Magnetic Field Measurements on Cool Stars

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Abstract: This review attempts to provide a simple introduction to the measurement of cool-star magnetic fields for the non-specialist. After a short historical overview the basics underlying the measurement of magnetic fields on cool stars are briefly introduced. The special role played by the sun in the study of stellar magnetism is pointed out and illustrated with the help of two examples. Stellar measurements in circularly polarized light are discussed. The Robinson technique for the measurement of stellar fields in unpolarized light is described and the problems associated with it, as well as possible solutions to them, are sketched out. Some trends resulting from the sum of the magnetic field detections on cool stars are discussed. A well observed star, ϵ Eri, is then considered in greater detail. The main conclusions of the talk are summarized.

1 Introduction

The first detection of a magnetic field on a cool star other than the sun is only ten years old. However, in the intervening decade a large amount of effort has been put into such work, making it impossible to cover every aspect of stellar magnetic field measurements in a single review. However, the subject has been extensively and competently reviewed in the past and more details may be obtained from the following papers: Marcy (1983), Linsky (1985), Saar (1987a, 1990), Pallavicini (1987), Robinson (1986), Gray (1988) and Mathys (1989). For reasons of brevity the present review does not consider degenerate stars or stars earlier than F0. The structure and origin of the magnetic fields on hot or degenerate stars are quite distinct from those of cool-star fields. Finally, only magnetic fields in stellar photospheres are considered, since these are the only layers in which magnetic fields have been directly measured (excluding the sun where transition region and coronal fields have also been measured). However, see also Pallavicini (1987) and Güdel and Benz (1989) for a dicussion of limits on coronal fields set by radio observations. In the following I often abbreviate the terms 'cool star' or 'late-type star' simply as 'star'.

2. Historical Overview

Let me begin by listing in chronological order the first detections of magnetic fields on different types of stars.

1908: The first detection of a non-terrestrial magnetic field was made on the sun by Hale (1908). Using the Zeeman effect — discovered only a decade earlier by Zeeman (1897) — and polarimetry he measured field strengths of approximately 3000 G in sunspot umbrae.

1947: 78 Vir (A2p) was the second star on which a magnetic field was discovered. Babcock (1947) used essentially the same approach as Hale had applied to the sun to measure a field strength of approximately 1500 G at the pole of what he correctly assumed to be an almost dipolar field. This and further measurements (e.g. Babcock 1958, cf. Mathys 1989) have established the oblique rotator model of Ap star magnetic fields due to Stibbs (1950) and Deutsch (1970).

1952: The first reliable detections of 'weak' magnetic fields of a few G (i.e. magnetic fields outside of sunspots) were made possible by the invention of the magnetograph (Thiessen 1952, Babcock and Babcock 1952, Kiepenheuer 1953), although there had been earlier hints of their presence (Hale 1922). These 'weak' fields were later shown to be spatially unresolved. Their true field strengths were found to be 1000–1500 G in the line-forming layers (Stenflo 1973).

1970: Next, magnetic fields were detected on white dwarfs. Kemp et al. (1970) derived a field strength of 10^7 G for the peculiar DB star Grw +70° 8247 from the measured continuum polarization, which they explained with the mechanism of 'grey body' magneto emission proposed by Kemp (1970).

1977: A field strength of $3-5\times10^{12}$ G was derived by Trümper et al. (1977, 1978) for the neutron star Her X-1 from quantized cyclotron emission features in its pulsed hard X-ray spectrum. Such spectral features between individual Landau levels had been predicted by Gnedin and Sunyaev (1974) and Basco and Sunyaev (1975).

1980: Finally, 72 years after the discovery of solar magnetism, a field was also detected on another lower main sequence star, ξ Boo A (G8 V), by Robinson et al. (1980). They employed a technique based on the Zeeman effect and developed by Robinson (1980). A field of strength

2400–2900 G covering 20–45 % of the stellar surface was deduced from the spectra.

1983: There followed the detection of a field on the first cool giant/subgiant λ And (an RS CVn binary with a G8 III–IV primary), by Giampapa et al. (1983) after adapting the Robinson technique to the infrared.

1990: Mathys and Lanz (1990) detected a magnetic field on an Am star, o Pegasi (A1 IV). In contrast to Ap stars, o Peg was found to have a complex magnetic field distribution reminescent of late-type stars, with a spatially averaged field strength of approximately 2000 G.

1990: Finally, a magnetic field detection on the T Tauri star TAP 35 has recently been reported by Basri and Marcy (1990). Their preliminary value for the spatially averaged magnetic field strength is 2000 ± 500 G.

3. The Case for Stellar Magnetic Field Measurements

Magnetic fields with a complex spatial structure, as produced by dynamo action, are responsible for a whole variety of effects. Some of these, together with their observational consequences are listed below.

1. Stellar coronae (i.e. gas at $10^6 - 10^8$ K), transition zones (10^5 K) and, at least partly, chromospheres (10^4 K). These features are responsible for the stellar X-ray and microwave flux, many of the UV lines, line core emission from Ca II H and K and Mg II h and k, etc.
2. Stellar suface inhomogeneities, e.g. starspots, whose presence may be deduced from modulations of the stellar luminosity, colour and spectral line profile shapes.
3. Stellar flares, i.e. sudden brightenings in the stellar X-ray, UV and microwave emission.
4. Stellar activity cycles, observed as long-term quasi-periodic changes (with periods of years) in, e.g., the Ca II H and K line core flux.
5. A considerable part of the rotational spin-down of a large fraction of all stars. This may be deduced from age-rotation relationships and from their comparison with theoretical predictions.

Phenomena of the types listed above — collectively labeled active phenomena — are exhibited by stars lying in the shaded portions of the HR diagram plotted in Fig. 1. These stars have been called 'solar like' by Linsky (1985), in that the dynamics and energetics of their outer atmospheric layers are controlled by their magnetic fields. They include main sequence stars later than approximately F0, as well as subgiants and giants between approximately F0 and approximately K3. Particularly active are members of relatively short period binaries (mainly RS CVn type stars). In order to understand the atmospheres of solar-like stars it is imperative to know the strength and structure of their magnetic fields. Unfortunately, although the magnetic field has a strong influence on stellar emission through its influence on the thermodynamics of the stellar atmosphere, its direct influence on the spectrum is small and it is difficult to quantitatively measure the field.

