SPECTROSCOPY AND GEOGRAPHY OF MAGNETIC AP STARS: IMPLICATIONS FOR STRUCTURE

J. D. LANDSTREET
Department of Astronomy
University of Western Ontario
London, Ontario N6A 3K7
Canada

ABSTRACT. Some main sequence A and B stars have strong, ordered magnetic fields. These Ap and Bp stars usually have anomalous chemical abundances, and often rather non-uniform distributions of at least some elements (e.g. He, Ca, Ti, Cr) over their surfaces. Maps of magnetic field structure may provide a means of testing theories of how large coherent fields form, and of probing large-scale hydrodynamic flows (meridional circulation) inside stars. Maps of distributions of various elements can help to elucidate the mechanisms, such as diffusion under competing influences of gravity and radiation, turbulence, meridional circulation, mass loss, and perhaps accretion from the interstellar medium, that lead to the distinctive abundances and surface abundance distributions. This kind of mapping is important as an aid to understanding how the Ap and Bp stars develop. It is even more important because the processes involved in producing Ap and Bp stars probably have significant effects on surface chemical abundances of "normal" upper main sequence stars, and so understanding the relevant physics is essential to correctly relating observed surface chemistry to stellar and galactic evolution. In this paper, efforts to map field and abundance structures in Ap stars are reviewed, and some of the principal results obtained thus far are discussed.

1. Introduction

A significant fraction, of the order of 10%, of upper main sequence stars are spectroscopically peculiar. Some of these peculiar stars have strong (~ 3×10^2 - 3×10^4 G), globally ordered (roughly dipolar) magnetic fields. These magnetic Ap and Bp stars occur for T_e in the range of about 7000 to 20,000 K, with distinctive chemical abundance anomalies that are roughly correlated with T_e. The coolest magnetic Ap's show unusually strong lines of such elements as Sr, Cr, and

G. Michaud and A. Tutukov (eds.), Evolution of Stars: The Photospheric Abundance Connection, 161–171.

rare earths. Between about 10,000 and 14,000 K the most obvious anomaly is excess Si. Still hotter magnetic stars have an obvious He deficiency, and the hottest magnetic stars show anomalously strong He lines. Other spectrally anomalous stars are found in this temperature range that are not known to have strong fields. At the cool end ($T_e \sim 7,000 - 10,000$ K), the Am stars have modestly overabundant Fe peak elements and underabundant Ca and/or Sc. The λ Boo stars, also mid to late A stars, appear to have mild underabundances of most elements. In the temperature range of 11,000 - 16,000 K, the Ap HgMn stars have striking overabundances of a few elements such as P, Mn, Ga, Zr, and Hg. At still higher temperatures, some He-weak stars appear to be without strong fields. (A general review of upper main sequence peculiar stars may be found in Wolff (1983)).

The large variety of chemical anomalies in this range of effective temperatures testifies to the occurrence of powerful chemical segregation processes. These processes are revealed particularly clearly in the Ap and Bp stars, but they almost certainly occur to some extent in all upper main sequence stars. *It is therefore essential to understand these processes so that we can correctly interpret observed atmospheric abundances in A and B stars to know to what extent observed abundances reflect the abundances in the interstellar medium from which the stars form, and to what extent the initial abundances have been modified by envelope and atmosphere processes and by internal evolution.* In understanding the physics of the segregation processes that operate, the peculiar stars will play a very important role, since it is in these stars that the separation processes have had the most marked effect.

An example of what may eventually be learned by studying peculiar upper main sequence stars is provided by the magnetic Ap and Bp stars. Such stars are pervaded by global magnetic fields, whose structures are not observed to change dramatically on short time scales ($\lesssim 10^2$ years). It is widely suspected that the fields are fossil fields, left over from the epoch of star formation. These fields might have been produced by compressing the weak interstellar field as the star formed, or by dynamo action during the convective pre-main sequence phase. After arrival of the star on the main sequence, the initial field structures are further modified by global hydrodynamic flows inside the star; by structure changes due to stellar evolution; and by ohmic decay, especially of magnetic structures considerably smaller in size than the whole star (cf. Borra et al. (1982), Moss (1989), and references therein). Because the magnetic field structure, including the surface morphology, is affected by the internal structure and evolution of the star as well as by initial conditions, it should be possible to use maps of surface field structure in a variety of stars to probe stellar interiors.

