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A STUDY OF TWENTY-ONE SHARP-LINED COOL PECULIAR A STARS

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ABSTRACT

Elemental abundance analyses have been performed for 21 cool Ap stars, also known as Sr-Cr-Eu stars, which are not known to be spectrum variables, and whose projected rotational velocities are not greater than 10 km s^{-1}. Zeeman and thermal Doppler broadening are the basic line-intensification mechanisms considered. Effective temperatures estimated initially from *UBV* photoelectric data are modified by requiring that the Fe abundances derived from both Fe I and Fe II lines be equal. Log *g* has been assumed to be 4.0. In addition, this study includes two normal stars for comparison.

The cool Ap stars, in general, have normal abundances or overabundances with respect to hydrogen, for every element studied. The Fe abundance is found to increase with effective temperature. Similar dependences are found for Cr, Mn, Nd, Gd, and perhaps several other elements. The abundances are not dependent on the apparent rotational velocity or magnetic-field strength. All cool Ap stars show the same characteristic abundance anomalies, but not all to the same degree.

Substantial differences in certain abundance ratios are found which distinguish Am and cool Ap stars. The elemental abundances of the cool Ap stars are similar to those of Sr-Cr-Eu spectrum variables and agree reasonably well with the results of other studies of cool Ap stars. Several stars have properties similar to those of the Si stars studied by Sargent, Searle, and Lungershausen, and support the suggestion that the Si stars and the cool Ap stars are closely related.

All theories which purport to account for the elemental abundances of Ap stars have difficulties in explaining the results of this study. Some features of the abundance anomalies are similar to those produced by *r*- and *s*-processing. Theories which require mixing of the Ap star or binary companions are excluded. The magnetic-accretion hypothesis of Havnes and Conti is, nevertheless, more in agreement with observation than the other theories of Ap stars.

Subject headings: abundances, stellar — atmospheres, stellar — peculiar A stars — spectrum variables — magnetic stars

I. INTRODUCTION

The study of A-type stars with peculiar spectra began at the turn of the century (Maury 1897; Cannon 1901; Lockyer and Baxandall 1906). During the next few years, unusual enhanced lines in the spectra of these abnormal stars were identified; for example, Baxandall (1913) found lines of Eu II in α^2 CVn. The fact that some Ap stars are spectrum and light variables was also discovered at this time (Lundendorff 1906; Belopolsky 1913; Guthnick and Prager 1914). Many years later, Morgan (1933) showed that the brighter early-type stars with spectral pecularities formed a well-defined group whose members showed spectral anomalies that seemed to be correlated with the surface temperature.

After his discovery in 1946 of a stellar magnetic field in the Ap star 78 Vir (HD 118022) (Babcock 1947), Babcock (1958, 1960) surveyed many kinds of stars, especially those of A-type, and found that most Ap stars possess measurable magnetic fields if their lines are not greatly broadened by rotation, and that all stellar magnetic fields are variable, some being periodic. These magnetic periods are the same as those of light and spectral variability. Several models have been formulated to explain magnetic phenomena, the most successful of which has been the oblique rotator (Stibbs 1950;

Deutsch 1954, 1958), which received strong support from the discovery that the line widths of periodic Ap stars tend to vary inversely with their periods (Deutsch 1956).

Bunker (1940), Aller (1947), and Burbidge and Burbidge (1955*a*, *b*, 1956) performed pioneering abundance analyses of the Ap stars. Since then other investigators have added details about the abundances of elements, especially those whose lines can be detected only on high-dispersion spectrograms, by analyses of individual stars and by surveys of selected elemental abundances.

The continuous energy distributions in the region λ3200 to λ10,800 and profiles of the Balmer lines of peculiar A and normal stars are indistinguishable (Baschek and Oke 1965; Mihalas and Henshaw 1966; Hyland 1967; Jugaku and Sargent 1968; Durrant 1970*a*). In addition, if we examine a peculiar A and a normal star which are similar in these respects, we find that they have identical Si III/Si II ratios (Sargent and Searle 1967). Abundance analyses of Ap stars show that all lines of an ion give similar abundances. For these reasons, it is believed that the magnetic fields of the Ap stars do not greatly affect the atmospheric structure, and furthermore, that the deduced abundance anomalies are real.

The properties of the Mn stars are different from the magnetic Ap stars in regard to (1) magnetic properties, the Mn stars being nonmagnetic; (2) abundance anomalies; (3) spectrum, light, and magnetic variability, none found for the Mn stars; (4) binary membership, the Mn stars being binaries significantly more often than the other Ap stars; and (5) rocket-ultraviolet flux discrepancy with respect to normal main-sequence stars, the Mn stars being the least deficient. This suggests that there are two kinds of Ap stars (Preston 1971*b*, Sargent and Searle 1967, Guthrie 1969, Leckrone 1972). As we shall see in § VIII, the separation of the magnetic Ap stars into Si and Sr-Cr-Eu stars may be merely a temperature effect.

II. DEFINITION OF THE PROBLEM

Elemental abundances have been derived for a set of cool Ap stars (designated variously as Sr-Cr-Eu, Sr-Cr, Cr, Cr-Sr, and Eu-Cr stars) defined approximately by the condition $B - V \geq 0.0$. This study unifies previous research, and provides a good basis of comparison with other types of stars and with the predictions of the theories of abundance anomalies for Ap stars. Known spectrum variables were excluded. Without detailed study it is not known which phase, if any, is representative of their surfaces. Furthermore, the probable nonuniformities of the abundance distributions complicate the analyses of the spectra observed in integrated light.

Attention was restricted to sharp-lined stars since in their spectra the process of line identification, especially those of line blends, is simplified, and the detection of weaker lines is easier. Thus 21 cool Ap stars were selected for which apparent rotational velocities do not exceed 10 km s^{-1} and for which estimates of the surface magnetic field strengths are available (Preston 1971*a*). In addition to these Ap stars, two normal sharp-lined main-sequence stars, ν Cap and o Peg, are included as a control on the method of analysis.

The results of these analyses have been used to ascertain (*a*) the dependence of the abundances on effective temperature, magnetic field strength, and apparent rotational velocity; (*b*) how these results compare with those of low-dispersion classification spectroscopy and of criteria derived from Strömgren photometry; and, most importantly, (*c*) if these results, when compared with those deduced from normal stars, the Sun, other magnetic stars, and metallic-lined stars, can be understood in the context of the theories which purport to explain the derived abundances.

Table 1 contains the observational data on the stars studied (Preston 1971*a*; Huchra and Willner 1973). Columns (1) and (2) give the HD number and the name; column (3), the apparent rotational velocity in km s^{-1}; columns (4), (5), and (6), the *UBV*

TABLE 1

OBSERVATIONAL DATA FOR THE Sr-Cr-Eu STARS

HD (1)	Name (2)	$v \sin i$ (3)	V (4)	$B - V$ (5)	$U - B$ (6)	Ap Class (7)	H_s (8)
2453	...	≤6	6.9	+0.08	+0.03	Sr-Cr-Eu	3.8
5797	...	≤6	8.6	+0.24	+0.15	Sr-Cr	1.8
8441	...	≤6	6.6	0.00	+0.13	Sr-Cr-Eu	0.0
12288	...	≤6	7.9	+0.09	+0.03	Cr	7.0
18078	...	≤6	8.2	+0.21	+0.17	Sr-Cr-Eu	3.8
22374	9 Tau	7	6.7	+0.13	+0.11	Cr-Sr	0.5
50169	...	< 10	9.0	0.00	−0.03	Sr-Cr	5.6
81009	HR 3724	< 10	6.5	+0.22	+0.09	Sr-Cr-Eu	7.9
89069	...	9	8.4	0.00	−0.01	Sr-Cr-Eu	2.3
110066	HR 4816	≤6	6.3	+0.07	+0.02	Sr-Cr-Eu	3.6
111133	HR 4854	10	6.4	−0.05	−0.06	Sr-Cr-Eu	3.7
118022	78 Vir	10	5.0	+0.03	0.00	Sr-Cr	2.9
137909	β CrB	≤3	3.7	+0.27	+0.11	Sr-Cr-Eu	5.5
137949	33 Lib	10	7.2	+0.38	+0.14	Sr-Cr-Eu	4.6
165474	...	≤6	7.4	...	...	Sr-Cr-Eu	6.6
176232	10 Aql	≤6	5.9	+0.25	+0.09	Sr-Cr	2.1
191742	...	≤6	7.8	+0.22	+0.20	Sr-Cr-Eu	1.8
192678	...	≤6	7.3	−0.02	−0.01	Cr	4.6
201601	γ Equ	≤3	4.8	+0.26	+0.10	Sr-Cr-Eu	1.8
204411	HR 8216	≤6	5.3	+0.09	+0.15	Cr-Eu	0.5
216533	...	7	7.9	+0.08	+0.10	Sr-Cr	2.3

colors; column (7), the Ap subclass; column (8), the surface magnetic-field strength, H_s, in kilogauss. HD 81009 is a visual binary whose components are too close to be easily separated. It was analyzed as if it were a single star. If the star is one of the 21 sharp-lined cool Ap stars studied, it will be referred to by its number in the Henry Draper Catalog, while the two normal stars will be referred to by name.

III. LINE IDENTIFICATIONS

The spectrograms used in this study are primarily 4.5 Å mm^{-1} IIa-O coudé spectrograms obtained by Preston for his study of rotational velocities of peculiar A stars either at Lick or Palomar Observatories. Many program stars have complicated spectra in which much blending occurs. In general, above the Balmer jump, the shorter the wavelength examined on a IIa-O spectrogram of a sharp-lined cool Ap star, the worse the line-blending problem becomes. In a major survey it is expedient to choose the smallest wavelength range which yields a sufficient number of usable lines for many elements. The interval λλ4200–4635 satisfies this condition reasonably well, but in order to include some important ions, particularly Pm II, Os I, Os II, Pt II, and U II, a few additional regions were used.

