COOL MAGNETIC CP STARS

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ABSTRACT. We review progress in research on the cool magnetic CP stars especially during the past four years. Studies of energy distributions and abundances are analyzed to reveal their systematics. Model atmospheres do not yet accurately describe the average energy distributions much less the variability with the rotational periods of these stars.

1. INTRODUCTION

In this review we are concerned with magnetic Cp stars cooler than the silicon stars: the SrCrEu stars and their variants. These objects have anomalous chemical compositions and magnetic fields which are not homogeneously distributed over their stellar photospheres. Radiative diffusion theory suggests that at a given location on the surface the abundances are functions of optical or physical depth. Wolff (1973) gave a general introduction to these stars, with extensive literature references.

2. OPTICAL ENERGY DISTRIBUTIONS

Following the discovery by Kodaira (1969), spectrophotometric studies of Adelman and Pyper (e.g. Pyper and Adelman 1985) and photometry by Maitzen and his collaborators (e.g. Maitzen 1976) have shown that the presence of broad, continuum features near λ4200 and λ5200 are signatures of the magnetic Ap star phenomena in the optical region. In some stars these features are variable on rotational timescales. For the most part the energy distributions of these stars, especially the cool Ap stars, remain anomalous over their entire rotational periods.

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There has been considerable interest in the origin and structure of these broad, continuum features. Maitzen and Seggewiss (1980) concluded that the λ5200 feature was composed of two main components with a different temperature behavior. There is a narrow, rather deep feature centered near λ5175 which shows its greatest strength in the hottest Ap stars and a broad, rather shallow feature which peaks at somewhat longer wavelengths and at a lower temperature. This pattern is consistent with results by Adelman and Pyper (1986) who find, besides the deep feature, subminima in some stars near λ5000 and λ5556. Subminima near λ5000 can also been seen in the work by Maitzen and Muthsam (1980) who find that they can synthesize the broad feature in the coolest Ap stars, but cannot model the narrow component in hotter Ap stars. The 4d-4f transitions in Fe II (Johansson and Cowley 1984) fall in this region. Since they are not in the Kurucz and Peytremann (1975) compilation, it would be of interest to re-synthesize this region by including Kurucz's (1981) Fe II gf-values.

North (1980) demonstrated that for the hottest cool Ap stars Δ(V1-G) and Δa are correlated with the surface magnetic field if it is not too large. This suggests that magnetic fields play some role in the formation of the λ5200 feature, but not necessarily a dominant one.

Carpenter (1985) constructed magnetic, line-blanketed model atmospheres with slightly distorted dipolar magnetic fields and a solar composition. The Zeeman splitting of the contributing atomic lines was taken into account in computing the opacity distribution function. As the magnetic effects are latitude dependent, the emergent spectrum varies with viewing inclination. A magnetic 15000 K model matches the fluxes of a 15200 K non-magnetic model with the same abundances in the optical and also displays a 10% flux discrepancy in the ultraviolet. As most magnetic Ap stars have larger flux deficiencies, this paper provides useful guidance in interpretation and is consistent with the usual interpretation that the abundances of magnetic Ap stars are greater than solar.

The structure of the atmosphere of a magnetic star is surely not homogeneous and probably not plane parallel, yet most of our analytical work thus far has been based on this assumption. The errors made by the use of such crude modeling depend on the application of the models. The magnetic structure affects both continuum and line features. The predicted fluxes in the optical region do not greatly depend on whether a magnetic field is or is not present (Carpenter 1985) or whether the metallicities are solar, three-times, or ten-times solar (comparison of results given by Kurucz 1979). But observationally the models are inadequate in the optical and more so in the ultraviolet.

Examples of the vicissitudes of attempts to fit optical continua to calculated models are given by Pyper and Adelman (1985) and references therein. The optical energy distributions of some Ap stars, which are often cool Ap stars, can be only crudely fit with predictions based on normal stellar abundances. At best in this temperature region the predictions can fit only those values not affected by the Ap star anomalies such as the broad, continuum features. This raises the question of whether observations at lower resolution, i.e. intermediate and broad-band photometry, can be calibrated to yield temperatures, gravities, and metallicities. Finding the true continuum between lines in the optical region is not too difficult for the silicon stars, but for the cooler Ap stars it can be quite difficult shortward of λ4500. The ultraviolet spectra for both silicon and cool Ap stars are heavily line blanketed.

3. PROBLEMS WITH ABUNDANCE ANALYSES

In his survey of the cool Ap stars Adelman (1973) gave tables of the errors to be expected in the abundances of various elements as a result of the uncertainties in T_{eff}. These errors vary considerably, depending both on the element and stage of ionization. There will also be similar errors if the surface gravity is not correct.

