Strong dipole magnetic fields in fast rotating fully convective stars

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M dwarfs are the most numerous stars in our Galaxy, with masses between approximately 0.5 and 0.1 solar masses. Many of them show surface activity qualitatively similar to our Sun and generate flares, high X-ray fluxes and large-scale magnetic fields⁷. Such activity is driven by a dynamo powered by the convective motions in their interiors⁸,⁹. Understanding properties of stellar magnetic fields in these stars finds a broad application in astrophysics, including theory of stellar dynamos and environment conditions around planets that may be orbiting these stars. Most stars with convective envelopes follow a rotation–activity relationship where various activity indicators saturate in stars with rotation periods shorter than a few days⁴,⁶,⁸. The activity gradually declines with rotation rate in stars rotating more slowly. It is thought that, due to a tight empirical correlation between X-ray radiance and magnetic flux⁶, the stellar magnetic fields will also saturate, to values around 4 kG (ref. ⁹). Here we report the detection of magnetic fields above the presumed saturation limit in four fully convective M dwarfs. By combining results from spectroscopic and polarimetric studies, we explain our findings in terms of bistable dynamo models¹⁰: stars with the strongest magnetic fields are those in a dipole dynamo state, whereas stars in a multipole state cannot generate fields stronger than about 4 kG. Our study provides observational evidence that the dynamo in fully convective M dwarfs generates magnetic fields that can differ not only in the geometry of their large-scale component, but also in the total magnetic energy.

Our understanding of origin and evolution of the magnetic fields in M dwarfs is based on models of the rotationally driven convective dynamos. Modern observations provide two important constraints for these models.

First, from the analysis of circular polarization in spectral lines, we infer that large-scale magnetic fields tend to have simple axisymmetric geometry with a dominant poloidal component in stars that are fully convective. In contrast, M dwarfs that are hotter and therefore only partly convective tend to have more complex fields with strong toroidal components¹¹. However, there are a number of exceptions when a rapidly rotating fully convective star generates a large-scale magnetic field with a complex multipole geometry. This dichotomy of magnetic properties in stars that have similar stellar parameters may be explained in terms of dynamo bistability: stars can relax to either dipole or multipole states depending on the geometry and the amplitude of an initial seed magnetic field¹²,¹³. Note, however, that dynamo bistability has been observed only in models of stars with masses $M \leq 0.2 M_{\odot}$.

The second observational constraint is the rotation–activity relation²,⁴,⁴,¹³. A remarkable feature of this relation is the existence of two branches, a saturated and a non-saturated branch. In the non-saturated branch, the amount of non-thermal (for example, X-ray) emission generated by the star grows with rotation rate. On the saturated branch (corresponding rotation periods shorter than about four days), the level of activity shows only little dependence on rotation.

In observations of solar active regions and some young stars, absolute X-ray luminosity has been found to be proportional to magnetic flux⁶ ($4\pi R^2 (B)$, where $R$ is the stellar radius and $(B)$ is the surface-averaged magnetic flux density). This correlation suggests that, as long as X-ray luminosity saturates in fast rotating stars, a similar saturation of the magnetic flux (and/or magnetic flux density) may also take place. A growing database of stellar magnetic field measurements has shown that the strength of the maximum possible surface magnetic field reaches around 3–4 kG in the coolest M-dwarf stars¹⁴,¹⁵. Mean fields stronger than this have not been detected in any low-mass star, which has been viewed as evidence for the magnetic field saturation¹⁶. It occurs for stars with rotational periods shorter than a few days, implying that the generation of magnetic flux itself does not grow beyond a level proportional to the bolometric luminosity, as supported by theoretical studies¹⁷. Strong kilogauss-level magnetic fields are equally found in stars with dipole and multipole states, suggesting that these stars may share a common mechanism of saturation.

