Seventh Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun
ASP Conference Series, Vol. 26, 1992
Mark S. Giampapa and Jay A. Bookbinder (eds.)

MAGNETIC FIELDS IN STELLAR PHOTOSPHERES

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ABSTRACT An overview is given of the basic classes of techniques for measuring magnetic fields on cool stars. The main results of magnetic field measurements on late-type stars are then briefly summarized before the assumptions underlying the interpretation of the measurements are considered in detail. Their validity is discussed and methods of improving the interpretation are presented. Finally, it is argued that current measurements overestimate the magnetic fluxes on at least some cool stars.

Keywords: Stellar magnetism, stellar activity

1. INTRODUCTION

One of the key parameters underlying stellar magnetic activity is the magnetic field. Unfortunately, accurate observations of the magnetic field are difficult. Stars which freely exhibit an abundance of exotic behaviour — such as strong variations in luminosity or in Ca II H and K core flux, strong X–rays and microwave emission, energetic flares, etc. — suddenly become shy and secretive when it comes to revealing their magnetic fields. Special, and often quite involved, techniques have to be applied in order to trick cool stars into revealing their magnetic secrets.

In Sect. 2 I give a rough overview of the classes of techniques developed to measure solar and stellar fields, together with their relative advantages and disadvantages. No details about the individual techniques are given here. For more details see, *e.g.*, Robinson (1980), Giampapa *et al.* (1983), Marcy (1983, 1984), Gray (1988), Saar (1988, 1991b), Basri and Marcy (1988), Mathys (1989) and Solanki (1991).

Underlying every measuring technique is a model of the structure of the stellar magnetic field. The commonly used model assumes that for the purposes of magnetic measurements the stellar atmosphere is described with sufficient accuracy by 2-components: a magnetic component with a fixed field strength B covering a fraction f (the filling factor) of the stellar surface and a non-magnetic component ($B = 0$) covering a fraction $1-f$. Furthermore, it is assumed that the magnetic component is composed of many individual magnetic features distributed evenly over the stellar surface (*cf.* Sect. 5).

2. CLASSES OF TECHNIQUES FOR MEASURING MAGNETIC FIELDS

In addition to the magnetic field many stellar, atomic and instrumental parameters affect a spectral line profile (*e.g.* atomic abundance, oscillator strength, excitation potential, temperature, velocity gradients, stellar rotation, instrumental broadening). The main difficulty in measuring stellar magnetic fields is due to the fact that it is not straightforward to separate the effects of these parameters from the often subtle influence of the magnetic field. Of the techniques developed to circumvent such problems we consider only those based on the Zeeman effect.

A. The most certain signature of a magnetic field is the detection of net polarization (Stokes Q, U, V) of the distinctive spectral form produced by the Zeeman effect. Due to its sensitivity, reliability and ease of measurement Stokes V (*i.e.* net circular polarization) is the most common spectral diagnostic of solar magnetic fields. Unfortunately, Stokes Q, U and V depend sensitively on the geometry of the field. In particular, Stokes V responds only to the longitudinal component of the field and changes sign if the polarity of the field reverses. Therefore, if both polarities are present in equal amounts on the visible hemisphere of a star, then the Stokes V flux profile is completely cancelled. Since this is generally the case Stokes V profiles have been measured on only few stars (see Donati *et al.* 1992). Stokes Q and U, *i.e.* net linear polarization profiles, are only visible if the transverse component of the field has a preferred orientation (*e.g.* a bipolar configuration).

B. Somewhat less reliable, but in the case of Stokes V still an almost certain indicator of a magnetic field, is the detection of a net polarization with limited spectral information (*e.g.* broad-band polarization). Note that the problem of cancellation of polarities remains equally acute for Stokes V. Due to the increased S/N ratio and less stringent instrumental requirements many more such observations have been carried out. In the vast majority of the cases a null result was obtained (*e.g.* Borra *et al.* 1984), again due to flux cancellation, although a few detections do exist.

C. If the net polarization cannot be used then the most reliable magnetic field diagnostic is the profile shape of Stokes I. If fB is not very large then the influence of the field on Stokes I is quite subtle and much more difficult to detect than in Stokes V. To detect a field at least two lines must be observed, a magnetically sensitive and an otherwise similar insensitive one (it is also possible to use the same line on an active and an inactive star). Almost all magnetic measurements on cool stars have been made using a technique of this type, first developed by Robinson (1980). Often B and f can be obtained separately, although for incomplete Zeeman splitting it is fB^2 which is most reliably determined (Stenflo and Lindegren 1977, Gray 1984). Although the Stokes I profile shape is insensitive to the polarity of the field, it is heavily influenced by noise, blends and stellar rotation — it only works for stars with small $v\sin i$.