4. Basics of Stellar Magnetic Field Measurements: The Zeeman Effect

Although a number of physical effects allow direct measurements of stellar magnetic fields, the only one so far successfully applied to the photospheres of non-degenerate late-type stars other than the sun has been the Zeeman effect. The magnetic field manifests itself through the Zeeman effect primarily by splitting a spectral line into a number of components. In the simplest case of a magnetic field aligned along the line of sight and a 'normally' Zeeman split line there are only two components. The wavelength difference $2\Delta\lambda_H$ between these components is in Å:

$$2\Delta\lambda_H = 9.34 \times 10^{-13} g \ \lambda^2 \ B,$$

where λ is the wavelength of the line in Å, g is the Landé factor and B is the field strength in G. Another important property of the Zeeman effect is that it polarizes the individual Zeeman components. In the above example the two components are oppositely circulary polarized.

Unfortunately, for the following reasons it is generally not possible to determine the stellar field strength directly from the Zeeman splitting, $\Delta\lambda_H$.

1. In the visible part of the spectrum $\Delta\lambda_H$ is smaller than the half width $\Delta\lambda_D$ of the unsplit line for $B \lesssim 1500$ G. $\Delta\lambda_D$ includes line saturation effects and 'turbulence' velocity broadening, but in this estimate neglects

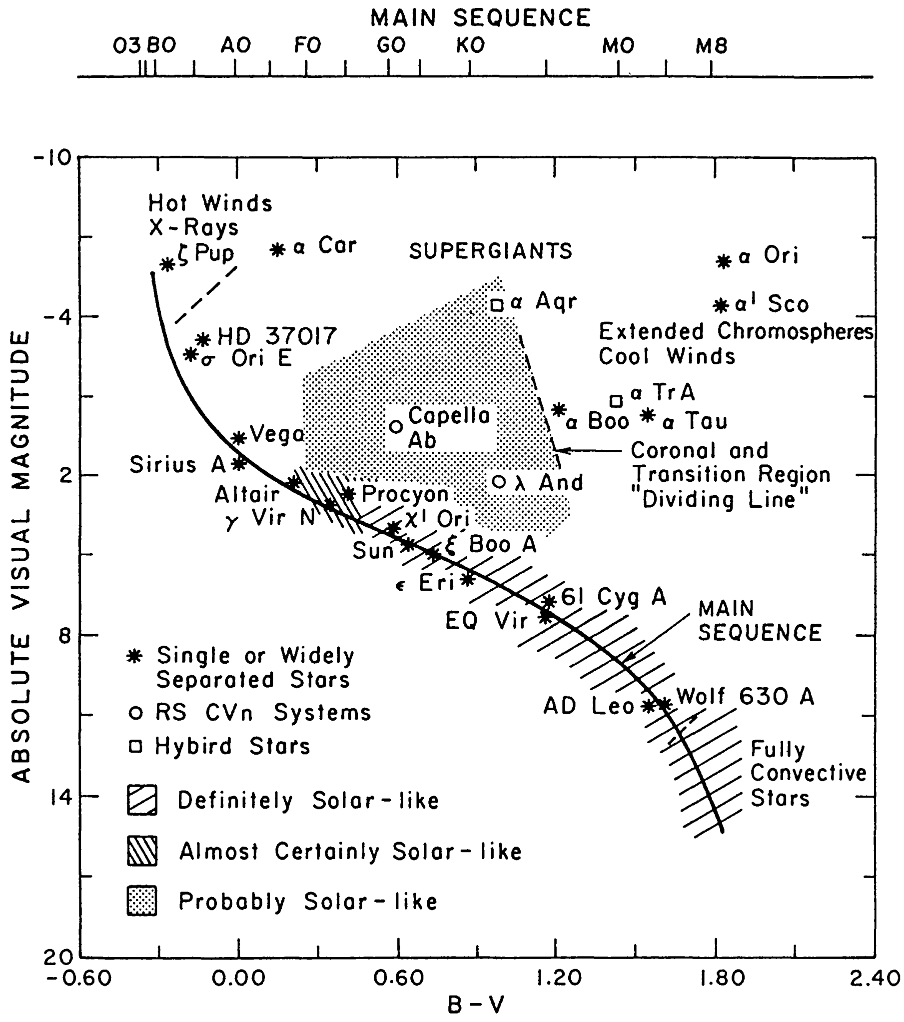

Fig. 1. An H-R diagram. The stars in the shaded areas are definitely or probably solar-like on the basis of direct or indirect indicators of strong, turbulent magnetic fields, which dominate the energetics and dynamics of the outer stellar atmospheres. Adapted from Linsky (1985).

broadening due to stellar rotation. Accordingly, for a field strength typical of a cool star the lines are not split, but only broadened. Unfortunately, line broadening is a less than ideal diagnostic of the magnetic field, since a number of other physical agents also broaden the lines. If the influence of stellar rotation on $\Delta\lambda_D$ is also taken into account, then the ratio $\Delta\lambda_H/\Delta\lambda_D$ is further decreased, making magnetic field detections even more difficult.

One solution to this problem is to make use of the is approximate proportionality of $\Delta\lambda_H/\Delta\lambda_D$ to the wavelength and to observe in the infrared. However, until recently the detectors in the infrared beyond 1μ were grossly inferiour to those in the visible.

2. In general, magnetic fields cover only a small fraction of the stellar surface. The simplest description of such an inhomogeneous field is by a model with the following two components: i) A magnetic component with a field of strength B covering a fraction f of the visible surface, where f is called the magnetic filling factor. ii) A field-free component covering the remaining fraction, $1-f$, of the visible surface. Neglecting for the moment the spherical shape of the stellar surface and related projection and field line inclination effects, we can write the measured intensity I as:

$$I = f\ I_{\mathrm{m}} + (1-f)I_{\mathrm{nm}},$$

where I_{m} is the intensity of light from the magnetic component and I_{nm} is the intensity from the non-magnetic component. If f is small then clearly the observed line profile will only be slightly affected by the magnetic field, making its detection even more difficult.