Measurements of the magnetic fields in M dwarfs usually use either unpolarized light (Stokes I) or circularly polarized light (Stokes V). The important difference between the two is that Stokes V carries information about polarity and geometry of the magnetic field that is organized at large spatial scales on the stellar surface. However, Stokes V cannot see small-scale magnetic fields, because these fields have different polarities, and thus their contribution is cancelled out when the star is observed from a large distance as a point source. In contrast, both large- and small-scale fields contribute to the unpolarized Stokes I light. Thus, using Stokes I enables measurement of the strength of the total magnetic field¹⁸. However, all previous studies made use primarily of either Stokes I or Stokes V radiation without detailed analysis of the link between the two. For instance, it is known¹⁸ that measurements using Stokes V can miss up to 90% of the total magnetic flux density of the star, while for many stars with published Stokes V magnetic maps, only coarse measurements of the magnetic field strength from Stokes I are available.

The analysis of the magnetic fields has significantly improved over the past decade thanks to development of new methods and
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We report the strongest average magnetic field in four M dwarfs. We chose a sample of M dwarfs with known rotational periods and surface average magnetic field \( B_s \). Rotation periods are taken from works on magnetic mapping. The magnetic field was calculated from distributions of filling factors, and we show here only one chosen solution. In the case of WX UMa, we measured a clear splitting in atomic \( \text{Rb}^1 \) lines, and the separation of Zeeman components corresponds to a minimum magnetic field of \( \approx 6 \text{ kG} \). Employing different values of \( \log(g_i) \), and we measured values of \( T_{\text{eff}} \) and spectral lines result in magnetic fields between 7.0 kG and 7.5 kG.

Our analysis resulted in the detection of very strong magnetic fields in four M dwarfs. We report the strongest average magnetic field \( (B) \approx 7.0 \text{ kG} \) in the star WX Ursae Majoris (WX UMa; Gliese 412 B (GI 412 B)), a field of \( (B) \approx 6.0 \text{ kG} \) in stars Wolf 47 (GI 51) and UV Ceti (GI 65 B), and a field of about 5.0 kG in V374 Pegasi. Note that WX UMa is the only cool active star known to date where the Zeeman splitting in single atomic lines is clearly observed at optical wavelengths (Zeeman splitting at near-infrared wavelengths is easier to see, and therefore it has already been detected in some objects\(^{16,23}\)). Figure 1 demonstrates example fits to magnetically sensitive spectral lines in these and in three other magnetic M dwarfs that we have chosen for comparison. For WX UMa, we measured a minimum magnetic field of about 6 kG from Zeeman splitting in rubidium (\( \text{Rb}^1 \)) \( \lambda 794.76 \text{nm} \) and titanium (\( \text{Ti}^1 \)) \( \lambda 837.7 \text{nm} \) lines, and larger values when applying the radiative transfer model to fit full line profiles.

Figure 1 | Magnetic field diagnostics in selected M dwarfs. We show example fits to magnetically sensitive spectral lines of the FeH molecule (left column), \( \text{Rb}^1 \) \( \lambda 794.76 \text{nm} \) line (middle column) and \( \text{Ti}^1 \) \( \lambda 837.7 \text{nm} \) line (right column) in WX UMa and three other magnetic M dwarfs. The \( \gamma \) axis is the normalized flux. For better viewing, the flux of each star is shifted along the \( \gamma \) axis. Black symbols, observed spectra; red dashed line, predicted zero field model; red line, predicted best-fit magnetic model. The text on the left side lists for each star its name, spectral class, projected rotational velocity \( v \sin i \), rotational period and surface average magnetic field \( B_s \). Rotation periods are taken from works on magnetic mapping\(^1\). The magnetic field was calculated from distributions of filling factors \( \langle B \rangle = \sum B f_i \), (see Methods). Our measurements of \( \langle B \rangle \) may vary with assumed stellar parameters (for example, \( T_{\text{eff}} \) and \( \log(g_i) \)), and we show here only one chosen solution. In the case of WX UMa, a clear splitting is visible in atomic \( \text{Rb}^1 \) and \( \text{Ti}^1 \) lines, and the separation of Zeeman components corresponds to a minimum magnetic field of \( \approx 6 \text{ kG} \). Employing different values of \( T_{\text{eff}} \) and spectral lines result in magnetic fields between 7.0 kG and 7.5 kG.