D. The final and least sensitive direct diagnostic of cool-star fields is based on Zeeman desaturation: In the presence of a field the individual Zeeman components move apart, so that some of them absorb in what is virgin continuum for $B = 0$. Thus the equivalent width of a saturated line is increased by a field. Zeeman desaturation has been applied to the measurement of stellar fields by Mathys and Lanz (1990) and to cool stars by Basri *et al.* (1992). Zeeman desaturation is insensitive to stellar rotation or instrumental broadening, but for slow rotators it is considerably less sensitive than the Robinson type techniques (Basri *et al.* 1992) In addition, this technique does not allow f and B to be separated, but only gives their product fB.

3. SELECTED RESULTS

In the years since the first definite detection of a magnetic field on a late-type star other than the sun (ξ Boo A, G8V) by Robinson et al. (1980) the number of stars on which a magnetic field has been reliably detected has risen to approximately 30 (see *e.g.* Saar 1990, 1991a). For a sample of similar size only upper limits have been obtained. The relatively high percentage of detections reflects the bias in the total observed sample towards stars showing high levels of activity. The stars for which definite detections have been reported range in spectral type from M4.5 to G0. All but three stars with detected fields are dwarfs (one of the exceptions being a T Tauri star). Reasons for the non-detection of further giants have been discussed by Marcy and Bruning (1984).

One of the first applications of the magnetic measurements has been the search for correlations between magnetic and other stellar parameters (*e.g.* stellar rotation frequency, inverse Rossby number, gas pressure, X-ray flux, CaII H and K flux). Such correlations have been presented by *e.g.* Marcy (1983, 1984), Schrijver *et al.* (1989), Marcy and Basri (1989) and Saar (1990, 1991a). Two examples are shown in Figs. 1 and 2. The figures are based on the compilations of Saar (1990, 1991a).

Fig. 1 relates the surface-averaged magnetic field strength fB to the rotational frequency Ω. Dynamo theories predict relations between fB and Ω or fB and $\tau_c\Omega$ (where τ_c is the convective turn-over time). In agreement with these predictions the observed fB increases with Ω, although the scatter in the observed relation is at present too large to distinguish clearly between rivalling models.

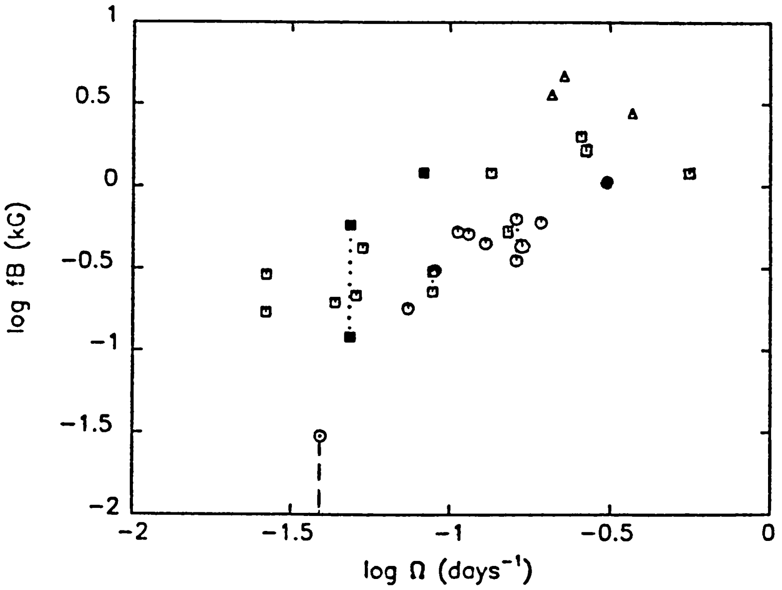

Fig. 1: Magnetic flux density $\log fB$ vs. angular rotation frequency Ω (circles: G, squares: K, triangles: M stars. Open symbols: dwarfs, filled symbols: giants).

Fig. 2 shows the measured B vs. the "equipartition" value B_{eq}, where B_{eq} is the field strength at unit continuum optical depth in the non-magnetic atmosphere, scaled such that $B_{eq}(\text{sun}) = 1500$ G. The solid diagonal line represents $B = B_{eq}$. The two dashed lines give the limits within which solar features carrying a non-negligible amount of the solar magnetic flux are observed. For most stars $B \approx B_{eq}$ appears to be satisfied, but for 5–6 stars measured B values are substantially smaller than B_{eq}. I see three possibilities to explain this discrepant behaviour: 1. Since f and B are less reliably measured then $\sqrt{f}B$ it is possible that f has been systematically over- and B underestimated for these stars. 2. For the majority of the anomalous dwarfs the B field has been measured using lines around 8000Å, which are formed higher in the atmosphere than the lines used to measure the rest of the stellar sample (Grossmann-Doerth and Solanki 1990). The field strength is expected to decrease with height, so that lines formed higher measure a smaller field strength (*cf.* Sect. 4.2). 3. The processes leading to the formation of strong filamented magnetic fields need not be equally efficient or even the same in stars of different types. Therefore, not all stars need fulfill a single scaling relationship.

