTION

Magnetic fields play a fundamental role in the physics of late-type stars, influencing their activity and, most probably, evolution. Accurate measurements of stellar surface magnetic field strengths and fractional area coverages (filling factors) can provide empirical constraints on such important theoretical problems as the nature of dynamos, mechanisms of non-radiative heating in the outer atmospheres, the evolution of stellar angular momentum and interior structure of late-type stars. Understanding magnetic properties of active M dwarfs (dMe) is of particular interest due to the enormous enhancement of their activity indicators relative to those of normal solar-like stars. The M dwarf flare stars exhibit many phenomena, including strong chromospheric and coronal emission and powerful flares, that indicate the presence of intense magnetic fields with a large filling factor. At the same time, cooler M dwarfs are fully convective and, therefore, lack an interface between the radiative core and convective envelope where conventional dynamo processes are thought to operate. Thus, the presence of substantial magnetic fields and the remarkable activity of M dwarfs are at odds with many theoretical expectations and, possibly, indicate the action of a completely different type of dynamo process [1, 2].

The development of more successful theoretical models of dynamos in M dwarfs requires detailed observational knowledge of the field strengths, field geometries and the rotation-activity relation for these objects. However, despite numerous indirect ev-
idences for the existence of strong magnetic fields in the photospheres of dMe stars, we still lack and definitive magnetic measurements, capable of placing meaningful constraints on the theoretical models of the origin of magnetic fields in low-mass stars and their role in stellar activity.

Early attempts to measure magnetic fields on late-type stars using polarized light [3, 4] have failed, presumably due to the complex magnetic topologies. On the other hand, modern, highly sensitive polarimetric observations of early and mid M dwarfs are able to reveal large-scale poloidal fields with mean field strengths of \( \leq 0.5 \text{ kG} \) [5, 6, 7]. In contrast, systematic positive identifications of the kG-strength magnetic fields on the surfaces of M dwarfs were obtained with the study of magnetically sensitive lines observed in unpolarised light [8, 9]. Magnetic field measurements reported for several active M dwarfs relied on the analysis of the Fe I 846.8 nm line. Although this spectral feature provides an enhanced sensitivity to magnetic effects, its magnetic components are never fully resolve for the typical fields encountered on M dwarfs and the line is strongly blended with TiO molecular bands. Nevertheless, analyses of Fe I 846.8 nm leave little doubt that some M dwarfs possess 1.5–4 kG fields, covering significant fraction of the stellar surface.

A recently proposed technique of detecting magnetic fields in low-mass stars using the differential broadening of strong FeH lines at \( 1 \mu \text{m} \) [10] opened another possibility to investigate magnetic fields in late M as well as L dwarfs. But in practice this method cannot be applied independently from the magnetic analysis of atomic lines because the Landé factors are poorly known for the magnetically sensitive FeH features. The necessity to rely on a set of standard dMe stars for which magnetic field strength is assumed to be known yields systematic errors of 0.5–1.0 kG for the FeH technique.

It was demonstrated [11] that observations in the infrared (IR) are of enormous potential for the magnetic diagnosis of active M dwarfs. Due to the \( \lambda^2 \) wavelength dependence of the Zeeman effect, the magnetic splitting of lines at 2.2 \( \mu \text{m} \) is 5–10 times larger than for most Zeeman-sensitive atomic and molecular lines below 1 \( \mu \). The sensitivity to weak magnetic fields is increased correspondingly. This unique potential of the IR magnetic observations was utilised to test the presence of magnetic fields in T Tauri stars [12, 13], but was never fully exploited for M dwarfs because with previously available instrumentation many hours of exposure time were required to obtain necessary S/N even for the brightest dM stars.

**INFRARED SPECTROSCOPY OF M DWARFS**

The availability of the CRIRES (CRyogenic high-resolution InfraRed Echelle Spectrograph) instrument [14] at the ESO VLT provided the first possibility to utilise the enhanced Zeeman sensitivity of IR lines for the detection and analysis of magnetic fields in M dwarfs and other late-type stars. We have initiated a survey of a sample of M dwarfs with the aim to increase the number of stars with known surface field strengths and to attempt disentangling field strengths and filling factors for several stars with strong fields.

In the period from October 2007 to March 2008 we obtained observations of 35 active and inactive M dwarfs in the spectral class range K7–M6. The CRIRES spectrograph
Our original goal was to analyse the 2222–2234 nm region containing three Ti\textsc{i} lines with moderately large Landé factors ($g_{\text{eff}} = 1.58–1.67$) and a unique Ti\textsc{i} line at 2231.1 nm, which has $g_{\text{eff}} = 2.5$. This Ti multiplet has been extensively employed in the studies of solar [15] and T Tauri star [13] magnetic fields, and potentially represents one of the most useful sets of atomic absorption features for the magnetic diagnosis over the entire IR spectral region accessible to CRIRES.

