THE MEASUREMENT OF STELLAR PHOTOSPHERIC MAGNETIC FIELDS

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1. INTRODUCTION

The credit for the first detection of magnetic fields on a star belongs to Hale who, in 1908, spectroscopically examined sunspots and determined their Zeeman splitting. Routine measurements of fields, however, did not come until the late 1940's, with the development of the magnetograph by Babcock. This measurement technique relied on the fact that the split components of a magnetically sensitive line profile had opposite senses of circular polarization. Since the displacement of these components from the central wavelength was directly proportional to the strength of the magnetic field, it was found that the degree of circular polarization measured in the wings of an appropriate spectral line could be directly related to the magnetic flux present within the resolution element, provided the degree of magnetic splitting did not exceed the Doppler width of the line. The technique was applied to the Sun with highly successful results. It was possible to show that the magnetic fields were influential in nearly every form of solar activity. They structured the atmosphere and affected the energy transport, cooling some areas (sunspots) and heating others (e.g., plages and the corona). It was also found that the fields could act as resevoirs of energy. This energy can be explosively released, resulting in flare and mass ejection events.

The Babcock technique was also highly successful in detecting magnetic fields on the Ap stars, which is a class of stars ranging from late B through early F and which have peculiar metal abundances. The fields on these stars were found to be strong and well ordered, with fluxes as high as 34,000 Gauss being reported. The technique has been less successful, however, when applied to cooler, solar like stars. Despite numerous attempts using highly sensitive instruments, reliable field detections have been rare. This might seem surprising, since many of the stars examined show activity such as chromospheric emissison, flares and starspots which, by solar analogy, are expected to be closely tied to kilogauss magnetic fields. The absence of detections, therefore, has been interpreted as implying a substantial complexity of the field configuration (e.g., Mullan, 1979). The validity of this argument is supported by the solar model. Solar plages and sunspots are commonly

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seen with field strengths of 1000-1500 gauss and 2000-4000 gauss respectively, whereas the integrated solar flux amounts to less than 1 gauss (Scherrer et al., 1977).

The object of stellar magnetic field measurements should be to measure the actual field strength, and not just the flux. To do this requires a direct measurement of the Zeeman splitting. Preston (1971) succeeded in doing this for the Ap stars, where the field strengths are sufficiently large that the Zeeman split components of a spectral line can be resolved. This is not generally the case in cooler stars. It was suggested by Robinson (1980) that the degree of magnetic splitting may be deduced by accurately comparing the profile of a magnetically sensitive spectral line with a similar, magnetically insensitive line. This technique has developed rapidly over the last 5 years and is now one of the primary means of measuring magnetic fields on cool stars.

2. THE METHOD

Consider a spectral line formed in the presence of a uniform, unidirectional magnetic field. We assume that the magnetic fields are sufficiently weak that only Russell-Saunders (L-S) coupling need be considered and that the line is a simple triplet. We further assume that the line is formed in LTE and that each component of the line is optically thin, so that effects of saturation are unimportant. Finally, we ignore the various magneto-optical effects which can influence the radiative transfer calculation. Under these conditions the observed line profile, $F(\lambda)$, will have the form:

$$F(\lambda) = C_1 F_o(\lambda) + C_2 [F_o(\lambda + \Delta) + F_o(\lambda - \Delta)] \tag{1}$$

where $F_o(\lambda)$ is the profile in the absence of magnetic splitting, C_1 and C_2 are constants dependent upon the magnetic field orientation (e.g. Unno, 1956) and Δ is the magnitude of the magnetic splitting.

We next consider the case of a line profile originating on a star which is partially covered by areas of magnetic field. For simplicity we assume a two component model in which all the magnetic field areas possess the same field strength. Taking α as the fraction of the surface covered by the fields and R to be the ratio in brightness between magnetic and non-magnetic areas, the observed line profile can be expressed as:

$$F(\lambda) = (1-\alpha)F_q(\lambda) + \alpha RC_1'F_m(\lambda) + \alpha RC_2' [F_m(\lambda+\Delta) + F_m(\lambda-\Delta)] \tag{2}$$

where F_m and F_q refer to the non-split line profiles in the magnetic and non-magnetic areas respectively. In this equation C_1' and C_2' are the constants C_1 and C_2 integrated over the orientation angles (Φ) of the field. Since the field morphology is unknown, it is normal to assume that the field elements are radially directed and more or less uniformly distributed over the surface of the star. Including foreshortening and limb darkening, the value of $\langle\Phi\rangle$ is then found to be 34 degrees (Marcy, 1982).

