THE STRUCTURES AND SPECTRA OF MAGNETIC, LINE-BLANKETED MODEL ATMOSPHERES

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ABSTRACT

Magnetic, line-blanketed model atmospheres for upper–main-sequence stars with normal elemental abundances and a slightly distorted dipolar magnetic field have been constructed. These were computed with a modified version of the Kurucz ATLAS6 model atmosphere code and newly computed opacity distribution functions (ODFs), which take into account the Zeeman splitting of the contributing atomic lines. The inclusion of magnetic forces changes the structure of an atmosphere by altering the net gravity and thus the pressure distribution in the upper layers of the atmosphere. These magnetic forces cause the structure of the stellar model to vary with latitude and to differ from the nonmagnetic case. The enhanced blanketing represented by the “magnetic” ODFs in combination with the structure changes and Zeeman broadening of individual lines causes the emergent spectrum to vary with viewing inclination and to differ from the nonmagnetic case. The structure and spectrum computations are described and results compared with those for nonmagnetic models. The results are discussed in light of existing observations of Ap stars, which are thought to have magnetic field configurations similar to the ones included in these models.

Subject headings: stars: atmospheres — stars: magnetic — stars: peculiar A

I. INTRODUCTION

Peculiar A stars are distinguished from other upper–main-sequence stars of similar mass and luminosity not only by the presence of strong magnetic fields but also by the numerous anomalies seen in their spectra. This leads us to wonder what part, if any, the magnetic fields present in these stars may play in the production of the spectral peculiarities. This investigation attempts to answer that question by calculating and comparing theoretical models, both with and without magnetic fields, of the structures and spectra of stars with masses and luminosities corresponding to those of the peculiar A stars and their more normal nonmagnetic counterparts. Previous investigations into the structure of a magnetic atmosphere (Stepień 1978), and the structure of an atmosphere which suffers heavier than normal line blanketing (Muthsam 1979), indicate that the atmospheric structure of an Ap star may vary quite significantly from that of normal A stars, especially at small optical depths, where line formation can be critically affected. Therefore, it seems quite possible that the spectral anomalies seen in Ap stars may be produced, at least in part, by the different atmospheric structure of such stars combined with the effects of the magnetic field on the transfer of line radiation. The modeling done in this study should help us to evaluate the effects of the changes in structure on the spectrum of a magnetic star and thus to discover the extent to which a magnetic field can produce spectral peculiarities in a star with normal chemical abundances.

Determinations (see Preston 1969; Landstreet 1970; Borra and Vaughan 1976; Borra and Landstreet 1977) of the average longitudinal and average transverse components of the fields, as well as the average surface field and the variations of these values with time, indicate that the magnetic field in the atmosphere of an Ap star can be approximated by a near-dipole field, although in individual cases the field is usually decentered or distorted to some degree. In order to keep our model calculations manageable, we assume that the field configuration in all our models is a star-centered dipole, slightly distorted by additional toroidal currents. Such a magnetic field affects the structure of a stellar atmosphere in two major ways: (1) Zeeman splitting of the numerous atomic absorption lines enhances the opacity of the stellar material, and (2) the variation of magnetic forces with height in the atmosphere alters the hydrostatic equilibrium and thus changes the distribution of gas pressure, temperature, and density with height.

We discuss line blanketing in a magnetic atmosphere in § II and atmospheric structures in § III. In § IV we examine the spectra of the magnetic models and compare them with those of the nonmagnetic models. Finally, in § V we discuss the results in light of existing observations of Ap stars.

II. ATOMIC LINE BLANKETING IN A MAGNETIC ATMOSPHERE

The contribution of atomic line blanketing to the total opacity is significant in both normal A and peculiar A stars. Therefore, to accurately model and compare Ap and normal A stars, this component of the opacity must be included. Stepień (1978) did not include line blanketing at all in his modeling of magnetic atmospheres. Muthsam (1979), on the other hand, examined the effects of the enhanced blanketing that would occur if the anomalous abundances suggested for Ap stars are real, but did not include the effects of magnetic pressure in his structure calculations. In this investigation we shall include both the magnetic pressure and line-blanking effects. In contrast to Muthsam (1979), the line blanketing in these models is represented by opacity distribution functions (ODFs) calculated assuming normal chemical abundances and with the Zeeman broadening of each line approximated by a normal Zeeman triplet pattern. Like Muthsam, this investigation also assumes no true microturbulence.