The simplest solution to this problem is to measure the spectrum in polarized light as well. For a complete description of the magnetic field vector four different states of polarization must be measured. However, in practice mainly the spectrum of the net circular polarization (Stokes V) has been measured and is the only polarization state discussed further in the present review. The Stokes V profile of a spectral line gives a measure of the line-of-sight component of the magnetic field. In particular, it can easily be shown that light coming from a field-free portion of the stellar atmosphere is free of net circular polarization, i.e. Stokes $V = 0$. Therefore, by measuring Stokes V it is possible to obtain information exclusively on the magnetic features, even if they are spatially unresolved. This property is employed extensively for the investigation of the solar magnetic field. The other relevant property of Stokes V is its dependence on magnetic polarity. The sign of Stokes V reflects the sign of the longitudinal component of the field, B_{long}:

$$V(-B_{\mathrm{long}}) = -V(B_{\mathrm{long}}).$$

This relationship implies that the presence of opposite polarity fields within a spatial resolution element leads to a partial and sometimes even complete cancellation of the Stokes V signal. For most late-type stars a cancellation of polarities over the visible stellar hemisphere hinders the use of the Stokes V signal for magnetic field detections (more details are to be found in Sect. 6).

5. The Best Studied Star: The Sun

It is no coincidence that I start the survey of stellar magnetic field measurements with a discussion of the sun. We know much more about the structure and the properties of the solar magnetic field than we do about the fields of all other cool stars put together. There are two main reasons for this, both of which have to do with the sun's relative proximity:

1. The solar surface is spatially resolved, so that the spatial structure of the magnetic field can be determined relatively easily.
2. The large photon flux allows spectra with a very high signal-to-noise ratio to be obtained (values of 10^4 in the continuum are not uncommon), making detailed interpretations of subtle spectral features possible.

Consequently the sun allows us to develop and rigorously test both observational and theoretical techniques for studying magnetic fields. Once the techniques have achieved sufficient maturity and reliability, they may often also be applied to other stars.

Another point, whose importance should not be underestimated, is that our knowledge of the solar magnetic field gives us an idea of what to expect on other stars and helps us to interpret stellar observations. Of course there are dangers inherent in this approach, since the field of other cool stars may in some respects differ qualitatively from that of the sun. However, the interpretation of some observations requires additional assumptions. In such cases taking the sun as a reference is often unavoidable.

From the large body of solar magnetic field research I have chosen two examples that appear particularly relevant to the measurement of magnetic fields on other stars.

5.1. Full-Disk Magnetograms

Figure 2 shows a magnetogram of the full solar disk obtained with the vacuum telescope at Kitt Peak. A magnetogram is simply a map of the distribution on the solar surface of the Stokes V strength in the wing of a spectral line and corresponds roughly to a map of the longitudinal magnetic field. In Fig. 2 gray regions are field-free, while white and black patches correspond to magnetic features with opposite polarity. Three points are evident at a glance:

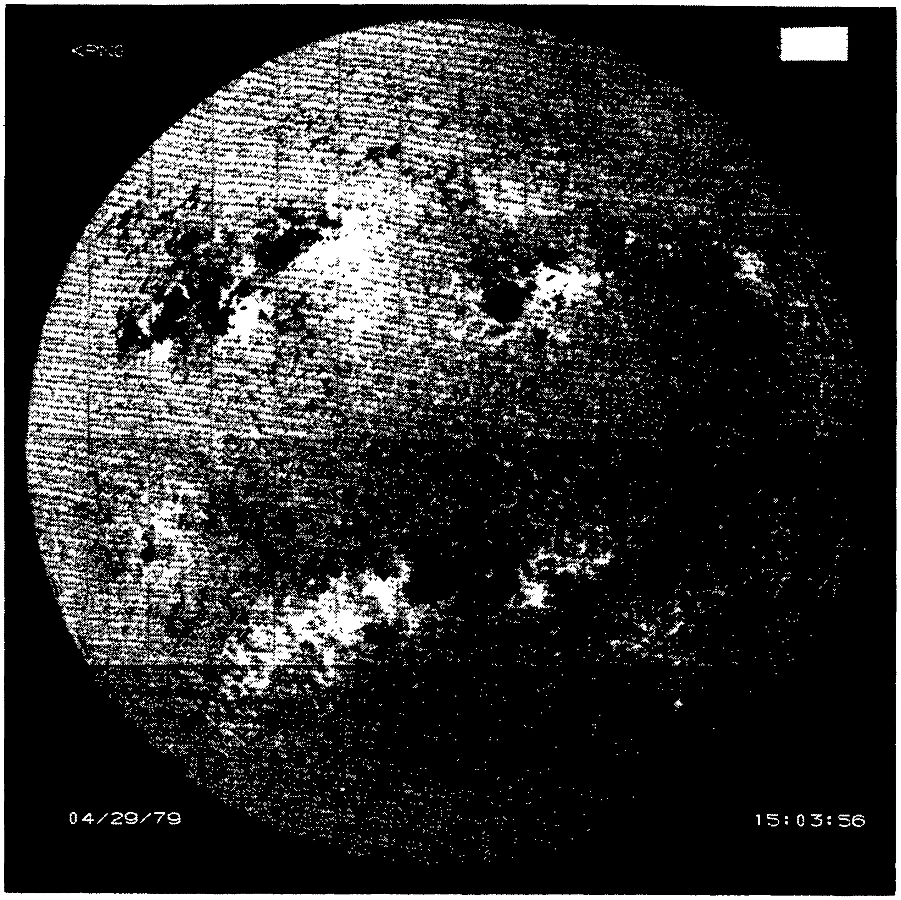

Fig. 2. Solar full-disk magnetogram obtained at solar activity maximum. Grey areas are field-free. Black and white patches represent magnetic features with opposite polarities. Courtesy National Solar Observatory, Kitt Peak.