Wavelengths of all usable spectroscopic features were measured with a Grant comparator between λλ3850 and 3870 and between λλ3968 and 4650. The chief sources of line identifications were the Revised Multiplet Table (Moore 1945) and Meggers, Corliss, and Scribner (1961). For the normal stars, line-identification lists by Adelman (1973*a*) and Maestre and Deutsch (1961) were used. The line identifications agree fairly well with those of Wolff (1971) for HD 111133, Hiltner (1945) for HD 137909, Auer (1964) for HD 176232, Bidelman (1971) for HD 201601, and Sargent, Strom, and Strom (1969) for HD 204411. The criteria used to accept the line identifications, and the quality of the abundance determinations based on them, are discussed by Adelman (1972, 1973*b*).

IV. METHOD OF ELEMENTAL ABUNDANCE DETERMINATONS

Model atmospheres were generated by the ATLAS program (Kurucz 1970). They include hydrogen-line opacities except those from the Lyman series, and continuum opacities due to H I, He I, He II, H^-, H_2^+, Si I, Mg I, A I, C, N, O, and electron and Rayleigh scattering. Radiative, hydrostatic, and local thermodynamic equilibria were assumed as well as a uniform composition. Metallic-line blanketing is not included. A grid of model atmospheres with effective temperatures between 7500° and 11,000° K was calculated for $\log g = 3.5$ and 4.0.

The Hγ profile can be measured fairly accurately in the spectra of some cool Ap stars, but for other stars the great line density makes this determination very difficult. Wolff (1967) found by use of Hγ profiles that normal and peculiar A stars have similar values for their gravities. Popper (1959), Conti and Strom (1968), Schild, Peterson, and Oke (1971), and Adelman (1973*a*) have deduced values of $\log g$ between 3.7 and 4.4 for normal main-sequence stars in the appropriate temperature range. Thus, Wolff's result implies that the value of $\log g$ for the cool Ap stars must be close to 4.0.

High-dispersion studies of HD 137909, HD 188041, and HD 201601 (Preston 1967*a*, *b*; Wolff 1969; Preston and Cathey 1968; Evans and Elste 1971) show that the Zeeman effect is responsible for most of the line broadening in magnetic Ap stars. Each line is broadened by its particular Zeeman pattern. In a coarse analysis, such broadening can be treated to first approximation as a pseudo-microturbulence that is particular to each line. If the shape of the curve of growth and the amount that its axes shift with microturbulent velocity are known, all equivalent widths can be reduced to the values that they would have with a common effective microturbulent velocity. No classical microturbulence, i.e., mass motion of turbulent elements whose size is small with respect to the mean free path of a photon, has been assumed to exist in these stars.

The effective microturbulent velocity V for each line, in km s^{-1}, was found by equating the Doppler half-width with the wavelength displacement of z, the centroid of the σ components of the Zeeman pattern. Hence

$$V = 1.40 \times 10^{-4} z \lambda H$$

where λ is the wavelength in Å and H is the stellar magnetic field in kilogauss. In another astrophysical context, the analysis of sunspot spectra, ten Bruggencate (1939), Warwick (1954), and Unno (1956) have also considered the effects of the magnetic field.

For normal stars, the author used a microturbulent velocity of 3 km s^{-1}. This estimate is based on the following values: 2.75 km s^{-1} for ν Cap (Adelman 1973*a*), 2.5 to 3.0 km s^{-1} for four field A stars (Conti and Strom 1968), 2.9 km s^{-1} for α CMi (Danziger 1966), and 3.1 km s^{-1} for α Lyr (Baschek and Searle 1969).

The value of the magnetic-field strength used is the mean surface field, H_s, which is insensitive to aspect, and whose derived values are based on resolved doublets for stars with large values of H_s and on differential Zeeman broadening for stars with small values of H_s. The errors in the derived values are estimated to be 1 kilogauss or more for those stars with $H_s \leq 3$ kilogauss.

Since most lines have similarly shaped curves of growth, reduction factors were calculated for representative lines of the various elements at an effective temperature typical of the cool Ap stars studied. A computer program, WIDTH 4, which incorporates the techniques of Strom, Gingerich, and Strom (1966), was used to construct curves of growth for a number of microturbulent velocities. By comparison of a given curve of growth with the one for zero microturbulence, a correction factor can be obtained that converts the observed equivalent width to the one that would result for no microturbulence.

Then, for representative lines, diagrams were constructed which relate equivalent width, effective temperature, and elemental abundance in the case of zero microturbulence. By use of the reduced equivalent widths, the proper abundances for these lines are found by interpolation. Abundances were derived for the remaining lines by use of the diagrams and scaling factors derived from the axes of the curve of growth.

V. EFFECTIVE TEMPERATURES

Crude estimates of the effective temperatures were obtained initially from *UBV* data (Preston 1971*c*) (see table 2), and then modified by requiring that the Fe abundances derived from the Fe I and Fe II lines agree. The effective-temperature scale used was that of Wolff, Kuhi, and Hayes (1968), which is similar to that of Schild *et al.* (1971). There were two stars without *UBV* photometry for which the initial estimates of the effective temperature were simply guessed.

There are several recent determinations of Fe I transition probabilities, which include those of Garz and Kock (1969), Bridges and Wiese (1970), and Wolnik, Berthel, and Wares (1970), that are in reasonably good agreement with one another and do not contain the systematic errors of older determinations. Baschek *et al.* (1970), using the same arc as Garz and Kock, measured oscillator strengths of Fe II on their absolute scale. Their solar value of log Fe/H $= -4.42$ compares with -4.45 determined by Garz *et al.* (1969) from Fe I lines (these values are scaled to the $\lambda3720$ log *gf*-value of Bell and Tubbs [1970]). These determinations are supported by values of -4.5 from the solar [Fe II] lines (Grevesse and Swings 1969) and -4.45 from chondritic meteorites (Urey 1967). On the other hand, after consideration of the damping of the Fe I lines, Cowley (1970) and Ross (1970) have proposed lower solar Fe abundances with -4.8 as an upper limit. Wolnik, Berthel, and Wares (1971) have measured Fe II oscillator strengths which are approximately 1.6 times greater than those of Baschek *et al.* (1970). They imply a solar Fe abundance of -4.60.

Most continuum energy distributions published in the last few years use the calibration of Oke (1964) rather than the recent recalibrations by Oke and Schild (1970) and by Hayes (1970). By recalibrating these scans and comparing them with ATLAS model-atmospheres continuum-energy distributions, improved effective temperatures can be derived. It is found that these temperatures agree better with those derived by use of the Baschek *et al.* (1970) Fe II oscillator strengths than those derived by use of the Wolnik *et al.* (1971) values, which give temperatures approximately 340° K cooler, or somewhat better with a mean of the choice of the oscillator strengths. Since this difference will not affect the conclusions to be drawn, the Baschek *et al.* Fe II oscillator strengths were adopted.

Table 2 gives the adopted effective-temperature determinations along with the initial estimates of effective temperatures derived from *UBV* photometry and the results of other studies. On the average, the adopted effective temperatures are 420° K hotter than those based on *UBV* photometry. There are, nevertheless, several groups: (*a*) six stars for which the difference is not greater than 100° K, (*b*) six for which the difference is between 125° and 400° K, and (*c*) seven for which the difference is greater than 500° K.

This is probably due largely to line blanketing and the attendant back-warming effect in the stellar atmosphere. When the ratio of the metallic-to-hydrogen line blanketing is small, then the model atmospheres used are a good representation. However, for many stars, e.g., HD 137909, the effects of metallic line blanketing are important.

Since metallic line blanketing is in general greater for the B magnitude than for V, it makes the star appear cooler as judged by the $B - V$ index. Wolff's (1967) conclusion that the differential effects due to line blanketing on B and V are small, except for the coolest Ap stars, suggests that the initial estimates and the adopted effective

TABLE 2

COMPARISON OF EFFECTIVE TEMPERATURES

Star	Initial Estimate (*UBV*) (° K)	Adopted (° K)	Other Determinations (° K)
HD 2453	9420	10,300	
HD 5797	9250	9550	
HD 8441	9840	10,150	
HD 12288	9840	10,500	
HD 18078	9300	10,000	
HD 22374	9300	9400	
HD 50169	10,200	10,100	
HD 81009	8300	9200	
HD 89069	...	9900	
HD 110066	9600	10,000	10,100:-W
HD 111133	10,580	10,550	10,100-W
HD 118022	9900	9950	9350-SS; 9900-W, JS; 10,250-MH
HD 137909	8020	9700	7300-MH; 8000-H1; 8850-BO, JS, W
HD 137949	7960	8800	
HD 165474	...	9100	
HD 176232	8100	8100	7400-MH; 7900-W
HD 191742	8600	8800	
HD 192678	10,140	10,350	
HD 201601	8100	8100	7500-MH, SL; 7600-H2; 7900-W
HD 204411	9250	9500	8550-SS; 8750-MH; 9175-S3; 9200-SL
HD 216533	9780	10,300	
ν Cap	...	10,400	10,200-A, W; 11,000-C; 11,200-SS; 12,300-SL
o Peg	...	10,100	9550-CS; 10,050-W; 11,200-SL

NOTE:—Sources of other determinations: A = Adelman 1973*a*; C = Conti 1970; CS = Conti and Strom 1968; H1 = Hack 1958; H2 = Hack 1960; MH = Mihalas and Henshaw 1966; S3 = Sargent *et al.* 1969; SL = Searle *et al.* 1966; SS = Searle and Sargent 1964.

The following are sources of the continuum energy distributions which were corrected to the Oke and Schild (1970) calibration. The temperatures were derived by comparison with ATLAS model atmospheres continuum fluxes: BO = Baschek and Oke 1965; JS = Jugaku and Sargent 1968; W = Wolff 1967.

temperatures should agree, but they do not for many stars. There are five stars common to both studies: HD 111133, HD 118022, HD 137909, HD 176232, and HD 201601, four of which belong to group *a*. Only HD 137909, which belongs to group *c*, has corrections due to line blanketing sufficiently large that the effective temperature derived from the continuum energy scan has to be corrected for this effect.