The ODFs computed for the magnetic models differ from...
the ones used to model normal A stars (see Kurucz 1979) in the
assumption of zero microturbulence (as opposed to 2 km s \(^{-1}\)
for the standard ODFs) and in the inclusion of the Zeeman
splitting of the lines by the magnetic fields (using a mean
Z-value of 1.3). In all other respects, the computation of these
magnetic ODFs was kept as close as possible to the techniques
used by Kurucz (1979 and private communication) to ensure
that differences found would be due to the different input condi-
tions assumed for the magnetic atmosphere rather than to
differences in our techniques. The ODF computations are
described in detail in Carpenter (1983).

Three sets of "magnetic" ODFs, at magnetic field strengths
of 10, 20, and 30 kilogauss, have been computed for use in the
magnetic structure calculations. For each of the three ODF
sets, a subset of 103 \(T-N_e\) pairs, chosen from the original 159
point grid used by Kurucz (1979), plus 27 points at higher
temperatures and densities (to allow computation of the deep
polar reference atmospheres described in § III), provides com-
plete coverage of the physical conditions expected in our
models of early-type magnetic stars while keeping ODF com-
puting time to a reasonable level. Magnetic ODFs were calcu-
lated at these values, which cover the range \(T = 3.56-5.50\)
and \(\log N_e = 9-19\). The remainder of the \(T-\log N_e\) grid
was filled out by linear extrapolation in \(\log N_e\) to facilitate
interpolation near the edges of the computed portion of the
tables.

The major effect of the magnetic field on an ODF is to
increase the fraction of an interval covered by a given value of
the opacity—or, equivalently, to increase the value of the ODF
across most of the interval. The effect is larger at the lower end
of the distribution function, since the Zeeman splitting of the
numerous weaker lines tends to fill in the spectral regions
which would otherwise have had very low opacity because of
a lack of lines at those wavelengths. The proportional effect on
the ODF is much larger in such regions than in regions of large
opacity, since the total opacity in these latter areas changes
only slightly, owing to the movement of the Zeeman com-
ponents of the relatively weak lines into them. A comparison of
the magnetic ODFs with the standard Kurucz no-hydrogen-
line ODF for a wavelength region near the flux maximum of a
12,000 K blackbody is shown in Figure 1 for \(T = 4.10\).
Since simultaneous calculations of the magnetic atmospheric
structures and hydrogen line profiles are necessary to ensure
self-consistent results for both, the hydrogen line opacity is
included explicitly in the structure calculations rather than in
the ODFs. Figure 1 shows the curves for several values of
\(\log N_e\) for the ODFs with magnetic fields of 0, 10, and 30
kilogauss. Since the 20 kilogauss ODFs are virtually identical
with those at 30 kilogauss in this spectral region, they have
been omitted from this diagram for the sake of clarity. The
electron densities for which ODFs are shown all lie within the
regime of densities for which ODFs were actually computed
for this temperature. The figure shows functions for the 2350-
2450 Å region at a temperature chosen to be representative of
the layers around optical depth unity. At these wavelengths,
the effect of the magnetic field is greater at higher temperatures
for constant density and at lower densities for a given tem-
perature.

III. THE ATMOSPHERIC STRUCTURE OF A MAGNETIC STAR

Since a slowly rotating nonmagnetic upper–main-sequence
star is spherically symmetric, its atmosphere can be represen-
ted by a single plane-parallel model. The spherical symmetry of
a magnetic star, however, is destroyed by the latitude variation
of the magnetic forces that causes the local gravity to vary with
latitude. Hence, a series of local plane-parallel models is
required, to represent various latitudinal zones on a given star.
The computation and characteristics of such models are
described in this section.

Accuracy requirements on the intensity quadrature scheme
described in § IV are satisfied if the stellar structure is repre-
sented by a grid of eight local atmospheres for eight magnetic
latitudes covering the region from pole to equator. These local
atmospheres are computed with a modified version of the
ATLAS6 (Kurucz 1979) model atmosphere code. The changes
in the code are required by the fact that the hydrostatic equi-
librium equation is two-dimensional for an atmosphere with a
poloidal magnetic field. This two-dimensional equation is
solved using a technique similar to that described by Stepied
(1978), who calculated single plane-parallel unblanketed
models to approximate the structure of selected portions of a
magnetic atmosphere for stars with near-dipole fields. Stepich
shows that these equations can be written as follows:

\[
\frac{\partial P(r, \theta)}{\partial r} = -\rho g + \frac{2P_m(r, \theta)}{r},
\]

(1)

\[
P(r, \theta) + P_m(r, \theta) = P(r, 0),
\]