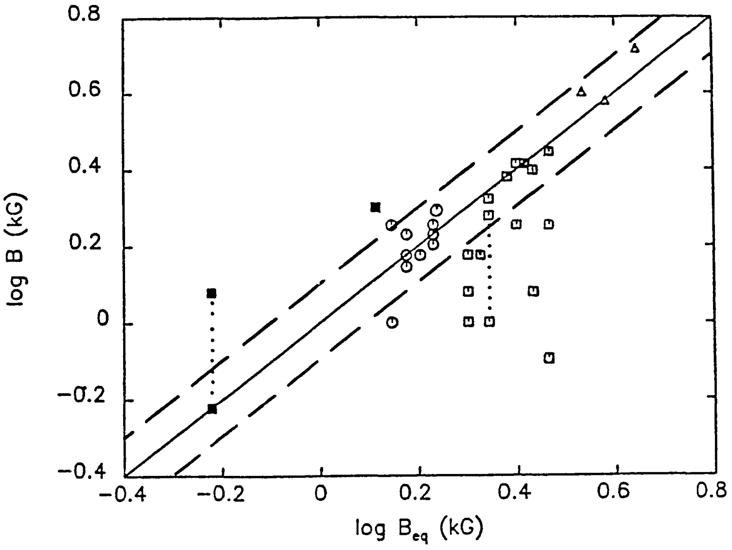

Fig. 2: Measured field strength B vs. equipartition field strength B_{eq}. Symbols as in Fig. 1. See the text for details.

4. INTERPRETATION OF STELLAR MAGNETIC MEASUREMENTS

Consider the question of how the measured B and f values relate to the true field on the star. In order to simplify the discussion we assume that the B and f values obtained from the data are uncorrupted by noise, blends, insufficient Zeeman sensitivity of the lines and insufficient realism of the radiative transfer. The influence of these parameters has been discussed by *e.g.* Gondoin *et al.* (1985), Hartmann (1987), Saar (1988) and Landolfi *et al.* (1989). In other words we assume that f and B are correct ***within the constraints of the model underlying the analysis of the stellar observational data.*** The main assumptions underlying the current interpretations of magnetic measurements are:

1. The structure of the field is described by a simple 2-component model (briefly outlined in Sect. 1), *i.e.* there is no horizontal distribution of field strength.
2. Thre are no vertical gradients of B (and f).
3. The magnetic features (flux tubes) are distributed homogeneously over the star.
4. The atmosphere within the magnetic features is the same as the non-magnetic atmosphere of the star.

Some techniques make additional assumptions, but we do not consider these here. Although the main assumptions appear reasonable and some of them are at present unavoidable for most stars, it is nevertheless worthwhile to consider how these assumptions influence the derived B and f values. We test their validity by confronting them with solar observations, with theory and with observations of cool stars.

4.1. Assumption 1: 2-Component Model

The 2-component description, *i.e.* no significant horizontal distribution of field strengths, is to first order a good representation of magnetic fields in solar plages. Recent observations confirm the theoretical picture that most of the flux is concentrated into small flux tubes, *i.e.* discrete bundles of field lines emerging through the stellar surface, with similar field strength and with little variation of the field strength across the diameter of a tube (Zayer *et al.* 1988, 1990, Solanki *et al.* 1992a). Theory does not rule out strong horizontal variations within individual flux tubes, but the simplest and least artificial models have a horizontally almost constant field bounded by a sharp current sheet. Furthermore, convective collapse calculations by Spruit (1979) predict that $1280 \lesssim B(z=0) \lesssim 1650$ G for different flux tubes. Therefore, at least for solar plages, theory supports the 2-component view.

