

Magnetic Fields in Cool Stars

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Abstract. A number of recent results and open problems concerning magnetic fields in cool stars were presented by the three authors of the present contribution for general discussion with the audience. Although no report can be given of the lively discussion that took place, the main points proposed by the authors are summarized in the following.

1. Introduction

The topic of this discussion session has experienced remarkable progress in the past decade. New measurement techniques, installation of larger and improved telescopes and better detectors, space missions, order-of-magnitude advances in computation, etc, have allowed an impressive step forward in our knowledge both of solar and stellar magnetic fields. For this discussion, we chose three topics, namely

- the subsurface origin of active regions,
- the link between solar and stellar magnetism,
- magnetic fields on stars.

Each of the authors of this contribution addressed one of the previous topics, and presented recent results and open questions about them. In all cases, an open (and lively!) debate ensued. In the various sections that follow, summaries of the presentations are given.

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2. The origin of magnetic activity in the interior of cool stars

(F. Moreno-Insertis)

The key to the 22-year solar magnetic activity cycle lies buried in the solar interior. There may be generation of magnetic field at different levels in the convection zone, perhaps via different dynamo mechanisms depending on the nature of the local convective flows (in particular, on their Rayleigh and Reynolds numbers, timescales and influence of rotation, etc). Yet, there is general agreement that the field that appears at the surface in the form of large bipolar active regions is generated via a dynamo mechanism at the bottom of the convection zone, where there is both a high shear in differential rotation (specially in the region known as the *tachocline*) as well as a stably stratified overshoot region. The latter, in particular, may provide for the possibility of storage of the generated magnetic flux along each individual activity half-cycle.

2.1. Emergence of magnetic flux across the convection zone: sunspots and starspots

A standard active region results from the rise across the convection zone of a magnetic rope. The research into this process (e.g. Moreno-Insertis 1986, 1992; Choudhuri 1989; D'Silva & Choudhuri 1993; Moreno-Insertis et al 1994; Fan et al 1994; Caligari et al 1995) centered around two general (and closely linked) questions, namely, first, the evolution of the magnetic ropes before they reach the stellar photosphere and, second, whether one can relate the observed distribution and properties of the active regions to the structure and properties of the field in the convection zone and overshoot region. Explanations have been given for a number of observational features of the active regions in the Sun, most of them on the basis of the action of the Coriolis force on the rising ropes. Among the latter we find the latitude of appearance of active regions in the activity belt instead of close to the poles (Choudhuri & Gilman 1987; Schüssler et al 1994), the average tilt angle of the active region's main axis with respect to the equator (D'Silva and Choudhuri 1993; Fan et al 1994; Schüssler et al 1994; Caligari et al 1995; Fisher et al 1995; Longcope and Fisher 1996), and a number of morphological and kinematic asymmetries between the preceding and follower polarities of the active region (Moreno-Insertis et al 1994).

Magnetic buoyancy is the central mechanism for the rise of magnetic ropes, even though the rise is likely to be started by the Parker (or undulatory) instability, in which magnetic buoyancy acts alongside the magnetic tension and rotational forces (for a recent study of the initial state of the tubes see Caligari et al 1998). Once the tube is rising, the Coriolis force and the strong stratification of the convection zone may play important roles in determining the trajectory, the field intensity and, hence, the shape of the magnetic tube. In the Sun, the fact that active regions appear at low latitudes imposes an upper bound on the risetime: if the latter were comparable to the solar rotation period, the Coriolis force could impose a trajectory parallel to the solar rotation axis, against the observations (Choudhuri & Gilman 1987). In turn, this implies that the field strength of the unstable tubes at the bottom of the convection zone must be above some 10^5 G. Another way to come to this result is through the strong stratification of the convection zone, specially its uppermost layers (Moreno-

Insertis 1992): the rising tubes suffer an enormous expansion (at least a few orders of magnitude in density) and a consequent weakening of their magnetic intensity. If the initial field at the bottom of the convection zone were below 10^5 G, then the top of the rising tube would reach the uppermost convection zone with extremely weak field values, again against the observation of emerging active regions.