Wolff (1967) proposed that the strength of the Eu II lines, the average value of the line-blocking coefficient, the Strömgren metal index m_1, and the apparent rotational velocity are correlated. The values of m_1 determined by Cameron (1966) and this study's Eu abundances are poorly correlated. However, one can determine, by comparison of the colors of the cool Ap stars and the means of the standards (Crawford and Barnes 1970 and sources therein), an index Δm_1 which represents the excess metal index. Δm_1 is loosely correlated with the Eu abundance and with the difference between adopted and *UBV* photometry effective temperatures. Hence this effective-temperature difference is somewhat dependent on metallic line blanketing.

Strom and Strom (1969) and Peterson (1970) have suggested that normal C abundances, overabundance of O, Mg, Si, and Fe by factors of 10, and overabundances of other abundant elements such as Cr, by factors of 100, can make important contributions to the ultraviolet opacity, and can significantly affect the emergent flux and hydrogen-line profiles for A and late B stars. Wolff and Wolff (1971) noted that discrete absorption by the large number of doubly and triply ionized rare earth lines in $\lambda\lambda$2000–3000 (Dieke, Crosswhite, and Dunn 1961) could play a similar role in cool Ap stars. In addition, the effects of the various elements can compete with one another. Such difficulties are ignored in this study.

Some of the differences between the adopted and scan-determined effective temperatures may be due to undetected spectrum variability. However, for HD 137909, this is not the case. Its blanketing corrections are sufficiently large as to make determinations based on its continuum energy distribution quite uncertain. The remaining effective temperatures deduced by other authors were determined by a variety of methods, including those which involve curve-of-growth techniques, most of which are not as reliable as the above method, due to errors such as those which were subsequently detected in the Fe oscillator strengths.

VI. ABUNDANCES

Figure 1 shows the elemental abundance anomalies, [N/H], which are the logarithmic absolute abundances in units of the solar values, as a function of atomic number. Gaps have been left for missing elements. No cool Ap star has a well-determined elemental abundance with respect to solar values less than -0.6 dex. The errors in the best-determined absolute abundances are 0.4 dex, while in the worst cases they are 0.8–1.0 dex and marked uncertain. The mean error is 0.5 dex.

Silicon has a mean overabundance of $+0.5$ dex compared with Mg's nearly solar value. Between Ca and V, the mean overabundance is near $+0.65$ dex. At Cr, it jumps to $+2.02$ dex, then drops to $+1.06$ for Fe with Mn in between. It appears to increase for Co and decrease for Ni. Strontium has a very large mean overabundance compared with Y. Zirconium is very indeterminant, although some stars have greater Zr than Y overabundances. The Ba values are poorly determined and have a large scatter, with a mean value near 0.0. The rare earths show increasing overabundances from La through Eu, with those of Gd systematically less than those of Eu. Gadolinium and uranium have similar overabundances. The individual stars have values which, in general, follow these trends.

Magnesium and yttrium are the only elements with reasonably well-determined abundances which have nearly solar mean values. If we consider a mean overabundance of 0.50 dex as significant, then for the cool Ap stars as a class, those elements which are overabundant are Si, Ca, Sc, Ti, Cr, Mn, Fe, Co, Sr, Ce, Nd, Eu, Gd, and U while V, Zr, La, Pr, and Sm may be. Nickel and barium may have solar mean abundances. For Cr and Mn the minimum stellar overabundance is $+0.6$ dex, while for Gd and Eu it is $+1.9$ dex. These elements are overabundant in all cool Ap stars. Since the maximum Mg overabundance for any cool Ap star is $+0.35$ dex, then the Cr, Mn, Gd, and Eu overabundances are always greater. Similar results come from examining the abundances of the individual stars which are given in Adelman (1972, 1973*b*). The most interesting and certain of these are given in the Appendix.

In figure 2, the iron-peak elements with odd values of the atomic number, Z, have lower absolute abundances than adjacent elements with even values of Z. Adjacent elements in the [N/H] diagram show no such effects. Thus, the process responsible for the overabundances does not fill in the solar abundance wells. Strontium has a significantly greater mean abundance than Y, although their solar abundances are not that dissimilar. There is a possible decline from $Z = 26$ to $Z = 56$ in abundance. Among the rare earths, the absolute abundances tend to increase with atomic number. The total increase in absolute abundance is over 2.0 dex between La and Eu.

For some elements the range of values is less than that for others. One way to judge how closely the stars show the same abundance anomalies is to examine the mean

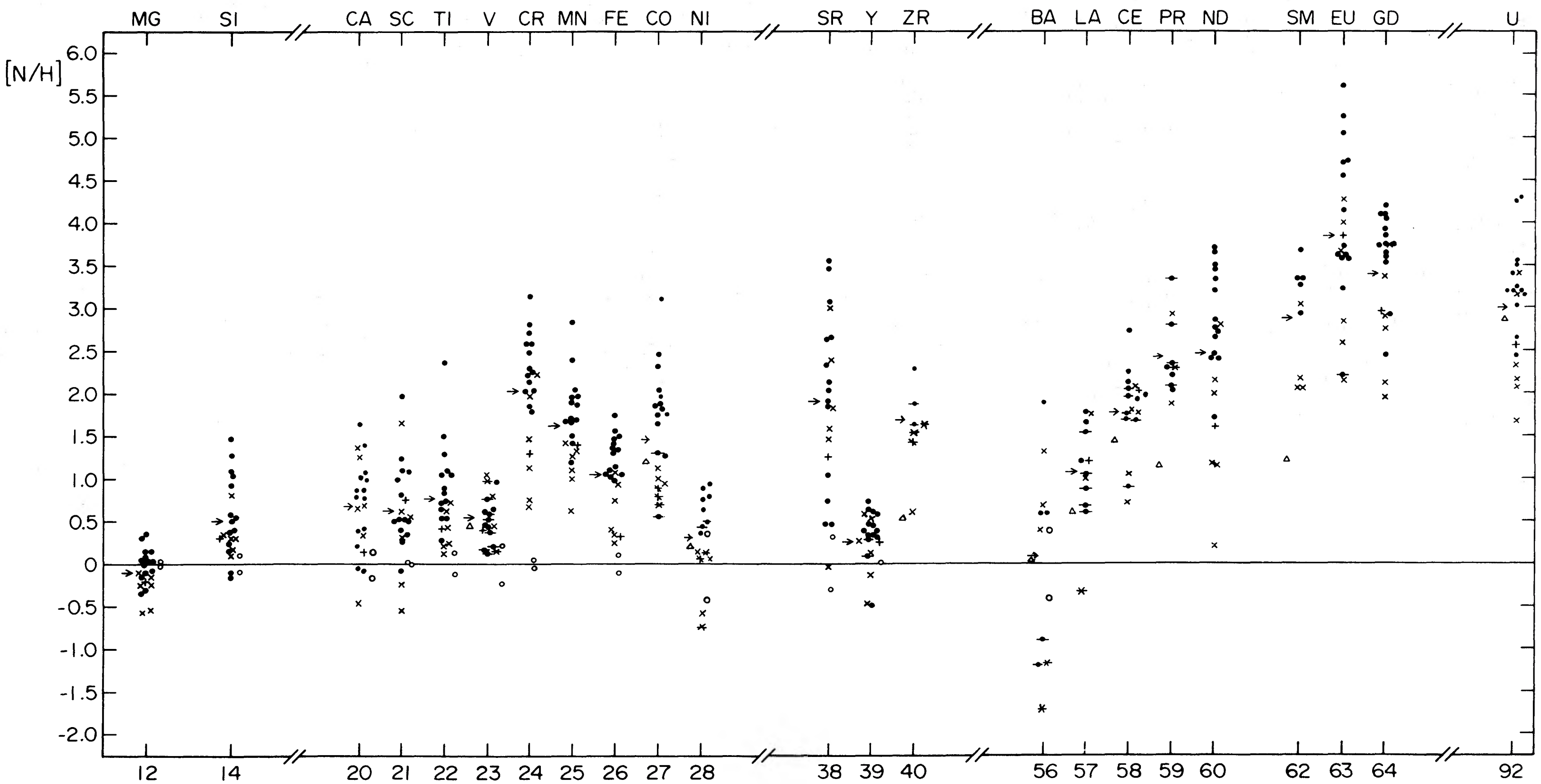

FIG. 1.—[N/H] values, the logarithmic abundances with respect to H and relative to solar values, as a function of atomic number. *Closed circles*, cool Ap stars with $T_{eff} > 9450°$ K; +, HD 81009; *crosses*, the other cool Ap stars; *open circles*, normal stars. Uncertain values are indicated by bracketing horizontal lines except for HD 81009 when a plus sign with a diagonal is the symbol. Arrows indicate the mean elemental abundances for those cool Ap stars with deduced abundances. In case all the cool Ap program stars did not have abundances deduced for an element, a second average was made by assuming that those cool Ap stars without lines measurable for equivalent widths had solar abundance values. These averages are indicated by open triangles. The atomic number for each element with deduced abundances is given below the diagram, while the corresponding chemical symbol is above it.