Large flux tubes, such as sunspots, on the other hand, do not have a horizontally homogeneous field. The field strength drops from 2000–3000 G in the umbra to 750–1000 G at the outer penumbral boundary, as suggested by theoretical models (*e.g.* Pizzo 1986, Jahn 1989) and observations (*e.g.* Lites and Skumanich 1990, Solanki *et al.* 1992b). However, the quantity most relevant for comparison with stellar measurements is the field strength averaged over a whole sunspot. Such average values lie in the range 1000–1600 G (Solanki and Schmidt 1992) and are not too different from the field measured in plages (1200–1700 G, *e.g.* Rabin 1992, Solanki *et al.* 1992a). For stars of other spectral types the existence of multiple magnetic components cannot be ruled out (Saar 1992), although vertical field gradients may also be able to reproduce the observations.

Even if the 2-component model is not correct, this should not affect the measured magnetic parameters of most stars significantly. For example, the measured field strength would simply be a weighted average of the two or more magnetic components. There is currently no compelling reason to drop the 2-component assumption for the field. Note that although the magnetic field may be well described by two components the thermal structure of the magnetic features requires at least three components (hot plage flux tubes and cold spots), but more about temperature later.

4.2. Assumption 2: No Vertical Gradient of the Field Strength

The field strength averaged over a magnetic flux tube which is confined by pressure balance decreases exponentially with height, since in the simplest case (isothermal atmosphere, no tension) $B(z) \sim \sqrt{p(z)} \sim exp(-z/2H_p)$, where H_p is the pressure scale height. On the sun this model can account for all data (Zayer *et al.* 1988, Solanki *et al.* 1992a). The detection of broad-band circular polarization on λ And (Kemp *et al.* 1987) and on HD 129333 (Elias and Dorren 1990) indicates the presence of a vertical field-strength gradient on these stars. A longitudinal gradient is needed to produce a broad-band circular polarization of the observed magnitude, as calculations for the solar case show (*e.g.* Illing *et al.* 1975, Grossmann-Doerth *et al.* 1989, Solanki 1989).

A vertical field-strength gradient affects the interpretation of magnetic measurements in mainly three ways:

1. Lines formed at different heights do not give the same B and f, although Bf remains constant. Lines formed lower in the atmosphere should give larger B (and smaller f) than lines formed higher (Grossmann-Doerth and Solanki 1990).
2. A vertical B gradient affects line shapes in the same way as a horizontal distribution of field strengths. If the vertical gradient is not taken into account in the data interpretation it can lead to a false detection of a horizontal field-strength distribution.
3. A vertical gradient of the field, unlike a horizontal distribution, affects the equivalent width of the σ-components (it enhances their Zeeman desaturation). Consequently filling factors determined without taking a dB/dz into account are too large compared with the true values, particularly for cool stars on which dB/dz is larger.

4.3. Assumption 3: Homogeneous Surface Distribution of Magnetic Features

On the sun a homogeneous distribution of the field is an acceptable first-order approximation, although during activity maximum the presence of large active regions concentrates the field near the equator. The amount of theoretical work predicting the distribution of magnetic flux on a stellar surface is limited to studies of the solar case. And even here the theoretical models have difficulty in explaining the emergence of (large scale) flux near the equator (Choudhuri and Gilman 1987). In these calculations most of the flux emerges near the poles, being pulled there by the Coriolis force. Obviously some mechanism overrides the Coriolis force on the sun. According to Choudhuri and D'Silva (1990) one possibility of making the flux rise towards the equator is to put it into small flux tubes which can exchange angular momentum through interaction with turbulence. But in a fast rotator the Coriolis force can be over an order of magnitude stronger than on the sun, and it is proportionately more difficult to keep the field from appearing predominantly at the poles of these stars. A homogeneous surface distribution may then well be a poor representation of the field on such stars. This idea is in good agreement with the frequently observed polar spots on RS CVn or BY Dra stars. The concentration of the field at the