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To simplify equation 2 we assume that the unsplit line profiles F_g and F_m are identical and equal to F_o. This is not strictly true, since it is expected that the atmospheric structure and turbulence in the two regions should be different. However, tests on the Sun show that the assumption is not too bad (Sun et al; 1985). We further assume that the magnetic and non-magnetic areas have roughly the same brightness (as in solar plages).

The equation then takes the form (Gray, 1984):

$$F(\lambda) = (1-A_o)F_o(\lambda) + 0.5\ A_o\ [\ F_o(\lambda + \Delta) + F_o(\lambda - \Delta)\ ] \qquad (3)$$

where A_o is defined as:

$$A_o = 0.5\ \ \alpha(1 + \cos^2 \langle\Phi\rangle\ ) \qquad (4)$$

By obtaining a measure of the unsplit profile, F_o, it is thus possible to deduce the amount of magnetic splitting, Δ, from observations of a magnetically sensitive line. The value of A_o will also be obtained in the process of deconvolving the reference profile from the magnetically sensitive profile. This can then be used to derive the filling factor. Note, however, that the measured value of α will be model dependent, since we must assume a value for $\langle\Phi\rangle$.

One of the main problems with this technique is the determination of the reference profile, F_o. Robinson (1980) initially suggested that the reference line should be a magnetically insensitive absorption line whose properties were otherwise identical to the magnetically sensitive line. This method has the advantage of automatically compensating for various line broadening effects, including turbulence, rotation and instrumental broadening. The principal disadvantage is the requirement of unblended line pairs. Because of the abundance of spectral lines in cool stars this requirement severely restricts the number of available lines; Robinson (1980) was only able to find 6 suitable line pairs in the entire optical solar spectrum. Even these had some blends and in no case was the reference line completely insensitive to magnetic field splitting.

To overcome these problems several groups have successfully tried modelling the reference line (e.g., Gray, 1984; Saar and Linsky, 1985; Saar, Linsky and Beckers, 1985). In this method the basic properties of the atmosphere are determined from magnetically insensitive lines. This atmosphere is then used to deduce the unsplit profile for the magnetically sensitive line. The reference line will therefore be free of noise and blends. Further, a variety of magnetically sensitive lines can be examined and consistency of the results determined; i.e., all lines should give nearly the same field strength and the degree of splitting should be linearly proportional to the magnetic sensitivity of the line. The main disadvantage, of course, is the uncertainties in the radiative transfer calculations.

A final method, employed by Giampapa et al., (1983), uses a reference line measured from an inactive, slowly rotating reference star. The profile is then broadened so that the magnetically insensitive line profiles for the two stars match. It has been claimed that this method will account for small blends present in the profile. This may not be the case, however, if there are significant inhomogeneities on the surface of the active star (e.g. starspots).

Once the reference profile has been deduced it is necessary to use it to determine the degree of magnetic splitting. Thus far, two analysis techniques have been used. The first involves a non-linear, least squares analysis using the two component model presented in equation (3). This was first suggested by Marcy (1982), who used a measured reference line and then adjusted the magnetic filling factor, α and the splitting, Δ, until the model matched the observation. This method was later improved by Saar (1985), who used modelled reference lines and incorporated the line to continuum opacity ratio as well as α and Δ into his non-linear fitting procedure. In this way he was able to take saturation effects into account.

The original technique, suggested by Robinson (1980), involved Fourier deconvolution. Here it was noticed that a Fourier transform of equation (3) had the form:

$$f(\kappa) = (1-A_o)\ f_o(\kappa) + A_o\ f_o(\kappa)\cos(2\pi\Delta\kappa) \qquad (5)$$

where $f(\kappa)$ and $f_o(\kappa)$ are the Fourier transforms of the split and un-split profiles. Thus, dividing $f(\kappa)$ by $f_o(\kappa)$ resulted in a function which had a constant term related to the strength of the central component and a cosine term whose amplitude measures the strength of the split components and whose frequency relates to the degree of Zeeman splitting.

3. LIMITATIONS

Regardless of the details of analysis, it is important to recognise that this field measurement technique has a number of limitations. In illustrating these I will refer to the Fourier transform technique, since the various effects are most apparent in this case. Note, however, that the same limitations apply to the least squares fitting analysis.