The results mentioned in the previous paragraph were obtained by simplifying the magnetic structures as one-dimensional continua moving in two- or three-dimensional surroundings (Spruit 1979), and then solving the corresponding equations with a computer code (Moreno-Insertis 1986). This technique has more recently been applied also to the calculations of the rise of magnetic tubes in stars in different regions of the HR diagram (Schüssler et al 1996; Granzer et al 2000). The condition that the stars must have a convective envelope imposes strict limits to the range of mass and/or evolutionary stage to consider. As a result of their calculations those authors obtained:

- high latitude spots in fast rotators, as predicted by Schüssler and Solanki (1992), on the basis of the results of Choudhuri and Gilman (1987),
- bimodal starspot distributions for very young stars,
- unimodal latitudinal ranges of appearance of spots for ZAMS stars and pre-main sequence stars.

The increasingly detailed mapping of the stellar surfaces achieved using Doppler imaging may eventually lead to the confirmation of these results. This may provide both an alternative test to the stellar interior models as well as further hints for the working of the stellar dynamo.

Some open questions

- **The internal structure of the rising magnetic tubes and surrounding flows.** The calculations mentioned above disregard the internal structure of the magnetic tubes (in particular, the field distribution on the cross section of the tube) as well as the role of the surrounding flows ensuing from its motion. Both features are fundamental to understand the time evolution of the magnetic ropes. There are already a number of two- and three-dimensional calculations which study in detail the field distribution and other physical quantities within and around the tube, but still many questions remain (see Sect. 2.2.). Perhaps the greatest difficulty is posed by the fact that the flow surrounding the actual rising tubes in stars has an extremely large Reynolds number whereas today's 2D and 3D computer codes only reach up to $Re \approx 10^3$ at best.
- **The distribution and average intensity of the magnetic field in the deep convection zone.** In spite of the recent substantial avances in understanding the differential rotation in the solar interior and the process of emergence of the magnetic field toward the solar surface, there is no

general picture of the distribution and structure of the magnetic field in the convection zone and the dynamo mechanism that sustains it and leads to the activity cycle.

- **The final stages of the rise of a magnetic rope through the convection zone.** This is a very fast phase of the rise in which the magnetic tube is far away from equilibrium and subject to extreme expansion. Additionally, once at the surface, radiative cooling quickly changes the entropy of the magnetized matter. Finally, the magnetic ropes interact with the surface convection cells (granules and supergranules). All these processes are difficult to model and calculate using computer codes.
- Can the variety of stellar cycles and starspot distributions in cool stars be explained on the basis of magnetic flux ropes which become unstable in the lower part of their convective envelope and rise to the photosphere?

2.2. The internal structure of the magnetic tubes and the surrounding flows, non-vanishing helicity and kink instabilities

In the past few years, much research has been devoted to phenomena having to do with the helical structure of the field in the magnetic tube, and, more generally, with the two- and three-dimensional structure and instabilities of the rising tubes. This research has been triggered by a number of observational and theoretical results. Some of them are summarized in the following, alongside further recent results of multidimensional simulations.

- **Vector magnetograph observations.** The observation of active region fields using Stokes polarimetry has provided evidence of non-vanishing helicity in the rising magnetic ropes breaking out at the surface (see, e.g., Leka et al 1996; Pevtsov et al 1995). More precisely, the following quantity

$$\alpha_{obs} = \frac{|(\nabla \times \vec{B})_z|}{|B_z|} \neq 0$$

is observed to have a non-vanishing value in the active region fields. In fact

- the average $\langle \alpha_{obs} \rangle$ is seen to have opposite sign in the northern and southern hemisphere (Pevtsov 1995)
- Vector magnetographs of growing bipoles in a given active region analyzed by Leka et al (1996) yielded a non-zero value of α_{obs} , namely $-0.8 \text{Mm}^{-1} < \alpha_{obs} < -0.2 \text{Mm}^{-1}$. Moreover, the potential field extrapolation of the surface fields to higher levels does not fit with H α and X-Ray images of the overlying field. Additionally, the proper motions of the bipoles were indicative of the evolution of a kinked rope

A general conclusion from all the foregoing is that *the magnetic flux bundles that reach the surface are twisted before they emerge*. This may be the consequence of the interaction of the convective zone flows with the rising

tubes (Longcope et al 1998). The flux tubes may also have a non-zero twist from the initial stages of the rise in the deep convection zone, as explained in the following.