Lanz (1984) found that the magnetic Ap stars have larger Bolometric corrections than normal stars with the same Paschen continuum slope. The mean difference was 0.16 ± 0.07 mag. Further it was not possible in general to infer the Bolometric correction of peculiar stars with only the Geneva photometric system as the flux deficiency is related to the temperature, surface magnetic field, and chemical abundances (see also Adelman 1985).

Hauck and North (1982) have found that in the T_{eff} vs. B2-G diagram, Ap stars lie between the normal star class III and V relations. The interpretation of such a plot may not be unique, but one possibility is that the appropriate values of log g are slightly less than those of comparable normal stars. This is consistent with the effects of the magnetic fields. In fact analyses of HgMn stars (Adelman 1984a) and of the cool Ap stars (Adelman 1984b; Table 1) suggest log g = 3.5 ± 0.5 dex for CP stars. When one compares the Balmer line profiles of magnetic Ap stars with those predicted by model atmospheres, one has to be aware that the models may have been calculated with the solar He/H ratio rather than a smaller value appropriate for such stars. This effect can amount to about 0.10 dex in log g.

Errors which result from neglect of concentration of the elements into patches (departures from plane-parallel geometry) are somewhat harder to assess. We expect that calculations such as those carried out by Khokhlova and her colleagues (c.f. Piskunov and Khokhlova 1984) for the silicon stars could be applied to the cooler Ap stars. Sadakane's (1976) study of 73 Dra showed surprisingly little dependence of the overall abundances on magnetic phase. Nevertheless stars such as HR 465 must have abundance variations over the photosphere amounting to several orders of magnitude.

Adelman (1973)'s survey as well as more recent abundance analyses (c.f. Muthsam and Cowley 1984) have used a simple algorithm to account for Zeeman broadening, by simply adding a term to the Doppler width which behaves, analytically, like a microturbulence term. The usefulness of this approximation has been recently exploited by Ryabchikova and Piskunov (1984). Detailed calculations, for example, by Hardorp, Shore, and Witmann (1976) show this more explicitly.

Clearly, for a given line, there will be some microturbulence that approximates rather well the curve-of-growth behavior of Zeeman broadening, but it is not a simple matter to select the proper values, accurately, for a large number of lines. The analysis of high resolution high signal-to-noise data of some sharp-lined relatively non-variable cool Ap star with spectral synthesis techniques should illuminate the problems of this simple approximation. Magnetic null lines and lines with very simple Zeeman patterns will provide important checks on such analyses (Shore and Adelman 1974).

Saturation effects of various kinds are avoided by the use of truly weak lines although the problems due to errors in effective temperature and surface gravity remain, as do those of surface inhomogeneities (abundance patches). Still, we expect that the errors due to patches will be larger, usually, for stronger lines than for weak ones. In the case of the magnetic stars, few studies have had the benefit of sufficiently high quality material (low noise and high dispersion) to use truly weak lines, so the discussion below will apply to material that is subject to all of the sources of error that we have discussed.

4. UPDATE OF THE ABUBDANCE SURVEY OF ADELMAN

Since the largest survey of abundances of cool, magnetic stars is still that of Adelman (1973), we shall attempt an adjustment of his results. A start on the reanalysis of individual stars has been made by still assuming that the observed hemisphere is homogeneous. Then the values of the optical energy distributions unaffected by the broad, continuum features and the Hγ profiles were compared with the predictions of Kurucz's (1979) model atmospheres. The final choice of model was made by demanding that the values of log Fe/H from Fe I and Fe II lines be the same and the model metallicity was selected to be consistent with the adopted value of log Fe/H.

In HD 8441 for which H_s = 0.0 km s^{-1}, Adelman (1984b) found ξ = 0.0 km s^{-1}. But an unpublished re-investigation using Fe II gf values from a new critical compilation by Martin, Fuhr, and Wiese (1986) and better estimates of the line broadening for Fe I and Fe II suggests ξ = 0.7 km s^{-1} which is about 1/3 of that for a normal star of comparable temperature. Analyses following this prescription, especially with low noise data and metal enhanced model atmospheres, should be able to produce more realistic abundances than in the literature. But it is non-ideal due to the neglect of surface inhomogeneities and the failure to model the ultraviolet correctly. We hope that the relative abundances of some elements will be accurate (e.g. the rare earths).

Effective temperatures, surface gravities, and iron abundances derived consistent with the study of Adelman (1984b) are given for five of the hottest cool Ap stars of the 21 Ap stars of Adelman (1973) in Table 1. The values for HD 8441 are similar to those of Ryabchikova and Ptitsyn (1985).