In figure 1 we have plotted sample experimental points which might be found after dividing $f(\kappa)$ by $f_o(\kappa)$. Note that the error bars for these samples tend to increase towards higher Fourier frequencies. The decrease in strength towards higher frequencies is a definite indication that magnetic fields are present. However, as pointed out by Gray (1984), there may be an ambiguity concerning the actual strength of these fields. In the figure I have plotted the variations expected from three different model stars, containing fields of different strengths and filling factors. As seen, these three models could be separated provided reliable measurements exist to sufficiently high Fourier frequencies. If these measurements do not exist, then only the factor $BA_o^{1/2}$ can be determined. Further, if only the lowest frequencies can be measured it would be impossible to detect any magnetic fields at all. Thus, our ability to measure magnetic fields rests largely on the ability to measure the high Fourier components of the relevant spectral lines. Factors which affect these measurements include the following:

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1. The spectral resolution places an upper limit on the frequency which can be measured.

2. The signal to noise ratio determines the reliability of the measurements. This is especially important at high frequencies where the strength of the noise can equal or exceed that of the signal. The effects of noise are enhanced when the Fourier transforms are divided.

3. The width of the spectral lines governs the frequency at which a given amount of noise will dominate the signal. This is because the broader the spectral line, the more rapidly the Fourier transform decreases.

4. Blends with other spectral lines will produce an effect very similar to noise. A weak blend, for example, will produce a small cosine component to the Fourier transform whose frequency depends on the relative position of the line (Gondoin et al., 1985). Stronger blends may show up as a false magnetic signal, so that measurements from a number of magnetically sensitive lines are desirable.

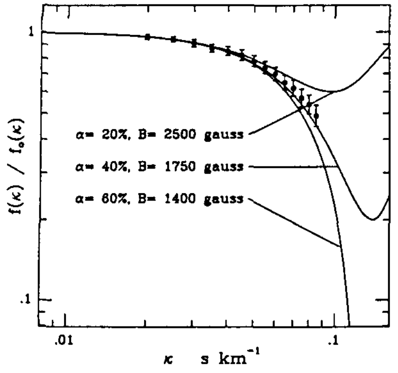

Figure 1. Ambiguity in field measurements. Filled circles show possible experimental measurements of $i(\kappa)/i_o(\kappa)$. Solid lines show three possible model fits. The spectral line is assumed to have a lande-g value of 2.5 and a wavelength of 6000A.

There are also a number of uncertainties related to our basic assumptions. For example, ignoring saturation effects results in an overestimate of the area coverage (Saar, 1985), while a breakdown in the triplet approximation causes us to underestimate the area (Gray, 1984). Fairly serious problems can also result from ignoring the distribution of field strengths, especially if fields having a wide range of intensities are present. In this case the assumption of a single field strength will result in an overestimate of the average field intensity and an underestimate of the filling factor (Gray, 1984). In extreme cases the errors can be 50% or more. This is an inherent weakness of The least squares fitting analysis, since it must implicitly assume a single field strength. In principal, however, the Fourier transform method could detect a variety of strengths (Robinson, 1980). The quality of data required, though, would have to be much higher than any obtained thus far.

4. RESULTS

Despite the difficulties involved in making the measurements and the uncertainties in their interpretation there have been a number of significant results to emerge over the last few years. Possibly the most important of these is the experimental verification that kilogauss fields exist on a wide variety of cool stars (see Marcy, 1984; Gray, 1984, 1985). These detections have been made by a variety of groups, using several different analysis schemes and a variety of spectral lines. Overall, they confirm observationally the long held hypothesis that stellar activity is closely connected to the presence of magnetic fields.

From a sample of 60 stars observed to date, a total of 31 have had positive field detections. In all but one case these detections have occured on dwarfs, with spectral types ranging from G0 (Gray, 1984) through M3.5 (Saar and Linsky, 1985). The single reported detection on a giant was for the spotted RS CVn star λ And (Giampapa et al, 1983). Subsequent attempts to repeat this detection, however, have been unsuccessful (Gondoin et al., 1985). Field strengths ranging from 600 gauss to 3800 gauss have been deduced along with magnetic filling factors, α, ranging up to 89%. In all cases these seem to represent fields present in plage-like regions, firstly because all but 3 of the stars thus far observed have no evidence of starspot activity and secondly the magnetic filling factors derived for the spotted stars are too large (e.g., Saar, Linsky and Beckers (1985); Giampapa et al., 1983). Thus, the question of the presence and strength of magnetic fields in starspots remains open.

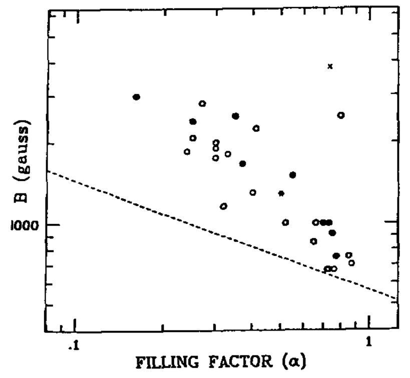

Figure 2. A summary of stellar magnetic field strengths and filling factors observed to date. Solid circles, open circles and crosses represent G, K and M stars respectively. The dashed line represents the detection limit (Marcy, 1982) for profiles with a signal to noise ratio of 100:1.