- **Need for a non-zero twist for the rising magnetic tubes**

The rising magnetic ropes have to have a minimum amount of twist around their central axis for them not to lose their unity along the rise: below that minimum, the rising ropes just produce vortex tube pairs whose behavior is dominated by aerodynamic lift forces (Longcope et al 1996; Moreno-Insertis & Emonet 1996). This can be seen as follows: as the tube rises, a trailing wake is formed consisting of two vortex rolls rotating in opposite directions, very much like the wake behind a rigid cylinder moving in a fluid. Magnetic flux is dragged along the sides of the magnetic tube toward the wake by the surrounding flow. If the tube is sufficiently twisted, the transverse field component (i.e., the field component on the plane perpendicular to the tube axis) can resist the action of the surrounding flows: a *magnetic core* is formed in the tube interior into which the external flows cannot penetrate. The magnetic flux outside this *core* is swept to the wake. If the twist is below a threshold, namely if

$$\left| \frac{B_{trans}}{B_{long}} \right| \lesssim \left(\frac{R}{H_p} \right)^{1/2}$$

where R is the tube radius and H_p the ambient pressure scaleheight, then almost all the magnetic flux of the tube is carried to the wake. The rising tube thus turns into two vortex rolls, whose further evolution is dominated by the lift force. For a typical tube in the deep convection zone, the threshold angle of twist is between 5 and 10 degrees.

Open question is, of course, the formation of magnetic tubes with this degree of twist. Cattaneo et al (1990) have shown that twisted tubes can result from the fragmentation of a buoyantly-unstable magnetic layer if the latter has a horizontal flux vector pointing in a direction which rotates as one goes from top to bottom of the layer. Further mechanisms of twist have been discussed by Moreno-Insertis (1997).

- **Deviation of the rise from a vertical plane: wake instabilities and kink instability**

In recent years a number of further phenomena related with the two- or three-dimensional structure of the tube have been studied with the help of large MHD codes. For instance, the dynamics of the wake behind a rising tube can lead to the sideways motion of the latter away from a vertical plane. This has been shown by Emonet et al (2001) to be a consequence of the formation of a Von Karman vortex street behind the tube as a result of the development of a wake instability at sufficiently high Reynolds number ($Re \gtrsim 100$). The alternating loss of a vortex roll from the wake leads to a lift force acting sideways and to a zig-zag path for the rising tube. Open question is the behavior of the wake and the resulting trajectory of the tube for much higher Reynolds numbers, like those expected in the actual

convection zone. The calculations carried out up to now have Reynolds numbers up to order 10^3 (e.g., Hughes et al 1998).

The development of the kink instability in a highly twisted tube also leads to motion of the magnetic field lines away from the original vertical plane containing the tube. The evolution of a kink-unstable tube has been calculated by a number of authors (Matsumoto et al 1998; Fan et al 1998, 1999). The latter authors, in particular, have used an anelastic code which allows for the fast computation of the emergence of flux. A particularly interesting result of their calculations is the simulation of the evolution of an active region that could result from these kink-unstable tubes in an advanced phase of the instability: the authors study the evolution of the magnetic field on a horizontal plane in the top part of their integration box and find that the motion of the *magnetic elements* on that plane closely resemble the evolution of the so-called δ -spots.

3. What can we learn about stellar activity by extrapolating from the Sun? (S. K. Solanki)

The Sun and the other cool stars allow complementary approaches to the study of stellar magnetic activity. Whereas the Sun allows us to investigate the magnetic field and related processes in detail at the physically relevant spatial and temporal scales, stars exhibit magnetic activity over a much wider parameter range and demonstrate how it depends on such quantities as stellar rotation, evolutionary state, convective properties, binarity and chemical abundances.

In this section we are concerned with predictions that can be made for other stars on the basis of our knowledge of the Sun. Typically such predictions are made via theory. Thus, scaling laws derived from solar X-ray loops have been successfully applied to stars (Golub 1983; Rosner et al. 1985; Fisher & Hawley 1989). Also, the theory of emergence of magnetic flux on the Sun has successfully reproduced polar and high latitude spots on rapidly rotating stars (Schüssler & Solanki 1992; Schüssler et al. 1996; cf. Schüssler 1996). Instead of presenting these and other examples of a similar nature, we consider here more direct extrapolations. Thus we compare the results obtained from spatially resolved with those of unresolved observations. This allows us to judge how strongly observations are falsified by spatial averaging. Also, through the fact that the solar magnetic field and associated activity varies strongly with spatial location and with time, the Sun provides us with different levels of magnetic activity to study. This property can be employed in order to either compare the scaling of solar and stellar phenomena with a given parameter (cf. Güdel 1996) or to extrapolate from the Sun to stars with other activity levels.