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we also measured a very strong field, but high \( v \sin i \approx 11 \text{ km s}^{-1} \) makes it impossible to observe corresponding Zeeman splitting in this star (see Fig. 1). In our final measurements of magnetic fields, we used numerous lines of iron hydride (FeH) molecule at \( \lambda \lambda 990–995 \text{ nm (Wing–Ford } P^3 \Delta –X^3 \Delta \text{ transitions) and near-infrared Ti lines at } \lambda \lambda 960–980 \text{ nm. The details of our analysis are given in the Methods section. Thus, we report for the first time a definite detection of the magnetic fields in M dwarfs well beyond its recent maximum value of about 4 kG. Figure 2 demonstrates that new detections make a clear difference because they substantially extend the range of measured to-date magnetic fields in stars with saturated activity levels.

Our discovery allows us to draw several important conclusions. First we note that, according to published magnetic field maps, WX UMa and Wolf 47 belong to the dipole branch and show concentration of strong magnetic fields around rotation poles (so-called magnetic polar caps)\(^ {13} \). In contrast to this, none of the multipole stars with similar parameters and rotation rates exhibits a field stronger than \( B \approx 4 \text{ kG} \). Thus our analysis implies that stars with dipole states may generate stronger fields compared with stars with multipole states at the same rotation rate. This conclusion is in agreement with the predictions of bistable dynamo models\(^ {11,12} \).

Next, we emphasize that the magnetic field we derive in stars with a dipole-dominated geometry does not necessarily reflect the surface-averaged magnetic flux density. Indeed, because of geometric projection, we observed fields stronger than the surface average field in stars oriented to us with their magnetic poles, and weaker fields in stars that rotate equally fast but seem equator-on. From the magnetic maps corresponding to dynamo models\(^ {26} \), we estimate that WX UMa, with its 7.3 kG magnetic field and inclination of \( i = 40^\circ \), would show ‘only’ 6.4 kG should it have the inclination \( i = 60^\circ \), which matches well enough the field that we measured in, for example, Wolf 47, which has \( i = 60^\circ \) (ref. \(^ {11} \)). The magnetic flux density averaged over the whole stellar surface for WX UMa amounts now to 6.8 kG (against the measured 7.3 kG), which is still significantly higher than the maximum field strength in stars with a multipole regime. (See Supplementary Fig. 1 for visualization of the geometric effect.) Note that this geometric effect should be absent in stars with multipole fields because these fields are randomly distributed over the stellar surface without any preferred axis.
By analysing the dependence between the measured magnetic field and rotation period, we observed that the magnetic flux density in stars with dipole-dominated geometry still grows with rotation rate. In Fig. 3, we plot our magnetic field measurements for all M dwarfs with known magnetic geometries\textsuperscript{29-31}. We find the same trend of increasing magnetic field strength as rotation periods decrease to about four days (so-called unsaturated regime), as has been found in previous studies\textsuperscript{32}. However, we now show that magnetic fields in M dwarfs with a multipole dynamo state saturate below periods of about four days with the saturated magnetic flux density ($B$) $\approx$ 4 kG (corresponding Rossby number $Ro = \frac{Pr}{r_c} < 0.1$, where $P$ is the stellar rotation period and $r_c$ is the convective turn-over time; see Supplementary Fig. 2), while some stars with a dipole state exhibit surface fields unambiguously above 4 kG and demonstrate no obvious saturation effect. However, from our limited data set it remains unclear whether these stars saturate at faster rotation, or whether the saturation value for the magnetic field is only stronger in comparison to stars with a multipole state. Nevertheless, from this plot we can see that dynamo processes may behave differently with rotation rate in dipole and multipole branches. It is thus important to address this question with future observations in more detail.

