

EVIDENCE FOR DYNAMO BISTABILITY AMONG VERY LOW MASS STARS

J. Morin¹, X. Delfosse², J.-F. Donati³, E. Dormy⁴, T. Forveille², M. M. Jardine⁵, P. Petit³ and M. Schrunner⁴

Abstract. Dynamo action in fully convective stars is a debated issue that also questions our understanding of magnetic field generation in partly convective Sun-like stars. During the past few years, spectropolarimetric observations have demonstrated that fully convective objects are able to trigger strong large-scale and long-lived magnetic fields. We present here the first spectropolarimetric study of a sample of active late M dwarfs (M5-M8) carried out with ESPaDOnS@CFHT. It reveals the co-existence of two distinct types of magnetism among stars having similar masses and rotation rates. A possible explanation for this unexpected discovery is the existence of two dynamo branches in this parameter regime, we discuss here the possible identification with the weak *vs* strong field bistability predicted for the geodynamo.

Keywords: dynamo, stars: magnetic fields, stars: low-mass, planets and satellites: magnetic fields, techniques: spectropolarimetry

1 Introduction

In cool stars, which possess a convective envelope, magnetism is thought to be constantly regenerated against ohmic decay by dynamo effect. For Sun-like stars the interface layer between the inner radiative zone and the outer convective envelope is generally thought to play a major role in the dynamo processes (see e.g., Charbonneau 2010). Since fully-convective stars – either main sequence stars below $0.35 M_{\odot}$ (i.e. with spectral type later than $\sim M4$) or young T Tauri stars – do not possess such an interface layer, generation of magnetic field in their interiors is often thought to rely on a non-solar-type dynamo. However, the precise mechanism and the properties of the resulting magnetic have been a debated issue (Durney et al. 1993; Chabrier & Küker 2006; Dobler et al. 2006; Browning 2008).

Two main complementary approaches are successfully applied to study magnetic fields close to the fully-convective transition. On the one hand, by modelling Zeeman broadening of photospheric spectral lines it is possible to assess the magnetic field averaged over the visible stellar disc (e.g., Reiners & Basri 2006). This method is therefore able to probe magnetic fields regardless of their complexity but provides very little information about the field geometry. On the other hand, the Zeeman-Doppler imaging technique models the evolution of polarization in spectral lines during at least one rotation period in order to reconstruct a map of the large-scale component of the vector magnetic field on the stellar photosphere.

Spectropolarimetric studies of a sample of M0–M4 dwarfs, conducted with ESPaDOnS and NARVAL, have revealed for the first time a strong change in large-scale magnetic topologies occurring close to the fully-convective boundary. Stars more massive than $0.5 M_{\odot}$ exhibit large-scale fields of moderate intensity featuring a significant toroidal component and a strongly non-axisymmetric poloidal component, with evolution happening on a timescale of less than 1 yr (Donati et al. 2008, D08). For those in the range $0.25\text{--}0.50 M_{\odot}$ much stronger large-scale fields are observed, which are dominated by the axial dipolar component and show only very limited evolution over successive years (Morin et al. 2008a,b, M08a,b). Comparisons of these large-scale magnetic field

¹ Dublin Institute for Advanced Studies, School of Cosmic Physics, 31 Fitzwilliam Place, Dublin 2, Ireland

² Université. J. Fourier (Grenoble 1)/CNRS; Laboratoire d’Astrophysique de Grenoble (LAOG, UMR 5571); F-38041 Grenoble, France

³ IRAP-UMR 5277, CNRS & Univ de Toulouse, 14 av E Belin, F-31400

⁴ MAG (ENS/IPGP), LRA, Ecole Normale Supérieure, 24 Rue Lhomond, 75252 Paris Cedex 05, France

⁵ School of Physics and Astronomy, Univ. of St Andrews, St Andrews, Scotland KY16 9SS, UK

measurements with X-ray activity indices or with measurements of the total magnetic field (i.e. at all spatial scales) derived from the analysis of Zeeman broadening of FeH molecular lines, suggest that fully-convective stars are much more efficient at generating large-scale magnetic field than partly-convective ones (D08, Reiners & Basri 2009).