Table 1: Cool Ap Star Parameters

Star	Adelman (1973) T_{eff}	This Review Paper T_{eff}	log g	log Fe/H	model
HD 8441	10150	9325	3.40	-3.82	3x
HD 50169	10100	9550	3.60	-3.26	10x
HD 89069	9900	9425	3.95	-3.34	10x
HD 111133	10550	9500	3.40	-3.45	10x
HD 192678	10350	9300	3.80	-3.14	10x

There is a mean systematic shift of 800 K in effective temperature between the two sets of results. Log g = 3.63 ± 0.24 instead of 4.0 as assumed previously. The new values are preliminary. If the microturbulences in the other stars are like that of HD 8441, the use of the new critically compiled Fe II gf values and better damping constants will result in small changes in the final effective temperatures, surface gravities, and log Fe/H values (of order 25 K, 0.1 dex, and 0.05 dex, respectively). The model atmospheres are now fully line-blanketed rather than hydrogen-line blanketed. There have also been improvements in the gf-values of Fe I and other atomic species since 1973. For these five stars, the new analyses presented here suggest that the average value of [Fe/H] is +0.93 rather than +1.22 as published. This is a reduction of a factor of two. Our expectation is that HD 5797, the most iron-rich star of Adelman (1973) will have its mean iron abundance reduced to about 20 times solar, which is comparable with the Muthsam-Cowley (1984) value for iron in HR 6870. There may well be regions on the surface with greater than the mean enhancement. A substantially enhanced iron abundance may prove to be a difficulty for the diffusion theory, but current uncertainties in both the theory and the observational determination makes a clear statement impossible at this time.

At the cool end of the Ap star sequence, van Dijk et al. (1978) found that the ultraviolet flux discrepancies seen in the hotter Ap stars disappeared. This result was confirmed by Adelman (1985a), who re-examined the data from the ANS, IUE, OAO-2, and TD-1 satellites as well as optical spectrophotometry and derived both optical and ultraviolet region color temperatures. The large amount of line blanketing complicates the process of estimating temperatures. For the coolest Ap stars such as 10 Aql, the change in T_{eff} from the values given by Adelman (1973) is probably much less than for the stars included in Table 1.

Table 2 gives some indication of the order of the overall changes in abundances now thought to be appropriate to Adelman's (1973) survey. This table of mean abundances does not necessarily represent our best estimate for a 'typical' cool magnetic Ap star. Indeed, the star-to-star abundance variations are such that a set of mean abundances, even if they were based on accurate determinations, might never actually apply to an individual star. We note in presenting these new results that an approximate correction method has been used which probably yields slightly different results than a more careful star-by-star analysis would. Nevertheless our procedure should indicate the proper magnitudes of the corrections for the mean abundances.

The procedure adopted to give an estimate of the corrected mean abundance is as follows. The old mean abundances were corrected for a temperature change of 600K and allowance was made for changes in gf values by comparing the old and new analyses of HD 8441. Table 2 contains the results for elements between magnesium and yttrium wherever possible along with solar values and the mean values from a study of 10 normal B and A stars (Adelman 1986) which use the same gf values as the most recent study of HD 8441. We did not have lines in HD 8441 to guide us for some other elements while for the singly-ionized rare earths one should carefully re-evaluate the presence of each species before performing re-analyses. As a guide to the changes we have included the change in log N/H for HD 8441.

Table 2: Abundance Values

Element	cool Ap star mean Adelman (1973) [N/H]	cool Ap star mean This Review [N/H]	Change in HD 8441 log N/H	The Sun log N/H	Ten B & A Stars log N/H
Mg	-0.08 ± 0.19	-0.10	-0.13	-4.38	-4.29
Si	+0.51 ± 0.35	+0.07	-0.22	-4.37	-4.40
Ca	+0.68 ± 0.43	+0.46	-0.46	-5.66	-5.71
Sc	+0.64 ± 0.41	+0.02	-0.75	-8.96	-9.16
Ti	+0.79 ± 0.37	-0.32	-0.73	-7.02	-6.97
V	+0.53 ± 0.24	-0.08	-0.40	-7.79	-7.40
Cr	+2.02 ± 0.51	+1.00	-0.62	-5.88	-5.92
Mn	+1.60 ± 0.38	+1.59	-0.18	-7.16	...
Fe	+1.06 ± 0.33	+0.71	-0.42	-4.37	-4.34
Co	+1.47 ± 0.56	+1.56	+0.11	-7.08	...
Ni	+0.33 ± 0.40	+0.95	...	-6.70	-6.57
Sr	+1.90 ± 0.80	+1.98	-0.01	-9.10	-8.88
Y	+0.28 ± 0.27	+0.39	-1.00	-9.76	...