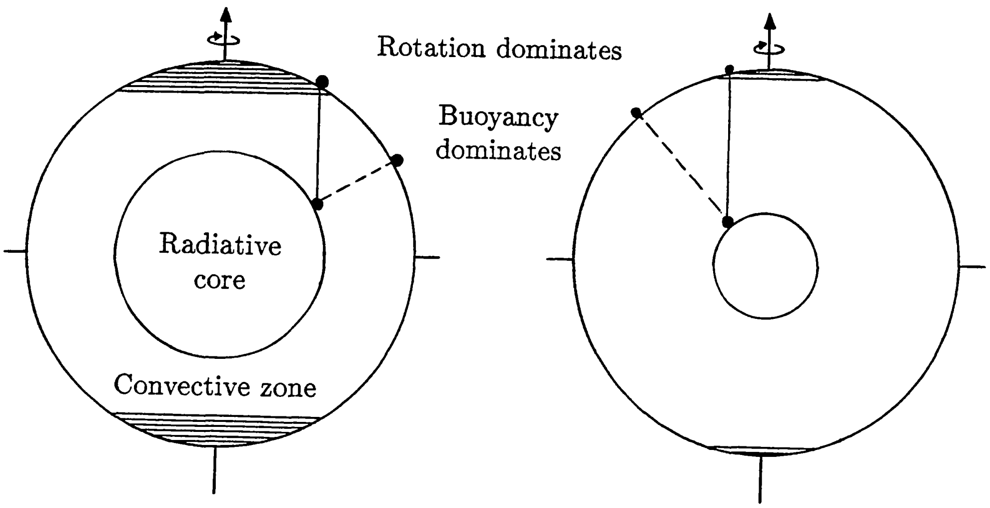

Fig. 3: Cross-section through a late G (left) and late K (right) star showing the rise of a magnetic flux tube (or toroidal ring) from the base of the convection zone if buoyancy (dashed line) and if rotation (solid line) dominates. The shaded regions near the stellar poles represent the areas of magnetic flux emergence if rotation dominates.

poles of rapid rotators should become even stronger for later spectral types as the depths of their convection zones increase (Fig. 3).

What is the directly measured distribution of magnetic fields on other late-type stars? Rotation remains the key to mapping the magnetic distribution of stellar surfaces. For slow rotators information on the distribution can be obtained, mainly by noting modulations of f and B over a stellar rotation period. The ensuing curves of f and B vs. stellar longitude can be used as an input to improve the determination of f and B in a second iteration. Further iterations may be carried out if necessary.

Rotational modulation of f and B on ξ Boo A is seen by Saar *et al.* (1987), who conclude that it has four main active areas that are roughly equally spaced in longitude, but have different sizes. On the other hand, Basri and Marcy (1988) find no changes in f and B for ϵ Eri and ξ Boo A monitored at a number of epochs.

For a few stars Stokes V can be used. It has the advantage that one can obtain information on the distribution of magnetic polarities, but, on the other hand, flux cancellation implies that only the *net* uncancelled field contributes to the measured signal. The broad-band Stokes V signal of λ And was followed over a number of rotation periods by Kemp *et al.* (1987). They saw clear temporal variations of Stokes V on the general time-scale of the rotation period. By taking measurements of solar broad-band circular polarization measurements as a guide Mürset *et al.* (1988) could roughly reconstruct the position of the 1–2 fairly localized features giving rise to the Stokes V signal.

For fast rotators more detailed information on the distribution of the field can be obtained by using Stokes V or Stokes I Zeeman Doppler imaging

(ZDI). Stokes V ZDI relies on the fact that rapid rotation can keep the Stokes V signals from regions of opposite polarity from canceling if the regions are sufficiently separated in stellar longitude. Stokes V ZDI was developed by Semel (1989), tested by Donati *et al.* (1989) and applied to the RS CVn system HR 1099 by Donati et al. (1990, 1992), who find that the uncancelled net field is rather inhomogeneously distributed. Stokes I ZDI uses the difference between the equivalent widths of magnetic and non-magnetic spectral lines to derive information on the surface distribution of the product fB. The equivalent width of the Zeeman sensitive line is larger (due to Zeeman desaturation, Sect. 2) in those parts of the rotationally broadened profile formed at a longitude with a substantial field. Since Zeeman desaturation is less sensitive to fB than other techniques, Stokes I ZDI is expected to work only for the most active stars. On the other hand, it, unlike Stokes V ZDI, is not restricted to fields whose polarities are sufficiently separated. Saar and Piskunov (1992) have applied Stokes I ZDI to the BY Dra variable HD 82558. They also find a relatively inhomogeneous distribution of the field.

4.4. Assumption 4: Horizontally Homogeneous Temperature

The temperature of most solar magnetic features is not equal to that of the quiet sun — sunspot umbrae can be up to 2000K cooler, while small flux tubes generally are 250–500K hotter. Both types of features carry substantial amounts of magnetic flux. The temperature near $\tau = 1$ within a stellar magnetic feature depends on the ratio of horizontal photon mean-free-path to diameter of the feature: The larger this ratio, the hotter the magnetic feature. According to theory only a small fraction of all magnetic features should have a temperature similar to the non-magnetic atmosphere. However, predicting the quantitatively correct temperature of magnetic features from first principles is extremely complex (*e.g.* Spruit 1976, Deinzer *et al.* 1984, Steiner and Stenflo 1990, Knölker *et al.* 1990) and requires complex model calculations. Such calculations have so far been carried out only for the sun.

There are three ways of observationally determining whether the magnetic fields on active cool stars are concentrated mainly in hot and bright or in cool and dark features.