A summary of the results is presented in Figure 2. In viewing these results it is important to keep in mind the fact that the product $B\alpha^{1/2}$ is more precisely determined than either B or α alone. Note also that many of the measurements of small field strengths are very near the detection limit.

A striking feature of this diagram is that the majority of stars of spectral type G and K follow a moderately tight relation which has the form $\langle B\alpha \rangle = 500$ gauss. This led Gray (1985) to suggest that there existed a universal magnetic constant for cool, active stars which was independent of both rotation rate and spectral type. While this is an intriguing possibility, it apparently does not hold for all stars. Recent observations by Saar and Linsky (1985) and Saar et al., (1985), for example, have shown that the extremely active stars EQ Vir and AD Leo have values of $\langle B\alpha \rangle$ of 2000 and 2700 Gauss respectively. At the other extreme the Sun has an overall value of $\langle B\alpha \rangle$ of order 30, i.e., well below the predicted value. Even in a solar plage the value of $\langle B\alpha \rangle$ seems to reach values of only 400 gauss (Sun et al., 1985).

In examining the current magnetic field detections it becomes readily apparent that the strength and/or area coverage of the fields can vary substantially, sometimes over very short time scales. The magnitude of these variations was not appreciated initially and caused some early concern regarding the reliability of the measurement technique. For example, Robinson, Worden and Harvey (1980) reported fields on ξ Boo A with a strength of 2600 Gauss and covering 20-45% of the surface. Later, Marcy (1981) was unable to reproduct this observation, despite the fact that his data would have been able to detect a 2600 Gauss field provided it covered at least 6% of the stellar surface. Marcy (1984) later succeeded in detecting the fields on ξ Boo A, though his deduced strength was smaller and area coverages larger than those reported by Robinson, Worden and Harvey (1984). Since these fluctuations were accompanied by changes in both the CaII H and K and the X-ray fluxes, it is now thought that they relate to a type of activity cycle. More dramatically, substantial changes in magnetic intensity have been observed from one night to the next. For example, Marcy (1984) reports a series of observations on ϵ Eri, one measurement per night for 4 consecutive nights, which show field strengths of 620, 700, 2800, and 700 Gauss for the respective nights. It is interesting to note that the filling factor decreased from 88% to 20% as the field strength increased, so that $\langle B\alpha \rangle$ remained relatively constant at 600 Gauss. This behaviour, if real, lends support to Gray's concept of a magnetic constant, at least on some stars. Surprisingly, integrated Ca H and K fluxes taken at the same time as the field measurements showed no substantial variation.

Despite the field variations and the basic ambiguities in separating the field strength from the filling factor, there are several trends emerging which relate the field properties to the spectral type and rotation rate of the stars. On the Sun, plage fields are confined to small knots whose maximum field pressure equals the phtospheric gas pressure (Galloway and Weiss, 1981). This also seems to be the case on other stars, where field pressures equalling the gas pressure have been measured on a few highly active objects (Saar et al., 1985; Giampapa et al., 1983). In no case has the field pressure been observed to exceed the gas pressure, though there are a number of cases where the gas pressure dominates (Marcy, 1984; Gray, 1984). This fact has been used by Marcy and Bruning (1984) to explain the lack of magnetic field detections for their sample of spotted giants.

Attempts to relate the field properties to the stellar rotation rate are generally inconclusive. Thus far the rotation does not appear to greatly affect the field strength, though there are indications that the filling factor and possibly the value of $\langle B\alpha \rangle$ increase with increasing rotation (e.g. Marcy, 1984). This trend is consistent with the behaviour predicted by most dynamo theories (Gilman, 1982). Note, however, that the number of samples is small and the measurement technique is restricted to slowly rotating objects.

Finally, it is possible to compare the field measurements to observations of magnetically related stellar phenomena. Marcy (1984) examined the relationship between the field characteristics and the strength of the CaII H and K flux. He concluded that CaII flux was related to the quantity $(B\alpha)^{1/2}$ and that this was most consistent with slow-mode MHD waves as the source of chromospheric heating. Comparisons with soft X-ray measurements have been made by a variety of authors including Marcy (1984), Giampapa et al., (1983) and Saar and Linsky (1985). Using scaling laws derived from the solar observations these authors have shown that the observed X-rays are compatible with values expected using the measured magnetic fields. The physical processes responsible for solar X-rays are thus likely to be similar to those operating on other stars.

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