SOLAR AND STELLAR MAGNETIC FIELDS AND STRUCTURES: OBSERVATIONS

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"If the Sun did not have a magnetic field, it would be as uninteresting a star as most astronomers believe it to be."

attributed to ROBERT B. LEIGHTON

"Magnetic fields are to astrophysics what sex is to psychoanalysis."

HENK VAN DE HULST (1988)

Abstract. This review of stellar magnetic field measurements is both a critique of recent spectral diagnostic techniques and a summary of important trends now appearing in the data. I will discuss both the Zeeman broadening techniques that have evolved from Robinson's original approach and techniques based on circular and linear polarization data. I conclude with an ambitious agenda for developing self-consistent models of the magnetic atmospheres of active stars.

1. Perspective

Six years ago the topic of solar and stellar magnetic fields was the centerpiece of two IAU meetings – Colloquium No. 71 'Activity in Red Dwarf Stars' (Catania) and Symposium No. 102 'Solar and Stellar Magnetic Fields: Origins and Coronal Effects' (Zürich). As I reread the review papers by Marcy (1983), Golub (1983), and Linsky (1983a, b), I was struck by the enormous progress made in this field in the few years since then. Six years ago few direct measurements were available and the spectral diagnostic techniques were rudimentary. Now we have available a much richer data set from which sophisticated diagnostic methods are extracting more reliable magnetic field parameters for many late-type stars.

In view of this rapid progress, it is important to review and critique the spectral diagnostic techniques now employed and to understand the propagation of systematic and random errors into the derived magnetic parameters. Hartmann's (1987) thoughtful discussion of several of these problems is a useful introduction. I will then summarize what I believe are the important trends emerging from the observations, but I encourage the reader to consult earlier reviews by Linsky (1985), Saar (1987b), and Gray (1988). Finally, as a challenge to both theoreticians and observers, I will lay out an ambitious agenda for the next 6 years to develop a self-consistent model for the magnetic atmospheres of active stars that should explain the magnetic field, X-ray, ultraviolet, and radio data in a manner consistent with the dynamics, energetics, and geometry of these atmospheres. This may appear to be an unreachable goal, but it is no more ambitious

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than what has been accomplished during the past 6 years. One motive for this review is to stimulate the development of such comprehensive models.

2. Spectral Diagnostics of Stellar Magnetic Fields

Solar physicists have long known that magnetic fields play critical roles in heating the chromosphere and corona, determining the geometry of structures in these regions, and otherwise influencing the dynamics and energetics of the diverse phenomena that are called 'solar activity'. The spatial correlation between magnetic fields and phenomena on specific regions on the Sun is well established, because the proximity of the Sun permits spatially-resolved observations. X-ray, ultraviolet, and radio observations of dwarf stars of spectral type F–M and certain subgiant and giant stars, such as components of RS CVn-type binary systems, indicate active phenomena on these stars as well, but often orders of magnitude more energetic, indicating that these stars probably also have strong pervasive magnetic fields.

Magnetic fields in the solar photosphere are typically measured from the difference in absorption line shapes obtained in opposite circular polarizations for magnetically-sensitive transitions (i.e., large Landé g factors). This procedure works because the fields very likely have the same direction in the small regions on the Sun defined by the instrumental aperture and seeing. However, the measured quantity is the magnetic flux rather than the field strength because the magnetic elements may only partially fill the aperture. Application of analogous methods for measuring magnetic field properties in solar-type dwarf stars have yielded null results (e.g., Babcock, 1958; Vogt, 1980; Borra, Edwards, and Mayor 1984). The classical method has failed for these stars because for unresolved stellar observations the contributions of oppositely-directed field elements cancel to high precision, just as they do in integrated sunlight. Thus to measure magnetic fields on late-type stars, one must first devise a better diagnostic procedure.

2.1. Zeeman broadening techniques using unpolarized light

Robinson (1980) proposed that the average magnitude of the stellar photospheric magnetic field could be derived from a careful study in unpolarized light of the enhanced Zeeman broadening of a magnetically-sensitive line (high Landé g factor) compared with another spectral line very similar in shape and formation, but with smaller magnetic sensitivity. Extreme care must be taken in applying this diagnostic technique, because the splitting of a simple Zeeman triplet from line center is only 42 mÅ or 2.1 km s^{-1} for a 6000 Å line with $g = 2.5$ in 1000 G field. The splitting is small compared with the typical width of stellar line profiles; the magnetic field slightly broadens the profile in the inner wings. Since the Zeeman broadening increases as the square of the wavelength, infrared lines should have more pronounced broadening. Indeed, Saar and Linsky (1985) have resolved the Zeeman triplet pattern in Ti I lines located near 2.2 microns in the spectrum of the dM3.5e flare star AD Leo, which they interpret as due to a field of 3800 $\pm$ 260 G covering 0.73 $\pm$ 0.06 of its surface. Stellar observations of the 12 micron Mg I lines detected in the solar spectrum (Brault and Noyes, 1983) should reveal completely split Zeeman patterns.

