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Theoretical Models of Stellar Activity Cycles

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Abstract. We discuss possible mechanisms underlying the observed features of stellar activity cycles, such as multiple periodicities in very active stars, non-cyclic activity observed in moderately active stars, and spatial distribution of stellar magnetic regions. We review selected attempts to model the dependence of stellar activity cycles on stellar properties, and their comparison with observations. We suggest that combined effects of dynamo action, flux emergence and surface flux transport have substantial effects on the long-term manifestations of stellar magnetism.

Keywords. stars: activity, stars: late-type, stars: magnetic fields

1. Modelling stellar magnetic cycles

Cool stars with convective envelopes exhibit long-term photometric and spectroscopic variations, which indicate long-term changes of surface magnetic flux. Many stars show single or multiple cycles with some irregularities, while others are characterised by relatively unchanging total radiative flux, hence they are called *flat activity stars*. Whether these stars represent grand minimum states is not yet certain.

The current paradigm concerning the physics of activity cycles in cool stars is based on solar dynamo models, which incorporate the generation and transport of magnetic flux within the convection zone. There are several unknowns regarding rapidly rotating cool stars, in particular the internal rotation, flows, magnetic field geometry, and their complex interplay. Therefore it is probably more appropriate to extrapolate the solar paradigm *gradually* towards faster rotating Sun-like stars or to cooler dwarfs. We expect the dynamo strength to increase with decreasing Rossby number, in parallel with the empirical rotation-activity relation. Simple mean-field dynamo models suggest that the cycle period decreases as the dynamo number increases. However, recent flux transport dynamo models by Jouve., *et al.* (2010) have shown that, to match the observed dependence, meridional flow should either increase its strength with the rotation rate (hereafter Ω), which is incompatible with 3D full-sphere simulations, or have preferred patterns which are difficult to justify. As an alternative explanation for the observed relation, Do Cao & Brun (2011) have shown that turbulent pumping of magnetic flux throughout the convection zone can decrease the cycle period with increasing Ω and decreasing meridional flow speed. However, it should be noted that recent mean-field models of differential rotation indicate an increase of meridional flow speed with Ω (Kitchatinov & Olemskoy 2012). Magnetoconvection simulations in 3D of the entire stellar convection zone have been presented by Brown *et al.* (2011), who demonstrated self-organisation of large-scale toroidal magnetic structures in the midst of the convection zone of a Sun-like star. These structures turn out to be anti-symmetric around the equator, stationary for $3\Omega_{\odot}$, and exhibit occasional polarity reversals for $5\Omega_{\odot}$.

We have recently presented numerical simulations combining generation, buoyant rise, and surface transport of magnetic flux in various cool star convection zone configurations (Işık *et al.* 2011). Our composite models are based on a mean-field overshoot dynamo, the period of which decreases with Ω. With increasing Ω the latitudinal distribution of the emerging flux at the surface deviates significantly from that of the dynamo waves at the base of the convection zone, owing to a poleward deflection of rising flux tubes.

When the rotation period is 9 days for a Sun-like star, our models indicate that the periodic dynamo in the deep convection zone can lead to a non-cyclic surface activity. The existence of such moderately active but non-cycling stars were reported by Hall & Lockwood (2004). A similar situation can occur for coronal X-ray cycles in some cool stars: McIvor *et al.* (2006) have shown that sufficiently overlapping magnetic cycles in the surface activity can lead to the absence of X-ray cycles.

Considering mean-field dynamo models, Moss., *et al.* (2011) have suggested that the dynamo must be operating in two distinct layers within the convection zone, to explain the observed poleward moving starspots in the K1-subgiant component of HR 1099. Our simulations of a K1-type subgiant star with Ω and surface shear adopted from HR 1099 have demonstrated that a deep-seated stellar dynamo with a well-defined period and amplitude can co-exist with fluctuating cycles of surface magnetic flux (Işık *et al.* 2011). Further analysis indicates that the short-period cycle at the surface results from the underlying dynamo, while the long-period cycle signal is caused by stochastic emergence of bipolar regions at very high latitudes, where the effects of surface transport are relatively weak (Işık 2012). This can be an explanation for the long-term 'cycle' in HR 1099 reported by Oláh., *et al.* (2009).

2. Open problems and outlook

It is clear that we still lack a rigorous physical understanding of the relations between the emerging flux, rotation rate, convection zone structure, and cycle properties of cool stars (Rempel 2008). How does the link between a tachocline dynamo and surface transport change with rotation rate and convection zone structure, as we depart from solar parameters? How do turbulent transport properties change with Ω? How does the dynamical disconnection of rising magnetic flux tubes vary with stellar parameters?

Such problems will remain as challenges in the future, but observations will reduce the theoretical degrees of freedom. The recent successes of the Babcock-Leighton type solar dynamo models in explaining various aspects of solar magnetism is encouraging for stellar modelling. Based on our recent models, we conclude that the combined effects of flux generation, emergence and transport should be considered in models of stellar magnetic fields, because their interrelations are sensitive to changes in stellar parameters.

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