These magnetic stars are often observed to show periodically variable spectra, which is interpreted as revealing non-uniform surface distributions of chemical elements, in addition to the non-solar average abundances noted above. Clearly powerful chemical separation mechanisms operate. Chemical segregation mechanisms such as diffusion are sensitive to internal hydrodynamic flows, to convection, and to mass loss, and maps of element distributions for a variety of stars should provide powerful tests of, and constraints on, theoretical models of flows, convection, and mass loss as they occur in these stars.

At present we are just learning how to derive reasonably adequate maps of magnetic field structure and element distribution from observations in the most favourable cases. We are still far from being able to obtain unique, reasonably high resolution maps for the majority of magnetic Ap and Bp stars. However, some results are now available from which at least a few conclusions may be drawn. In this paper, I shall survey current methods for mapping magnetic stars, and examine the conclusions that are suggested by the limited results so far.

2. The Magnetic Field Distribution

The basic model of a magnetic Ap or Bp star with which current mapping efforts proceeds is the oblique rotator model (Stibbs 1950). According to this model, a magnetic Ap or Bp star has a surface magnetic field strength distribution that has an important dipolar component. The intrinsic field strength distribution over the star is believed to be essentially unchanging with time, at least on time scales of interest to observers. However, the dipole axis is typically inclined to the rotation axis of the star, and so as the star rotates, the field is presented from various aspects to the observer. In favourable cases, where the stellar rotation axis has an inclination $i \sim 90^\circ$ (the axis is roughly normal to the line of sight to the star), and the dipole component of the field makes a large angle $\beta \sim 90^\circ$ with respect to the rotation axis, rotation of the star allows the observer to examine the field structure from one magnetic pole to the other.

A surface magnetic field is detectable via the Zeeman effect, which splits spectral lines into groups of π and σ components with separation (for the field strengths of interest here) that are proportional to the local field strength. This splitting can sometimes be directly detected in disk-averaged line profiles, especially of spectral lines that have unusually large splitting. In this case, a measurement of the field modulus $|B|$ averaged over the visible hemisphere (with appropriate weighting by limb darkening, line weakening, and perhaps abundance non-uniformity) is possible. (The inferred mean field modulus is often called the mean surface field, B_s.) In practice it is very difficult to measure B_s unless the field is large and v sin i is small; the field must satisfy roughly B_s(kG) $\gtrsim$ v sin i (km s^{-1}) to be detectable. Only a

https://doi.org/10.1017/S0074180900227344 Published online by Cambridge University Press

small fraction of known magnetic Ap and Bp stars satisfy this relationship (Preston 1971a; Mathys 1990).

A more robust means of measuring the stellar magnetic field is made possible by the fact that the Zeeman components of a line are polarized. If the local magnetic field is perpendicular to the line of sight, the π component of the local absorption line is linearly polarized normal to the local field, while the σ components are linearly polarized parallel to the field vector. If the local magnetic field is parallel to the line of sight, no π component absorption occurs, and the two σ components have opposite circular polarizations. The last fact offers a particularly effective means of measuring the line of sight component of a stellar magnetic field, since it means that the radial velocity of a spectral line will be different when the line is observed in right and left circularly polarized light. Equivalently, if the circular polarization through a spectral line formed in a magnetic field with a net longitudinal field is measured, the two wings of the line are found to be circularly polarized with opposite signs. These effects may be detected with purely differential measurements, and do not require accurate knowledge of the intrinsic non-magnetic line profile. Consequently, a non-zero mean longitudinal field component (B_l) may be measured in the most favourable cases when it is as small as ~100 G (Borra and Landstreet 1980; Landstreet 1982; Bohlender and Landstreet 1990; Donati et al. 1990). This field moment has been measured for a large number of Ap and Bp stars, using both metal lines, mostly observed photographically (see Babcock 1960), and Balmer lines of H, measured photoelectrically (Borra and Landstreet 1980).