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Robinson's technique requires observation of a pair of spectral lines carefully selected to have similar equivalent widths, central intensities, heights of formation, and temperature sensitivities, but with very different magnetic sensitivities. He proposed to derive the magnetic field strength from the excess width determined from a Fourier analysis of the magnetic/nonmagnetic line pair. This technique was initially used by Robinson, Worden, and Harvey (1980) to derive magnetic field strengths (B) and fractional disk filling factors (f) for two stars: ξ Boo A (G8V) and 70 Oph A (K0V). Later Gray (1984) used a modified Fourier analysis technique to derive magnetic field parameters in 7 of 18 dwarf stars studied, and Marcy (1984) used a profile fitting variation of this technique to determine field parameters in 19 of 29 dwarf stars observed.

Because the observed quantity is a subtle increase in line width, the inferred magnetic field properties depend crucially upon the accuracy of the diagnostic technique, and systematic errors can be critical. Several authors, in particular Hartmann (1987), have raised the following questions:

(1) Weak line blends, especially those located in the inner wings of the magnetically-sensitive line, can mimic spurious magnetic fields especially in the coolest stars where line blending is nearly ubiquitous. Saar (1988) has evaluated this effect quantitatively. His solution for the problem (cf., Saar, Linsky, and Beckers, 1986) is a line difference technique in which one subtracts the profile of the same magnetically-sensitive line in a less active star from that of a more active star of the same spectral type, after adjusting the profiles of the two stars for differences in their nonmagnetic broadening parameters. The difference profile is then analyzed for the excess Zeeman broadening, but some limitations to this technique are discussed below.

(2) The spectral lines commonly analyzed for Zeeman broadening are not optically thin. Typically their equivalent widths place them near or on the flat part of the curve of growth, so their shapes depend upon line optical depths and on the line/continuum opacity ratio. The Robinson (1980) technique implicitly assumes that both the magnetically-sensitive and insensitive lines are optically thin, but Hartmann (1987) showed that the difference between two lines with different degrees of saturation can be appreciable in the inner line wings and thus produce a spurious magnetic signature. This problem may be ameliorated by comparing observed line profiles with computed profiles that include line saturation effects. Saar (1988) has employed an analytical solution to the radiative transfer equation in which the LTE line source function depends linearly upon optical depth, and the line/continuum opacity ratio is independent of depth. Basri and Marcy (1988) have instead solved for the Stokes vector in an LTE model atmosphere in which all parameters were allowed to vary with depth. Since their technique yields magnetic field parameters fairly similar to those found by Saar for stars in common, Saar's simpler analytical technique appears to be approximately valid. Nevertheless, the complete model atmosphere approach is preferred when line saturation is a concern.

(3) The magnetic field parameters inferred from a comparison of observed and computed line profiles depend sensitively on the assumed stellar rotational velocity, and microturbulent and macroturbulent broadening (Hartmann 1987; Saar 1988). Thus even the model atmosphere technique has its limitations to the extent that the nonmagnetic broadening parameters are uncertain.

(4) The comparison of profiles of the same magnetically-sensitive line in two different stars does cancel the effects of line blends to first order, but the two stars may have somewhat different thermal structures and abundances and thus different line saturation and widths: these effects must be compensated for in order for the diagnostic procedure to be reliable.

(5) The measurement of small differences in line width due to Zeeman broadening requires high quality observations. Saar (1988) showed that for lines in the optical spectrum, the minimum requirements are signal/noise >80, $v \sin i < 8$ km s^{-1}, and a spectral resolution $>70\,000$.

(6) The thermal structure of the magnetic regions of a stellar atmosphere may differ considerably from that of the nonmagnetic regions, whereas all approaches to date have assumed that the two atmospheric regions have the same thermal structures. If the magnetic regions are hotter with a brighter continuum adjacent to the magnetically-sensitive line (analogous to solar faculae as observed near the limb), then the magnetic regions will contribute disproportionately to the disk-integrated line profile, and the true magnetic filling factors will be smaller than computed for a homogeneous atmosphere. This effect may partly explain the large filling factors (as large as $f = 0.9$) that Saar, Linsky, and Giampapa (1987) have deduced from infrared spectra of M dwarf stars. Mathys and Solanki (1988) provide evidence that the magnetic regions for ε Eri are indeed hotter. On the other hand, if the magnetic regions are cooler than the surrounding photosphere (e.g., pores on the Sun), then the filling factors have been underestimated.