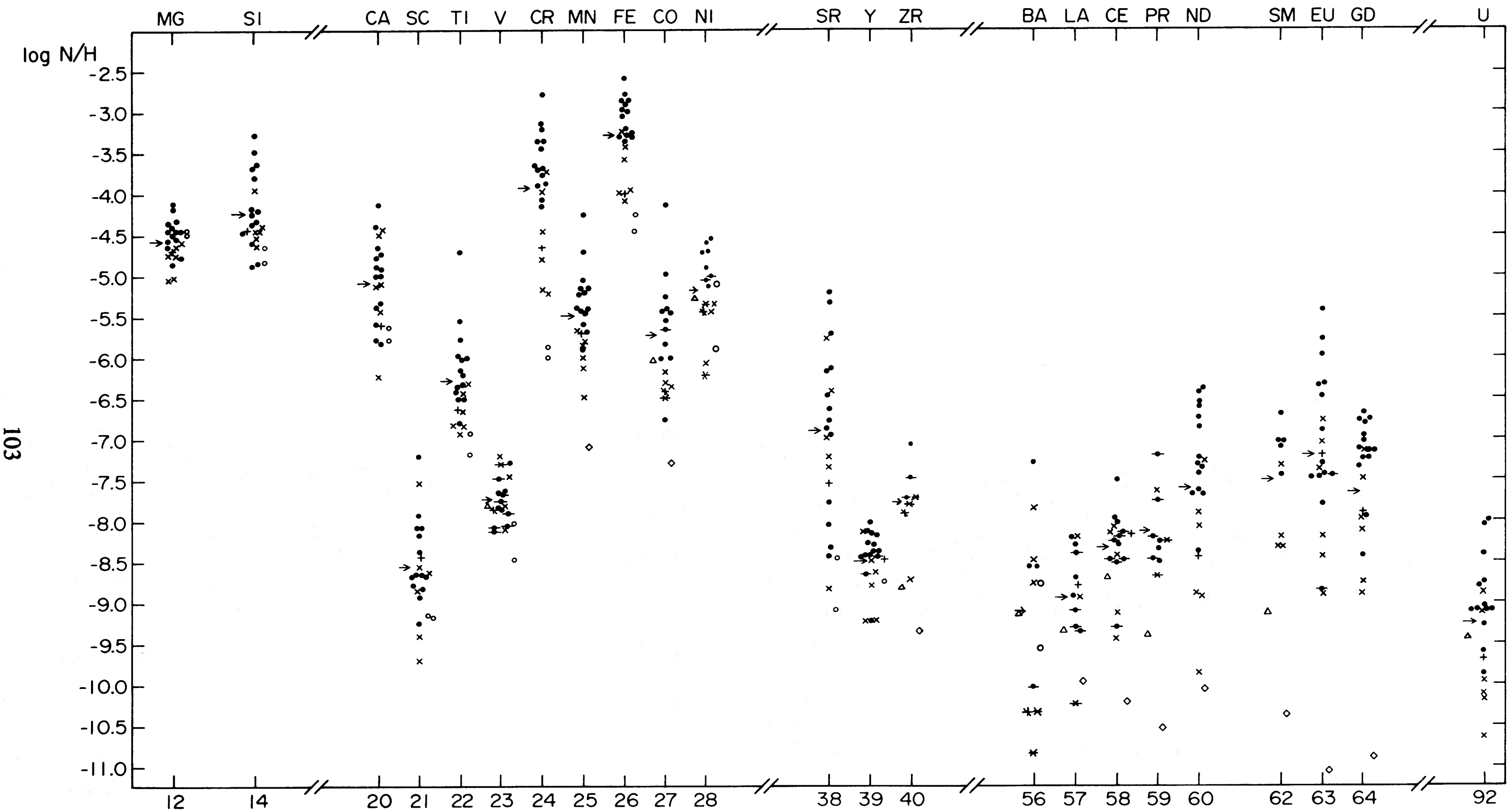

FIG. 2.—Log N/H values, the absolute abundances, as a function of atomic number. Symbols, same as fig. 1. In addition, the elements whose abundances were not determined in the normal stars have their solar abundances indicated by open diamonds, except for U which has a solar value of log U/H = −12.30.

TABLE 3

RELATIVE ABUNDANCES [N/H] OF SPECTRUM VARIABLES COMPARED WITH THE MEAN OF THE COOL Ap STARS AND THEIR MEAN DEVIATIONS

ELEMENT	MEAN COOL Ap STARS	α^2 CVn $\Phi = 0.0$	α^2 CVn $\Phi = 0.5$	HD 34452	HD 176350	HD 221568
Mg	−0.08 ± 0.19	−0.2:	...	+1.2	...	+1.0
Si	+0.51 ± 0.35	+1.6	+1.9	+1.9	−0.5:	+1.2
Ca	+0.68 ± 0.43	+1.8:	...	...	...	−1.5
Sc	+0.64 ± 0.41	+1.9:	...	...	...	...
Ti	+0.79 ± 0.37	+1.6	+1.3	+2.1	+0.5	+0.7
V	+0.53 ± 0.24	+2.5:	...	...	...	...
Cr	+2.02 ± 0.51	+1.8	+2.3	+2.0	+1.5	+1.0
Mn	+1.60 ± 0.38	+3.0:	...	< +1.4	+2.0	...
Fe	+1.06 ± 0.33	+1.6	+2.0	+1.7	+1.0	+1.0
Co	+1.47 ± 0.56	...	...	< +0.9	...	...
Ni	+0.33 ± 0.40	...	...	< −0.5	...	...
Sr	+1.90 ± 0.80	+2.0:	...	+2.7	+2.3	+2.3
Y	+0.28 ± 0.27	+2.9	+2.7	...	...	...
Zr	+1.57 ± 0.33	+2.2	+1.8	...	...	+2.3
Ba	+0.07 ± 1.03	< +1.6	...	...	...	...
La	+1.06 ± 0.42	+2.5	+2.2	...	...	...
Ce	+1.78 ± 0.29	+4.2	+3.7	...	...	+2.0
Pr	+2.38 ± 0.36	+4.3	+3.5	...	...	+3.6
Nd	+2.42 ± 0.71	+4.2	...	...	...	+3.2
Sm	+2.88 ± 0.51	+3.9	+3.4	...	...	+3.8
Eu	+3.79 ± 0.72	+6.2	+5.0	+6.2	+4.0:	+3.5
Gd	+3.36 ± 0.54	+4.8	+4.1	...	< +3.9:	+3.8
U	+3.01 ± 0.53	...	...	...	...	...
T_{eff} (° K)		12,000°		18,000°	10,100°	10,100°
log g		4.0		4.2	...	3.7

NOTES:—All values are approximate for HD 221568. The model atmospheres used for the analysis of α^2 CVn make allowance for the effects of the Si overabundance. Sources of data: α^2 CVn, Cohen 1970; HD 34452, Tomley *et al.* 1970; HD 173650, Rice 1970; HD 221568, Kodaira 1967.

deviations (table 3). Except for Sr, Ba, Nd, and Eu, the mean deviations are similar to or smaller than the acknowledged errors. Hence all cool Ap stars show the same abundance anomalies within well-defined range. Consequently, any dependence of the abundances on the physical properties of the stars, effective temperature, magnetic field strength, and apparent rotational velocity, must not in general be very strong. There are, however, substantial differences in abundance even for stars which we regard as of approximately the same effective temperature.

To consider the similarity and degree of abundance anomalies further, the best-determined elemental abundances, namely those of Mg, Si, Ca, Sc, Ti, Cr, Mn, Fe, Sr, Y, Nd, Eu, and Gd, were studied. Five stars, HD 81009, HD 165474, HD 201601, HD 176232, and HD 22374, which are rather cool, usually have smaller abundance anomalies than the other cool Ap stars, while HD 5797, HD 110066, HD 2453, and HD 216533 usually had the largest ones. On the other hand, there are two stars, HD 8441 and HD 204411, which have relatively small abundance anomalies for only some groups of elements, Mg–Ti and Sr–Gd, respectively. The center of the range of elemental abundances is well mixed.

We conclude that all cool Ap stars exhibit the same characteristic abundance anomalies although not all to the same degree, and they especially exhibit the tendency for the mean abundance of the rare earths to increase with atomic number between La and Eu. Significant Cr, Mn, Eu, and Gd overabundances are characteristic of all cool

Ap stars. Most deduced elemental abundances are overabundances with respect to solar values. The process that is responsible for the abundance anomalies does not fill in the solar abundance wells in the Fe peak. The errors in the abundances due to incorrect effective temperatures, gravities, and magnetic-field strengths are not likely to change these conclusions.

VII. COMPARISON OF THE NORMAL STAR ABUNDANCES

Table 4 gives the abundances of ν Cap, o Peg, and the Sun. This study's abundances of ν Cap agree to within 0.2 dex of those of the fine analysis (Adelman 1973*a*) (see this reference for a discussion of Conti's [1970] study). As for o Peg, the abundances derived in this study are generally larger than those derived by Conti and Strom (1968), since the adopted effective temperature is greater by 600° K. The remaining discrepancies are attributable to oscillator-strength differences.

Except for Ti, Cr, Ni, Sr, and Ba, the solar and the average abundances of ν Cap and o Peg agree to within 0.2 dex. The Ba difference is partially due to the use of a blended resonance line. The star o Peg has overabundances of Ni, Sr, and Ba, and is a moderate Am star according to Conti and Strom. Hence, when the solar and mean abundances from ν Cap and o Peg disagree, this may be due to the mild Am phenomenon which the latter star exhibits. For Ni and Sr, the correction for o Peg's overabundances brings the solar abundance and the mean normal-star abundance into agreement. Part of the remaining discrepancies are due to the inequality of the oscillator-strength scales used in this study and in the solar-abundance studies. The degree of agreement of the abundances of the normal stars with solar values suggests that both the effective temperatures and the derived absolute abundances are reasonably well-determined.

