Magnetic Stars, 2011, pp. 81 – 85

Polar Branches of Activity Waves in HR 1099 and Stellar Dynamo Models

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Abstract. We discuss how the observational data for HR 1099 concerning poleward branches of stellar activity might be connected with the ideas from the stellar dynamo theory.

Key words: stellar activity – magnetic fields – dynamo theory

1 Introduction

It is widely accepted that the solar activity cycle is more than just a quasiperiodic variation of the number of sunspots, but it is rather an activity wave, propagating from the middle solar latitudes towards the solar equator. A solar dynamo based on the joint effects of differential rotation and mirror–asymmetric convective motions in the form of the so–called α–effect (and/or meridional circulation) is considered to be the underlying mechanism for the activity wave propagation.

Indeed, this mechanism gives an equatorward propagating wave of a large–scale magnetic field for a suitable choice of parameters governing the dynamo action. It is natural to expect that such a phenomenon appears in various stars with convective envelopes, and we might be led to expect equatorward waves of stellar activity. In fact cyclic activity is known now for many stars of various spectral types (e. g., Baliunas et al., 1995; Oláh et al., 2009). Clarification of the spatial configuration of the assumed activity wave is a much more delicate undertaking. However contemporary astronomy possess a range of tools, such as the technique of Doppler Imaging, with which the problem can be investigated. A comprehensive investigation of the problem still remains a desirable milestone for stellar astronomy. However, some early results are already available (e. g., Berdyugina & Henry, 2007; Katsova et al., 2010). The point here is that at least some stars demonstrate an activity wave that propagates polewards. For instance, the K–type subgiant component of the RS CVn system HR 1099 has been extensively studied through Doppler Imaging by Vogt et al. (1999) and shows migration of spots from mid–latitudes towards the rotation poles on a timescale of a few years. Indirect evidence of the same phenomenon is found for several late–type main–sequence stars and young solar analogues from the chromospheric line flux monitoring or photometric optical monitoring, respectively.

In the mean field dynamo models the direction of migration of large–scale magnetic field features depends in principle on two key factors — the signs of the α coefficient in the relevant hemisphere and the radial gradient of angular velocity. The situation is however not so straightforward. The point is that in addition to the equatorward branch demonstrated by sunspots, the solar activity displays a relatively weak poleward branch, seen in some other tracers, e. g., polar faculae (Makarov & Sivraman, 1989).

Here we investigate how the observational data for HR 1099 concerning poleward branches of stellar activity might be connected with the ideas from the stellar dynamo theory. We acknowledge that the observational situation after these pioneering results still remains quite uncertain, and hence study just the most traditional forms of stellar dynamos, i. e. the mean field dynamos based on differential rotation and α–effect with simple algebraic quenching. We appreciate that more recent ideas in solar dynamo theory, such as flux transport dynamos based on meridional circulation (e. g., Dikpati & Gilman, 2006) or the dynamical schemes of dynamo saturation (e.g., Kleeorin et al., 2003; Subramanian & Brandenburg, 2004) are likely to be important. We believe however that a simple initial approach is desirable and therefore we consider a classic dynamo wave model with a simple non–linearity as a basic model in our research.

2 Butterfly Diagrams and Poleward Activity Waves for HR 1099

Results obtained through Doppler Imaging applied to rapidly rotating late–type stars were listed by Strassmeier (2009). A necessary prerequisite for the application of such a technique is that the broadening of spectral lines has to be dominated by stellar rotation which limits the minimum projected rotational velocity of the star to about $v \sin i \simeq 20 - 25$ km/s for the subgiants in close active binaries, and to $v \sin i \simeq 10 - 15$ km/s for single main–sequence stars. Therefore, most of the Doppler Imaging results have been obtained for stars which are quite different from the Sun – either in their evolutionary stage or binarity, or in their rapid rotation. Stars more similar to the Sun, in both their evolutionary stage and rotational velocity have been extensively studied only through the long–term chromospheric monitoring or wide–band optical photometry. Extended Doppler Imaging studies of stars for which the long–term photometric monitoring is also available allow to check the assumptions, applied to derive spot migration from photometric modelling alone.