If now the field moments B_l and perhaps B_s can be measured for a particular star as a function of phase as the star rotates, they provide information about the magnetic field distribution over the surface of the star. The most common situation is that B_l can be measured but B_s cannot. The variation of B_l with rotation is usually found to be nearly a simple sine wave (Borra and Landstreet 1980), and often shows both positive and negative values during one rotation period. This is precisely what one would expect if the mean longitudinal field of a dipolar field distribution is observed in a star with $i \sim \beta \sim 90$ (both dipole field axis and line of sight roughly normal to the stellar rotation axis),as first shown by Stibbs (1950). The common observation of sinusoidal B_l variation is taken to indicate that the field distribution of an Ap/Bp star usually contains a large dipolar component. The occasional detection of a star in which the observed value of B_l never changes sign, although it may still vary sinusoidally, is easily explained as a situation in which both i and β are considerably smaller than 90°; in this case the observer only sees one magnetic hemisphere as the star rotates.

The sinusoidal variation of B_l usually observed does not imply that the field distributions of most Ap and Bp stars are actually

https://doi.org/10.1017/S0074180900227344 Published online by Cambridge University Press

nearly dipolar. It is found from calculations (Schwarzschild 1950) that higher multipoles have enough field cancellation over an observed hemisphere to make only a small contribution to B_l unless the field distribution is actually dominated by a non-dipolar component. The observed variation of B_l thus usually serves only to constrain the dipole field component. If one can deduce i from the known rotation period, v sin i, and an estimated stellar radius, the observed variation of B_l allows one to infer the approximate strength of the dipole component of the field distribution (measured for example by the polar field strength B_d) and the obliquity β (e.g. Landstreet 1980; Borra and Landstreet 1980).

In rare cases the variation of $B_l(\phi)$ is strikingly non-sinusoidal. In these situations the field distribution is certainly not well approximated as a simple dipole. HD 133880 appears to have a quadrupole field component (measured by its polar value B_q) at least 1.3 times stronger than the dipole component (Landstreet 1990). HD 32633 (Renson 1984) and HD 37776 (Thompson and Landstreet 1985) may have still more complex field distributions.

Measurements of B_l are now available for more than 100 stars (Didelon 1983). From these data a number of statistical deductions may be made. Looking at a magnitude-limited sample of bright Ap and Bp stars (Borra and Landstreet 1980), we may form for each star the rms average $\langle B_l^2\rangle^{1/2}$ of the observed $B_l(\phi)$. The median value of this quantity in the sample is about 250 G. For a single star the dipole polar field B_d is about three times larger than the value of B_l observed when the star is observed pole-on (Schwarzschild 1950),and so we infer typical surface fields of the order of 1 kG for the magnetic Ap and Bp stars. The highest known surface fields reach ~ 30 kG. The smallest seem to be of the order of 300 G (Bohlender and Landstreet 1990a).

The fraction of stars in a sample for which B_l reverses sign gives information about the statistical distribution of the obliquity angle β, even for stars for which i is so uncertain that β cannot be derived with any precision. This question has been examined by Preston (1967, 1971b), Landstreet (1970), Stibbs (1975), and Borra and Landstreet (1980). Sample size still strongly limits the conclusions that may be drawn, but the observations are consistent with both a random distribution of magnetic axes relative to the rotation axis (which of course leads to most values of β being large), and with a bimodal distribution having roughly equal numbers of stars with $\beta \sim 20^\circ$ and $\beta \sim 80^\circ$. The assumption that almost all stars in the sample have large β ($\sim 80^\circ$) is not consistent with observation

When the distribution of $\langle B_l^2\rangle^{1/2}$ is considered as a function of stellar mass, there is evidence that the typical fields in stars earlier in spectral type than about B4 are roughly a factor of three larger than those of cooler magnetic stars (Thompson _et al_. 1987).