An alternative explanation of the dichotomy in magnetic field geometries is to assume that M dwarfs can have magnetic cycles during which the magnetic field can change its geometry and strength over the cycle period. This would explain the difference in magnetic fields between individual objects. Note that the signs of activity cycles have been found in some M dwarfs based on photoelectric/photometric/spectroscopic observations\textsuperscript{33}, including a recent detection of a clear seven-year photometric cycle in fully convective and slowly rotating ($P \approx 83$ d) M-dwarf Proxima Centauri\textsuperscript{34}. By computing a model for this star it has been shown that the dynamo in fully convective M dwarfs can indeed generate magnetic cycles with repeated reversals of the magnetic polarities at different latitudes with time, provided that these stars rotate slowly enough to develop differential rotation in their convection zones\textsuperscript{35}. In contrast, the same model\textsuperscript{36} has shown that as rotation increases, the generated magnetic fields finally become strong enough to quench the differential rotation and thus the magnetic cycles are expected: once reached, a star never changes its dynamo state. This theoretical prediction is supported by Zeeman–Doppler imaging observations of fast rotating ($Ro < 0.1$) M dwarfs, though magnetic cycles could be as long as decades in these stars\textsuperscript{36}. Thus, to test which of the two scenarios (that is, bistable dynamo versus cyclic dynamo) is responsible for the observed magnetic properties of M dwarfs, long-term spectro-polarimetric monitoring is required.

**Methods**

**Details of theoretical modelling.** Our strategy to measure Zeeman splitting is to compare observed spectra to synthetic spectra computed with a polarized radiative transfer code that is based on the custom routine taken from the model atmosphere code LIMODES\textsuperscript{37} and extended by the complete treatment of polarized radiation in all four Stokes parameters\textsuperscript{38}. The radiative transfer equation is solved with the DELO (diagonal element lambda operator) method\textsuperscript{39,40}, which have proved their capabilities for accurate solution of the transfer equation.

In our equation of state, we include 99 atoms (from hydrogen to einsteinium) and 524 molecules. This results in a total of 930 individual plasma components (atoms, molecules and their ions). Most of the atomic partition functions are those provided by R. L. Kurucz\textsuperscript{41} (http://kurucz.harvard.edu). For molecules, we utilize partition functions and equilibrium constants available from the literature\textsuperscript{42-45}. Molecular data can be used in wide temperature ranges from 1,000 to 9,000 K, that is, suitable for conditions found in atmospheres of M dwarfs. The final system of linear equations is solved using LU factorization methods available from the LAPACK numerical library (http://www.netlib.org/lapack/). We tested solutions of our equation of state against those implemented in such codes as SYNTH\textsuperscript{46}, SSynth\textsuperscript{47} and SYN4D\textsuperscript{48} and found good agreement in the resulting number densities of the most abundant species. We treat pressure broadening by including contributions from hydrogen and helium atoms only. Normally, a contribution from the molecular hydrogen $H_2$ is also expected. However, similar to previous studies\textsuperscript{49}, we find that inclusion of $H_2$ overestimates the widths of line profiles in benchmark inactive M dwarfs. This problem is most prominent in strong alkali lines. It increases with decreasing temperature and starts to affect noticeably other atomic and molecular lines, too.

Another source of line broadening is the velocity field caused by convective motions. However, as shown by three-dimensional hydrodynamical simulations\textsuperscript{42}, the velocity fields in atmospheres of M dwarfs with temperatures $T_{\text{eff}} < 3,500$ K are well below 1 km s$^{-1}$. This only has a weak impact on line profiles, leaving on the Zeeman effect and rotation to be the dominating broadening mechanisms. Therefore we assumed zero micro- and macroturbulent velocities in all calculations.