1. The solar magnetic field has a complex spatial structure, composed of bipolar active regions and a quiet network that may either be unipolar over large stretches, or may exhibit locally mixed polarities (salt and pepper).
2. Much of the structure in the magnetogram is at small scales. The sizes of magnetic features can be followed down to the smallest spatial scales currently resolvable (approximately 200–300 km on the sun). Indirect techniques indicate the existence of even smaller magnetic features. Of importance for the interpretation of stellar spectra is that the properties of the smallest magnetic features, often called magnetic elements, determine to a considerable extent the observations averaged over a large area. Therefore, in order to correctly interpret spatially unresolved observations, we must know the physical properties of the small-scale magnetic features.

3. Almost equal amounts of opposite polarity flux are present on the solar surface. This implies that due to the cancellation effect mentioned in Sect. 4 the Stokes V signal averaged over the solar surface is very small ($10^{-5} - 10^{-6}$ in units of the continuum intensity for the broad-band signal, Kemp et al. 1987a) and little evidence for a magnetic field is obtained in this manner. Since the best currently achievable accuracy of stellar polarimetry is approximately 10^{-4} it appears unlikely that many solar-like stars can be detected if their fields show a distribution similar to that of the sun.

5.2. Small-Scale Magnetic Features

The magnetic field in the solar photosphere is mainly concentrated into so-called flux tubes, i.e. bundles of magnetic field lines passing from the solar interior into the outer atmosphere. The field is confined by the deficit in gas pressure within the flux tubes. The decrease in gas pressure with height causes the field strength to decrease and the tubes to expand until they merge in the lower chromosphere.

Photospheric flux tubes come in various sizes. The largest are visible as sunspots, i.e. dark structures with diameters often larger than 10'000 km. The field strength varies from approximately 1000 G at their outer penumbral boundary to approximately 3000 G in their core (umbra). Dark structures of intermediate size, having diameters of around 1000–2000 km are called pores and have field strengths between 1500 and 2000 G. Finally, the smallest and by far the most common of the solar magnetic features are the magnetic elements. These are bright structures with field strengths of 1000–1500 G in the line-forming layers. Their sizes are not accurately known, but for many of them are probably still below the best current spatial resolution of 200–300 km. More about the general properties of small-scale magnetic features may be obtained from Sect. 8.2 of Stix (1990) and from the reviews by Spruit and Roberts (1983), Solanki (1987b), Stenflo (1989) and Spruit et al. (1990).

To be able to predict the influence of small-scale magnetic features on the spatially averaged observed spectrum we must determine their detailed physical structure. Spectra and images in polarized light serve as the ideal empirical tools for such an undertaking. From such data it is possible to obtain, for example, the stratifications of field strength, temperature and stationary flow velocity in the magnetic features and partly also in their surroundings. In addition the data give an idea of the direction of the magnetic vector, the dynamics of the flux tubes and their interaction with the surrounding convection, etc. More details may be obtained from the following reviews devoted to the discussion of empirical results: Stenflo (1984, 1985, 1986), Solanki (1987a, 1990), Martin (1990).

Theoretical flux tube models have developed in parallel with the empirical advances. State of the art flux tube models now not only satisfy the MHD equations, but also include multi-dimensional non-grey radiative transfer as part of the energy balance. The models resulting from such ab initio calculations reproduce many of the observed features, for example, a decrease of the field strength with height, the absence of sizeable stationary flows within the flux tubes, the concentration of the tubes into downflowing intergranular lanes, the temperature enhancement within the magnetic features, etc. The correspondence between the best theoretical and empirical models has moved beyond the qualitative stage and become increasingly quantitative. The quantitative accuracy of theoretical flux tube models is expected to constitute an important aid to new techniques of stellar magnetic field measurement (cf. Sect. 7). Reviews containing additional details on the theoretical aspects of solar flux tubes have been given by Spruit (1981, 1983), Nordlund (1986), Schüssler (1986, 1987, 1990). Also of interest are various articles in Russell et al. (1990) as well as recent papers by Steiner and Stenflo (1990) and Knölker et al. (1990).

6. Circular Polarization Measurements on Cool Stars

Circular polarization measurements may appear to be attractive magnetic diagnostics, since the detection of net circular polarization can generally be equated with the detection of a magnetic field (Sect. 4). However, until the mid 1980s no positive detection of circular polarization was reported despite numerous surveys with ever-increasing sensitivity (e.g. Boesgaard 1974, Boesgaard et al. 1975, Vogt 1980, Brown and Landstreet 1981, Bonsack and Simon 1983, Borra et al. 1984). On the other hand, a number of stars showing no net circular polarization exhibit distinct signatures of a magnetic field in unpolarized light (Sect. 7). In combination these observations imply that the magnetic field on cool stars has a complex geometry, qualitatively similar to that of the solar field.

In recent years net circular polarization has finally been detected on a handful of objects. Borra et al. (1984) reported a detection at the 3.9 σ level on ξ BooA (G8 V) on a single night.

Kemp et al. (1987b) detected broad-band circular polarization on λ And on numerous nights spanning five years. Clear temporal variations on the approximate time scale of the rotation period were seen (cf. Fig. 3). There are two main conclusions to be drawn from their work. a) The temporal variation of the circular polarization and its correlation with variations of the stellar photometric brightness suggests that the field giving rise to the signal is concentrated into a few large regions that evolve over the years (Fig. 3).[1] If measurements of the solar broad-band circular polarization are taken as a guide, then an idea of the distribution and the photometric properties of large-scale magnetic features on λ And may be obtained (Mürset et al. 1988). b) The very fact that a broad-band circular polarization signal is measured is proof that on λ And the Stokes V profiles must be asymmetric, just as they are on the sun. This suggests that the mechanism giving rise to the asymmetry is not particular to solar conditions. The Stokes V asymmetry has recently been explained in terms of the interactions of magnetic fields and convection (Grossmann-Doerth et al. 1988, 1989b, Solanki 1989, Bünte et al. 1990, Knölker et al. 1990) in faculae and due to the Evershed effect in sunspots (Skumanich and Lites 1987). The observations of Kemp et al. (1987b) indicate that these or similar mechanisms may also be working on other, quite different stars (red giants).