Efforts have also been made to see if systematic changes in field strength with stellar age occur, at least during the main sequence phase of evolution. Theoretically one might expect some decline in average field as a star evolves away from the zero-age main sequence, due to geometrical expansion of the star, which will dilute field strengths roughly as $B \sim R^{-2}$. There may also be some ohmic decay, but this is expected to be small. Rotation should lead to internal meridional circulation currents that may steadily distort an initial field (Moss 1984 a, b). The observations suggest that at most a modest decline in field strength occurs as a star evolves from the zero-age main squence to about the middle of its main sequence lifetime, and this is roughly consistent with present theory (Thompson et al. 1987).

Thus even with rather crude and limited information about stellar magnetic fields, we can begin to provide some constraints or theories of how coherent magnetic fields form and evolve.

For a few stars, the variation of B_s (or of magnetically distorted line profiles) has also been measured as a function of rotational phase. In these cases much more highly constrained models of magnetic field distribution are possible. If the actual stellar field is a combination of colinear dipole and quadrupole components with $B_q \sim 0.5\ B_d$, for example, the variation of B_l is still nearly the same as with $B_q = 0$. However, because a quadrupole has opposite parity to a dipole, the polar fields add in one hemisphere but cancel in the other, so the value of B_s is considerably larger around one pole than around the other. Thus observing Zeeman splitting in line profiles can constrain higher order multipole components of the field distribution.

At present, the available models of even the best observed stars are still restricted to at most a three term expansion, with colinear dipole, quadrupole, and octupole components. The most striking feature that emerges from these models is that an important quadrupole component is always present. In β CrB, the ratio B_q/B_d seems to be around 0.3 (Wolff and Wolff 1970); for 53 Cam, we find $B_q/B_d = 0.45$ (Landstreet 1988); in HD 215441 the ratio seems to be larger than 0.3 and may be as large as 1.0 (Landstreet et al. 1989); and in HD 126515 it appears that the ratio is larger than one (Preston 1970). In other words, all the stars for which measurements sensitive to higher order multipoles are available seem to have field distributions that are not simply dipolar. In general the field strengths at the two magnetic poles are not equal. But finer details of the field structure are not yet available.

None of the modelling discussed above makes full use of the available data that could be used to constrain the magnetic field structure observationally. Some modelling is based only on measurement of one or two simple moments of the field; other work models only a small number of spectral lines. Further information may be obtained by using to more spectral lines simultaneously and by obtaining detailed spectropolarimetry through lines. A promising approach to more constrained models of field structure is based on statistical analyses of line profiles (Mathys 1988). The numerical modelling technique used by Landstreet (1988) is capable of being expanded to considering several lines at once (Landstreet et al. 1989) and polarization data, but this scheme assumes a model for the field structure (an expansion in multipoles), and requires a very large computational effort. A still more powerful method of modelling field structure that makes no assumptions about field geometry, and that is numerically more efficient is currently being developed by Piskunov. This new modelling programme will no doubt press the available observations to the limit.

3. Chemical Abundance Distributions

Spectrum variability is a common but not universal phenomenon among magnetic Ap and Bp stars. It occurs in a very distinctive form that easily sets it apart from the spectrum variability of pulsating stars: lines of some elements stay roughly constant as the star rotates, while lines of other elements vary dramatically with the period of rotation. When lines of one element are variable, both the neutral and ion lines vary in strength in phase.

These spectrum variations are now universally ascribed to a non-uniform distribution of the variable elements over the surface of the star. When comparisons of spectrum variations are made with magnetic observations, it is apparent that the distribution of individual elements is in some way closely tied to the dipolar magnetic field component. The maximum line strength of an element usually occurs as one of the magnetic poles passes closest to the line of sight, and one is led to imagine a patch of enhanced abundance of that element near the pole. A striking feature of such patches is that normally several elements will have patches of enhanced abundance only near one pole. The other pole will usually have enhanced patches of some other elements. This feature of element distributions was very puzzling until it was realized that the field strengths at the two poles are typically unequal; a simple centred dipole is not a very close approximation to the actual field distribution. The commonly present quadrupole component describes the fact that concentration of flux lines is different at the two poles, and this apparently leads to element distributions that are not symmetric to reflection through the magnetic equator (Landstreet 1970).