Specifically, among the RS CVn systems, the K–type component of HR 1099 has a long record of DI maps, spanning over a period of about twenty years and a simultaneous coverage in wide–band optical photometry. Berdyugina & Henry (2007), extending a previous work by Lanza et al. (2006), have analysed the long–term photometry of this system to build maps of the distribution of starspots versus longitude on the K–type subgiant, the light modulation of which dominates the optical flux variation of the system. Using the surface differential rotation law, measured by Petit et al. (2004), they were able to derive the latitude of each starspot from its angular velocity of rotation, thus building a butterfly diagram for the active component star extending over almost two activity cycles. Two main active regions were found in the star, one migrating from high–latitudes ($\approx 70^\circ$) towards mid–latitudes ($\approx 40^\circ$), and the other from mid–latitudes ($\approx 40^\circ$) towards high latitudes ($\approx 70^\circ$), occurring more–or–less simultaneously. A comparison with nearly simultaneous Doppler Imaging maps showed that the starspot latitudes estimated from the differential rotation law are in general agreement with those, given by Doppler Imaging maps, thus validating the approach applied to long–term photometry to derive stellar butterfly diagrams.

3 Activity Pattern of HR 1099 in the Light of Dynamo Theory

Now we address the problem from the other aspect and discuss how the poleward activity branches appear in the stellar (and solar) dynamo models. We give here a review of the results obtained for the most simple cases from the viewpoint of dynamo theory, i. e. standard mean–field dynamos.

We start from the traditional statement concerning the direction in which the stellar activity wave propagates in the dynamo theory. The conventional idea is that the cyclic stellar magnetic activity is driven by the action of differential rotation $d\Omega/dr$ together the with mirror–asymmetric convection, which results in the so–called α–effect (Parker, 1955). In the 1D Parker model the dynamo driving mechanisms can be parametrised by the single quantity $D \propto \alpha \, d\Omega/dr = \mathrm{const}$, and if $D<0$ in the Northern hemisphere, then the observed equatorward migration is obtained. If $D<0$ in the Northern hemisphere, then the activity wave propagates poleward. The sign of the product $\alpha\, d\Omega/dr$ must somehow be reversed to produce a poleward activity wave driven by a stellar dynamo.

We will see that this simple scheme explains the direction of the activity wave propagation in a crude approximation. However, in 2D models (with quantities depending on polar coordinates (r,θ)) the rotation law $\Omega=\Omega(r,\theta)$ is more complex, and detailed variations, as well as the choice of $\alpha(r,\theta)$ can affect the details of results. Deviations from axisymmetry and/or more sophisticated dynamo models are likely to further complicate the situation.

Different physical mechanisms can co–operate to produce the α–effect. Hence, the level up to which its radial and latitudinal distributions are known theoretically or observationally (e.g., Zhang et al., 2010) remains quite preliminary, and thus we adopt here simple parametrisations only. Speaking in general, we explore a number of options to investigate the sensitivity of butterfly diagrams to the underlying assumptions.

If there is a simultaneous migration PW and EW through the same latitudes, then it is hard to see how any simple mean field model can reproduce it. Of course, if we really have discrete spots that migrate PW and EW, then they can (at least in principle) maintain their identities, and the waves can perhaps pass through one another with little interference — however, a description of such a phenomenon would be beyond simple dynamo models. This is why we accept below that two oppositely propagating activity patterns belong to different spatial volumes.

We checked that the desired configuration is absent in the simple models with solar–like or quasi–cylindrical rotation laws and try to find how to adopt the dynamo governing parameters to fit the case of HR 1099. The first idea is to add a meridional circulation to the simplest 2D dynamo model based on differential rotation and α–effect. Indeed, models with solar–type rotation (for an appropriate choice of parameters) show a hint of the desired behaviour in the butterfly diagram.

Note however that HR 1099 is a quite rapid rotator so the solar–like rotation law might not be an adequate model for its rotation. However, we failed to reproduce the desired butterfly diagrams with a quasi–cylindrical rotation law, at least without sign changes in α. Nevertheless, it looks plausible that the HR 1099 rotation law is something between the solar–like and quasi–cylindrical rotation curves. Hence, we tried to use a synthetic rotation curve mixing both of these curves with the ratios of about 50%. Using this $\Omega(r,\theta)$, we obtained butterfly diagrams for B_ϕ in both deep and shallow parts of the convective zone that broadly resemble that, inferred for HR 1099, even without meridional circulation. By themselves, neither the solar–like, nor the quasi–cylindrical curve have revealed such a behaviour.