(2)

where \(P(r, \theta)\) is the total nonmagnetic pressure, \(\rho\) is the mass
density, \(g\) is the mass gravity, \(P_m(r, \theta)\) is the nondipole com-
ponent of the magnetic pressure, and \(P(r, 0)\) is the pressure at
the pole. If we assume that the deviation from a dipole is a
function of radius only, then \(a = 1\) and \(P_m(r, \theta) \sim \sin^2 \theta\) (see
Carpenter 1983). The value of \(P(r, 0)\) is obtained from a polar
"reference atmosphere" which is computed with the usual one-
dimensional hydrostatic equilibrium equation, since there are
no magnetic forces at the pole where the field is radial. This
atmosphere must extend to much deeper levels than are ordi-
narily required, since the gas pressure at its base must be equal

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to the combined magnetic and gas pressure at the base of the lower latitudes. Despite the lack of radial forces at the pole, Zeeman splitting still affects the atomic line blanketing so the enhanced opacity ODFs described earlier still must be used.

The value of the magnetic pressure (here, and for the remainder of this paper, this should be understood to mean the non-dipole component of the magnetic pressure) at the base of the equatorial model atmosphere is a free parameter that controls the overall strength of the magnetic forces throughout the atmosphere of the star. The base magnetic pressure at intermediate latitudes is obtained from the relation \( P_B(r, \theta) \sim \sin^2 \theta \), given above. The magnetic pressure is assumed to decrease with radius, since Stepien has shown that inward-directed magnetic forces have little effect on the structure of a stellar atmosphere. We note, however, that many interior models suggest that the radial component of the Lorentz force may be directed inward in the outer regions. If this is indeed the case in real magnetic stars, then we would expect only minimal differences in the structures of magnetic and nonmagnetic stellar atmospheres. Further modeling of this case using Stepien's approach would thus likely produce little of interest. In this paper, we therefore consider only models with outward-directed magnetic forces, where significant structural differences are to be expected and we may thus hope to learn something useful and interesting about the possible influence of strong magnetic fields on stellar atmospheres and spectra. Once the lower boundary values of the magnetic and non-magnetic pressures are specified for a given latitude, the hydrostatic equilibrium equations can be solved for the complete radial distributions of the gas pressure, magnetic pressure, and mass density. The emergent radiation field for this latitude model can then be computed and stored for later use by the global integration routines. A complete description of this process is presented in Carpenter (1983).

We have computed three full-star models spaced about 2000 K in effective temperature. This coarse grid is quite sufficient to represent the slow and monotonic variation of the effects of a given magnetic field with effective temperature. We estimate the range of the magnetic effects by constructing a model at each temperature with magnetic forces near the limits of what can be expected in real stars. Sample computations confirm that, for a given effective temperature, fields yielding weaker forces produce effects which are qualitatively identical, but quantitatively smaller than those in these limiting models. Thus, each of our models has a magnetic field configuration producing the largest atmospheric magnetic forces which a model of the given mass, radius, and luminosity can suffer and remain stable. That configuration was found by increasing the magnetic pressure at the base of the equatorial atmosphere (i.e., adjusting the boundary condition) until it become impossible to compute a converged atmosphere. We cannot prove that this corresponds to a physical limit in actual stars, but we do believe that such forces cannot be substantially larger in real stars, since the net gravity in the equatorial regions of these models is already quite small. These magnetic pressures and forces can be created either by large fields with relatively small deviations from a dipole or by small fields with relatively large deviations from a dipole, although the latter case is not very plausible (cf. interior models of Wright 1969; Monaghan and Robson 1971; Mestel and Moss 1977; Moss 1984). Thus, a given model could represent approximately a star with a 30 kilogauss dipole and a 0.4 kilogauss mean deviation or, less plausibly, a star with a 10 kilogauss dipole and a 1 kilogauss mean deviation. In the tables giving the model parameters we list the magnetic pressure and the corresponding deviation from a 20 kilogauss field at the base of the equatorial atmosphere. In all cases, the 20 kilogauss ODF was used for the lower latitude atmospheres and the 30 kilogauss ODF for the highest latitudes. We note that using different ODFs would alter the computed continua but would not substantially change the computed structures.

Models have been computed for effective temperatures of 15,000, 13,000 and 11,000 K and a mass gravity of \( \log g = 4.0 \). Table 1 lists the global characteristics of each model star. The magnetic forces lead to a significant variation in the radial effective gravity and gas pressure distributions from pole to equator in these models. Figures 2 and 3 show the net gravity versus the log of the Rosseland optical depth for each latitude band in models with effective temperatures of 15,000 and 11,000 K, respectively. We note that the minimum net gravities (and thus peak magnetic gravities) are nearly the same for a given latitude on either model, but that the total depth range affected at a given latitude is slightly smaller in the cooler model. These figures also illustrate that the magnetic forces visibly change the net gravity only in the three or four lowest latitude zones and are truly significant in determining the structure of the atmosphere only in the three lowest latitude zones, i.e., within about 35° of the equator.