2 Surface magnetic fields of late M dwarfs

A sample of 11 active M dwarfs with masses significantly below the fully-convective boundary ($0.08 < M_{\star} < 0.21 M_{\odot}$ or spectral types M5–M8) has been observed with the ESPaDOnS spectropolarimeter (Morin et al. 2010, hereafter M10). Below $0.15 M_{\odot}$, we observe two radically different categories of large-scale magnetic fields: either a strong and steady almost dipolar field (hereafter SD, similar to stars in the range 0.15 – $0.5 M_{\odot}$); or a weaker multipolar, non-axisymmetric field configuration undergoing dramatic evolution on a timescale of at most 1 yr (hereafter WM). However the two groups of objects cannot be separated in a mass-rotation diagram, see Fig. 1. No object is observed to evolve from one type of magnetism to the other during the survey (some objects were observed for 4 years). In terms of large-scale magnetic field values, a gap exists between these two types of magnetism, with no object with $200 < B_V < 900 G$ in this mass range, see Fig. 3. Both stars hosting weak multipolar (WM) or strong dipolar (SD) fields have very strong total magnetic fields (2–4 kG). No systematic correlation is found between the type of large-scale magnetic topology and the total magnetic field B_I (see Fig. 2). Hence, the two different types of magnetic field configurations are only detected when considering the large-scale component (probed by spectropolarimetry, and which represents 15–30 % of the total flux in the SD regime, but only a few percent in the WM regime) and not the total magnetic flux derived from unpolarised spectroscopy. This unexpected observation may be explained in several different ways: for instance, another parameter than mass and rotation period (such as age) may be relevant, two dynamo modes may be possible or stars may switch between two states in this mass range, etc.

3 Weak and strong field dynamos: from the Earth to the stars

In this section we briefly detail one of the hypothesis that could explain the observation of two groups of late M dwarfs with very different magnetic properties: the fact that two different dynamo modes could genuinely operate in stars having very similar mass and rotation. We focus here on the weak *vs* strong field dynamo bistability, initially proposed for the geodynamo. The underlying idea is that both, magnetic fields and rotation, taken separately tend to inhibit convection, but that if both effects are combined the impeding influences of the Lorentz and of the Coriolis forces may be reduced, allowing convection to set on at lower Rayleigh number and to develop on larger length scales (Chandrasekhar 1961). This led Roberts (1978) to conjecture that in a rapidly rotating system, for magnetic fields stronger than a threshold value, the Lorentz force would enhance convection and hence dynamo action, resulting in a runaway growth of the magnetic field. The corresponding bifurcation diagram is depicted on Fig. 3. On the weak-field branch the Lorentz force is balanced by viscous or inertial terms in the momentum equation, this force balance requires small-spatial scales. On the strong field branch, however, the magnetic field strength is set by a balance between Lorentz and Coriolis forces, which requires larger spatial scales, this is the magnetostrophic regime. A similar bifurcation diagram, but based on the fact that magnetic buoyancy would be negligible close to the dynamo onset has been proposed for stars by Weiss & Tobias (2000).

We now briefly discuss the identification between WM (SD) magnetism and weak-field (strong-field) dynamo regime, the reader is referred to Morin et al. (2011) for a more detailed discussion. The usual control parameter in the weak *vs* strong field dynamo scenario described above is the Rayleigh number, which measures the energy input relative to forces opposing the motion. Mass can be used as a good proxy for the available energy flux in M dwarfs, Fig. 2 can therefore be interpreted as a bifurcation diagram for the amplitude of the large scale magnetic field versus a control parameter measuring the energy input. In order to compare the driving of convection with the impeding effect of rotation, we can use $M_{\star} \times P_{\text{rot}}^2$ as a rough proxy for the Rayleigh number (see Fig. 2) based on rotation rather than diffusivities (e.g., Christensen & Aubert 2006).