(7) The distribution of magnetic flux across a stellar surface is assumed homogeneous in all widely used modeling techniques. If this assumption is invalid, then the derived magnetic flux will be overestimated when the flux is concentrated near disk center and underestimated when the flux is concentrated near the limb.

(8) What is the proper physical interpretation of the derived magnetic field strengths? Because starspots are very dark in the visible, the disk-integrated line profiles include very little contribution from spots even when they cover a large portion of the stellar surface as is the case for dMe stars. The inferred fields must, therefore, refer to penumbrae of spots or to localized bright magnetic regions perhaps analogous to solar plages or faculae. The empirical correlation of observed field strengths with the values computed by balancing magnetic with gas pressure forces in the photosphere (Saar and Linsky, 1986; Saar, Linsky, and Giampapa, 1987) suggests that convective motions enhance the photospheric fields until pressure equilibrium is achieved. In the solar photosphere typical field strengths of 1200–1500 G in small structures (Tarbell and Title, 1977) are consistent with this explanation. Thus the inferred field strength represents an average of the 'pressure-equilibrium' field over the whole stellar disk. The computed line profiles that are compared with observed profiles to determine the field parameters should thus be proper averages over the stellar disk rather than profiles computed at an average viewing angle (e.g., Bopp *et al.*, 1989).

Mathys and Solanki (1988) discuss a technique that analyzes statistically the shift in the center of gravity of a large number of spectral lines observed in unpolarized light. This technique, pioneered with solar data by Stenflo and Lindegren (1977), requires

high-resolution spectra of many lines to infer field parameters from correlations of absorption line depths, widths, and equivalent widths (below specified line depths) with atomic parameters. Mathys and Solanki (1988) have applied this technique to four dwarf stars, obtaining values of fB and B significantly larger than those obtained with the line broadening technique (Saar, 1988) for the two stars in common (ε Eri and 40 Eri A). The explanation for the differences is not known. For ε Eri, Mathys and Solanki (1988) deduced that the magnetic regions are hotter than the nonmagnetic regions, so that the filling factor is less than inferred with the usual assumption that the atmospheric models for the magnetic and nonmagnetic regions are the same.

2.2. Circular and linear polarization techniques

While most recent empirical studies of magnetic fields in late-type stars are based on measurements of the excess Zeeman broadening of line profiles in unpolarized light, polarization techniques have been pushed to their limits to obtain information on the fields complementary to the broadening analyses. For example, Kemp *et al.* (1987) detected variable broad-band circular polarization of amplitude 0.002–0.004% in observations of the single-lined RS CVn system λ And (G8III–IV + ?). They interpreted the net polarization signal as due to ordered magnetic fields, perhaps in large spots near the rotational pole and thus always near the limb, that are not fully cancelled in the disk-averaged flux because of their concentration near the limb.

Broad-band circular polarization measurements include many spectral lines and the continuum. The interpretation is necessarily complex, but Murset, Solanki, and Stenflo (1988) have provided some insight by simulating broad-band measurements (roughly 100 A bandpass) from high spectral resolution solar Stokes V profiles. They explain the wavelength dependance and center-to-limb variation of their simulated broad-band circular polarization measurements as due to line rather than to continuum polarization. The net line polarization could be due to the presence of a large bipolar region on the disk with each component at a different projection angle μ. The two polarities do not cancel either due to different angles of the magnetic flux lines to the line-of-sight or to a change in the asymmetry in the Stokes V profile with μ. Murset, Solanki, and Stenflo (1988) also say that differences in temperature or other properties between the magnetic elements of the two polarities could give rise to a net circular polarization signal. They interpret the Kemp *et al.* (1987) circular polarization observations of λ And as due to the rotation across the disk of either a single spot at intermediate latitude or to the rotation of a plage and a spot of the same polarity but different longitudes.

Linear polarization from magnetic regions distributed across the disk does not cancel in integrated starlight, and has been recorded in broad-band measurements for a few stars (e.g., Huovelin, Saar, and Tuominen, 1988). While the interpretation of these data in terms of magnetic parameters is difficult and not unique (cf. Landi Degl'Innocenti, 1982), the polarization amplitude is a measure of the net tangential component of the magnetic field and will be largest when sufficient magnetic flux is concentrated asymmetrically near the stellar limb. In contrast, the magnetic filling factor derived from unpolarized line broadening measurements is weighted towards disk-center regions

because of projection and limb-darkening effects. Thus the combination of simultaneous broad-band linear polarization data and line broadening data for the same star provides positional information from which a 'magnetic image' might be assembled. Saar *et al.* (1988) have constructed a magnetic image of ξ Boo A (G8V) on the basis of a coordinated observing campaign in June 1986.

