DYNAMO ACTION IN M-DWARFS

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\begin{abstract}
Magnetic activity in M-dwarfs present enigmatic questions: On the one hand they have higher field strengths and larger filling factors than the magnetic field on the Sun, on the other hand, they are fully convective and their atmospheres are more neutral, hence they do not have an undershoot layer for magnetic flux storage and as we show here, cannot have small-scale dynamo action in their photospheres either. We present a discussion of these facts and propose a new numerical model to investigate M-dwarf magnetism.

Key words: Stars: late-type, dwarfs, activity
\end{abstract}

1. Introduction

M-type dwarf stars display a high degree of magnetic activity. Both indirect tracers as X-ray and H\textalpha emission, as well as Zeeman broadening of magnetically sensitive photospheric lines has been observed (Johns-Krull & Valenti 1996, Kochukhov et al. 2001). The photospheric lines show no rotational modulation or net polarization, indicating that fields of small scale relative to the stellar radius exist on the surfaces of M-dwarfs. These fields can have strengths of a few kG and can cover a substantial area with filling factors up to 50%.

On the theoretical side of things, it has long been considered a problem that M-dwarfs are fully convective, lending no helping hand to the storage of magnetic flux through the presence of a stable stratified convective undershoot layer (e.g. van Ballegooijen 1982). Furthermore, as we show below (see also Dorch \& Ludwig 2002), it seems that their upper atmospheres are not capable of providing a small-scale network magnetic field, similar to that in the Sun, sometimes assumed to be stemming from local small-scale dynamo action in the photosphere (Cattaneo 1999). However, recent global scale simulations of M-dwarfs seem to render the storage problem obsolete (Dobler 2004), and in this contribution we propose future possibilities regarding numerical simulations of M-dwarf magnetic activity. First, however, we discuss results from models of M-dwarf local dynamo action.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Snapshot of the vertical component of the magnetic field at optical depth unity (contours), emergent intensity (grey tones), and the velocity field (arrows) towards the end of an evolutionary sequence of a model with $Rm=20$.}
\end{figure}

2. Local small-scale dynamo action

In order to study local small-scale dynamo action in the photosphere of M-dwarfs we adopted a velocity field from a radiation-hydrodynamics simulation of a prototypical M-dwarf atmosphere from Ludwig et al. (2002), see Fig. 1. Here $T_{\text{eff}}=2800$ K, $\log g = 5.0$ and the chemical composition is solar. Magnetic fields can potentially influence the flow structure significantly provided the field is strong. However, this corresponds to the full MHD case which is beyond the scope of this contribution. We selected a sequence which comprises roughly 10 convective turn-over time scales. The sequence consists of 150 snapshots of the flow field, each comprising $125 \times 125 \times 82$ grid points corresponding to $250 \times 250 \times 87$ km$^3$. At any instant in time about 10 granular cells were present in the computational domain, ensuring a statistically representative ensemble.

To compute the evolution of the magnetic field in responds to the adopted velocity field, we assume the kinematic regime of MHD, where one can neglect the back-
reaction of the magnetic field on the fluid motions. Then solving the MHD equations reduces to the problem of seeking the solution to the time-dependent induction equation:

\[ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}, \]  

where \( \mathbf{u} \) is the prescribed velocity field, \( \mathbf{B} \) the magnetic field, and \( \eta \) the magnetic diffusivity that we assume a spatially constant magnetic diffusivity that we vary by setting the magnetic Reynolds number \( R_m \) defined as \( R_m = U/\ell/\eta \) (where \( U \) is a characteristic velocity, \( \ell \) a characteristic length scale, and \( \eta \) the magnetic diffusivity).

We solve Eq. (1) using staggered variables on the grid of the hydrodynamical flow field. The numerical method was originally developed by Galsgaard and others (Galsgaard & Nordlund 1997) for general MHD purposes, but a special version is the code used by Archontis, Dorch, & Nordlund (2003) for studying dynamo action in prescribed flows. The kinematic approximation to the MHD equations becomes inaccurate when the magnetic field becomes sufficiently strong, limiting us to weak fields.

In the following we discuss kinematic MHD models with \( R_m \) as low as 20. In the astrophysical context, low values of \( R_m \) are uncommon, mostly due to the large spatial scales usually involved. However, in M-dwarf atmospheres we can be confronted with the situation of rather low \( R_m \) (Meyer & Meyer-Hofmeister 1999): Fig. 2 shows \( R_m \) in the M-dwarf model (\( \ell = 80 \) km, \( v = 0.16 \) km/s) as well as the Sun (\( \ell = 1500 \) km, \( v = 2.4 \) km/s). \( R_m \) primarily reflects the run of the electric conductivity in the atmosphere, which in turn is mostly controlled by the electron to gas pressure. The conductivity has been evaluated assuming a weakly ionized plasma.

At sufficiently cool temperatures \( R_m \) reaches order unity in the surface layers. This is a consequence of the declining electron density, the shrinking of spatial scales, and smaller convective velocities: This refers to the surface layers, but qualitatively we expect a strong increase of \( R_m \) with depth, and beyond a certain depth the regime \( R_m > 1 \) is reached again. However, gas motions in this depth will generally be slower and the tangling of magnetic field lines less rapid, which may reduce the efficiency of chromospheric and coronal heating. Whether this plays a rôle for the observed decline of stellar activity at the transition from M- to L-dwarfs (Gizis et al. 2000) is presently a matter of debate (Mohanty et al. 2002, Berger 2002).