TABLE 4

COMPARISON OF SOLAR AND NORMAL A STAR ABUNDANCES

	log N/H				
	ν Cap		o Peg		The Sun
Ion(s)	A(2)	A(1)	CS(68)	A(1)	
Fe I, II	−4.5	−4.5	−5.2	−4.3	−4.4
Mg II	−4.4	−4.5	−4.3	−4.5	−4.6
Si II	−4.5	−4.6	−4.0	−4.8	−4.5
Ca I	−6.0	−6.0	−6.2	−5.7	−5.7
Sc II	−9.2	−9.2	−9.5	−9.2	−9.0
Ti II	−7.4	−7.2	−7.2	−7.0	−7.5
V II	−8.6:	−8.5	−8.4	−8.0	−8.1
Cr I, II	−6.0	−6.0	−6.5	−5.8	−6.4
Mn II	...	...	−6.5	...	−7.1
Ni I	...	...	−5.6	...	−5.8
Ni II	−6.0	−5.9	−6.4	−5.1	−5.8
Sr II	−9.4	−9.2	−8.3	−8.5	−9.2
Y II	...	...	−9.3	−8.8	−8.8
Zr II	...	...	−8.6	...	−9.4
Ba II	−9.6	−9.6	−8.4	−8.8	−10.1
T_{eff} (° K)	10,200	10,400	9500	10,100	
log g	3.75	4.00	4.00	4.00	
ξ	2.75	3.00	3.00	3.00	

NOTES:—A(1) = This study; A(2) = Adelman 1973*a*; CS(68) = Conti and Strom 1968.

VIII. COMPARISON WITH OTHER ABUNDANCE STUDIES OF NONVARIABLE COOL Ap STARS

There are six relatively recent analyses of cool peculiar A stars: HD 137909 (Hack 1958), HD 176232 (Auer 1964), HD 201601 (Hack 1960; Evans 1966), HD 204411 (Sargent *et al.* 1969), and HD 151199 (Burbidge and Burbidge 1956). Their derived abundances are compared with those of this survey in table 5. Except for the last star, these stars are included in this survey.

Most of the differences in the derived abundances between this study and those of other authors are due to differences in effective temperatures, gravities, oscillator strengths, and choice of lines used. The use of a common microturbulent velocity can also induce errors into the derived abundances. The overabundances of HD 151199 (Sargent 1964) fall within the range of this study's cool Ap star determinations except for those of Cr and Fe, which are 0.3 dex below the minimum values measured.

The relative abundances with respect to Fe of this survey and of Wolff's (1967) study agree poorly for the stars in common, although the measured equivalent widths are similar. She adopted the solar Fe abundance for the Ap stars and obtained microturbulent velocities by use of the equivalent width of Fe II (38) λ4508.28. This method of analysis is invalid for the cool Ap stars, and introduces errors into the relative abundances of the other elements.

The cool Ap stars studied only by Sargent and Searle (1962), Searle and Sargent (1964), and Searle, Lungershausen, and Sargent (1966), and those in common with this study have similar abundances. This study shows that the average cool Ap star has both a [Cr/Fe] and a [Mn/Fe] overabundance with a [Ti/Fe] marginal underabundance while Searle *et al.* find that all three ratios have normal values. For [Cr/Fe], they examined the cool Ap stars with the most normal ratios. Furthermore, their values of the microturbulent velocity are too large for some cool Ap stars (Preston and Cathey 1968; Evans and Elste 1971). The mean z values of the lines of Ti and Cr that they studied are smaller than those of Mn and Fe. Thus, the use of a common microturbulent velocity causes a compression of the [Ti/Fe] and [Cr/Fe] values. Despite these differences, the results for the stars in common show a fair agreement ($\approx$0.3 dex, table 6). Hence the comparison with the other abundance studies of cool Ap stars indicates that the stars of this survey have abundances representative of the cool Ap stars as a whole.

Silicon stars have values of [Si/Mg] greater than 1.4 dex (Searle and Sargent 1964), and are cleanly separated from the other Ap stars in a [Si/H] versus [Mg/H] diagram by a gap of 0.7 dex in [Si/Mg]. Most of the cool Ap stars studied have normal values of [Si/Mg]. Two stars fall in the Si star band, HD 50169 and HD 192678, while at least four others fall in the gap in Searle and Sargent's diagram: HD 12288, HD 22374, HD 110066, and HD 191742. Since these stars possess the line strength and line-ratio properties of the Si stars as given by Searle and Sargent, they may be an extension of the Si stars to cooler effective temperatures.

The [Ti/Fe] values of these six cool Ap stars are similar to those of normal Si stars; those for [Mn/Fe] are marginally higher than those of normal Si stars; but those for [Cr/Fe] are significantly greater than those of normal Si stars. Some of these differences may be due to techniques of analysis. On the other hand, the range of abundances for the Si stars may be greater than now known. Durrant (1970*b*) measured the equivalent width of Si II $\lambda\lambda$6347–6371 in a large number of A and B stars. He found, contrary to the results of Searle and Sargent, that the equivalent width versus $B - V$ diagram did not show a clear-cut separation into normal and anomalous types.

The abundance anomalies are similar, but not identical, for Si and cool Ap stars, although they are quite different from those for the Mn stars (Sargent and Searle 1967; Sargent 1964, 1966; Hack 1968). An abundance survey of sharp-lined Si stars

TABLE 5

COMPARISON OF COOL PECULIAR A STAR ABUNDANCE DETERMINATIONS

	Log N/H				[N/H]						
	HD 204411		HD 201601		HD 201601		HD 137909		HD 176232		HD 151199
Element	S3	A(1)	E(66)	A(1)	H(60)	A(1)	H(58)	A(1)	A(64)	A(1)	B(56)
Mg	-4.5	-4.6	-4.1	-4.6	+1.2	-0.1	+0.2	+0.0	+1.6	-0.2	+0.1
Si	-4.5	-4.5	-3.6	-4.4	+0.5	+0.4	...	+0.2	+0.3	+0.2	+0.1
Ca	-5.3	-4.4	-4.8	-5.1	+0.7	+0.7	+0.1	+1.6	+0.2	+0.6	+0.4
Sc	-9.2	-8.7	...	-9.4	+0.7	-0.2	+0.4	+2.0	-1.6:	-0.5	...
Ti	-7.2	-6.0	...	-7.0	+0.2	+0.2	+0.9	+1.5	-0.1	+0.2	...
V	-7.3	-8.1:	...	-7.2	+0.8	+1.0	+0.4	+0.8:	-0.4	+0.4	...
Cr	-5.8	-4.2	-6.2	-5.2	+1.3	+0.7	+1.5	+1.8	+0.4	+0.8	+0.3
Mn	-6.4	-5.9	-6.0	-6.1	+1.8	+1.0	+1.6:	+1.7	+0.6	+0.6	+1.0
Fe	-4.9	-3.3	-4.2*	-4.0	+0.6	+0.4	+0.8	+1.3	+0.0	+0.2	+0.0
Co	-7.3	-6.0	...	-6.4	+1.7	+0.9	+1.0:	+1.6:	+1.2	+1.0	+1.8
Ni	-6.2	-5.1:	...	-6.1	+1.6	-0.6	+0.3	+0.8	-0.5	-0.7:	...
Sr	-8.7	-8.1	-7.4	-7.4	+2.6	+1.5	+1.6	+1.9	+1.8	+1.8	...
Y	-9.2	-9.3	...	-8.2	+0.6	+0.5	...	+0.7	+0.3	-0.1	...
Zr	-8.3	...	...	-8.7	+0.8	+0.6	+2.0	+2.3	-0.2	...	...
Ba	-9.3	-8.6	...	-8.7	+1.2	+0.4	+0.7	+0.6	-0.8	-1.7:	-0.2
La	...	...	...	-9.0	+2.3	+1.0	+2.8	...	...	-0.3:	...
Ce	-9.2	...	...	-9.2	+2.0	+1.0	+2.9	+2.7	...	+0.7	...
Pr	...	...	...	-8.3:	+2.4	+2.3:	+2.7	+3.3	...	...	...
Nd	-10.2	-8.4	-8.8	-8.9	+2.3	+1.2	+2.2	+2.4	...	+0.2	...
Sm	...	...	-9.6	-8.4	+1.7	+2.0	+2.3	+3.6	...	+2.0	...
Eu	...	-8.9:	-8.4	-8.2	+2.6	+2.8	+3.2	+5.6	...	+2.2	+2.1
Gd	-8.7	-8.4:	...	-8.9	+2.2	+1.9	+2.9	+3.7	...	+2.1	...
T_{eff}	8750°	9500°	7750°	8100°	7600°	8100°	8000°	9700°	7200°	8100°	8700°
log g	4.3	4.0	3.5	4.0	...	4.0	...	4.0	4.2	4.0	...

Sources of Abundance Determinations

A(1) = This study
A(64) = Auer (1964)
B(56) = Burbidge and Burbidge (1956) and Sargent (1964)
E(66) = Evans (1966)
H(58) = Hack (1958)
H(60) = Hack (1960)
S3 = Sargent et al. (1969), ξ = 3.5 km/sec
* = Evans and Elste (1971)

TABLE 6

COMPARISON OF THE RESULTS OF SARGENT, SEARLE, AND LUNGERSHAUSEN WITH THOSE OF THIS STUDY

Star	[Mg/H] SS	[Mg/H] A	[Si/H] SS	[Si/H] A
HD 118022	+0.2	+0.1	−0.6:	−0.1
HD 204411	+0.6	−0.1	+0.8	+0.3
ν Cap	+0.2	+0.0	+0.1	−0.1
mean	+0.3	−0.1	+0.3	+0.5

Star	[Ti/Fe] SLS	[Ti/Fe] A	[Cr/Fe] SLS	[Cr/Fe] A	[Mn/Fe] SLS	[Mn/Fe] A
HD 201601	+0.05	−0.23	+0.10	+0.31	−0.16	+0.63
HD 204411	+0.22	+0.01	+0.39	+0.73	+0.29	+0.14
mean	0.0	−0.28	0.0	+0.96	0.0	+0.56

NOTES:—SS = Searle and Sargent 1964; SLS = Searle *et al.* 1966; A = this study. The errors acknowledged are ±0.5 dex by A and ±0.6 dex by SS and SLS. "Mean" indicates the mean value for the cool Ap stars.

is in progress to determine their abundances in a manner consistent with this study. Analyses of individual Si stars in the literature use determinations of Fe oscillator strengths which contain serious systematic errors. These studies can only give tentative confirmation of the possibility that there exist Si stars with [Cr/Fe] values similar to those of the cool Ap stars (see, e.g., Burbidge and Burbidge 1955*a*). Hence, these two types of magnetic Ap stars may represent aspects of the same phenomenon which is differentiated by effective temperature.