![Fig. 2.—Net gravity versus Rosseland optical depth in model 1](image-url)
Figures 2 and 3 show the variation in the atmospheric structure of a magnetic star with latitude. It is also instructive to compare these structures with the structures of nonmagnetic models with the same effective temperature and mass gravity. In Figure 4, the distribution of gas pressure with temperature in the equatorial zone (where the magnetic effects are greatest) of magnetic model 1 is compared with that in a nonmagnetic plane-parallel atmosphere of the same effective temperature (15,000 K) and mass gravity (log g = 4). As expected, at a given temperature the gas pressure in the magnetic model is reduced relative to that in the nonmagnetic case, since in the magnetic case the atmosphere is partially supported by magnetic forces.

These calculations have thus shown that, given our assumptions, the effects of a magnetic field on the structure of a magnetic star are strongly concentrated toward the equatorial regions. In those regions, the net gravity and gas pressure are reduced significantly in the outer layers of the atmosphere. The vertical extent of the gravity–gas pressure reduction is a slight function of temperature—decreasing in size with decreasing effective temperature. Both the magnitude and the vertical extent of the reduction also decrease from equator to pole on each model.

IV. THE SPECTRUM OF A MAGNETIC STAR

We now examine the predicted continua and selected line profiles from these models. We describe the variation of these spectra with viewing inclination and compare them with theoretical spectra from nonmagnetic models. In § V we discuss these results in light of existing observations of Ap stars.

We have computed the energy distributions that would be observed from each of these models for a set of five viewpoints at inclinations to the magnetic pole of 0°, 30°, 45°, 60°, and 90°. The integrated specific intensity in the direction of the observer was computed for the wavelength interval from 229 Å to 200,000 Å, using the numerical integration scheme described by Collins and Harrington (1966).

An examination of the continua from the magnetic models shows that there is little variation in the overall flux distribution with changes in viewing inclination. The small decreases in UV flux from the low latitudes due to structure changes are quite nearly matched by the decrease in UV flux from high latitudes due to the increased dipole field strength and corresponding increase in UV line blanketing.

However, the continuous spectra of the magnetic models do differ from those of nonmagnetic models. Figure 5 compares the continuum of model 1 (T_e = 15,000 K) with that of a nonmagnetic model with an effective temperature of 15,200 K. We see that the two continua match nicely in the visual, but that the magnetic model exhibits a flux deficiency in the ultraviolet. The discrepancy is on the order of 10% or so below 2700 Å and is most visible in the Fe II and Fe III features at 1400, 1550, 1800, and 2400 Å and in the continuum window between Lyman-alpha and Lyman-beta near 1100 Å. The redistribution of the flux from the UV to the visual by the enhanced UV line blanketing causes the magnetic model to mimic a hotter nonmagnetic star in the visual but a cooler one in the ultraviolet.

Since the major effect of a magnetic field on the structure of a star is to reduce the gas pressure and gravity in the upper layers of an atmosphere, it is likely that one of the most sensi-
tive indicators of structure alterations will be detailed profiles and intensities of selected lines. The lines most sensitive to these changes will be those formed primarily in the upper portions of an atmosphere where the magnetic effects are strongest. The best structure diagnostics should be lines which are luminosity- and thus gravity-sensitive but which show little sensitivity to Zeeman broadening (i.e., any Zeeman broadening must be much less than broadening from other sources), so that the latter does not hide the effects of the structure changes. Since the $H_\gamma$ line fulfills these criteria for the B7–A3 spectral range, we have chosen to model it to evaluate its actual sensitivity to structure changes. We have also chosen to model in an approximate manner the Si [II] 4130 Å line, which is strongly affected by Zeeman broadening and is anomalously strong in many magnetic stars, in order to demonstrate the behavior of a typical anomalous line in these stellar models.

The $H_\gamma$ profiles are found to vary with viewing inclination in all the models. The latitudes near the magnetic pole produce a nearly normal $H_\gamma$ profile, while the lower latitudes yield a weaker line, especially in the wings of the profile. Thus, a view from high inclinations to the magnetic axis shows a significantly weaker $H_\gamma$ line compared with an $H_\gamma$ line from a nonmagnetic model of the same $T_e$, while the view at low inclinations shows a profile which differs very little from the nonmagnetic case. Figure 6 shows the variation of the $H_\gamma$ profile with inclination in model 1 ($T_e = 15,000$ K).