As these abundance patches rotate around the stellar rotaion axis, they produce variations in line profile as well as equivalent width, and these profile changes can be extremely valuable in locating patches on the stellar surface. The amount of blue shift as a patch comes into view depends on its latitude on the star; matter close to the rotational pole has only a small doppler shift while matter near the equator has a much larger shift. This fact

https://doi.org/10.1017/S0074180900227344 Published online by Cambridge University Press

means that detailed line profiles contain information about the two-dimensional distribution of an element over the stellar surface that may be recoverable by suitable modelling, and a number of individuals and groups have worked on the problem of deriving a surface abundance map from observed line profile variations. An excellent review of work on this problem may be found in Khoklova (1985).

A variety of analytical and numerical techniques have been used to attack this modelling problem (see references in Khokhlova 1985). At present, most modelling is being done using two rather different approaches.

One line of attack is to work on stars that have observed line profiles dominated by rotational broadening. In practice this means studying stars that satisfy roughly $20 \lesssim v \sin i \lesssim 50$ km s^{-1}. At lower v sin i instrumental and magnetic broadening dominate and the essential information furnished by doppler shifts is lost; at high v sin i blending becomes too severe. In general this line of work has concentrated on stars with intrinsically weak magnetic fields ($B_s \lesssim$ 1 kG) so that the local line profiles are not greatly widened or intensified by the field. In this regime, modelling of the variation with rotation of a single unblended spectral line can be made to yield a surprisingly detailed two-dimensional map of the distribution of local spectral line parameters (essentially local equivalent width). To obtain a unique model, an auxiliary requirement must be imposed; this is normally a requirement that the model have the "smoothest" abundance distribution consistant with the observations. In addition, the inclination i must be estimated; this is not usually furnished by the mapping solution. Tests of this technique include creating artificial data and then using it to recover the initial assumed abundance distribution, and producing maps from two or more lines of the same chemical element. It is found that the most successful maps (wide coverage of the stellar surface, discrimination between the two rotational hemispheres) are possible for stars with $30^\circ \lesssim i \lesssim 70^\circ$. As the observed spectral lines are formed mainly within 40 or 50° of the subsolar point on the observed stellar disk, the maps are most reliable for a stripe about 90° wide around the rotation axis centred on latitude $(90^\circ - i)$ and are much less reproducible outside this band. Of course, if i is much different from 90°, a region near one rotational pole is never seen, and maps will always lack this region.

One limitation of this method of mapping is that the stars studied are generally those for which only minimal information about the magnetic field is available. Since the stars are selected to have large v sin i and small B_s, only the constraints provided by $B_1(\phi)$ are available, which means that β is known only if i can be determined fairly well, and nothing is known about any field component except the dipole. However, the maps obtained can be compared with estimated locations of the poles of the dipole in some cases.

Modelling of this sort has now been carried out for a number of stars including ε UMa (Wehlau et al. 1982; Hatzes 1988; Rice and Wehlau 1990), α^2 CVn, CU Vir and χ Ser (Goncharskii et al. 1983; Khokhlova and Pavlova 1984), ϑ Aur (Khokhlova et al. 1986), and γ^2 Ari (Hatzes et al. 1989).

A clear feature of the maps derived is the occurrence of large variations in local equivalent width over the surface of the stars, although since the maps have not mainly been converted into abundances (a conversion which may depend on magnetic field structure), it is not straightforward to interpret the results theoretically. In some cases (Eu in α^2 CVn, Si in γ^2 Ari, Cr and Fe in ε UMa), the abundance maxima or minima appear to occur around one magnetic pole (or around both, but typically with different strengths). In others (Si in CU Vir; Fe, Cr, and Ti in α^2 CVn; Fe, Cr, and Si in ϑ Aur) the nominal pole position is not close to any of the abundance maxima (which for some reason tend to occur in the maps close to the latitude of the subsolar point). In still other stars (χ Ser), not enough information is available about the field to say anything about the locations of magnetic poles. Notice that for most of these stars there are significant uncertainties in the longitude as well as the latitude of the magnetic poles, due to uncertainties in period or epoch of maximum observed B_l.