IX. COMPARISON OF THE RESULTS WITH THOSE OF LOW-DISPERSION SPECTRAL CLASSIFICATION AND PHOTOMETRIC INDICES

Twelve of the cool Ap stars are classified as Sr-Cr-Eu, six as Sr-Cr or Cr-Sr, one as Cr-Eu, and two as Cr stars. This suggests that all cool Ap stars should have large Cr abundances, as we have found. The Cr stars HD 12288 and HD 192678, and the Eu-Cr star HD 204411, have smaller Sr abundances than the other cool Ap stars studied except for HD 22374. This survey's stars with the smallest equivalent widths of Sr II λ4215.5 are HD 12288, HD 22374, HD 89069, HD 192678, and HD 204411. The value of log Sr/H for HD 89069 is about 0.2 dex greater than that for HD 204411, which has an abundance greater than those of the remaining three stars. Thus, the subclasses isolate those stars with Sr overabundances as well as those with large Sr II line equivalent widths. HD 22374 is a puzzle. Perhaps this discrepancy is a clue to the variability of this star.

Do the 12 Sr-Cr-Eu stars and the Cr-Eu star have greater Eu abundances than the other cool Ap stars studied? HD 204411, the Cr-Eu star, has the weakest Eu II lines of the cool Ap program stars. This star may be a long-period spectrum variable (Preston 1970). The Sr-Cr-Eu and the Sr-Cr stars are well mixed with respect to effective temperature and Eu abundance. The Cr stars, which are the hottest cool Ap stars studied, are in the below-average part of the Eu abundance distribution. Hence, the subclasses are based on the appearance rather than on the stellar abundances.

Cameron (1966) investigated the peculiar A stars by means of photoelectric intermediate-band Strömgren and Hβ photometry. He found that if a star has an m_1 index greater than 0.21 mag, then it possesses a strong magnetic field. The cool Ap program stars cover most of the ranges indicated for their subclasses. Cameron plotted m_1, the metal index, versus c_1, the Balmer discontinuity index, for the stars whose [O/H] and [Si/Mg] ratios were found by Sargent and Searle (1962) and Searle and Sargent (1964). Stars with similar abundance ratios are close together.

The cool Ap stars with the largest values of [Si/Mg] do not occupy the same region of the (c_1, m_1)-diagram as do the Si stars studied by Searle and Sargent. This study's cool Ap stars are distributed in a narrow band in m_1 within the (c_1, m_1)-diagram. Correlations between c_1 and log N/H were tried for many elements. However, they are basically scatter diagrams except the one for Cr which suggests that the Cr abundance increases with effective temperature. The effects of line blanketing upon the values of the Strömgren indices may cause part of the scatter. Hence, low-dispersion classification spectroscopy and Strömgren photometry pick out the Ap stars, but do not tell us much about their elemental abundances.

X. COMPARISON OF THE COOL Ap AND Am STAR ELEMENTAL ABUNDANCES

The cool Ap and the Am stars occupy overlapping regions in the H-R diagram. Smith (1971) studied the abundances of 16 Am stars which he determined are representative of this class as a whole. Figure 5 of his paper shows his results given with respect to Fe relative to the means of the standards, while figure 3 of this paper gives the results for the cool Ap stars presented in the same manner. This presentation of the data illustrates the character of the abundance anomalies of Am stars better than the absolute abundances or overabundances. The values of [N/Fe] generally increase with atomic number except for a few elements.

The range of derived abundances is larger for the cool Ap stars than for the Am stars. The [N/Fe] values of the cool Ap stars are all greater than those of the Am stars for Cr, Sm, and Gd, while for Y the reverse is true. In addition, there is nearly complete separation for Mn, Nd, and Eu similar to that in the Cr relative abundances, while that for Ni is similar to Y. The other elements have overlapping abundance ranges, but there are still differences in the distribution of abundances and in the mean abundances.

The scatter in the relative abundances for the Am stars is similar to that of the standards. This is not so for the cool Ap stars. For absolute abundances, the scatter is larger than the normal stars' for both Am and cool Ap stars. The mechanism which produces the overabundances with respect to Fe for the Am stars does not allow variations from one star to another by more than a factor of 2 for most elements. Also, the cool Ap stars lack the Am stars' relationship in which the stars with the largest Fe enhancement for a given temperature also have the largest log Sr/Fe value, and conversely.

In general, the absolute abundances are not as great for the Am stars as for the cool Ap stars. The Am stars have similar abundances for the rare earths. For most elements, the ranges of abundances overlap for the Am and the cool Ap stars. However, for Cr, Sm, and Gd, there is complete separation, with the cool Ap stars having the greater absolute abundances. Ti, Mn, Nd, and Eu show virtually complete separation in the same sense.

Similar to the results for the cool Ap stars, the Fe abundance in the Am stars increases with effective temperature with a similar slope (see § XI). For the Am stars, the abundances of all elements correlate with one another both in their absolute and relative abundances with respect to Fe. With the cool Ap stars there are correlations between Ca and Sc, Gd and Ce, and between many iron-peak elements: Sc with Ti, Cr with Mn and Fe, Fe with Mn, and Ti with Fe. On the other hand, many elements have abundances which do not correlate with those of Fe, while the abundances of the elements which do so, correlate with one another.

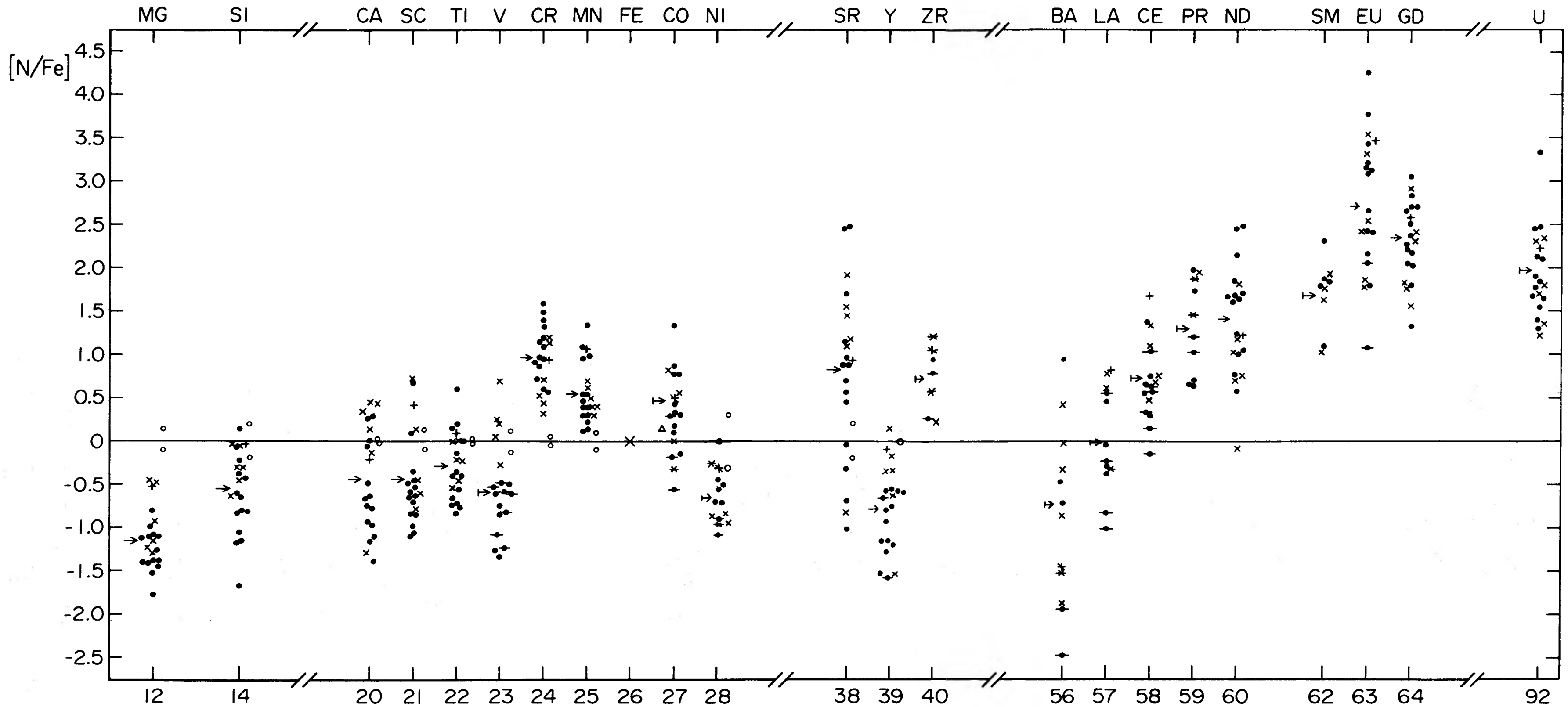

FIG. 3.—[N/Fe] values, the logarithmic abundances with respect to Fe and relative to solar values. Symbols have the same meanings as in fig. 1. In case all the cool Ap program stars did not have abundances deduced for an element, a vertical bar was attached to the shaft of the arrow.

The abundance-anomaly characteristics imply that different mechanisms produce the cool and Am stars. Furthermore, the Am stars do not have the substantial magnetic fields (Conti 1969) of the cool Ap stars. Thus, if a diffusion mechanism working in a subsurface elemental-separation zone produces the abundance anomalies of the Am stars (Watson 1970; Smith 1971), it is unlikely it can do so for the cool Ap stars.