We may also make a direct comparison of the magnetic atmosphere $H_\gamma$ profiles with profiles from nonmagnetic models. Figure 7 presents profiles from magnetic model 3 ($T_e = 11,000$ K) and a nonmagnetic atmosphere of the same effective temperature. The dark line represents the profile from the magnetic model seen from an inclination of 90°. The line wings are weakened considerably by structure changes, while line center is only slightly altered. The central line depths, as well as the visual continua, can be brought into agreement if the effective temperature of the comparison nonmagnetic atmosphere is raised by several hundred degrees; however, even in that case, the line wings remain stronger in the comparison spectrum. $H_\gamma$ profiles from the other magnetic models are similarly related to profiles from corresponding nonmagnetic models; they agree closely for low inclinations and show significant weakening at high inclinations.

The variations and comparisons of $H_\gamma$ profiles are summarized in Table 2, which gives for each model the ratio of the width at half-maximum at inclinations of 90° and 0°, and the same width comparison of the magnetic profile at $i = 90°$ with the corresponding nonmagnetic profile.

The modeling of the Si [II] (multiplet 3) 4131 Å line is considerably more complicated than that of the $H_\gamma$ line because of its sensitivity to the anomalous Zeeman effect. A magnetic field splits this line into either two or three groupings of six components each, depending upon the angle between the observer’s line of sight and the magnetic field lines. When the observer looks across the field lines, three groupings are seen: the six linearly polarized $\pi$-components are grouped symmetrically about line center, while two other six-component sets of opposing circular polarization (the $\sigma$-components) are displaced symmetrically to the red and blue sides of line center by an amount proportional to the magnetic field strength. When the observer looks along the field lines, only the two sets of $\sigma$-components are visible. Thus the number of components and

<table>
<thead>
<tr>
<th>TABLE 2</th>
<th>COMPARISON OF $H_\gamma$ WIDTHS AT HALF-MAXIMUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODEL NO.</td>
<td>\begin{array}{ccc}</td>
</tr>
<tr>
<td>$i = 90°/i = 0°$</td>
<td>1</td>
</tr>
<tr>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>$i = 90°$/nonmagnetic</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Fig. 6.—Variation of the $H_\gamma$ specific intensity profile with inclination in model 1.
their relative intensities are a function of the angle between the observer's line of sight and the magnetic field lines. This angle in turn is a function of both the latitude on the star (the field is horizontal at the equator, radial at the pole) and the viewing perspective of the observer. Since our radiative transfer and global integration routines cannot properly handle an opacity which varies in this manner, we approximate the behavior of this line by modeling it for selected local atmospheres at the poles and equators of the magnetic models and for comparable nonmagnetic atmospheres. We also note that a completely realistic calculation of line strengthening by a magnetic field would involve solving equations of polarized light transfer. However, given our other assumptions, this level of sophistication is unwarranted, especially since we would not expect the total line strength to change substantially under the more sophisticated treatment.

The Si ii profiles presented here have, with one exception, been convolved with a triangular instrument profile with a full width at half-maximum of 0.5 Å to approximate what an observer might see with a moderate resolution spectrograph. It is, however, instructive to first consider the unconvolved profiles of a Zeeman triplet and doublet in comparison with a normal unsplit line. Here and in the remainder of this discussion “triplet” and “doublet” should be understood to mean the groups of \( \pi \)- and \( \sigma \)-components characteristic of the anomalous Zeeman effect and not the simple three- or two-line pattern of the ordinary Zeeman effect. However, the thermal broadening at these temperatures is sufficient to blend the components of each grouping together, so that the results looks very much like the ordinary Zeeman pattern. This can be seen in Figure 8, which shows a triplet pattern from an 11,000 K local magnetic atmosphere with a 20 kilogauss horizontal field compared with the same (unsplit) line from a similar nonmagnetic model. The nonmagnetic line profiles in this and succeeding figures include a microturbulence of 2 km s\(^{-1}\), while the magnetic profiles are based on zero microturbulence. This figure demonstrates the strong saturation of the original line, since the various Zeeman-split components, which are intrinsically weaker than the original line by factors of 2–4, are each still able, by virtue of the slight wavelength shift, to individually absorb nearly as much radiation as the original unsplit line. Thus we see that a 20 kilogauss field can increase the total line strength by a factor of nearly 3 for the triplet case and nearly 2 for the doublet case.