Donati et al. (1990) have observed Stokes V line profiles on the primary of HR 1099 (RS CVn, with K1 IV and G5 V components), a very fast rotator for which standard techniques of the type described in Sect. 7 do not work. By comparing the wavelengths of the relatively narrow V profiles with the very broad Stokes I line profiles and making use of Doppler imaging results for this star (Vogt and Penrod 1983, Vogt 1988), they were able to conclude that the largest uncancelled V signal is produced outside the prominent starspots.

Very recently Elias and Dorren (1990) have measured a broad-band circular polarization signal of 1% on HD 129 333, a young solar analogue. The size of the signal is surprising and worthy of further investigation.

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[1] Note that there may be a more uniformly distributed, more solar-like field component as well. However, due to flux cancellation it would not show up in Stokes V measurements.

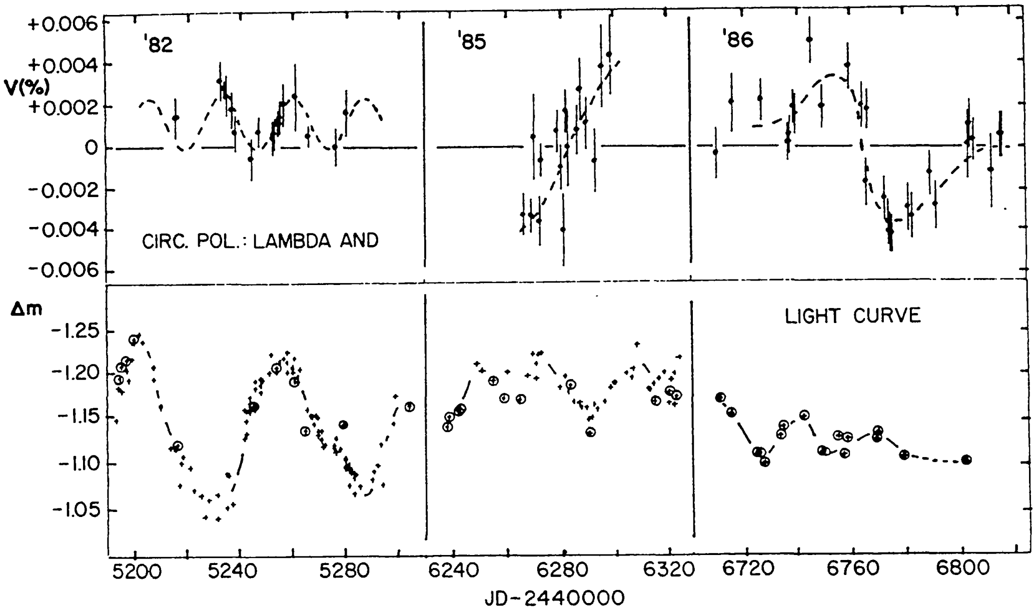

Fig. 3. Broad-band circular polarization (upper panels) and light curves (lower panels) of λ And in 3 seasons (1982, 1985, 1986). The dashed curve in the upper left panel is a least squares fit to the data, the rest are hand drawn. The rotation period of the star is approximately 54 days. After Kemp et al. (1987b).

Finally, although linear polarization is also expected to be produced by certain geometries of the magnetic field, I have not reviewed such measurements due to a current controversy about the reality of magnetic linear polarization detections on cool stars.

7. Stellar Magnetic Fields Derived from the Intensity Spectrum

7.1. Basic Idea

The combination of relatively small Zeeman splitting, small magnetic filling factor and the mixture of polarities on the stellar surface necessitates indirect techniques of detecting magnetic fields using unpolarized light. The basic idea underlying such techniques is due to Robinson (1980). The recipe is to take two spectral lines which, ideally, are identical (i.e. belong to the same ion, have the same oscillator strength and excitation potential and similar wavelengths), except for their Landé factors, i.e. their Zeeman sensitivity. Such a choice of lines ensures that in the non-magnetic part of the stellar atmosphere the profiles of the two lines are almost identical, irrespective of the thermodynamic structure of the atmosphere, surface gravity, etc. The magnetic field introduces a difference of a particular spectral shape between the two line profiles. The presence of such a spectral signature implies the probable detection of a magnetic field. The observations may then be interpreted with, for example, a two-component model, allowing the field strength B and the filling factor f to be determined.

7.2. The Real World

1. For most stars the Zeeman effect influences the line profiles only minutely, at least for spectral lines in the visible. Examples of observed (crosses) and calculated (curves) line profiles for an active star are given in Fig. 4. Note the small difference in the upper panel between the observed and synthetic profiles (calculated with $B = 0$) of the Zeeman sensitive line 8468Å. The implications are: i) The observational data must have a high S/N ratio of at least 100. Therefore, only relatively bright stars offer any hope of measuring magnetic fields. The condition of high S/N may be relaxed somewhat for very active stars observed in the infrared (e.g. dMe stars, Saar and Linsky 1985). ii) Even small blends can falsify the derived fields (Kurucz and Hartmann 1984, Hartmann 1987). Blends can work both ways, leading to spurious detections or hiding the presence of a magnetic field, depending on the details of the blending process (Gondoin et al. 1985). Blending due to atomic and molecular lines increases dramatically towards later spectral types and becomes a major problem for stars cooler than K5. Since the density of lines decreases somewhat with wavelength, the infrared is the spectral range of choice for observing the coolest stars (Saar and Linsky 1985). Another possibility is to use many spectral lines, since statistically the effects of blends are smoothed out (Mathys and Solanki 1989).
2. No 'ideal' line pairs (i.e. clean lines identical in all respects except their Landé factors) are available.[2] Since the two lines of a chosen pair often do not have exactly the same equivalent width it is dangerous to compare the two profiles directly. An indirect comparison using synthetic profiles as intermediaries is to be preferred, since it automatically

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[2] The Fe I line pair 5250.2 Å and 5247.1 Å come close to being ideal, but 5250.2 Å suffers from blending in cooler stars and the Landé factors may be somewhat too similar. However, see Sánchez Almeida and García López 1990.