We do not consider the above results as completely successful because the activity belts migrate from high and low latitudes towards an intermediate latitude, whereas in HR 1099 there are different spots, migrating simultaneously from an intermediate latitude towards a high latitude, and from a high latitude towards an intermediate latitude.

A more optimistic result can be obtained exploiting an α profile which changes sign with depth, producing clearly opposed waves near the top and bottom of the convective zones. This agrees with the results of Moss & Sokoloff (2007) concerning the dynamo waves propagating in two separate layers, what allows the behaviour, required for a proper choice of R_α in both layers. A separation of the layers presumed by Moss & Sokoloff (2007) artificially can be achieved here by exploiting the depth of the convective zone. Of course, this scenario assumes that both deep and surface activity somehow jointly contribute in the surface activity manifestations.

Note that Berdyugina & Henry (2007) stress the nonaxisymmetric behaviour of this star, whereas we restrict ourselves to axisymmetric models. We fully realize that departures from axisymmetry may play a role in the phenomena revealed by HR 1099, and seem essential to explain the "flip–flop" phenomenon. However, nonaxisymmetric dynamo models contain many additional uncertainties and the main features of the observations seem to be reproduced by a simpler model.

(Correspondingly, studies of the solar butterfly diagram proceed without including active longitudes.)

4 Discussion and Conclusions

Our general conclusion is that the recent progress in stellar activity observations opens new perspectives for our understanding of stellar dynamos. Apart from basically solar–like activity patterns, observers have obtained some more or less definite knowledge about the well defined activity patterns that propagate polewards.

We confirm that the sign of $D \sim \alpha\, \partial\Omega/\partial r$ is the main quantity which determines the direction of activity wave propagation.

An unexpected conclusion is that the observations hint at the fact that one hemisphere of a star can contain two oppositely propagating activity waves, which are pronounced enough to be observable. We mentioned that an additional poleward activity wave is known for the Sun (Makarov & Sivraman, 1989). However, such a weak phenomenon can hardly be expected to be detectable in stellar data. We conclude that at least for some stars rotation curves and spatial distribution of the other dynamo governing quantities should produce two activity patterns in a hemisphere, of more or less comparable intensity. We have demonstrated that dynamo models can provide such solutions, but it requires some careful choice of stellar hydrodynamics.

An important point is that the behaviour of HR 1099 cannot be explained by a simple one–layer model and addition of a meridional circulation does not change the result in any significant way. Quite restrictive suggestions about the rotation law are required to get something resembling the observations.

On the other hand, a two–layer model, such as that introduced by Moss & Sokoloff (2007) can explain the behaviour of HR 1099 if the two spots migrating in opposite directions are the result of magnetic flux tubes, originating in the upper and deeper dynamo layers, respectively. However, this interpretation requires a significant modification of the paradigm used for the main–sequence stars. In other words, while for main–sequence stars we use a single–layer dynamo and assume that the observed spots correspond to the field at the upper boundary of the dynamo domain, for the subgiant in HR 1099 (and **so** for subgiant stars in general) we must assume the presence of two dynamo layers separated by an inactive shell, with both layers contributing to the observed spots at the surface.

On the other hand, the main difference between the subgiant in HR 1099 and the main–sequence stars is the depth of the convection zone, so we may tentatively assume that the depth of the convection zone makes the dynamo structure different, i. e. with one or two layers.

Note that the convection zone of the active component of HR 1099 is so deep that its base is below the radius, where magnetic tension becomes equal to the magnetic buoyancy force in the case of a isothermal magnetic flux tube. Hence, the conventional magnetic buoyancy instability is not expected to occur close to the base of its convection zone. A different instability could be invoked to produce a destabilisation of the field when it exceeds some threshold there, similarly to the Tayler (1973) instability in the solar radiative zone. Therefore, it could well be that the α–effect is also different in such stars, if magnetic field instabilities play a role in producing the α–effect.

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