**Representation of surface magnetic field.** Our analysis relies on unpolarized Stokes I spectra, which means that we can measure the surface-averaged magnetic flux density (or simply magnetic field strength) ($B$) from magnetically broadened lines, but we derive no information about field geometry. However, in the case of complex magnetic fields localized in spots, spot groups or active regions across the stellar surface, the mean magnetic field cannot be represented by a simple homogeneous magnetic field configuration. Instead, the best approximation is to assume that the total field is the weighted sum over different field components. ($B = \sum B_i f_i$, where $f_i$ are corresponding filling factors that represent the fraction of the stellar surface covered by the magnetic field of the strength $B_i$). We use 11 magnetic field components, and corresponding filling factors are normalized so that $\sum f_i = 1$. In the case of stars with large values of $\sin i$, individual features in line profiles caused by complex magnetic fields are usually not recoverable, and we speed up computations by assuming a two-component model: non-magnetic and with a filling factor $f$ so that the total magnetic field strength is ($B = B_f f$). In all computations we assume that the magnetic field is dominated by its radial component\textsuperscript{50}.

**Details of spectroscopic analysis.** To compute theoretical line profiles, we used MARCS (Model Atmospheres in Radiative and Convective Scheme) model atmospheres\textsuperscript{51}. The effective temperatures of M dwarfs are not accurately known, and different sources sometimes list noticeably different values. Therefore, we fit each star assuming two different temperatures. The first follows from spectral types employing dedicated calibrations\textsuperscript{52-54}. The spectral types were taken from previous works on magnetic field measurements\textsuperscript{13,29} and from the SIMBAD (Set of Identifications, Measurements and Bibliography for Astronomical Data) online service. In our second estimate of the $T_{\text{eff}}$, we used lines of titanium oxide (TiO) $\gamma$-bands classified from the Vienna Atomic Line Database (VALD)\textsuperscript{55} with transition parameters calculated by B. Plez (personal communication), version 7 March 2012, with wavelengths corrected using polynomial fits to laboratory wavelengths\textsuperscript{56-58}. Our temperature estimates from TiO lines are in agreement (within error bars) with alternative independent estimates\textsuperscript{59}. The other essential parameter—stellar gravity ($\log(g)$)—was calculated from the stellar radii and mass assuming $R \propto M^{0.5}$, which provides surface gravities close to those predicted by stellar evolution models\textsuperscript{60,61}.

To derive magnetic fields, we used two sets of spectral lines. The first set includes lines of FeH molecule. In particular, we used lines of the Wing–Ford $P' / \Delta - \chi'$ & transitions between $\lambda 890.0 - 990.4$ nm and $\lambda 993.8 - 996.0$ nm regions, respectively. These lines are particularly good indicators of magnetic fields in cool stars because of their high magnetic sensitivity\textsuperscript{62,63}. The transition parameters of FeH molecules were taken from our previous investigations\textsuperscript{64-66}.

It is known that the Zeeman splitting in FeH lines could not be accurately predicted by available theoretical descriptions\textsuperscript{67-69}, and alternative semi-empirical methods are used instead\textsuperscript{70-72}. Therefore, extending our analysis to atomic lines provides important independent constraints on the measured magnetic fields. Therefore, as the second set of magnetic field indicators, we chose to use TiI lines in the $\lambda 960-980$ nm region. These lines originate from the same multiplet, and thus their relative oscillator strengths are known with a high precision. Therefore it was enough to cross-check the oscillator strengths of a few of these lines visible in the spectrum of the Sun\textsuperscript{73} to make sure that we did not miss lines in our analysis. These TiI lines have very different magnetic sensitivity, with Landé $g$-factors ranging from 0 to 1.55, and different Zeeman patterns, which make them very good diagnostics of the magnetic fields. In addition, we analysed profiles of TiI $\lambda 837.7$ nm and RbI $\lambda 794.8$ nm lines that show a clear Zeeman splitting in WX Uma, but because of very strong blending by TiO molecule in this spectral region, we could not use these two lines for the final magnetic field measurements in all stars. Instead, we used RbI $\lambda 794.8$ nm and TiI $\lambda 837.7$ nm only in Fig. 1 for illustrative purpose only, that is, to highlight a very strong magnetic field in WX Uma. Transition parameters of all atomic lines were extracted from VALD.

