Magnetic fields in fully convective M-dwarfs: oscillatory dynamos vs bistability

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ABSTRACT

M-dwarfs demonstrate two types of activity: 1) strong (kilogauss) almost axisymmetric poloidal magnetic fields; and 2) considerably weaker nonaxisymmetric fields, sometimes including a substantial toroidal component. Dynamo bistability has been proposed as an explanation. However it is not straightforward to obtain such a bistability in dynamo models. On the other hand, the solar magnetic dipole at times of magnetic field inversion becomes transverse to the rotation axis, while the magnetic field becomes weaker at times far from that of inversion. Thus the Sun resembles a star with the second type of activity. We suggest that M-dwarfs can have magnetic cycles, and that M-dwarfs with the second type of activity can just be stars observed at times of magnetic field inversion. Then the relative number of M-dwarfs with the second type of activity can be used in the framework of this model to determine parameters of stellar convection near the surface.

1 INTRODUCTION

The efforts of many observing teams over several decades have provided rich data concerning magnetic activity in stars of various spectral classes. However in many cases the general form of the activity of stars of a given spectral class remains debatable. In particular, observations find two distinct magnetic topologies for M-dwarfs: 1) strong (kilogauss) almost axisymmetric poloidal magnetic fields, and 2) considerably weaker nonaxisymmetric fields, sometimes including a substantial toroidal component (Morin et al. 2010). Stars with different topologies can have roughly the same rotation rates, mass, and other parameters. This finding has been interpreted as dynamo bistability, i.e. as two different regimes of dynamo action being stable for the same set of stellar parameters (Morin et al. 2011a,b; Gastine et al. 2013). However, two stable regimes of a dynamo in the same parameter range seems not to be very probable (cf. e.g. Rädler et al. 1990; Moss & Sokoloff 2009).

On the other hand, Chabrier & Küker (2006) suggest that fully convective stars host a non-axisymmetric global dynamo (such a possibility was also suggested in a slightly different context by, e.g., Barker & Moss 1994). This dynamo is steady (equatorial dipole drifting in longitude) and therefore showing no reversals. This model relies on the observational fact (Barnes et al. 2005) supported by numerical simulations (Küker & Rüdiger 2005) that differential rotation in fully convective stars is very small. As a result Chabrier & Küker (2006) neglect differential rotation and considered an $a^2$ dynamo.

The efficiency of differential rotation in winding up magnetic fields can be estimated by the dimensionless dynamo number

$$C_\Omega = \frac{\Delta \Omega H^2}{\eta_\Omega}, \quad (1)$$

where $\Delta \Omega$ is the angular velocity variation within the convection zone, $H$ is the convection zone thickness and $\eta_\Omega$ is the eddy magnetic diffusivity. Differential rotation modelling suggests that the decrease in $\Delta \Omega$ with decreasing temperature can be compensated by a simultaneous decrease in $\eta_\Omega$, so that $C_\Omega$ actually increases in cooler stars (Kitchatinov & Olemskoy 2011; Kitchatinov 2013). This means that the M-dwarfs have small but very efficient differential rotation and it is quite probable that they host oscillatory, axisymmetric mean-field dynamos.

Taking all this into account, it seems reasonable to consider another possible explanation of the M-dwarf activity phenomenon. We suggest that magnetic cycles in the form of oscillatory axisymmetric fields are present within the population of M-dwarfs, and that the stars that are observed to have weak nonaxisymmetric fields are observed at epochs of reversal, with the strong axisymmetric dipoles being present at the analogues of solar maxima. There are strong observational indications for a difference in magnetic topologies between fully convective stars and stars with convective envelopes, with magnetic fields of fully convective stars being dominated by axisymmetric poloidal configurations (Gregory et al. 2012). Nevertheless, an analogy with the dynamics of the (rela-
tively weak) solar poloidal field is possible and can be useful. Note that the solar activity is determined mainly by the toroidal magnetic field. There is a time lag between the cyclic oscillations of toroidal and poloidal magnetic fields so that the solar magnetic dipole is strong during the minima of solar activity. A straightforward verification of this explanation could be performed by monitoring of a sample of M-dwarfs over times exceeding the expected period. Estimates in the next section suggest however that magnetic cycles in M-dwarfs can last for several decades. If M-dwarfs do have cycles, the cycles could therefore be substantially longer than that of the Sun, while at the moment only a 3-year monitoring (2006-2009) is available (Morin et al. 2010).