First, in the SD regime the magnetic field strength has to be compatible with a Lorentz–Coriolis force balance. We note that this balance is valid spatial large-scales for which the Coriolis term is predominant over inertial terms in the momentum equation, in qualitative agreement with the observation that only the large-scale component of the magnetic field exhibits a bimodal distribution. This magnetostrophic force balance roughly

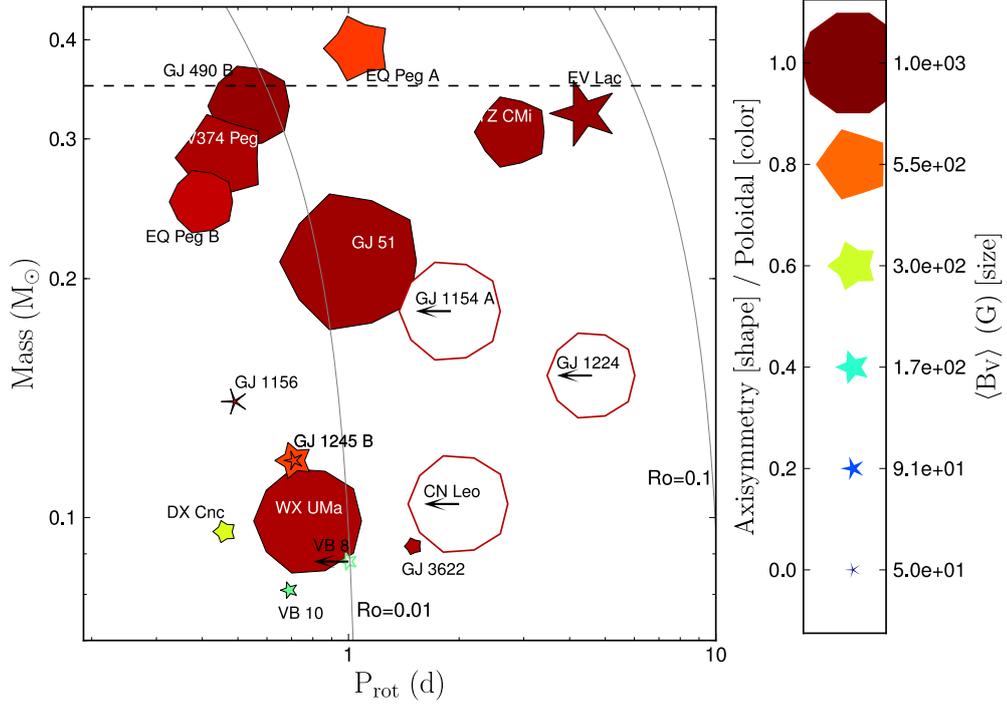


Fig. 1. Mass–period diagram of fully-convective stars derived from spectropolarimetric data and Zeeman-Doppler Imaging (ZDI). Symbol size represents the reconstructed magnetic energy, the color ranges from blue for a purely toroidal to red for a purely poloidal field, and the shape depicts the degree of axisymmetry from a sharp star for non-axisymmetric to a regular decagon for axisymmetric. For a few stars of the sample Morin et al. (2010) could not perform a definite ZDI reconstruction, in these cases only an upper limit of the rotation period is known and the magnetic flux is extrapolated, those objects are depicted as empty symbols. The theoretical fully-convective limit is depicted as a horizontal dashed line. Thin solid lines represent contours of constant Rossby number $Ro=0.01$ (left) and 0.1 (right), as estimated in Morin et al. (2010).

corresponds to an Elsasser number of order unity, i.e. :