Despite the 600 K mean temperature change for some elements the mean overabundance has not changed by more than 0.3 dex: magnesium, calcium, manganese, colbalt, strontium, and yttrium although some of these values depend on only one line. For yttrium there has been a substantial change in the adopted gf-values which results in the large change in the absolute abunance for yttrium. Silicon, scandium, and vanadium are now normal instead of being overabundant. The mean titanium anomaly has changed by a factor of 10. Titanium is now underabundant by a factor of 2. The quality of the Ti II-gf values has been improved substantially in the past decade. Chromium is overabundant by a factor of 10 instead of 100. The quality of the optical region Cr II-gf values is poor and systematic errors are probable. The mean iron abundance is now 5 times solar. It is

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consistent with the identification of high-level transitions of Fe II in the cool Ap stars β CrB and γ Equ (Johansson and Cowley 1984). Nickel may be 10 times overabundant on the average, but as for Cr II, Ni II-gf values are of poor quality. The large overabundance of cobalt is not surprising in light of the 10^3 times solar abundance in HR 5049 (Dworetsky et al. 1980), but it is uncertain in the cool Ap stars as it depends only on a weak line or two. Table 2 also contains the mean results for normal B and A stars. The differences from solar give some indication of how well the zero-points of the abundance anomalies are known. The largest differences are for scandium, vanadium, and strontium.

5. SUMMARY OF RARE EARTH ABUNDANCES

Cowley (1984) discussed the rare earth elements in stellar spectra so the present review will be limited to general comments and to a brief discussion of very recent work.

A point of major interest is whether observations of the lanthanides show a definite deviation from a pattern that might be expected from nuclear processing. Our attention has been focused primarily on deviations from the odd-even effect, known as the Oddo-Harkins rule in geochemistry. Clear deviations from this pattern are difficult to establish. Still in a few cases the evidence for deviations is very strong. In particular, there is an apparent odd-Z anomaly at europium in a few stars (e.g. 73 Dra, β CrB) which remains even after correction for hyperfine structure in Eu II (Hartoog et al. 1974). In addition for β CrB and HR 7575 the neodymium and samarium abundances appear depressed with respect to their light-lanthanide congeners. Such 'holes' possibly represent differentiation from some more primitive, possibly nuclear pattern.

Cowley (1980) pointed out that the strengths of the lanthanide lines in the Am and coolest, magnetic Ap stars were comparable, and that this implied their abundances must be similar. It is frequently thought that the magnetic Ap stars have abundances of the rare earths that are one or two orders of magnitude larger than those of the Am stars. This appears certain for some of the extreme magnetic Ap's, but the strong possibility exists that the abundance excesses of the lanthanides and of yttrium have been overestimated because of inadequate models or deviations from LTE. The observed, second spectra of the lanthanides, come from elements that are overwhelmingly doubly-ionized in the hotter magnetic stars.

Magazzu (private communication) carefully studied six lanthanides in the two cool Ap stars γ Equ and 10 Aql, and the classical Am star 32 Aqr. His work is based on carefully chosen weak (<40 mÅ) lines. The oscillator strengths were obtained from Meggers, Corliss, and Scribner's (1975) intensities using a formula similar to the one suggested by Cowley and Corliss (1983) with the exception of those for Eu II, where the Biemont et al. (1982) values were used. The abundance differences for La, Ce, Nd, Sm, Eu, and Gd in these stars are rather similar and there is no indication that the two magnetic stars are richer in the light and intermediate lanthanides than the Am star.

Cowley predicted on the basis of wavelength coincidence statistics that the Nd/Sm ratio in γ Equ and 10 Aql would be found to be different. Magazzu's work shows the effect, but only if one neglects the uncertainties, which are of order 0.2 dex. Possibly, the result found by coincidence statistics could be accounted for by an overall factor of two difference in the relative abundances [Nd/Sm] (γ Equ - 10 Aql) ≃ 0.3 dex, which was obtained by Magazzu. Since the differences seem rather clear in the raw coincidence data, further work should be undertaken to clarify this question of differentiation amoung the lanthanides. It is especially important that the stellar spectra be obtained at low noise levels and high resolution.

We do not report the 'mean abundances' for the lanthanides. In γ Equ and 10 Aql, Magazzu finds the abundances of the odd-Z lanthanides La and Eu to be less than those of the even-Z elements Ce, Nd, Sm, and Gd. The difference is 0.7 - 1.0 dex. Thus these two magnetic Ap stars clearly do not resemble Adelman's (1973) rare-earth mean pattern. The origin of that particular pattern, with the abundances increasing steadily from La to Eu, involves a variety of factors that depend on the individual stars and cannot be discussed here. It is possible that 73 Dra (Sadakane 1976) has a rare-earth pattern resembling Adelman's (1973) mean. However, apart from Eu II, the lanthanide lines in 73 Dra are considerably weaker than those in typical cool magnetic Ap stars.

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