A flow is a fast kinematic dynamo when the exponential growth rate \( \gamma \) is positive. That is, fast dynamo action requires a continuous increase of magnetic energy, even in the limit of vanishing diffusivity. This limit is relevant because most astrophysical systems have \( R_m \gg 1 \) and small but non-zero \( \eta \). It is believed that turbulent astrophysical systems are fast dynamos operating at \( R_m \gg 1 \). When \( R_m \) increases, the length scale of magnetic islands decreases and scales as \( R_m^{-1/2} \). There is a maximum value of \( R_m \), which can be achieved with our numerical resolution \( \Delta x = 2 \) km, and therefore the largest magnetic Reynolds number that we can allow is of the order of 400 corresponding to the Nyquist wavelength \( 2 \Delta x \). In the following, we concentrate on situations with \( R_m \leq 400 \).

In the absence of non-linear effects, in case of a dynamo, one expects a continuous exponential growth of magnetic energy \( E_M \). Figure 3 shows the result in terms of \( E_M(t) \) for five different models corresponding to varying \( R_m \): Most of the models in fact are dominated by decaying modes, with negative growth rates. In particular, the case with \( R_m = 20 \) is clearly an example of an anti-dynamo:

**Figure 2.** The magnetic Reynolds number as a function of Rosseland optical depth in a \( T_{\text{eff}} = 2800 \)K M-dwarf (solid line) and a solar model atmosphere (dashed line). Note the low magnetic Reynolds number in the M-dwarf model, primarily reflecting the low electric conductivity of the stellar gas in the rather cool M-dwarf atmosphere.

**Figure 3.** The total magnetic energy \( E_M/E_0 \) as a function of time in units of 150 seconds (the typical convective turn-over time). Five models are presented, with different amounts of diffusion: \( R_m = 800 \) (full), 400 (dotted), 200 (dashed), 100 (dashed dotted), and 20 (dashed triple dotted curve).
The diffusion works faster than the flows can sweep up the field and concentrate it in the inter-granular down-draft lanes, and the dominant magnetic mode is a decaying one. Increasing $R_m$ decreases $\gamma$, so that for $R_m = 200$ the decay time is 40 time longer than at $R_m = 20$. In terms of providing dynamo action, the most promising cases are those with lower diffusion and $R_m > 300–400$: At $R_m = 400$ a growing mode seems to be dominating.

In the high diffusion case the magnetic field varies smoothly across the domain, and its power peaks on scales approximately $\ell \approx 50$ km when considering $B_\gamma$ (see Fig. 4). At higher $R_m$ more small scales are generated mostly around the down-draft lanes.

3. Discussion and conclusion

Little is known about the structure of magnetic fields in the photospheres of M-dwarfs. From an observational point of view one would like to get some input from theory that would alleviate the problem of disentangling field strength and filling factor. To this end we started to investigate the kinematic effect of the convective velocity field on a magnetic seed field. This has become possible due to recent progress in the hydrodynamical modelling of atmospheres in the regime of cool M-dwarfs (Ludwig, Allard, & Hauschildt 2002).

We performed kinematic studies of the evolution of small-scale magnetic fields in the surface layers of M-dwarfs. We solved the induction equation for a prescribed velocity field, magnetic Reynolds number $R_m$, and boundary conditions in a Cartesian box, representing a volume comprising the optically thin stellar atmosphere and the uppermost part of the optically thick convective envelope. We find dynamo action for $R_m \geq 400$ and growth time scales of the magnetic field are comparable to the convective turn-over time scale ($\approx 150$ sec). The convective velocity field concentrates the magnetic field in sheets and tubular structures in the inter-granular down-flows. Perhaps surprisingly, $R_m$ is of order unity in the surface layers of cooler M-dwarfs, rendering the dynamo inoperative. In all studied cases we find a rather low spatial filling factor of the magnetic field.

- The geometry of small-scale magnetic fields looks similar to the situation for the Sun. The basic reason is that M-dwarf granulation is qualitatively similar to solar granulation.
- There are differences due to potentially quite different magnetic diffusivities.
- Depending on $R_m$, we get or do not get local dynamo action.

Future work along the lines of understanding M-dwarf magnetism will involve a more complicated treatment than that discussed above: It is our goal to combine both numerical theoretical modelling and detailed observations to begin to understand how M-dwarfs dynamos operate. We will use numerical models, such as the detailed radiative hydrodynamic models used here, together with detailed coronal models similar to those that have recently been successfully applied to the Sun (Gudiksen & Nordlund 2001). By constructing a model that connects the surface and subsurface magnetic field to the corona, it is our hope that the energetic events observed in the coronae of M-dwarfs will provide a link to understanding the dynamo. This goal will be achieved by employing a sequence from a radiative hydrodynamic model as a lower velocity boundary condition for a coronal model, yielding an output that can be compared directly to observations. The unknown magnetic surface topology enters as a “free parameter” as an initial lower boundary condition that is driven to reconnect by the braiding surface motions.

Acknowledgements

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