$$\Lambda = \frac{B^2}{\rho\mu\eta\Omega} \sim 1, \quad (3.1)$$

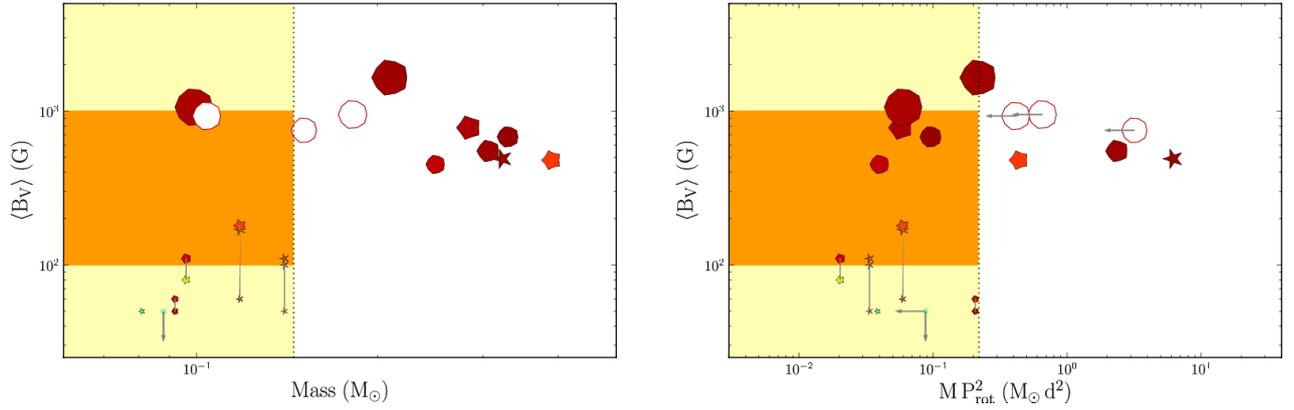


Fig. 2. Average large-scale magnetic fluxes of fully-convective stars derived from spectropolarimetric data and Zeeman-Doppler Imaging (ZDI), as a function of mass (**left panel**) and mass $\times P_{\text{rot}}^2$ (**right panel**). Symbols are similar to those used in the mass–period diagram (see Fig. 1). For stars in the WM regime symbols corresponding to different epochs for a given star are connected by a vertical grey line. The yellow region represents the domain where bistability is observed and the orange one separates the two types of magnetic fields identified (see text).

where B is the magnetic field strength, ρ the mass density, μ the magnetic permeability, η the magnetic diffusivity and Ω the rotation rate. With a few assumptions described in Morin et al. (2011), we find that the order of magnitude of the expected magnetic field strength on the strong field branch is set by:

$$B_{sf} \sim 6 \left(\frac{M_{\star}}{M_{\odot}} \right)^{1/2} \left(\frac{R_{\star}}{R_{\odot}} \right)^{-1} \left(\frac{L_{\star}}{L_{\odot}} \right)^{1/6} \left(\frac{\eta_{\odot}}{\eta_{\text{ref}}} \right)^{1/2} \left(\frac{P_{\text{rot}}}{1 \text{ d}} \right)^{-1/2} \text{ kG} \quad (3.2)$$

Where η_{\odot} is a reference value for the magnetic diffusivity in the solar convection zone, and $\eta_{\text{ref}} = 10^{11} \text{ cm}^2 \text{ s}^{-1}$. Taking stellar radius and luminosity for the stellar mass in the range $0.08 - 0.35 M_{\odot}$ from Chabrier & Baraffe (1997) main sequence models, and η_{\odot} in the range $10^{11} - 3 \times 10^{12} \text{ cm}^2 \text{ s}^{-1}$ (e.g., Rüdiger et al. 2011), we derive surface values in the strong field regime in the range 2–50 kG, compatible with the order of magnitude of measured B_V values. More conclusively, the gap in terms of B_V between the two branches depends on the ratio of inertia to Coriolis force in the momentum equation and can be estimated with:

$$\frac{B_{wf}}{B_{sf}} = Ro^{1/2}, \quad (3.3)$$

which is of the order of 10^{-1} for stars of our sample in the bistable domain, in good agreement with the typical ratio of large-scale magnetic fields measured between the WM and SD groups of stars (see Fig. 2).

We note that according to the Chabrier & Baraffe (1997) main sequence models, the product of the terms depending on stellar mass, radius and luminosity in the expression of B_{sf} is almost constant in the mid-to-late M dwarf regime. The expected magnetic field strength on the strong field branch hence almost scales with $\Omega^{1/2}$. This is not in contradiction with the fact all the stars in our sample belong to the so-called saturated regime of the rotation–activity relation. Indeed $B_{sf} \propto \Omega^{1/2}$ (derived from $\Lambda \sim 1$) should apply here to the large scale field alone, which is only a fraction of the total magnetic field of the stars (between 15 and 30 %). If a small scale dynamo operates, it does not need to follow the same dependency. Finally, the weak dependency of the large-scale magnetic field on stellar rotation predicted for stars in the strong-field regime cannot be ruled out by existing data and should be further investigated.

4 Conclusions

We present here the main results of the first spectropolarimetric analysis of a sample of active late M dwarfs (more thoroughly detailed in Morin et al. 2010). In particular we report the co-existence of two radically different types of magnetism – strong and steady dipolar field (SD) as opposed to weaker multipolar field evolving in time (WM) – for stars with very similar masses and rotation periods. One of the foreseen hypothesis to explain these observations is the genuine existence of two types of dynamo in this parameter regime, i.e. bistability.