When the $\sin i$ of a star is large, our measurements rely on the effect of magnetic intensification of spectral lines\textsuperscript{74}, which predicts that the depth of a magnetic sensitive line will be increased depending on its pattern. Of course, this technique is sensitive to fields that are strong enough to produce observable changes in the equivalent widths of lines (see, for example, Supplementary Fig. 9 for a clear example of magnetic intensification influencing the profiles of spectral lines). The TiI lines in the $\lambda 960-980$ nm region are therefore superior diagnostics of strong fields in fast rotating stars, and we successfully used their magnetic intensification in our analysis. The reason why these lines are normally
Determination of surface magnetic fields. We measured the average magnetic field for each of our sample stars by fitting synthetic spectra to the data as described above. We summarize our results in Supplementary Table 2 and show our best fit to the profiles of spectral lines in Supplementary Figs 4–22. Below we give detailed notes on our analysis.

Assuming two different temperatures from available photometric calibrations and from the fit to Τ10 γ-band, we can, in general, obtain similar magnetic field estimates from Ti and FeH lines for at least one of the two temperatures that we tried for each star. However, in some cases a cooler model would result in a weaker magnetic field when derived from FeH lines and at large 0 sin i values. This is simple to understand because at large 0 sin i we can measure only strong magnetic fields and only through the effect of magnetic intensification of spectral lines. When we decrease temperature, it makes FeH lines stronger, and because most of the FeH lines are very sensitive, it works just the same way as magnetic field intensification does. The code then tries to adjust the abundance of Fe to the level when a satisfactory fit is obtained for all FeH lines while keeping the magnetic field low. This degeneracy between temperature and abundance on the one hand and magnetic field on the other hand is partly broken for Ti lines because we have just a few lines, they are well separated from each other and one of these lines is completely insensitive to abundance. All this means that the desired physical parameters from Ti lines more accurately. In Gl 182, we measured a stronger field from FeH lines than from Ti lines, which is probably because of poor data quality in the region of FeH lines (see Supplementary Fig. 16).

For Gliese–Jahreiss 3622 (Gl 3622), we measured a magnetic field that is too weak for its rotation period of about 1.5 d (ref. 13). Together with another M dwarf, where the measured field seems to be inconsistent with its rotation period, Van Biesbroeck 10 (VB 10), the two lie considerably below the range of magnetic fields that we measured in other stars with saturated activity (see Fig. 3). We have no explanation why these stars have such weak fields. Note that our estimate of the magnetic field in Gl 3622 is consistent with previous studies21. One reason could be that rotation periods are not accurate: they were estimated from sparse Stokes V spectra for Gl 3622 and simply from stellar 0 sin i for VB 10, respectively. Thus, additional photometric monitoring is needed to confirm the periods.

In EQ Peg B we also measured the field at the boundary between dipole and multipole states (|B| > 4 kG), but the star has a short period and dipole-like magnetic field geometry that we would expect to see a field stronger than this. In contrast, in BL Cet we measured a field of ~4.5 kG, and its dynamo state is multipoles, so the star would be expected to have a field below 4 kG. We note again that for all stars with large 0 sin i our error bars are also large (±1 kG), so that these two cases do not contradict the overall picture. Note that the observations of EQ Peg B were carried out only during a short period of time in August 2006. Thus, it is still possible that these observations were done occasionally at times when the star’s global magnetic field had more simple geometry while the star itself is actually in a multipole dynamo state. It is thus important to monitor this star for a longer period of time to see any variations in its global magnetic field topology.