3.1. How much unsigned magnetic flux does the Sun have?

For many solar observations adequate spatial resolution is important, since for many quantities a linear spatial averaging can lead to imprecise results. This is the case when the quantity of interest is non-linearly related to the observable (e.g., the gas density depends quadratically on the observed optically thin intensity via the emission measure). This is also true when measuring the magnetic field on the basis of the longitudinal Zeeman effect via circular polarimetry.

This technique is employed, e.g., by solar magnetographs and classical Zeeman Doppler imaging (Semel 1989). In this case spatial resolution is extremely important if one wants to know the total amount of magnetic flux on a star. Even the difference in size between the pixels of a magnetogramme taken by, e.g., MDI, the Michelson Doppler Interferometer on the SOHO spacecraft ($2'' \times 2''$) and of typical synoptic charts [longitude \times sin(latitude) = $1^\circ \times 0.01$] leads to approximately a factor of 3 difference in the apparent total magnetic flux at solar activity minimum (Fligge & Solanki 2000). I.e. typically synoptic charts underestimate the total magnetic flux in the quiet Sun by a factor of three or possibly even more. This factor is largest when opposite magnetic polarities are intermingled on small scales, i.e. in the normal quiet Sun. It is smaller in active regions in which the magnetic polarities are in general well separated. The larger an active region, the less flux is *lost* at lower spatial resolution, since the areas of unipolar field increase. Similarly, we expect that Zeeman Doppler images (Donati et al. 1990, 1992; Donati 1999) are more accurate representations of the largest unipolar regions, with decreasing accuracy as the regions decrease in size. Hence we expect them to provide a better estimate of the magnetic structure far from the star than to give information on the workings of stellar dynamos.

3.2. Sizes of sunspots and starspots

An extrapolation of the size distribution of sunspot umbrae from the Sun to more active stars can help with the interpretation of Doppler images of rapidly rotating stars (see Rice 1996 for a review of Doppler imaging). Bogdan et al. (1988) demonstrated that sunspot umbral areas are lognormally distributed. This suggests that they are the result of a fragmentation process (Kolmogorov 1941). This in turn agrees with the idea that whole active regions are produced by the emergence through the solar surface of the fragments of a single large flux tube (see Sect.2.1.). This basic picture has met with great success not only in reproducing solar phenomena but also the latitudes of starspots on late-type stars. Thus we expect basically the same picture to hold also for more active stars: starspots are the cross-sections of stellar flux tubes that are the fragments of a larger flux tube anchored at the base of the stellar convection zone. Hence we expect starspot areas to be lognormally distributed, just like sunspot areas. The parameters of the lognormal distribution may, however, differ from star to star.

Solanki (1999) has extrapolated to the expected lognormal distribution on active stars by considering the difference between the distribution at solar activity maximum and minimum. They find that although the area fraction covered by large spots, such as those that can be resolved by Doppler imaging, increases with the activity level, even for the most active stars less than half of the total area covered by spots is due to starspots that can be resolved in Doppler images. Therefore most of the starspot coverage does not appear on Doppler images, unless the smaller spots are clumped together. This agrees with the finding that Doppler imaging gives a spot filling factor that is smaller by roughly a factor of three than that derived by molecular lines (O'Neal et al. 1998).

A more detailed comparison with the observations reveals that the very large spots, covering up to 5–10% of the stellar hemisphere, imaged on some stars

(Vogt & Penrod 1983; Donati et al. 1992; Strassmeier & Rice 1998) are probably not single, giant starspots, but rather clumps of many smaller starspots.

3.3. Solar and stellar luminosity variations

It has recently also become possible to extrapolate the sunspot darkening and facular brightening from the solar case (where it can be measured, respectively modelled in detail; Solanki & Fligge 2000, Fligge et al. 2000) to more active stars. The idea is that the intensity contrast of spots and faculae relative to the inactive parts of the star is independent of stellar activity. What changes is the total stellar surface area covered by spots and faculae. Chapman et al. (1997) determined that as solar activity increases the surface area covered by sunspots increases faster than that covered by faculae. By assuming that their relationship holds also for other cool stars it is possible to determine the relative increase of spot and facular area coverage to activity levels much higher than are reached by the present-day Sun.