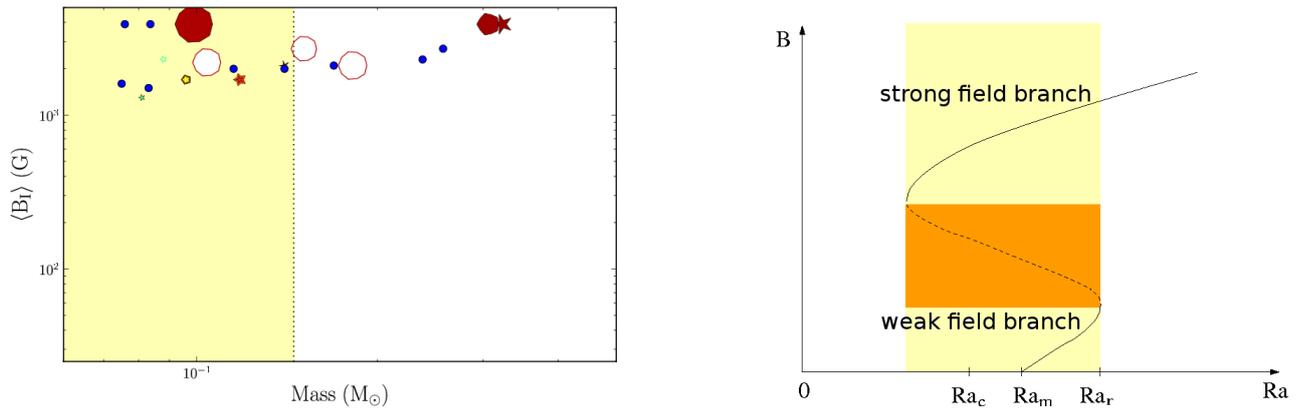


Fig. 3. Left: Total magnetic fluxes of fully-convective stars measured from unpolarised spectra of FeH lines. The values are taken from Reiners et al. (2009) and Reiners & Basri (2010), whenever 2MASS near infrared luminosities (Cutri et al. 2003) and Hipparcos parallaxes (ESA 1997) are available to compute the stellar mass from the Delfosse et al. (2000) mass–luminosity relation. Whenever spectropolarimetric data are available the properties of the magnetic topology are represented as symbols described in Fig. 2. Else small blue symbols are used, upward (downward) triangles represent lower (upper) limits. **Right:** Anticipated bifurcation diagram for the geodynamo (adapted from Roberts 1988). The magnetic field amplitude is plotted against the Rayleigh number. The bifurcation sequence is characterized by two branches, referred to as weak and strong field branches. The yellow and orange regions have the same meaning as in Fig. 2. Ra_c is the critical Rayleigh number for the onset of non-magnetic convection. The weak field regime sets in at Ra_m , and the turning point associated with the runaway growth corresponds to $Ra = Ra_r$.

We show that the weak *vs* strong field dynamo bistability is a promising framework. The order of magnitude of the observed magnetic field in stars hosting a strong dipolar field, and more conclusively the typical ratio of large-scale magnetic fields measured in the WM and SD groups of stars are compatible with theoretical expectations. We argue that the weak dependency of the magnetic field on stellar rotation predicted for stars in the strong-field regime cannot be ruled out by existing data and should be further investigated. We do not make any prediction on the extent of the bistable domain in terms of stellar parameters mass and rotation period, this issue shall be investigated by further theoretical work, and by surveys of activity and magnetism in the ultracool dwarf regime.

A dynamo bistability offers the possibility of hysteretic behavior. Hence the magnetic properties of a given object depend not only on its present stellar parameters but also on their past evolution. For instance, for young objects episodes of strong accretion can significantly modify their structure and hence the convective energy available to sustain dynamo action (Baraffe et al. 2009) initial differences in rotation periods of young stars could also play a role. Because stellar magnetic fields are central in most physical processes that control the evolution of mass and rotation of young stars (in particular accretion-ejections processes and star-disc coupling, e.g., Bouvier 2009; Gregory et al. 2010), the confirmation of stellar dynamo bistability could have a huge impact on our understanding of formation and evolution of low mass stars.

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