A straightforward objection to the last explanation could be that solar mean-field dynamo models driven by differential rotation and mirror-asymmetric turbulence ($\alpha\Omega$-dynamos) give axisymmetric mean magnetic fields, and the magnetic dipole has to vanish during its inversion, and be parallel to the rotation axis between its reversals. Recent progress in understanding solar observations and the solar dynamo (Moss et al. 2013a,b) have provided a new understanding of the reversals of the solar magnetic dipole. This allows us to elaborate the idea under discussion quantitatively, and to suggest a way to verify it that does not ultimately require a long-term monitoring programme (which of course still remains highly desirable).

2 OSCILLATORY DYNAMOS IN M-DWARFS

Taking into account the inherent uncertainties and arbitrariness of dynamo modelling for wide classes of stars, and that it is far from clear how generic any particular model (set-up, choice of parameters, etc.) can be, nevertheless we performed an exploratory modelling to establish the possibility of oscillatory dynamos existing in M-dwarfs, as follows.

We computed the differential rotation for a star with $M = 0.3M_\odot$, rotating with period of 10 days, using the numerical mean-field model of Kitchatinov & Olemskoy (2011). The result is shown in Fig. 1. Such a star is fully convective, but the model requires an (in this case artificial) inner boundary of the convection zone to be imposed at $r = 0.1R_{\text{star}}$. The model does not prescribe eddy transport coefficients but estimates them from the entropy gradient, so that the $C_\Omega$ parameter of Eq. (1) can also be estimated. Taking the turbulent Prandtl number,

$$P_m = v_t/\eta_t, \quad (2)$$

to have the value unity gives $C_\Omega = 290$, which is not small in spite of the small differential rotation in Fig. 1. The eddy viscosity $v_t \approx 1.2 \times 10^{11} \text{cm}^2\text{s}^{-1}$ used in this estimate is taken at the middle radius $r = R_{\text{star}}/2$ ($R_{\text{star}} = 212$ Mm). Thus the diffusive time is $\sim 100$ years. If the cycle time is close to the diffusion time, as it is for the Sun, very long cycles can be expected. The circulation time for the meridional flow is also long, $\sim 60$ yr (the typical flow velocity is 10 cm/s except in the thin surface boundary layer, where it is about 4 m/s). Thus the cycle time for an advection-dominated dynamo will also be long. We use these estimates to obtain the reference values for the dynamos governing parameters for M-dwarfs and experiment with numbers around these reference quantities.

Fig. 2 demonstrates the results for the simplest dynamo model with uniform diffusion, $\alpha = \alpha_0 \cos \theta$ uniform with radius and $\cos \theta$ dependence on co-latitude, isotropic diffusion and alpha. The model estimates the threshold value of the dimensionless parameter.

$$C_\Omega = \frac{\alpha_0 R_{\text{star}}}{\eta_t}, \quad (3)$$

for onset of dynamo together with the field structure and oscillation frequency. The eddy viscosity is estimated by the differential rotation code. We take the magnetic Prandtl number of Eq. (2) as a free parameter. We conclude from this limited modelling that an oscillatory dynamo model with solar type behaviour can be considered as a viable option at least at the present level of investigation. We stress that further modelling of dynamo action in M-dwarfs remains highly desirable.

The transition from steady to oscillatory dynamos with increasing $P_m$, seen in Fig. demonstrates the results for the simplest dynamo model with uniform diffusion, $\alpha = \alpha_0 \cos \theta$ uniform with radius and $\cos \theta$ dependence on co-latitude, isotropic diffusion and alpha. The model estimates the threshold value of the dimensionless parameter.

3 REVERSALS OF THE SOLAR DIPOLE AS A PARADIGM FOR REVERSALS IN M-DWARFS

We start by noting that many solar observers (e.g. Antonucci 1974; Zhukov & Veselovsky 2000; Livshits & Obridko 2006) have reported that the solar magnetic dipole does not vanish during the reversal. Recently De Rosa et al. (2012) presented a comprehensive data sample for the two last solar activity cycles which convincingly demonstrate that this is indeed the case.