Inspection of the line profile shapes of the Ti\textsc{i} lines shows unambiguous evidence of
the presence of strong magnetic field in the atmospheres of dMe stars. Fig. 1 illustrates the spectra in the region of the Ti\textsc{i} 2227.4 nm line for two active stars and four inactive M dwarfs of similar spectral types. For the field strength of 3–4 kG the line splits into two groups of $\pi$ and two groups of $\sigma$ components. The resulting characteristic profile shape can be recognized in GJ 285 (YZ CMi). For the weaker 1–2 kG fields, typical of early active M dwarfs such as GJ 1049, no splitting is seen but the Ti\textsc{i} line is broadened, acquiring triangular shape which cannot be ascribed to rotation or other effects.

Despite this prominent magnetic distortion of the Ti\textsc{i} lines their quantitative interpretation in terms of the magnetic field parameters becomes difficult already for mid M stars due to blending of the stellar H$_2$O. Theoretical understanding of the spectrum of this molecule [16] is not good enough to allow spectrum synthesis modelling of individual lines in the region studied with CRIRES. Thus, at the moment the Ti\textsc{i} multiplet is not suitable for the precise magnetic field analysis of stars cooler than about M2 but can be probably used for a coarse measurement of the product of the field strength and filling factor, similar to the studies utilising the near IR Fe\textsc{i} 846.8 nm line [8] and the FeH bands [10]. In this context a much cleaner appearance of this Ti\textsc{i} multiplet in the earlier FTS study of M3.5 star AD Leo [11] is at variance with our results and, possibly, represents an artifact of the special reduction procedure applied to the FTS spectra (Saar, private communication).

Fortunately, magnetic fields in active M dwarfs are strong enough to induce observable magnetic splitting or significant profile distortion even in the lines with moderate Landé factors ($g_{\text{eff}} \leq 1.5$). Fig. 2 illustrates this effect for the strong Na\textsc{i} line at $\lambda$ 2208.4 nm. This line dominates the observed spectral regions for the entire $T_{\text{eff}}$ range of M dwarfs included in our sample and, at the same, it exhibits a simple Zeeman splitting pattern. This line splits in only two groups of overlapping $\pi$ and $\sigma$ components for
the 2–4 kG field strength range typical of active M dwarfs. The simple Zeeman doublet pattern facilitates quantitative interpretation of the line profile shape leading to accurate determination of the magnetic field characteristics.

**SPECTRUM SYNTHESIS MODELLING**

Detailed spectrum synthesis analysis using realistic M dwarf model atmospheres and including effects of polarised radiative transfer is our preferred method of interpreting high-resolution observations of Zeeman resolved IR lines. In the preliminary analysis presented here we calculated spectra in the vicinity of the Na I 2208.4 nm line and adjusted magnetic field parameters to reproduce the shape of the Na I line in the inner core region not affected by the water vapor lines.

Our calculations are based on the atomic line list extracted from the VALD database [17] and further fine tuned to fit the FTS atlas of Arcturus [18]. We use recently updated MARCS model atmosphere grid [19] and compute theoretical spectra with the Synthmag code [20], which solves polarised radiative transfer equation and derives four Stokes parameter spectra assuming homogeneous magnetic field distribution over the stellar surface. We find that reproducing the observed Na I line profiles requires a combination of the spectral components with different field intensities and filling factors. The modelling presented here is based upon a grid of line profiles computed for each star for the field strength interval 1–7 kG with a 2 kG step. A least-squares fitting routine is used to determine corresponding filling factors.

Fig. 3 illustrates results of the magnetic spectrum synthesis modelling for the two well-known dMe stars GJ 285 (YZ CMi, M4.5) and GJ 388 (AD Leo, M3.5). We find \( \sum B \cdot f = 4.5 \) kG for the first star and \( \sum B \cdot f = 3.2 \) kG for the second object. In both cases the formal precision of these magnetic flux measurements is 0.1–0.2 kG, which is significantly better than in previous studies of these stars [11, 10]. Using the same analysis technique we also find a very strong field (4.3 kG) in GJ 398 (RY Rex, M3.5),
for which no direct magnetic field detections were reported previously, and confirm a moderately strong field (2.9 kG) in the early M dwarf GJ 1049 [9].

Considering uncertainties of the previous studies of magnetic broadening in M dwarf spectra, our results are in good agreement with earlier field strength measurements using unpolarised spectra. At the same time, magnetic field derived here is far more intense than the mean magnetic flux of 0.2–0.6 kG reported in the recent Zeeman Doppler Imaging (ZDI) analysis of the circular polarisation in GJ 285 and GJ 388 [6]. This could indicate that a major contribution to the magnetic energy comes from the scales smaller than can be resolved by ZDI. However, the two techniques are complimentary, suggesting that a comprehensive understanding of the magnetism in M dwarfs can be achieved by combining both techniques, i.e. performing a time-resolved polarisation observation in the IR spectral region.

REFERENCES