A rather different approach to the modelling problem is to concentrate on the few stars for which high resolution, high signal-to-noise spectra contain information both about doppler shifts due to abundance non-uniformities and about magnetic field structure. In such stars, simultaneous detailed modelling of magnetic and abundance distributions should be possible. In this case, the *local* line profiles are *strongly* affected by the magnetic field (Zeeman splitting is typically much larger than thermal line widths), with dependance on local abundance, field strength and direction, and inclination of line of sight to the local normal, and so a much greater effort must be devoted to modelling local line profiles than is required when magnetic effects may be neglected. Furthermore, at each point on the stellar disk, one has not only to determine the local abundance but also field strength and orientation. Intrinsically, then, this is a more complex modelling problem than the case where the magnetic field may be neglected. One may simplify the modelling process to compensate (for example, by reducing the resolution of the maps or by describing abundance and field distributions by simple models with few adjustable parameters); otherwise, a very large set of observational data and a huge computational effort are required.

Models calculated along these lines have been reported for 53 Cam (Landstreet 1988), HD 215441 = Babcock's star (Landstreet et al. 1989), and HD 64740 (Bohlender and Landstreet 1990b). Further modelling of other stars (CS Vir, HD 32633, HD37776, etc.) is in progress. In this work, the magnetic field is described by a simple three term expansion in co-linear dipole, quadrupole, and octupole components. The abundance distribution of each element (normally three or more elements are modelled), is assumed to be axisymmetric about the magnetic axis, and the resolution in magnetic co-latitude is 30° or coarser. However, fairly realistic line profiles are calculated, including magnetic splitting of each line, the effects of radiative transfer of polarized light, and blending. Such simple models are not really adequate to describe the stars studied in detail, but they do fit the observations fairly well. For such modelling, uniqueness is not enforced by a smoothness condition; instead, a search is made for various acceptable models to explicitly consider the uniqueness question and if necessary the resolution (number of parameters) is degraded until the model becomes unique. Note that these models yield (coarse) maps of abundance, not (local) equivalent width.

Several significant empirical results emerge from models of these high-field stars. First, absolute abundance levels of a number of elements are enhanced relative to solar abundances by large factors, typically 1-3 dex, even after magnetic line intensification effects are considered. Even the cosmically very abundant substances Si and Fe can be enhanced by 1-2 dex over most of a star. Secondly, as suggested by previous models, in a given star large abundance contrasts, of order 1-2 dex averaged over regions of ~ 30° in width, occur for some elements while other elements are nearly uniformly distributed. Furthermore, different elements have high contrast in different stars. For example, in 53 Cam ($T_e \cong 8500$ K) Fe, Cr, and some rare earths are roughly uniformly distributed, Ti is concentrated around the strong magnetic pole, and Ca is concentrated near the weak magnetic pole. In the slightly hotter ($T_e \cong 9500$ K) star CS Vir, Fe and Ti are roughly uniform, Cr is concentrated near one pole, and a number of rare earths are concentrated near the other pole.

A nice example of how abundance and field maps of stars may help to clarify the theoretical situation regarding important physics occurring in stellar atmospheres and envelopes is provided by some work recently completed by Babel and Michaud (1990). They have tried to account for the map of 53 Cam assuming that both the overall level of abundance anomalies and their geographic distributions relative to the magnetic field are due to diffusion only. They find that the overall abundances but *not* the distributions are compatible with the hypothesis. It seems to be necessary to involve at least one more process to explain the maps. Babel and Michaud identify a magnetically controlled stellar wind with a mass loss rate in the range of 10^{-12} - 10^{-14} $M_\odot$/yr as the likely additional process which must be included. They thus infer the existence of, and the possibility of studying, a wind at a level which is very hard to detect by direct observation.