3. Important Trends Emerging from the Stellar Magnetic Field Measurements

Altogether, magnetic field parameters have been obtained using some variant of the Robinson (1980) technique for about 50 late-type stars by Marcy (1984), Marcy and Bruning (1984), Gray (1984, 1985), Saar (1987a), Saar and Linsky (1986), Saar, Linsky, and Beckers (1986), Saar, Linsky, and Giampapa (1987), Bruning, Chenoweth, and Marcy (1987), and Basri and Marcy (1988). Linsky (1985) and Saar (1978b) have summarized the important trends emerging from these recent measurements. Here I will bring the summaries up to date.

(1) There is a trend of increasing magnetic field strength with decreasing effective temperature for late-type dwarfs. Since the gravity and thus the photospheric pressure at continuum optical depth unity at 5000 Å both increase systematically towards the lower Main Sequence, it is not clear *a priori* whether the effective temperatures or gravity is responsible for the observed trend. Saar and Linsky (1986) find that $B \sim P_{\rm gas}^{1/2}$ fits the data well and is consistent with the physically plausible situation in which the magnetic pressure in the magnetic flux tubes is the dominant factor balancing the photospheric gas pressure in the surrounding nonmagnetic region. The explanation is simplistic to the extent that the magnetic regions have some internal gas pressure and the height at which the magnetic field is measured lies above that at which the photospheric gas pressure is computed. Nevertheless, since the crude scaling law makes physical sense and fits the data, we adopt it as a working hypothesis. One consequence of the scaling law is that magnetic field strengths should be small (and thus more difficult to measure) in stars located above the Main Sequence, because of their lower gravities and thus their lower photospheric pressures. Indeed, Marcy and Bruning (1984) failed to detect fields in 8 active giants, and the marginal detection of a field of about 800 G in λ And (G8III–IV + ?) by Gondoin, Giampapa, and Bookbinder (1985) supports the scaling law. However, Bopp *et al.* (1989) have reported a field of $B = 2000 \pm 300$ G in VY Ari (K0IV–Ve + ?): possibly the first detection of a field in a pre-Main-Sequence star, and perhaps a counterexample to the scaling law.

(2) The derived magnetic filling factors for the nonspot fields are not correlated with B; thus Gray's (1985) suggestion that fB is a constant has not been supported by subsequent data (e.g., Saar and Linsky, 1986). Instead, f increases with angular rotation rate such that for $\omega \gtrsim 0.25$ days^{-1}, among the dMe stars, f approaches 0.80 and the stellar surface becomes saturated with magnetic regions. On the other hand, the inactive, slowly-rotating dM stars show no evidence of magnetic flux and likely have $f < 0.2$ (Saar, Linsky, and Giampapa, 1987). The dependence of f on rotation rate and its saturation are reasonably matched by the dynamo theory of Skumanich and MacGregor (1986).

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(3) The spatial correlations of bright ultraviolet emission lines and X-ray flux with magnetic flux on the Sun implies that similar correlations should also exist for stars. Schrijver *et al.* (1989) and Saar and Schrijver (1987) show that the correlations of stellar X-ray flux and Ca II flux with magnetic flux (fB) are sensibly tight and are consistent with the solar correlations derived from spatially-resolved data. This implies that monitoring of active stars which have asymmetric distributions of active regions across their disks should show the rise and fall of ultraviolet emission, X-ray flux and magnetic flux in phase as the major active regions rotate into and out of view. This prediction has been confirmed at a low level for ε Eri (K2V) by Saar, Linsky, and Duncan (1986) and at a much higher level for ξ Boo A (G8V) by Saar *et al.* (1988). Additional rotational modulation studies are needed to derive definitive correlations for a range of stars.