Hence the most clear-cut differences between the cool Ap and the Am stars appear by the comparison of a few abundance ratios, the most certain of which are [Cr/Fe], [Gd/Fe], [Y/Fe], [Cr/H], and [Gd/H]. The ratios [Mn/Fe], [Eu/Fe], [Nd/Fe], [Ti/H], [Mn/H], [Nd/H], and [Eu/H] may also be useful in this regard. These differences and the others cited imply that the abundance anomalies of these two types of stars are produced by different mechanisms.

XI. DEPENDENCE OF THE ABUNDANCES ON THE PHYSICAL PROPERTIES OF THE STARS

The apparent rotational velocities of the stars studied are less than 10 km s^{-1}, although for many stars only an upper limit is known. In addition, the lack of light variability for several of these stars over a period of several months (Wolff and Morrison 1971) suggests that their values of $v \sin i$ may be less than 1 km s^{-1}. By use of the values given in table 1, no convincing case can be made for the dependence of any of the deduced elemental abundances on apparent rotational velocity. Furthermore, correlations between elemental abundance and magnetic-field strength are at best speculative. This implies that either the magnetic fields are not important in the production of the abundance anomalies or that the time scale for their decay is shorter than the main-sequence lifetime of the Ap stars.

A diagram of log Fe/H versus effective temperature is shown in figure 4. This diagram is similar to the one which uses the values derived from the Fe II lines for log Fe/H versus the initial estimates of effective temperature from *UBV* photometry. The Fe abundance increases with effective temperature. In addition, the correlation line is parallel to the direction along which errors in the effective temperature and log g would be caused. This implies that it is real. Errors in oscillator strengths shift the stars with respect to effective temperature but do not change this correlation. At a given effective temperature, there are stars with significantly different Fe abundances. This scatter may be due to errors in log Fe/H and atmospheric parameters. However, a good part of it is real and should be regarded as a clue to the origin of the abundance anomalies.

Log Cr/H, log Mn/H, log Gd/H, log Nd/H, log Cr/Fe, and log Nd/Fe are also functions of the effective temperature, while several other abundance ratios may be. Furthermore, there are other abundance-ratio versus effective-temperature diagrams which have interesting divisions in the distribution of the abundance ratios. However, there are many scatter diagrams (Adelman 1972).

For most stars, the rare earth with the largest abundance is Eu. Of the 17 stars whose rare-earth abundances were determined in this study for at least five of these elements, 11 have maxima at Eu, two at Nd, two at Sm, and two at Gd. This shift of the rare-earth abundances causes scatter in some attempted correlation diagrams (i.e., log Eu/H and log Gd/H versus effective temperature).

Thus, there are no conclusive correlations of abundance with magnetic-field strength or apparent rotational velocity. Log Fe/H, log Cr/H, log Cr/Fe, log Mn/H, log Nd/H, log Nd/Fe, and log Gd/H increase with effective temperature. Furthermore, any two elements whose abundances increase with effective temperature have abundances which are correlated.

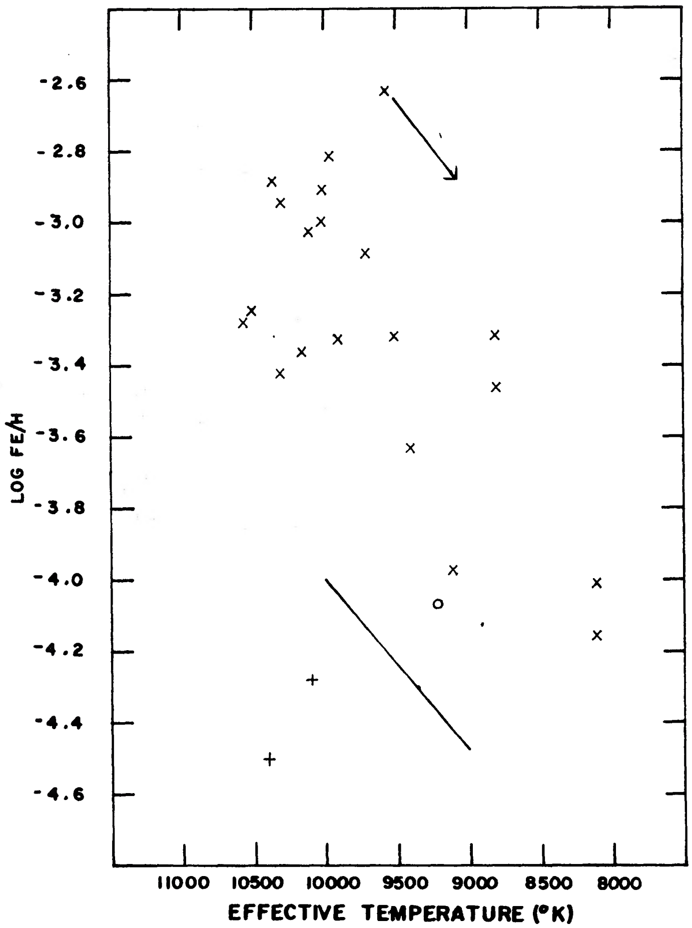

FIG. 4.—Log Fe/H versus effective-temperature diagram. The tip of the arrow indicates the position of HD 5797 in this diagram if its value of log g is 3.5 instead of 4.0. The ends of the solid line indicate the effect of a 1000° K change in effective temperature of log Fe/H values. This direction is virtually the same as that of the arrow. *Open circle* denotes HD 81009; *crosses*, the other cool Ap stars; *pluses*, the normal A stars. The Fe abundances and effective temperatures increase together. The mean log Fe/H value for the cool Ap stars is −3.33; for the normal stars, −4.39; for the Sun, −4.40.

XII. COMPARISON OF THE ABUNDANCES WITH THOSE OF SPECTRUM VARIABLES

In spectrum variables, lines of certain elements periodically vary in strength in a manner not compatible with changes in temperature or electron pressure. Often the spectrum variations are accompanied by those of light and radial-velocity with the same period. The extremes of the light and spectrum variations coincide in phase. All elements do not participate to the same degree, and in some stars there are elements which vary in antiphase with others (Preston 1971*b*). Studies of spectrum variables (Deutsch 1958; Kodaira 1967; Peterson 1966; Preston 1967*a*, 1969; Preston and Wolff 1970; Pyper 1969; Rice 1970) indicate that only the lines of the rare-earth elements always vary together. Lines of other elements show a large range of properties.

If a line is formed on only part of the stellar surface, then the observed equivalent width is smaller than one would find if only the region of formation was observed, and the deduced abundance will be smaller than that in the spot. If the magnetic field in the spot region is greater than the mean over the stellar surface, then the degree of

Zeeman intensification will be greater than that predicted by the mean field for the line in question. Without a detailed knowledge of the field geometry and the local contributions to the equivalent widths, it is impossible to get more than a crude abundance estimate. It is not known whether magnetic intensification can become more important than dilution effects.

Sargent and Searle (1962), Searle and Sargent (1964), and Searle *et al.* (1966) found that spectrum variables generally share the abundance anomalies of the other Ap stars of their peculiarity type. Four spectrum variables have been analyzed at high dispersion (table 3): α^2 CVn (most recently by Cohen 1970), HD 34452 (Tomley *et al.* 1970), HD 173650 (Rice 1970), and HD 221568 (Kodaira 1967). In general, the effects due to inhomogeneities of the surface abundances are ignored.

On the whole, the abundance anomalies of the spectrum variables are basically similar to those of the cool Ap stars. The abundances of HD 173650 are within the range of those of the cool Ap stars. The other spectrum variables have some elemental abundances which are greater than those of any cool Ap star: Si, Ca, V, Y, La, Ce, Pr, Nd, and Sm for α^2 CVn; Mg, Pr, and Sm for HD 221568; and Mg, Si, and Eu for HD 34452. The remaining abundance determinations fall within the range of the cool Ap stars except for that of Ca for HD 221568.

Some of the abundance anomalies seen in α^2 CVn and HD 34452 might appear in the cool Ap stars if they were hotter. On the other hand, the effective temperature of α^2 CVn is 1500° K greater than that of HD 111133, the hottest star studied. If this star's effective temperature were increased to that of α^2 CVn, then most of the rare-earth lines observed in its spectrum would disappear. The great elemental over-abundances observed in spectrum variables may be a clue to distinguishing them from the nonvariables, or merely due to analysis errors.

Surface maps of the spectrum variables HD 125248 (Deutsch 1958), HD 173650 (Rice 1970), and α^2 CVn (Pyper 1969) show a patchy distribution of elemental abundances with the rare earths typically near the magnetic poles, and the other varying elements near the magnetic equator. It is very peculiar to see similar abundance anomalies in the supposedly nonvariable cool Ap stars. This study's cool Ap stars are not all seen pole-on since they consist of 21 out of approximately 90 cool Ap stars whose apparent rotational velocities are known (Preston 1971*c*).

The nonvariable sharp-lined cool Ap stars might all be spectrum variables with long periods. However, the agreement of the equivalent widths for HD 176232 and HD 204411, and of the line lists for HD 137909 and HD 201601 which use spectroscopic plates taken many years apart, indicate that the periods for such variability have to be extremely long. Since the rotation period of HD 137909 is 18 days (Wolff and Wolff 1971) and no spectrum variability is known for this star in this period, it is not a spectrum variable. Although the nonspectrum variables have elemental abundances similar to spectrum variables, the distribution of elements on their surfaces has to be indistinguishable from complete uniformity to a distant observer. If there are undetected spectrum variables included in this study, their variety of elemental behavior has introduced scatter into these results.