In WX UMa, we clearly observed Zeeman splitting in Rb λ794.9 nm and TiI 838.3 nm lines. From these observed splittings we measured a field of about 6 kG. However, this is probably the lower limit for the strength of the field because complex magnetic fields in M dwarfs tend to produce narrow line cores and wide wings of magnetically very sensitive spectral lines23,24. When we try to fit FeH lines with our method (that is, by applying magnetic filling factors as described above), we find solutions around 7.6 kG. Applying the same procedure to Ti lines leads to a fit with a field of about 9.0 kG for both temperatures that we tried. However, we observed that strong fields appear because our fitting algorithm tries to fit tiny details in line profiles by increasing the contribution from strong magnetic field components when the adjustment of other free parameters (for example, abundance) does not help. Although our combined spectrum of WX UMa has a very high signal-to-noise ratio of about 350 in the region of Ti lines, there are additional uncertainties that complicate the fit, for example, artefacts of telluric removal and poor understanding of background molecular absorption. All these may be why we find systematically higher fields from Ti lines than those we measured from FeH. Note that if we ignore this high-field component, we obtain a magnetic field of about 7.3 kG, which is consistent with measurements from FeH lines. We still cannot rule out that FeH lines interact with molecular hydrogen in WX UMa and its small 0 sin i make the fit more challenging than those of other stars. Indeed, as mentioned above, we did not encounter this problem in stars that rotate faster than WX UMa, and we can still measure consistent fields from Ti and FeH, respectively. Considering all the uncertainties in our modelling of this star, we have the most confidence in the results from FeH lines.

Mass dependence of stellar magnetic fields. Our measurements show that stars with simple magnetic field configurations can generate the strongest magnetic fields. However, these objects can have very different masses, from 0.1 M⊙ of WX UMa to the 0.28 M⊙ of V374 Peg. In Supplementary Fig. 2 we plot our magnetic field measurements as a function of Rossby number 0 = P/τ, where P is the rotation period and 0 is the convective turnover time. We computed turnover times using commonly adopted empirical calibrations5. The symbol size on this plot scales with stellar mass. As expected, there are no additional trends seen from this plot compared with those shown in refs 14 and 44. However, (M > 0.35 M⊙) and most of the other stars have fields of about a few kilogauss. This result is in agreement with previous works from the analysis of Stokes V6. Note that all stars where we measured strong fields belong to the saturated activity branch (that is, log Ro < −1) where the activity level is believed to be independent of Rossby number7,8.

Comparison with previous measurements. In this work, we used a method of filling factors to derive magnetic field strength from unpolarized light. Our measurements are in a good agreement with previously published results7 within commonly adopted error bars of about 1 kG9. However, for Gl 1245 B and DX Cancri (DX Cnc), our magnetic field measurements from FeH lines are about 1.7 kG larger than those quoted before10. The reason may be that here we use direct radiative transfer modelling against a template interpolation that was used before. It may also be that we underestimate pressure broadening of FeH lines, which leads to the higher fields especially at the coolest temperatures, which is expected. Indeed, by including broadening by molecular hydrogen, we can obtain noticeably lower fields of 3.1 kG for Gl 1245 B and 2.7 kG for DX Cnc, respectively. Note that these values are still about 1 kG stronger than previously estimated10. This discrepancy results from the difference in fitting methods used in both works. However, note that stars with large 0 sin i are still subject to large fitting uncertainties in both approaches. From the direct comparison of Zeeman-sensitive lines, we see that Gl 65 B clearly has a stronger field than Gl 65 A because both stars have close spectral types. Considering that the magnetic field in Gl 65 A has complex multipole geometry and that in Gl 65 B has more simple dipole-like geometry9, our magnetic measurements for these two stars agree with the rest of our conclusions.

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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Author contributions
D.S. contributed general scientific ideas and conclusions, carried out the processing, modelling and analysis of observed data. A.R. contributed general scientific ideas and conclusions. A.E. carried out modelling and analysis of observed data. L.M. carried out telluric correction on selected targets. R.Y. provided theoretical dynamo models and magnetic maps. J.M. provided and analysed additional Stokes V data on some ESPaDOnS targets. O.K. contributed to development of atomic line analysis methodology. All authors contributed to the text of the paper and discussed the results.

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