A. **Common sense:** The continuum intensity of spot umbrae is so low, that they should be practically invisible in the flux spectrum of a star (Saar *et al.* 1986). This argument is confirmed by test calculations (Basri *et al.* 1990, Saar and Solanki 1992). However, not-so-dark features, such as penumbrae, may still give a significant contribution.

B. **High and low excitation lines:** On some stars with low $v \sin i$ the temperature in the magnetic features can be estimated by comparing fB determined from temperature sensitive lines with fB derived from temperature insensitive lines. If the two fB are equal, then the temperatures assumed for the magnetic and non-magnetic atmospheres are correct relative to each other, if not, then the assumed temperature of the magnetic relative to the non-magnetic atmosphere is wrong. It is possible to derive the correct relative temperature by changing it until both high and low excitation lines give the same fB. The additional constraint that the flux spectrum of the whole star must give the observed $B - V$ fixes the absolute temperature. A discrepancy between high and low excitation lines has been seen in ϵ Eri (Solanki and Mathys 1987, Mathys and Solanki 1989). It suggests that the temperature in the magnetic features of this star is higher than in its field-free part.

C. **Zeeman Doppler Imaging:** The ZDI techniques give a correlation between temperature and magnetic field. Note, however, that the higher or lower temperature correlated to large fB need not correspond to the temperature within the magnetic features. *e.g.*, if the true size of the stellar magnetic features is smaller than the spatial resolution of the "Doppler image", then the average temperature derived from Doppler imaging corresponds to neither the magnetic nor the non-magnetic parts of the atmosphere in the "Doppler resolution element". For such features Doppler imaging gives something akin to 1-component models of solar plages, which bear only limited resemblance to the atmosphere in the magnetic features (*e.g.* Solanki 1990).
For HR 1099 Donati *et al.* (1990) find from Stokes V ZDI that the net magnetic flux is concentrated outside the dark spots, *i.e.* probably in plage-like structures, while Donati *et al.* (1992) find the largest signal in and around dark patches at a later epoch. Saar and Piskunov (1992) find from an application of Stokes I ZDI to HD 82558 that the darker patches on the star are correlated with a magnetic field.

In summary, all the evidence seems to suggest that the temperature in stellar magnetic features is different from the temperature of the non-magnetic photosphere.

The only way to empirically obtain the *true* temperature in magnetic features from Stokes I flux is by applying method B. It is, in principle, possible to combine methods B and C and thus to determine the true temperature in the magnetic features on fast rotators as well.

Dropping the assumption of equal temperature can affect the derived f and B values considerably (*cf.* Grossmann-Doerth *et al.* 1987, Basri *et al.* 1990, Saar and Solanki 1992). Fig. 4 illustrates the expected enhancement, respectively reduction, of the spectral contribution of plage magnetic features to the measured spectral lines, for two hypothetical lines of neutral iron. An effective line strengthening greater than unity implies that measured fB values are larger than the true values, while a value below unity signifies an underestimate of fB. The Kurucz (1991) models for $\log g = 4.5$ and $3500 \leq T_{eff} \leq 5750$ K describe the non-magnetic atmosphere, while the magnetic atmosphere is given by Kurucz models that are 250 K hotter than the non-magnetic ones. Although the detailed dependence on T_{eff} obviously is a function of the line and of the details of the models used, the trend is probably quite general: For K and M type stars we expect plage f values to be overestimated. For G and F stars a slight underestimate of f is expected. The Ti I lines near $2.2\,\mu$, which have been used to measure magnetic fields on M stars should behave similarly. Note that spot fields are generally underestimated.

4.5. Are Very High Filling Factors Real?

Almost a third of the stars with measured filling factors have $f \gtrsim 50\%$. The main argument in favour of the reality of such large filling factors is that, even if the measured values are uncertain, there is still an unknown amount of magnetic flux hidden in the form of stellar spots. This implies that the true filling factor is even larger than the measured values. On the other hand, a number of arguments suggest that at least some measurements overestimate the true plage f values. For example:

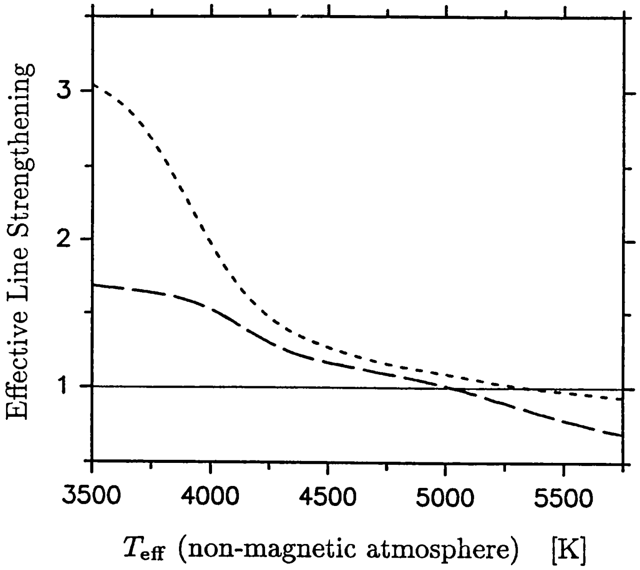

Fig. 4: Effective line strengthening in magnetic features vs. the effective temperature T_{eff} of the non-magnetic part of the star. Short dashes: Fe I line with excitation potential $\chi_e = 4$eV, long dashes: Fe I line with $\chi_e = 0$ eV.

1. The neglect of the vertical B gradient present on cool stars leads to an overestimate of f. Since B and dB/dz increase towards later spectral types this effect is expected to be larger for cooler stars.
2. If magnetic features are hotter than field-free regions then f is slightly underestimated on warm stars, but is overestimated (possibly by a large factor) on cooler stars.
3. We can measure f and B individually only on stars with small *v*sin*i*. Now, a star with $f = 50\%$ can hardly be a truly slow rotator. Indeed rotation periods, measured from *e.g.* Ca II H and K variations, are small. Therefore, we probably see such stars nearly pole on. An extrapolation of the work of Choudhuri and co-workers to rapid rotators shows that conservation of angular momentum forces most of the stellar magnetic flux to appear near the poles. Therefore the true total filling factor of these stars is expected to be considerably lower than the measured values, which are strongly weighted towards the heavily magnetized poles.

In summary, the currently measured filling factor of the magnetic field in the form of plages are expected to be overestimated, particularly for K and M dwarfs. However, an unknown amount of spot contribution is also present.

ACKNOWLEDGEMENTS

Discussions with M. Giampapa, S. Saar and M. Schüssler have been very fruitful.

REFERENCES

Basri, G.S., Marcy, G.W. 1988, *Ap. J.* **330**, 274

Basri, G., Marcy, G.W., Valenti, J.A. 1990, *Ap. J.* **360**, 650

Basri, G., Marcy, G.W., Valenti, J.A. 1992, *Ap. J.* in press

Borra, E.F., Edwards, G., Mayor, M. 1984, *Ap. J.* **284**, 211

Choudhuri, A.R., Gilman, P.A. 1987, *Ap. J.* **316**, 788

Choudhuri, A.R., D'Silva, S. 1990, *Astr. Ap.* **239**, 326

Deinzer, W., Hensler, G., Schüssler, M., Weisshaar, E.: 1984, *Astr. Ap.* **139**, 426

Donati, J.-F., Semel, M., Praderie, F. 1989, *Astr. Ap.* **225**, 467

Donati, J.-F., Semel, M., Rees, D.E., Taylor, K., Robinson, R.D.: 1990, *Astr. Ap.* **232**, L1

Donati, J.-F., Brown, S.F., Semel, M., Rees, D.E. 1992, these proceedings

Elias, N.N., Dorren, J.D. 1990, *Astr. J.* **100**, 818

Giampapa, M.S., Golub, L., Worden, S.P. 1983, *Ap. J.* **268**, L121

Gondoin, P., Giampapa, M.S., Bookbinder, J.A. 1985, *Ap. J.* **297**, 710

Gray, D.F. 1984, *Ap. J.* **277**, 640

Gray, D.F. 1988, Lectures on Spectral-Line Analysis: F, G and K Stars, The Publisher, Arva

Grossmann-Doerth, U., Pahlke, K.-D., Schüssler, M. 1987, *Astr. Ap.* **176**, 139

Grossmann-Doerth, U., Schüssler, M., Solanki, S.K. 1989, *Astr. Ap.* **221**, 338

Grossmann-Doerth, U., Solanki, S.K. 1990, *Astr. Ap.* **238**, 279

Hartmann, L. 1987, in Cool Stars, Stellar Systems, and the Sun, V., J.L. Linsky, R.E. Stencel (Eds.), Lecture Notes in Physics Vol. 291, Springer-Verlag, Berlin, p. 1

Illing, R.M.E., Landman, D.A., Mickey, D.L. 1975, *Astr. Ap.* **41**, 183

Jahn, K. 1989, *Astr. Ap.* **222**, 264

Kemp, J.C., Henson, G.D., Kraus, D.J., Dunaway, M.H., Hall, D.S., Boyd, L.J., Genet, R.M., Guinan, E.F., Wacker, S.W., McCook, G.P.: 1987, *Ap. J.* **317**, L29