4. References

Babcock, H.W. 1960, in *Stellar Atmospheres*, ed. J.L. Greenstein, University of Chicago Press, Chicago, p.282.

Babel, J. and Michaud, G. 1990, submitted to *Ap.J.*

Bohlender, D.A. and Landstreet, J.D. 1990a, *Ap.J. (Letters)*, in press.

Bohlender, D.A. and Landstreet, J.D. 1990b, *Ap.J.*, in press.

Borra, E.F. and Landstreet, J.D. 1980, *Ap.J. Suppl.*, **42**, 421.

Borra, E.F., Landstreet, J.D., and Mestel, L. 1982, *Ann. Rev. Astr. Ap.*, **20**, 191.

Donati, J.-F., Semel, M., and del Toro Iniesta, J.-C. 1990, submitted to *Astr. Ap.*

Goncharskii, A.V., Stepanov, V.V., Khokhlova, V.L. and Yagola, A.G. 1983, *Sov. Astr.* **26**, 690.

Hatzes, A.P. 1988, in *The Impact of Very High S/N Spectroscopy on Stellar Physics*, ed. G.C. Cayrel de Strobel and M. Spite, Kluwer Academic Publ., Dordrecht, p.199.

Hatzes, A.P., Penrod, G.D., and Vogt, S.S. 1989, *Ap.J.*, **341**, 456.

Khokhlova, V.L. and Pavlova, V.M. 1984, *Sov. Astr. Letters*, **10**, 158.

Khokhlova, V.L. 1985, *Sov. Sci Rev. E. Ap. Space Phys.*, **4**, 99.

Khokhlova, V.L., Rice, J.B., and Wehlau, W.H. 1986, *Ap.J.*, **307**, 768.

Landstreet, J.D. 1970, *Ap.J.*, **159**, 1001.

Landstreet, J.D. 1980, *Astr. J.*, **85**, 611.

Landstreet, J.D. 1982, *Ap.J.*, **258**, 639.

Landstreet, J.D. 1988, *Ap.J.*, **326**, 967.

Landstreet, J.D., Barker, P.K., Bohlender, D.A. and Jewison, M.S. 1989, *Ap.J.*, **344**, 876.

Landstreet, J.D. 1990, *Ap.J. (Letters)*, **352**, L5.

Mathys, G. 1988, *Astr. Ap.*, **189**, 179.

Mathys, G. 1990, *Astr. Ap.*, in press.

Moss, D. 1989, *M.N.R.A.S.*, **236**, 629.

Preston, G.W. 1967, *Ap.J.*, **150**, 547.

Preston, G.W. 1970, *Ap.J.*, **160**, 1059.

Preston, G.W. 1971a, *Ap.J.*, **164**, 309.

Preston, G.W. 1971b, *Pub. A.S.P.*, **83**, 571.

Renson, P. 1984, *Astr. Ap.*, **139**, 131.

Rice, J.B. and Wehlau, W.H. 1990, submitted to *Astr. Ap.*

Schwarzschild, M. 1950, *Ap.J.*, **112**, 222.

Stibbs, D.W.N. 1950, *M.N.R.A.S.*, **110**, 395.

Stibbs, D.W.N. 1975, in *Physics of Ap Stars*, ed. W.W. Weiss, H. Jenkner, and C. Jaschek, Universitatsternwarte Wien, Vienna, p.456.

Thompson, I.B. and Landstreet, J.D. 1985, *Ap.J. (Letters)*, **289**, L9.

Thompson, I.B., Drown, D.N. and Landstreet, J.D. 1987, *Ap.J. Suppl.*, **64**, 219.

Wehlau, W.H., Rice, J.B., Piskunov, N.E. and Khokhlova, V.L. 1982, *Sov. Astr. Letters*, **8**, 15.

Wolff, S.C. and Wolff, R.J. 1970, *Ap.J.*, **160**, 1049.

Wolff, S.C. 1983, *The A-Type Stars: Problems and Perspectives*, NASA SP-463, Washington.