Actual observations of such lines would of course be blurred by the instrument used to observe them. Figure 9 shows the Zeeman-split Si ii 4131 Å line at various magnetic field strengths, convolved with the instrument profile described above. The figure shows the profile of a convolved triplet line from the equatorial regions of an 11,000 K magnetic model (model 3) at 10 versus 20 and at 20 versus 30 kilogauss. We see that the convolution blends the various components together into one line. This also occurs in the doublet case, although the doublet shows clear indications of its two-component nature at 20 and 30 kilogauss. With this instrumental resolution, the line strength will grow with increasing magnetic field strength but will not actually split into different components until the magnetic field strength reaches about 50 kilogauss.

A comparison of a triplet line formed in the presence of 10, 20, and 30 kilogauss horizontal fields and no microturbulence with a line from a nonmagnetic atmosphere with 2 km s\(^{-1}\) microturbulence shows that the line increases in strength by a factor of 2–3 in the magnetic atmosphere. A comparison of the doublet profile at 10 and 30 kilogauss with the same nonmagnetic line indicates that the doublet splitting appears capable of increasing the line strength by 50%–100%.

Since the magnetic field strength and orientation vary with latitude, we should see a variation in this line as we view different regions of the star. We have estimated this variation by computing profiles from radial viewing perspectives over the near-equatorial and near-polar local atmospheres of several
magnetic models. The results for 11,000 K magnetic models with 5 kilogauss (top) and 20 kilogauss (bottom) equatorial fields, respectively, are shown in Figure 10. The variations at other temperatures are similar. We note that the polar doublet is stronger than the equatorial triplet at low field strength but weaker at high field strength. This reflects the fact that the triplet line remains more saturated at the lower field strength than the doublet line and that a larger field can increase the strength of the triplet line more than that of the doublet line.

Finally, we ask: Can Zeeman intensification explain the frequently observed anomalous strengths of this line? In Figure 11 we present a triplet line intensified by a 20 kilogauss horizontal field in the equatorial local atmosphere of model 3 ($T_e = 11,000$ K) and the same line from a comparison nonmagnetic model with its silicon abundance enhanced by a factor of 40. The strengths agree fairly well, and they differ in that a slightly larger abundance enhancement is needed to make the profiles match. We note the significance of this result: in order to increase the line strength by a factor of 2–3, as can easily be done with the Zeeman effect of a 20 kilogauss field, the abundance in a normal atmosphere must be increased by a much larger factor, up to 50 times. This is because of the saturation of this absorption line in these stellar atmospheres; placing more absorbers in a location where there is little radiation is a very inefficient mechanism for strengthening the line. The Zeeman effect, in contrast, can much more efficiently enhance the line strength by redistributing the absorbers to a wider range of wavelengths where there exists more radiation to be absorbed.

V. DISCUSSION

Observations indicate that the continua of Ap stars differ from those of normal A stars. The continua of Ap stars appear to mimic slightly hotter normal stars at visual wavelengths but more closely resemble the continua of cooler normal stars in the UV (Adelman 1981). Thus, comparisons of normal A and Ap stars of similar visual colors (Leckrone 1973; Jamar, Macau-Hercot and Praderie 1978) indicate a marked UV flux deficiency in the Ap stars. Our models show the same qualitative behavior, although a number of observations show substantially larger deficiencies (up to a magnitude or more) than the 0.1 m which the models typically produce. Both the observations and our models show the largest discrepancies in the Fe II and Fe III features at 1400, 1550, 1800, and 2400 Å, although Jamar, Mäcau-Hercot, and Praderie attribute this to an overabundance of Fe rather than considering it a direct effect of the magnetic field on the line opacity. It appears to be clear, whatever the cause, that the UV continuum regions which show the greatest discrepancies and are thus the most sensitive to the Ap phenomenon and/or magnetic field effects are those dominated by lines of singly and doubly ionized iron.

Studies of the variations of Ap star continua with time are more difficult to carry out, since the largest variations occur in the ultraviolet. To date, fewer than a dozen Ap stars have been examined for variations of their continua and total flux. Observations with the TD-1 (Jamar 1977, 1978) and OAO-2 (Molnar 1973; Leckrone 1974; Molnar et al. 1976; Mallama and Molnar 1977) satellites have generally found a variation in the UV of several tenths to over one-half magnitude. Comparisons of the timing of the variations with predictions of visual continuum variations using standard ephemerides indicate that the visual and UV continua vary inversely with each other, with a “null” intermediate wavelength region which shows no variation. These variations are such that the bolometric flux remains nearly constant. Thus an effective temperature based on the total flux and stellar radius is constant to within about 2%–3%, which amounts to several hundred degrees in these stars.