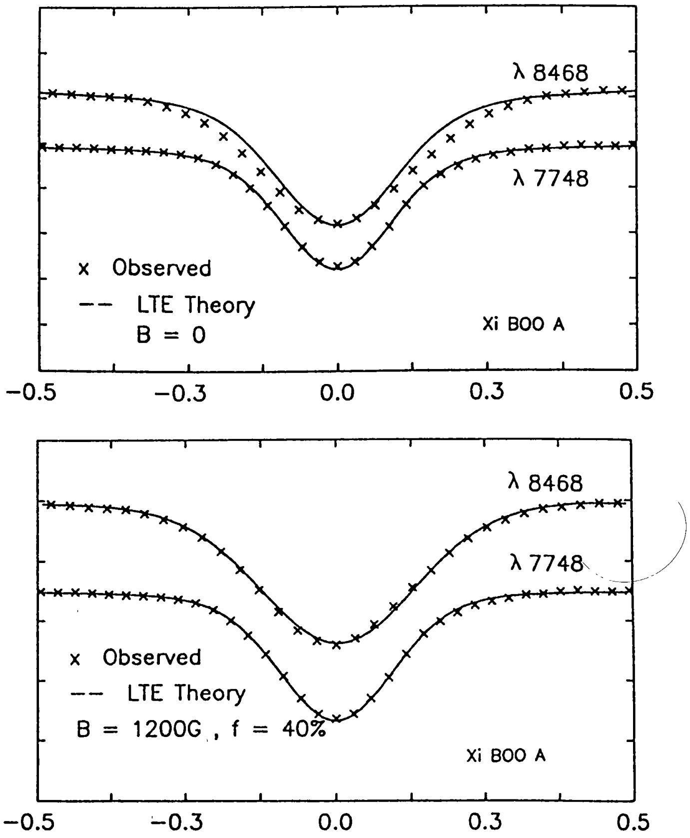

Fig. 4. Comparison of observed (crosses) to synthetic (solid curves) profiles of Fe I 8468Å (Zeeman sensitive line) and Fe I 7748Å (Zeeman insensitive line) for ξ Boo A (G8 V). The upper panel contains overlays of observed on synthetic profiles constructed with no magnetic field. Note the excess width of the observed λ8468Å profile. The lower panel shows the fit obtained when a magnetic field with a strength of 1200 G and a filling factor of 40% is included in the computations. After Basri and Marcy (1988).

compensates for differences in saturation between the two lines. This approach has been taken for most of the newer magnetic field determinations (e.g. Saar 1988a, Basri and Marcy 1988).

3. In general little is known about the geometry of the stellar magnetic field, except that it must be complex (Sect. 6). So far investigators have usually assumed that the field is fragmented into many small regions distributed evenly over the stellar surface. The spherical geometry of the stellar surface and stellar rotation then require the synthetic line profiles to be calculated at many points on the stellar disk and added together before being compared with the data (e.g. Saar 1988b). Time series measurements covering a full rotation period of a star (Saar et al. 1987a) may allow a rough idea of the distribution of the field to be obtained, if the field can be measured with sufficient accuracy. A combination of various direct and indirect magnetic field indicators that re-

act differently to the field distribution (e.g. Ca II K emission, Robinson technique, circular and linear polarization) may also give an indication of the distribution.

4. A major problem is the unknown thermodynamic structure of the magnetic features (Basri et al. 1990). Although B may in principle be determined with reasonable accuracy using current techniques, the derived f values are strongly affected by the unknown line weakening in and continuum intensity of the magnetic features relative to the non-magnetic atmosphere of the star.[3] One promising solution is to use self-consistent models of magnetic flux tubes including a sufficiently sophisticated energy equation (e.g. Grossmann-Doerth et al. 1989a, Steiner and Stenflo 1990, Knölker et al. 1990) to calibrate the measurements. The results of such calculations are getting increasingly realistic for the solar photosphere (Sect. 5.2.). Adapted to other stars the models should be able to predict the thermal structure of the stellar magnetic features and thus help with the interpretation of the observations.

7.3. Survey of Stellar Magnetic Field Measurements

Inspite of the problems discussed in Sect. 7.2., numerous attempts to derive magnetic parameters of cool stars have been undertaken, most of which have met with some degree of success. The following is an incomplete sample of such investigations, listed in roughly chronological order: Robinson et al. (1980), Giampapa et al. (1983), Marcy (1984), Marcy and Bruning (1984), Gray (1984), Gondoin et al. (1985), Saar and Linsky (1985), Saar et al. (1986a,b, 1987a,b), Saar (1987b, 1988a), Basri and Marcy (1988, 1990), Marcy and Basri (1989), Mathys and Solanki (1989), Bopp et al. (1989), Rípodas et al. (1990), Valenti (1990). For a given star the results of the more recent, more sophisticated investigations are in general more reliable and are to be preferred. For example, it is probable that some of the detections in the earlier investigations are spurious, or that some magnetic fields have gone undetected.

Some of the results of these investigations are now summarized with the help of two figures. Fig. 5 summarizes the "reliable" cool star field strengths measured to date (with two exceptions all are on main sequence stars). Plotted is the measured field strength vs. an 'equipartition field strength',

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[3] Since the determination of f and B is to some extent coupled, in practice the measured B values may also be affected by this uncertainty.