4. An Ambitious Agenda for the Next 6 Years of Stellar Magnetic Field Research

I conclude with a rather ambitious agenda for the next 6 years of stellar magnetic field research. Now that we have developed the basic diagnostic techniques and have acquired some confidence in their application to measuring stellar magnetic fields, it is useful to ask where we should go from here. I believe that we should aim towards developing self-consistent multicomponent models for the magnetic atmospheres of active stars that incorporate both the essential physics and the basic phenomenology that we are observing in these stars. Such models should include the following aspects:

(1) High-resolution solar observations indicate that magnetic atmospheres are highly structured and far from spherical symmetry. An approximate geometry would be one in which the hot magnetically-heated plasma is confined by closed magnetic loops with the surrounding material cooler and not confined by closed field lines. Since the gas pressure likely decreases with height (outside the loops) more rapidly than the magnetic pressure, the field lines should diverge with height above the photosphere, so that somewhere in the chromosphere the field lines become nearly horizontal for inactive stars like the Sun with small values of f in their photospheres, or they essentially fill the available volume for active stars like dMe stars with large values of f in their photospheres. In either case at least two atmospheric temperature structure models are required in a complex geometry.

(2) Transition zone lines formed in solar magnetic regions are often redshifted (e.g., Brueckner, 1981), implying that systematic downflows occur in these regions, presumably guided by the magnetic geometry. Since the magnetic fields are presumably closed and the flows cannot cut across the field lines, the observed flows must be transient or perhaps represent circulation patterns in which the downflow component is brighter than the upflowing component. Mariska (1988) has proposed an elegant explanation in which the concentration of heating close to one footpoint of a closed loop induces a syphon flow along the loop for which the temperature gradient in the upflow (from the footpoint closest to where the heating is concentrated) is much steeper than in the downflow. Thus the emission measure of the downflowing plasma far exceeds that of the upflowing plasma at temperatures below 200 000 K and the integrated spectrum

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shows a net downflow velocity of about 10 km s^{-1} at 100 000 K for all orientations of the loop. Transition zone emission lines in active dMe and RS CVn stars (Ayres, 1984; Ayres, Jensen, and Engvold, 1988; Elgaroy *et al.*, 1988) show global redshifts with comparable velocities. Thus realistic models of magnetic atmospheres should include flows along the loops.

(3) Thermal models for each component should be self-consistent with mechanical heating balanced by radiative cooling, thermal conduction, and the enthalpy of the flowing plasma. At present we have little information concerning the detailed heating processes; thus the energy equation can only be used to infer the rate of mechanical heating and its location in the atmosphere.

(4) Solar spectra in the 4.6 micron fundamental vibration-rotation bands of the CO molecule indicate that the lower chromosphere has two basic thermal structures – one with a hot temperature minimum (about 5000 K) and steep temperature rise in which CO is not present, and a second component with a cool temperature minimum (below 3700 K) and very little if any temperature rise in which CO is an important species (Ayres and Testerman, 1981; Ayres, Testerman, and Brault, 1986). Ayres (1981), Kneer (1983), Muchmore and Ulmschneider (1985), and others have interpreted this thermal bifurcation of the solar atmosphere as due to a thermal instability driven by the rapid increase in CO formation with decreasing temperature and the efficiency with which the CO infrared bands can cool the atmosphere. Thus the nonmagnetic regions are kept cool by the CO and the regions of strong magnetic heating remain hot as there is no CO to cool them. Stellar model atmospheres should include the thermal bistability due to CO, and to other molecules like SiO for stars much cooler than the Sun.

(5) Atmospheric models should be consistent with the measured photospheric magnetic flux (fB), f, and B. For the Sun one can extrapolate the measured fields upwards into the chromosphere and corona using, for example, the current-free approximation (e.g., Poletto *et al.*, 1975). This is not feasible for stars, but one may instead use the measured filling factor in the photosphere and a plausible estimate of its divergence with height to estimate the field strength in the magnetic component with height. Measurement of fB using lines formed at different heights will help in estimating these effects.

(6) Another set of constraints on multicomponent atmospheric models is that they must be consistent with such observables as the radio, X-ray, Ca II, Mg II, and other ultraviolet emission line fluxes. If either the X-ray or Ca II flux are not available, they may be estimated from the magnetic flux using empirical scaling laws (Schrijver *et al.*, 1989). Aside from the radio emission, the other observables may be computed from the emission measure distribution. The radio emission is typically gyrosynchrotron emission from mildly relativistic electrons, and is thus not simply related to the thermal distribution of electrons but is a function of the coronal magnetic fields. At present we must treat the distribution of nonthermal electrons and their volume as free parameters.

(7) Finally, the models should include the sizes and locations of starspots obtained from photometry (e.g., Rodono *et al.*, 1986) and Doppler imaging studies (e.g., Vogt and Penrod, 1983). The sizes and locations of active regions in the chromospheres and transition zones derived from emission-line Doppler imaging studies (e.g., Walter *et al.*,

1987; Neff *et al.*, 1989) are particularly useful in establishing the gross geometry of a stellar atmosphere.

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