The continua in our models do show the inverse variation in the two regions, but the absolute size of the variations is much
too small. In these models the continuum variations are controlled mostly by variations in the ODF's with latitude due to the stronger magnetic field strength and thus enhanced Zeeman splitting at higher latitudes. Thus, in order to match the currently available observations with models of this nature, the variation of the ODF's with latitude must be increased. The strength of an ODF at a given temperature and density is determined by several factors, including magnetic field strength, turbulent velocity, and elemental abundance. Hence, to increase the variation of an ODF with latitude, we would need to increase (or include) the latitude variation of one of these factors. Since the intent of this study is to model the effects of a magnetic field on a star with normal abundances, we cannot call upon a variation in that parameter. The configuration of the magnetic field could be altered from the near-dipole field we have used; a model with a very strong field concentrated on one portion of the stellar surface with the remainder of the surface having only a modest or negligible field would be capable of producing the type of variations reported thus far; however, other evidence of this type of drastic field variation has not been found. The only remaining adjustable parameter is the microturbulent velocity. We have used zero microturbulent velocity under the assumption that the atmosphere of a magnetic star is quite stable owing to the presence of the magnetic field. One could argue that the efficiency of this stabilization varies with latitude, since the orientation of the field lines with respect to the normal direction varies from perpendicular at the equator to parallel at the poles. It might therefore be appropriate to use a nonzero turbulence at the poles, where the field lines are radial, but a small or zero turbulence at lower latitudes, where the lines are more nearly horizontal. This would increase the size of the continuum variations and maintain the required anticorrelation of the UV and visual flux changes. These models would then more clearly approximate the observed data.

The $H\alpha$ profiles which we have computed show variations with viewing inclination in all our models. In all cases, the profiles also differ from those from a nonmagnetic star of the same effective temperature. The first effect reflects differences in the gravity (or pressure) distributions at different latitudes due to the variations in the magnetic forces with latitude. Thus the profiles of $H\alpha$ and their variations with time in Ap stars should be an excellent probe of the variation of the magnetic structure with position on the star. The differences in magnetic and nonmagnetic profiles should allow us to estimate the absolute effect of the magnetic field on the structure of a star. It is difficult to choose the proper nonmagnetic star whose $H\alpha$ profiles we could compare with those of a given magnetic star. Ideally we should compare stars of the same mass, radius, and luminosity (or same $T_e$ and mass gravity). However, we have no way to immediately identify a magnetic star of a given mass gravity, since the hydrogen lines which are the gravity indicators in the lower segment of the temperatures are altered by the magnetic effects, and we do not yet have a way independent of these models of separating the contributions of the two components of the gravity. To make a fair comparison, one would need to find an Ap star whose mass and radius (and thus gravity) can be determined by other means. This author is aware of no Ap star which has a sufficiently accurate independent measurement of the mass gravity. Thus, at this time, a comparison of individual magnetic and nonmagnetic profiles is confined to the comparisons of theoretical profiles made in § IV. We note, however, that a statistical comparison of normal and Ap stars by Gray and Evans (1973) showed that the functional relationship between hydrogen line strength and color indices was the same for the two groups to within about 1%.

We can compare our predictions of $H\alpha$ variations with observed values. Suitable observations of $H\alpha$ variations in Ap stars are limited, although enough exist to provide a rough estimate of the general behavior of $H\alpha$ in magnetic stars. Madej (1983) summarizes the available data, which indicate that Balmer line strength varies in some but not all magnetic stars and that the variations are generally stronger in stars with weaker total fields. He reports typical variations of 10%-35% in the equivalent widths of the lines in those stars in which the line strengths vary. Presumably, a larger sample of stars would indicate that the amplitude of the variations covers the entire 0%-35% range. Variations of $H\alpha$ strengths from our models are on the order of 10% or less. Since all of our models have relatively strong fields, it is not surprising that this result is in the lower segment of the observed range of variations.

Finally, what can these models tell us about the nature of the anomalous line strengths which are the hallmark of the Ap stars? We have addressed this question by modeling a line of an element whose apparent overabundance is the distinguishing characteristic of the hotter magnetic stars (the "Si stars"). The Si $\Pi$ 4311 Å line is one of the primary indicators of apparent abundance anomalies in the Si stars, but it is also visible in cooler Ap star spectra, where its strength is also frequently anomalous. The most comprehensive survey of silicon line strengths and apparent abundances are by Megessier (1971) and by Adelman (1973a, b). The former reported results for 18 Si stars, while the latter analyzed the spectra of 21 cool magnetic stars. Additional analyses of individual stars are given by Cohen (1970), Tomley, Wallerstein, and Wolff (1970), and Castelli, Faraggiana, and Hvala (1976). These studies show abundance enhancements ranging from approximately 0.5 to 2.0 dex (logarithmic abundance relative to the solar value) in the Si star and from 0.0 to 0.1 dex in the cooler stars. No correlation has yet been seen between the line strengths and longitudinal magnetic field strengths, but the fraction of these samples with well-determined field strengths is very small, and, in any case, we would expect that any correlation that might exist would be with total surface field rather than with the longitudinal component alone. However, it is true that no silicon overabundance is seen in the HgMn stars, which appear to have no significant global magnetic field.