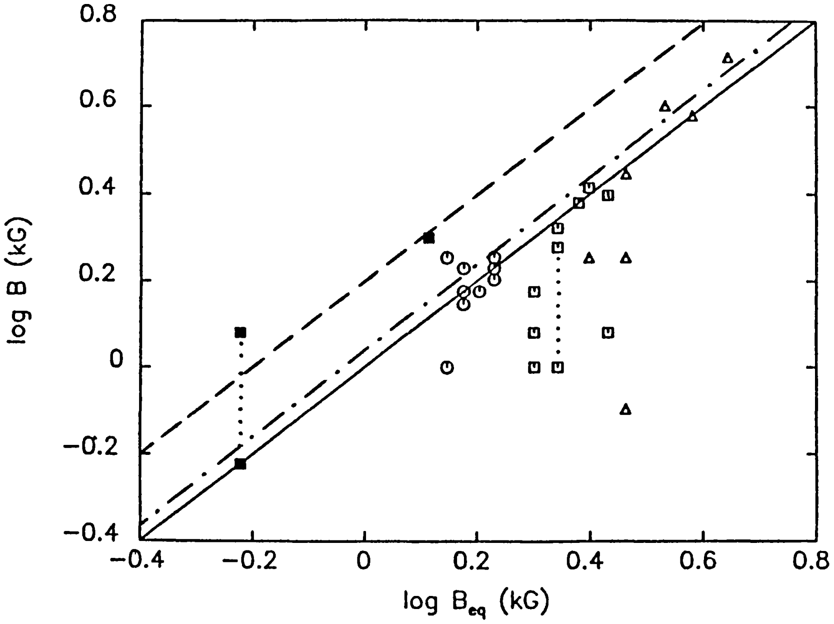

Fig. 5. Measured field strength B plotted vs. an "equipartition field strength" $B_{\rm eq}$. $B_{\rm eq}$ is the field strength expected if the stellar magnetic field is confined by the gas pressure deficit in the magnetic features and if the Zeeman split lines are formed at the continuum forming level of the non-magnetic atmosphere ($B_{\rm eq}$ is normalized to reproduce the solar case correctly). Circles, squares, triangles and filled squares represent G, K, M dwarfs and RS CVn binaries, respectively. The sun is indicated by ⊙. The relationship $B = B_{\rm eq}$ is shown as a solid line. Data points to the upper left of the dashed curve refer to magnetic fields in stellar spots, while points to the lower right of the dot-dashed curve correspond to measurements of fields in stellar faculae. Adapted from Saar (1990a).

i.e. the expected strength if the field is mainly confined by gas pressure and if the Zeeman broadened lines in the magnetic features are formed at the $\tau = 1$ level of the non-magnetic atmosphere ($\tau_{\rm nm} = 1$). If inside the magnetic features of a given star the lines are formed above the $\tau_{\rm nm} = 1$ level, then the corresponding data point should lie to the lower right of the solid diagonal, if they are formed deeper down then the point should lie to the diagonal's upper left. Due to the strong dependence of continuum opacity on temperature, lines are formed deeper in cool starspots than in hot faculae.[4] It is thus possible to tentatively separate the measurements into detections of stellar spots and of stellar faculae. The data points to the upper left of the dashed curve refer to stellar spots, those to the lower right of the dot-dashed curve to stellar faculae. The stars lying between the two curves may possess a mixture of spots and faculae, or may simply reflect uncertainties in the field strength determination. Fig. 5 suggests that,

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[4] For very cool stars (M dwarfs) the relation between opacity and temperature may well break down due to the presence of broad molecular bands. For such stars the conclusions drawn here must be considered with care.

with the possible exception of the two giants/subgiants, no star exhibits any reasonable magnetic signal due to stellar spots.

The above conclusion is supported by more direct observational indicators. For example, on ϵ Eri the comparison between the field derived from two independent sets of spectral lines with different temperature sensitivities indicates that the measured field is concentrated in hot, bright regions (Solanki and Mathys 1987). On HR 1099 the region showing the maximum of the Stokes V signal is spatially distinct from the dark spots on that star (Donati et al. 1990). Since many late-type stars show unmistakable signs of cool and dark spots on their surfaces (e.g. Vogt and Penrod 1983, Vogt 1988, Ramsey and Nations 1980, Huenemoerder and Ramsey 1987) does the absence of a magnetic signature from the dark stellar patches imply that they are non-magnetic? Not necessarily, since on a spatially unresolved star any magnetic field concentrated into localized dark structures is very hard to detect due to the low continuum light level in such structures. For example, in the visible solar spectrum the continuum intensity I_c of facular magnetic flux tubes lies in the range

$$I_c^{\text{quiet}} \lesssim I_c^{\text{faculae}} \lesssim 2 I_c^{\text{quiet}},$$

while for sunspots

$$0.1 I_c^{\text{quiet}} \lesssim I_c^{\text{spot}} \lesssim 0.5 I_c^{\text{quiet}}.$$

Here I_c^{quiet} is the continuum intensity of the quiet sun. Therefore, a considerable fraction of the stellar field may be present in the form of spots, yet may still escape detection (cf. Saar et al. 1986a).[5] It may nevertheless be possible to detect fields in stellar spots by considering purely umbral lines with large Zeeman sensitivities. Of particular interest are lines in the infrared, since the continuum contrast decreases with wavelength.

Another often used way of summarizing the results of magnetic field measurements on multiple stars is to plot the magnetic filling factor f, or average magnetic flux density fB vs. stellar rotation frequency Ω, stellar mean convective turnover time τ_c, or some product of the two. Such diagrams may, e.g., be compared to the predictions of different dynamo models and the hope is that they can distinguish between rivalling theories. An example of such a diagram with $\log(fB)$ plotted vs. $\log(\Omega)$ is shown in

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[5] A preponderance of faculae may, however, be a real effect on at least some active stars. There is evidence that the average upper photospheric temperature in active cool dwarfs is higher than of their inactive counterparts (Holweger 1988, Basri et al. 1989).