Moss et al. (2013a) suggested how to resolve this apparent contradiction between expectations from dynamo modelling and observation. The point is that a mean-field dynamo model deals with mean magnetic field and the averaging is performed over an ensemble of convective velocity cells, while the observational mag-

\[ r = \frac{R}{2} \]

\[ \frac{1}{2} \]
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The temporal evolution of the axisymmetric solar magnetic dipole is approximately sinusoidal (Moss et al. 2013a), i.e. much simpler than the evolution of the mean sunspot number. Assuming that the same is valid for M-dwarfs, and taking into account Eq. (4) we can say what physical parameters are required, e.g. \( \delta n/N \), to get a satisfactory correspondence with the observational data. In particular, if we want to explain that about 30% of M-dwarfs demonstrate the second type of activity, we have to assume that the number of convective cells at the surface of M-dwarfs is about two order of magnitudes lower than near the surface of the Sun, i.e. \( 10^2 \) instead of \( 10^4 \). (Given the much greater relative depth of the convection zone in M-dwarfs compared to the Sun, an increase in the size of convection cells is not implausible.) Then, Eq. (4) reads that \( \delta d/d \) increases by factor 10 in comparison with the Sun and because the oscillations of the dipole strength are near to sinusoidal, the time at which fluctuations are weaker than the mean value of the dipole grows by a factor \( 10^2 \), and now becomes about 1/3 of the cycle duration. As a result, the relative number of M-dwarfs which demonstrate the second type of activity increases by a factor 10, giving 30%.

5 DISCUSSION AND CONCLUSIONS

We have suggested a scenario which explains why observations identify two types of magnetic activity in M-dwarfs. We propose that a M-dwarf can either be observed at a time far from that of magnetic field inversion (giving the first type of activity), or near the inversion (giving the second type).

A quantification of the scenario under discussion can be performed on the basis of Eq. (4) by determination of the percentage of M-dwarfs that demonstrate the second type of activity. We stress that such quantification does not require an effort-consuming long-term monitoring of M-dwarf activity. Of course, such a monitoring remains highly desirable for further understanding of stellar magnetic activity.

Even a crude estimate of the relative number of M-dwarfs with the second type of activity will provide in our framework a perspective for monitoring activity in M-dwarfs. If, say, this number were about 10%, then it would only be necessary to perform monitoring during 1/10 of a stellar cycle in order to observe a transition from one activity type to the other one in a given object. Another problem of interest would be to determine how this relative number varies between solar type stars and M-dwarfs. Indeed, any star with periodic dynamo driven large-scale fields might be expected to display similar behaviour, but whether this could be detected by current observational techniques is another matter.

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REFERENCES

Antonucci, E. 1974, SUIPR Rep. 570
Barker, D.M., Moss, D. 1994, A&A, 283, 1009
Barnes J. R., Collier Cameron A., Donati J.-F., James D. J., Marsden S. C., Petit P. 2005, MNRAS, 357, L1
Chabrier, G., Kükner, M. 2006, A&A, 446, 1027

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DeRosa, M.L., Brun, A.S., Hoekema, J.T. 2012, ApJ, 757, 96
Gastine, T., Morin, J., Duarte, L., Reiners, A., Christensen, U. R.,
Wicht, J. 2013, A&A, 549, L5
Gregory S.G., Donati J.-F., Morin J., Hussain G.A.J.,
Mayne N.J., Hillenbrand L.A., Jardine M. 2012, ApJ, 755, 97
Kitchatinov L.L. 2013, in Kosovichev A.G., de Gouveia Dal Pino E., Yan Y., eds., Proc. IAU Symp. 294, Solar and
Astrophysical Dynamos and Magnetic Activity. Cambridge Uni.
Press, p. 399
Kitchatinov, L.L., Olemskoy, S.V. 2011, MNRAS, 411, 1059
Küker M., Rüdiger G. 2005, AN, 326, 265
Livshits, I.M., Obridko, V.N. 2006, Astron. Rep., 50, 926
Morin, J., Donati, J.-F., Petit, P., Delfosse, X., Forveille, T., Jardine, M. M. 2010, MNRAS, 407, 2269
Morin, J., Delfosse, X., Donati, J.-F., Dormy, E., Forveille, T., Jardine, M. M., Petit, P., Schrinner, M. 2011a, In SF2A-2011: Proc. Ann. meeting French Soc. Astron. Astrophys., G. Alecian, K. Belkacem, R. Samadi & D. Valls-Gabaud (eds), 503.
Morin, J., Dormy, E., Schrinner, M., Donati, J.-F. 2011b, MNRAS, 418, L133
Moss, D., Sokoloff, D. 2009 A&A, 497, 829
Moss, D., Kitchatinov, L.L., Sokoloff, D. 2013a, A&A, 550, L9
Moss, D., Pipin, V., Sokoloff, D., Hoeksema, J. T. 2013b, astro-ph
1312.6379, 2013
Rädler K.-H., Wiedemann E., Brandenburg A., Meinel R., Tuominen I. 1990 A&A, 239, 413
Zhukov, A.N., Veselovsky, I.S. 2000, ESASP 463, 467

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