Can this pattern of anomalous Si $\Pi$ line strengths be explained without requiring enhanced abundances? First we note that Megessier (1971) also examined a sample of "normal" stars corresponding to the Si stars and found a variation in line strength equivalent to abundance variations of $-0.10$ to $1.26$ dex. Thus we need not necessarily explain by magnetic effects the full 2.00 dex enhancement seen in some Si stars, since the normal cosmic scatter in Si abundance could account for a portion of the enhancement relative to solar values. However, to evaluate the potential of our models with regard to producing enhanced lines, we computed a Si $\Pi$ line profile from a nonmagnetic atmosphere with a Si abundance enhancement of 1.6 dex (40 x) and compared it with a normal-abundance but Zeeman broadened line from an atmosphere with a 20 kilogauss field. We have shown this comparison in Figure 11 and noted that the Zeeman intensification appears to be equivalent to an even larger abundance enhancement of perhaps 50 x. Thus, for this saturated line, a reasonable (although larger than average) size magnetic field can more...
than account for a typical enhancement of the line strength through the process of Zeeman intensification. An even stronger enhancement would be possible if the assumption of zero microturbulence were relaxed. Since it is possible to produce a wide range of Si II 4131 Å line strength enhancements by varying the size and configuration of the magnetic field, it may thus be possible to explain the observed range of anomalous Si line strengths without requiring large enhanced abundances.

This should also be true of other lines which are saturated in normal atmospheres. Even the vary large (≈ 1000 x) apparent overabundances of elements such as Eu, Pr, and Pb seen in some stars (Ledoux and Renson 1966) might be explained in this manner, since anomalous Zeeman splitting yields a larger number of components, and the original line has a smaller Doppler width for these heavier atoms. It will be more difficult to explain large strength enhancements of unsaturated lines, since the Zeeman intensification will not be capable of changing their total line strength by a large percentage. But it is also true that abundance enhancements will be much more efficient in those cases, and smaller enhancement will thus be required to increase line strengths by significant amounts.

Of course, these results should be verified with a more complete treatment of the opacity of the Zeeman-split line and its variation with latitude on the star and viewing perspective of the observer. However, since the Si line always shows an increased strength in these magnetic models relative to a “normal” line, independent of latitude or viewing angle, a fully self-consistent treatment of the global integration of the profile should still show a significant enhancement in line strength due to the magnetic intensification.

In stars with weaker fields than those considered here, the Zeeman intensification may be insufficient to explain fully the observed line strength enhancements. In such cases, however, at least part of the enhancement can be explained in this manner, and the implied overabundance factors, which must be explained by diffusion or some other mechanism, can thus be reduced.

We note, however, that Zeeman intensification by itself cannot account for all anomalous line strengths, since observations have shown that lines of different elements can vary in opposing phases (Ledoux and Renson 1966), while all enhancements due solely to the Zeeman effect would be expected to be in phase with one another. Also, it is clear that the apparent underabundances of some elements cannot be explained by Zeeman intensification.

We may summarize the main points of this investigation as follows. Motivated by the observations of approximately dipolar magnetic fields in the atmosphere of Ap stars, we have created line-blanketed model atmospheres containing slightly distorted dipolar magnetic fields. We have examined them for effects of the field on the structure and emergent radiation. A comparison of model and observed continua indicates that our models of the line-blanketing opacity require alteration to match the observations more closely. An examination of the behavior of the structure-sensitive Hγ profiles in our models and in the available observational data indicates that our structure calculations yield models of the atmospheric structures of Ap stars consistent with the observations. Finally, our approximate modeling of the Si II 4131 Å line demonstrates that the anomalous Zeeman effect is capable of producing, in a normally saturated line, line strength enhancements large enough to explain the observed enhancements without requiring the large overabundances normally used to explain the spectra of Ap stars. This mechanism does not explain all the observed spectral peculiarities, but it should lessen the need for extremely large overabundances of a number of elements. Further work in this area is definitely indicated.

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