Knölker, M., Grossmann-Doerth, U., Schüssler, M., Weisshaar, E.: 1990, *Adv. Space Res.* **11**, 285

Kurucz, R.L. 1991, in Stellar Atmospheres: Beyond Classical Models L. Crivellari, I. Hubeny (Eds.), Kluwer, Dordrecht, in press

Landolfi, M., Landi Degl'Innocenti, M., Landi Degl'Innocenti, E.: 1989, *Astr. Ap.* **216**, 113

Lites, B.W., Skumanich, A. 1990, *Ap. J.* **348**, 747

Marcy, G.W. 1983, in Solar and Stellar Magnetic Fields: Origins and Coronal Effects, J.O. Stenflo (Ed.), *IAU Symp.* **102**, 3

Marcy, G.W. 1984, *Ap. J.* **276**, 286

Marcy, G.W., Basri,G. 1989, *Ap. J.* **345**, 480

Marcy, G.W., Bruning, D.H. 1984, *Ap. J.* **281**, 286

Mathys, G. 1989, Fundam. Cosmic Phys. **168**, 184

Mathys, G., Lanz, T. 1990, *Astr. Ap.* **230**, L21

Mathys, G., Solanki, S.K. 1989, *Astr. Ap.* **208**, 189

Mürset, U., Solanki, S.K., Stenflo, J.O. 1988, *Astr. Ap.* **204**, 279

Pizzo, V.J. 1986, *Ap. J.* **302**, 785

Rabin, D. 1992, these proceedings

Robinson, R.D. 1980, *Ap. J.* **239**, 961

Robinson, R.D., Worden, S.P., Harvey, J.W. 1980, *Ap. J.* **236**, L155

Saar, S.H. 1988, *Ap. J.* **324**, 441

Saar, S.H. 1990, in Solar Photosphere: Structure, Convection and Magnetic Fields, J.O. Stenflo (Ed.), Kluwer, Dordrecht, *IAU Symp.* **138**, 427

Saar, S.H. 1991a, in The Sun and Cool Stars: Activity, Magnetism, Dynamos I. Tuominen, D. Moss, G. Rüdiger (Eds.), Springer-Verlag, Berlin, *IAU Coll.* **130**, 389

Saar, S.H. 1991b, in Memorie della Società Astronomia Italiana, R. Pallavicini (Ed.), **61**, 559

Saar, S.H. 1992, these proceedings

Saar, S.H., Huovelin, J., Giampapa, M.S., Linsky, J.L., Jordan, C. 1987, in Activity in Cool Star Envelopes, O. Havnes *et al.* (Eds.), Reidel, Dordrecht, p. 45

Saar, S.H., Linsky, J.L., Beckers, J.M. 1986, *Ap. J.* **302**, 777

Saar, S.H., Piskunov, N.E. 1992, these proceedings

Saar, S.H., Solanki, S.K. 1992, these proceedings

Semel, M. 1989, *Astr. Ap.* **225**, 456

Schrijver, C.J., Coté, J., Zwaan, C., Saar, S.H. 1989, *Ap. J.* **337**, 964

Solanki, S.K. 1989, *Astr. Ap.* **224**, 225

Solanki, S.K. 1990, in Solar Photosphere: Structure, Convection and Magnetic Fields, J.O Stenflo (Ed.), *IAU Symp.* **138**, 103

Solanki, S.K. 1991, *Rev. Modern Astron.* **4**, in press

Solanki, S.K., Mathys, G. 1987, in Activity in Cool Star Envelopes, O. Havnes *et al.* (Eds.), Reidel, Dordrecht, p. 39

Solanki, S.K., Rüedi, I., Livingston, W., Stenflo, J.O. 1992a, these proceedings

Solanki, S.K., Rüedi, I., Livingston, W. 1992b, *Astr. Ap.* to be submitted

Solanki, S.K., Schmidt, H.U. 1992, *Astr. Ap.* to be submitted

Spruit, H.C. 1976, *Solar Phys.* **50**, 269

Spruit, H.C. 1979, *Solar Phys.* **61**, 363

Steiner, O., Stenflo, J.O. 1990, in Solar Photosphere: Structure, Convection and Magnetic Fields, J.O. Stenflo (Ed.), Kluwer, Dordrecht , *IAU Symp.* **138**, 181

Stenflo, J.O., Lindegren, L. 1977, *Astr. Ap.* **59**, 367

Zayer, I., Solanki, S.K., Stenflo, J.O. 1988, *Astr. Ap.* **211**, 463

Zayer, I., Solanki, S.K., Stenflo, J.O., Keller, C.U. 1990, *Astr. Ap.*