The modelling firstly confirms that the Sun is brighter at solar activity maximum than at activity minimum due to the larger contribution of the bright faculae than of the dark sunspots. This is in good agreement with space-based radiometric observations (Willson & Hudson 1991; Fröhlich & Lean 1998). Secondly we find that for stars that are more than roughly three times as active as the Sun the cyclic brightness variation is anti-correlated with the magnetic activity (as given, e.g., by the Ca II HK index). These stars are thus darker at activity maximum than at minimum (Knaack 1999).

Exactly such a behaviour was found observationally by Lockwood et al. (1992) and Radick et al. (1998). At least in this case a straightforward extrapolation from the Sun to more active stars is successful in reproducing the observations. This increases our confidence also in the deductions made from the other extrapolations discussed in this section.

4. Magnetic fields on stars (S. H. Saar)

I evilly planned to stir up some interesting discussion and debate by posing a few (hopefully provocative) questions to the gathering, followed by a few minutes of background on each subject. It seemed to work - there was enough lively debate that we only got through two (and a bit) of the five question areas! The question areas were:

4.1. Magnetic field strengths

Measured photospheric magnetic field strengths (from unpolarized spectra) seem to generally be in approximate pressure balance with the surrounding gas, i.e., $B^2 \propto P_{\text{gas}}$ (Saar 1996; Johns-Krull & Valenti 1999), but there are now also some counter examples - active late M dwarfs like EV Lac (Johns-Krull & Valenti 1996), T Tauris (Johns-Krull et al. 1999, 2000), and possibly RS CVn's (Saar 1996). Why do some stars violate the "equipartition field" concept? Has the concept been invalidated? When observations indicate $B^2 > P_{\text{gas}}$, how much is the result of a vertical ∇B (and thus in some sense a depth of formation effect and not necessarily a true breach of "equipartition")? How much is due to regions where magnetic pressure is dominant (e.g., Solanki 1994)?

4.2. Saturation

The concept of *saturation* in one sense or another has been around for quite some time (e.g., Vilhu 1984). What is *saturation* really? Is the surface area coverage of magnetic regions $f \rightarrow 1.0$, or some sort of “maximum” level? Is it a saturation of the heating mechanism for the particular atmospheric diagnostic being studied (e.g., some limiting MHD wave amplitude)? What then is the *supersaturation* seen in rotation vs. X-ray emission (Prosser et al. 1996; Randich 1998)? Are we seeing an α - quenched dynamo where higher Ω actually yields less magnetic flux? Is magnetic flux now increasingly reaching the surface in the form of relatively less X-ray active umbrae (Sams et al. 1992)? Or are coronae being truncated at the co-rotation radius, (Jardine & Unruh 1999) and thus F_X declines beyond a certain Ω ?

4.3. Starspot properties and distributions

Much has been learned about starspots (e.g., Strassmeier 2000), but much is still unclear. Are they primarily in the form of nests of solar-like spots, or are they large, monolithic entities? What are their field strengths, temperatures, and are the two related? How much of the area covered by starspots is in a more-or-less uniformly distributed component, and thus largely invisible to photometry and Doppler imaging (see Saar et al. 2000)? There has been great progress in models of fluxtube emergence, which successfully predict concentrations of strong fields (and thus starspots) near stellar rotational poles on rapid rotators (Schüssler et al. 1996; DeLuca et al. 1997; Buzasi 1997; Granzer et al. 2001). Where do the near-equatorial spots on these stars come from?

4.4. Dynamos

There has also been some notable progress (both observational and theoretical) on stellar dynamos, which are presumably to blame for all this magnetic confusion. Where does dynamo theory stand? Are stellar phenomena such as multiple cycle periods, chaotic behavior, and sporadic *magnetic minima* understood theoretically (e.g., Baliunas et al. 1995)? Why do stars with turbulent dynamos (late dM stars) show such diverse behavior, when turbulent dynamos are supposedly relatively insensitive to rotation (Durney et al. 1993; Cattaneo 1999)? Is there any way these stars could show spots or cycles?

4.5. New insight with LSD

Least-Squares Deconvolution (LSD!) in Doppler and Zeeman Doppler Imaging – good drugs or bad? LSD, a clever method for increasing the S/N of stellar surface features in spectral data, has been recently implemented (Donati et al. 1997; Donati & Brown 1997). What are its strong points and weak points, what improvements are possible, and what is it beginning to tell us about stellar surfaces?

5. Final comment

In the three parts of the present discussion session there was a large number of comments and questions from the audience. There resulted a stimulating

debate with many interesting points raised. Unfortunately, insufficient recorded material makes any significant reconstruction of the discussion impossible.

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Conference Summary