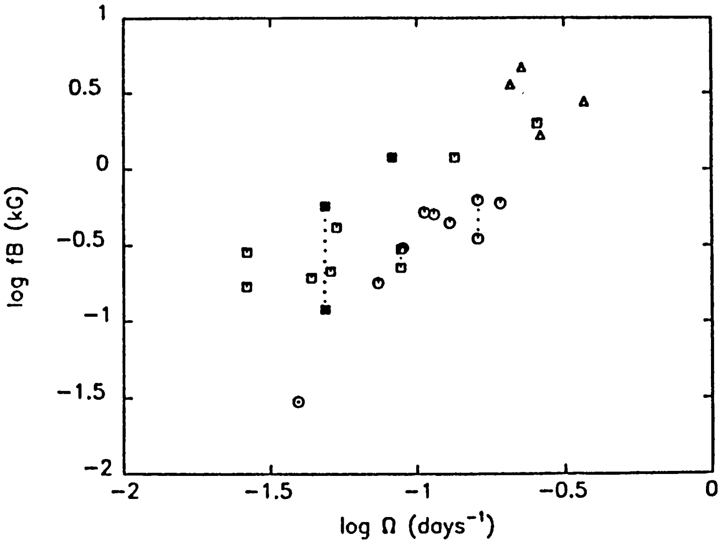

Fig. 6. Magnetic flux density fB vs. stellar rotation frequency Ω. The symbols have the same meanings as in Fig. 5. After Saar (1990a).

Fig. 6. A general trend is visible and a least squares fit to the data gives $fB \sim \Omega^{1.3\pm0.1}$ (Saar 1990). However, a caveat is in order. Even on the sun the magnetic filling factor and flux density are extremely difficult to measure without bias (e.g. Schüssler and Solanki 1988). The f values on other cool stars are yet more unreliable, since their determination does not take into account the influence of the thermodynamic properties of the unresolved magnetic features on the line profiles. This can lead to considerable errors in f (e.g. Basri et al. 1990) and may be responsible for a part of the scatter in Fig. 6. For stars with mutually similar magnetic structures (e.g. with a predominance of faculae) the errors in f may be systematically similar.

8. A Particular Case: ϵ Eri

The active dwarf ϵ Eri (K2 V) is one of the most thoroughly investigated cool stars. In his review Saar (1990) compiled a list of magnetic field measurements of this star (his Table 2). Four different groups have carried out 10 independent magnetic field measurements. The results agree only partially and the total bandwidth of measured B and f values is disturbingly large. Values of B range between 1kG and 3kG, f values between 8% and 67%. Even fB is found to vary by a factor of three between 0.24 kG and 0.78 kG. I see four possible causes of these differences:

1. One possibility is that mutually incompatible measurements simply reflect the magnetic field at different stages of its evolution. Early measurements suggested large temporal variations of the field strength and filling factor — Timothy et al. (1981) and Marcy (1984) found evidence for night-to-night variations. However, these variations have not been confirmed by newer, more sophisticated measuring techniques (Saar et al. 1986b). All in all, we currently can neither confirm nor rule out evolution effects as the cause of the discrepancies described above, but it appears unlikely that they are the sole cause. A systematic study of magnetic field variations with time on individual stars would be welcome.
2. The largest values of f and of fB are due to the two oldest and probably least reliable measurements. If we exclude these, then the scatter decreases significantly. In particular, the measured values of the average magnetic flux density fB are relatively similar for the rest of the investigations.
3. The derived magnetic field parameters depend on the used spectral lines. The choice of spectral lines can influence the results in three ways. *i*) Some lines are formed at greater heights in the atmosphere than others. Since the field strength decreases with height, two lines formed at different heights are also Zeeman split by different amounts. Grossmann-Doerth and Solanki (1990) showed that this effect can explain a large fraction of the approximately factor of 2 difference between the B values derived from lines in the visible (Saar 1988a, Mathys and Solanki 1989) and in the near infrared (Basri and Marcy 1988, Marcy and Basri 1989). The positive aspect of this effect is that it allows the vertical gradient of the field strength to be estimated. Besides being of intrinsic interest, this presently appears to be the most reliable way of testing whether the confinement mechanism of solar magnetic fields (horizontal gas pressure gradients) is also valid for cool stars. However, note that fB should be independent of the formation height. *ii*) The lines used by the different groups also have somewhat different temperature sensitivities, so that they react differently to the temperature in the magnetic features. The derived f value (and partly also the field strength) will therefore depend on the selected lines. This effect can be turned to advantage to derive the temperature in the stellar magnetic features (Solanki and Mathys 1987). *iii*) The strength and influence of weak blends also varies from line to line and may account for some of the discrepancies.

4. Finally, a part of the scatter is certainly due to noise in the data, and probably also to shortcomings of the present techniques. The improvement of these techniques must be given a high priority in the near future.

9. Conclusions

Let me end by summarizing some of the main points of this review and drawing some general and possibly rather obvious conclusions.

1. Magnetic fields have highly visible effects on the radiation from cool stars, mainly through their influence on the thermodynamic structure of the stellar atmospheres. However, the fields themselves are difficult to observe directly.
2. Nevertheless, magnetic fields have been detected on approximately 40 main sequence stars of spectral types between G0 and M4.5, on 2 giant/subgiant members of close binaries and on a pre-main sequence star. So far only facular fields on active stars with small $v \sin i$ (projected rotation velocity) have been definitely detected (exceptions are mentioned under points 3 and 5).
3. The only inactive star with a reliably measured magnetic field is the sun. Its field can be measured in great detail and theoretical models of the magnetic structures (e.g. flux tube models) can be rigorously tested. Such models, once they have been adapted in a physically consistent manner to the conditions on other stars, are expected to form an important part of improved techniques of stellar magnetic field measurement now under development.
4. Recent improvements in infrared detector technology and new efficient high dispersion gratings for the infrared should increase the sensitivity to stellar magnetic fields by a factor of 3–10. Possibly the new instruments will finally allow the reliable measurement of magnetic fields in starspots.
5. For rapid rotators Stokes V polarimetry shows the most promise. In particular, it may be possible to roughly derive the distribution of the field on the stellar surface through the application of Zeeman Doppler imaging (Semel 1989, Donati et al. 1989).

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