XIII. IMPLICATIONS OF THIS STUDY'S RESULTS FOR THE THEORIES OF Ap STARS

The best-determined properties of the cool Ap stars are the abundance characteristics. The [N/H], log N/H, and [N/Fe] values which are shown in figures 1, 2, and 4, as well as the absence of any dependence of the abundances on magnetic-field strength or apparent rotational velocity. In addition, certain abundance ratios increase with effective temperature. Four types of theories have been advanced to explain these abundance characteristics of the cool Ap stars: nuclear reactions on the stellar surface; nuclear reactions in stellar interiors followed by mixing or mass transfer; separation of elements by diffusion processes; and accretion of mass on the stellar surface due to the magnetic field.

Two boundary conditions apply (Searle and Sargent 1967):

1) *The abundances are a surface phenomenon.* (*a*) If the surface abundances of the cool Ap stars are typical of their interiors, then a large fraction of the galactic abundances of elements such as Eu are locked up in these stars. In addition, no He I lines are observed in the spectra of the hottest cool Ap program stars. This indicates, by comparison with the normal stars, that they are helium-poor, which is contrary to what would be expected if the abundance anomalies were created in stellar interiors. (*b*) Studies of clusters with Ap stars show that the material from which stars formed did not have an abnormal composition. Furthermore, since the solar abundances are similar to those of recently formed A-type stars (Smith 1971), the Ap stellar abundances have not greatly enriched the interstellar medium. (*c*) There are no giants with elemental abundances similar to those of Ap stars. As an A-type star evolves from the main sequence to the giant stage, its atmospheric structure changes from one basically in radiative equilibrium to one in convective equilibrium. Hence, the abundance anomalies could easily be diluted in this process.

2) *The process which produces the abundance anomalies is related to the loss of angular momentum and the presence of the magnetic field.* Slow rotational velocities and large magnetic fields distinguish magnetic Ap stars from other stars with similar masses.

Brancazio and Cameron (1967) modified the suggestion of Fowler, Burbidge, and Burbidge (1955) that the strong magnetic fields in Ap stars would accelerate charged particles and induce spallation reactions with the surface material. Protons with sufficient energy to induce spallation reactions cause a progressive breakdown of the target material into H and He. On the other hand, bombarding the surface material with a flux of alpha particles leads to a buildup of heavier elements. If equal fluxes of protons and alpha particles are involved, the destructive effect of the protons predominates.

The comparison given in table 7 shows that spallation reactions did not produce the basic overabundances observed. However, there is evidence for spallation reactions on the surfaces of some Ap stars, for example, HD 201601 (Wallerstein 1968). Perhaps these reactions are partially responsible for the relatively mild abundance anomalies exhibited by this star.

As an alternative hypothesis, Fowler *et al.* (1965) developed a theory in which nuclear reactions in stellar interiors build the heavy elements. Then by mixing or mass transfer from a companion, the processed material reaches the surface of the Ap stars. The iron-peak elements represent the end products of energy-generating processes

TABLE 7

COMPARISON OF THE PREDICTIONS OF THE THEORIES OF Ap STAR ABUNDANCE ANOMALIES WITH THE RESULTS OF THIS RESEARCH

Surface nuclear reactions (Brancazio and Cameron 1967)
a) Spallation reactions cannot greatly enhance the abundances of already plentiful elements such as Si and Fe. The maximum overabundance factors that Brancazio and Cameron calculated, starting with solar abundances, are less than the observed overabundances for Si and Fe.
b) Strontium and yttrium should be overabundant together, but they are not.
c) At the maximum Fe abundance, the odd-Z iron-peak elements should have similar abundances to the even-Z iron-peak elements, which is not found.
d) Contrary to observation, Fe and Si cannot be at their maximum excesses simultaneously since much of the excess Fe comes from the capture of alpha particles by Si and neighboring elements.

TABLE 7—*Continued*

Interior nuclear reactions (Fowler *et al.* 1965)

a) The abundances of the processed material would be helium-rich, contrary to observation.
b) The predicted abundances are different from those observed for high-temperature processing between 10^9 ° and 10^{10} ° K where, at suitable densities, the nuclear reactions may become so profuse that approximate statistical equilibrium occurs between the abundances of different nuclides (*e*-process) (Clifford and Tayler 1956).
c) There is a suggestion of fit of *s*-process abundances with those of the cool Ap stars for Sr, Y, and Zr, but none with the rare earths.
d) The *s*-process terminates at large atomic weights by alpha-decay to Pb isotopes (Clayton and Rassbach 1967). However, lines of Pb are not observed in the cool Ap stars as might be expected.
e) Comparison of the cool Ap star abundances with those predicted for the *r*-process (Seeger, Fowler, and Clayton 1965) show no agreement.
f) The presence of U II lines in cool Ap stars suggests that the material has been *r*-processed.
g) If the Ap stars were companions to the precursors of supernovae, then the expected abundances could not depend on the atmospheric parameters of the secondary. In addition, we might expect some systematic difference in the kinematic properties of peculiar and young normal stars, which is not observed.
h) The interstellar medium has not been enriched to the degree expected if the peculiar A stars were mixed.

Diffusion processes (Michaud 1970)

a) Large radiation forces will push out elements whose ionization potentials are larger than 10.5 eV but smaller than 13.6 eV in the cool Ap stars, including C, P, Cl, Ca, Sc, As, Br, Sr, Y, Zr, Xe, Rn, and the rare earths. Ca, Sc, Sr, and the rare earths are overabundant. C is not likely to be, while Zr may be in some stars. Y is definitely not.
b) If the relevant ionization potential is smaller than 10.5 eV or greater than 18 eV, the element will not absorb sufficient radiation to counter gravity. This is true for He, Li, Be, B, Ne, Na, Al, Ni, Cu, Ga, Se, Rb, In, Sb, Te, and Cs. Ni and perhaps Se are overabundant in some cool Ap stars, while the other elements have not been studied or have lines which are not observed.
c) Magnesium should be underabundant, but it is normal in the cool Ap stars.
d) This hypothesis predicts the Mn overabundances of the Mn stars, but not necessarily those of the cool Ap stars. Line absorption could also explain slight overabundances of other iron-peak elements. Ti and Fe are not affected by continuum radiation as much as Mn. Diffusion cannot cause large Cr overabundances. Hence, this hypothesis cannot produce most of the observed overabundances of the Fe peak.
e) Strontium, Y, and Zr should be overabundant. Y is, however, normal in the cool Ap stars.
f) No predictions are made as to which rare earths should be most overabundant; rather, it seems that all rare earths should have the same abundances as seen in the Am stars.

Magnetic accretion (Havnes and Conti 1971)

a) Magnesium will be near normal and Si may be somewhat overabundant as observed.
b) The Fe group is expected to behave similarly to Si, and together they should be overabundant. Si, Ca, Sc, Ti, V, and Ni are enriched by similar amounts, but Cr, Mn, and Fe are substantially more enhanced.
c) Strontium and Y should be preferentially overabundant with respect to Zr and perhaps Sr with respect to Y, and this group as a whole should be greater enhanced than the Fe group. However, there are cool Ap stars with greater Zr than Y overabundances. Sr is more overabundant than Y, which is normal. The mean Sr overabundance is less than that of Cr but greater than that of the other iron-peak elements.
d) The rare earths should be greatly overabundant as observed, but no predictions are made as to which ones.
e) Heavier elements should also be overabundant. Lines of Os and Pt are seen for only a few stars. However, these elements have high second-ionization potentials. The Os overabundances are similar to those for Eu in HD 5797 and HD 118022. Thus, the detection of these heavy elements is difficult even at the expected overabundances. In addition, lines of U II are seen in 20 out of the 21 cool Ap stars studied.

via charged-particle reactions. The heavy elements are synthesized, usually by chains of neutron captures on slow (*s*-process) and rapid (*r*-process) time scales. The *s*-process follows a path in the (N, Z)-plane near the line of beta-stability. It is very difficult to modify the abundances produced in this process. On the other hand, the *r*-process depends on the neutron flux and on the time of exposure.

Confirmation of the identification of U II lines in cool Ap stars is very important. Their presence implies that the material has been *r*-processed and hence exposed to a large neutron flux. Schramm and Fowler (1971) suggest that superheavy elements with atomic numbers near 110 can be produced in explosive stellar events. Eventually these nuclei fission asymmetrically to atomic masses near $A = 126$ and 155. The first region ($A \approx 126$) is one whose elements have lines which are difficult to detect, while the latter is the region of the rare earths. Changes in the physical conditions during which these elements are produced may lead to shifts of abundance maxima. This process will also reduce the *r*-process peaks near $A = 130$ and 195 by processing the material to higher A values. In addition, this process will also produce radioactive elements such as Th, U, Np, and Pu. The Th/U production ratios are near $\frac{2}{3}$ (Seeger and Schramm 1970) for the long-lived isotopes. Given the observed U abundances, the resonance line of Th II λ4019 is expected to be marginally detectable in some cool Ap stars.

There is no evidence of nuclear processing that occurs in normal stars, namely the *e*- and *s*-processes (see table 7). In the parts of the same stars which produce the superheavy elements, additional iron-peak elements might be produced. Mass transfer from a supernova companion and mixing of the star are now considered. For the following arguments it is assumed that all Ap stars have Eu abundances similar to those of the cool Ap stars, which have at least 10^3 times the solar Eu abundance.

Guthrie (1967) believes that every supernova, on the average, produces one Ap star. The excess abundances of the Ap stars are typical of the material expelled into the interstellar medium, since these stars are initially in orbits with radii between 10 and 100 a.u. about the supernova precursors. The amount of material captured depends on the geometrical cross-section, an extremely inefficient process. However, the abundances of the Ap stars are not at all like the cosmic abundances. Thus the supernovae which produce the Ap stars consist of only 10^{-3} of all supernovae.

If there were mixing of the peculiar A stars, approximately one-half of the processed material would be returned to the interstellar medium since their masses are about $2\ M_\odot$. Ten percent of the upper-main-sequence stars, which consist of 2 percent of the galactic mass (Mihalas and Routly 1968), are peculiar. There have been 10 generations of A stars since the Sun formed. About 20 percent of the galactic mass is in the interstellar medium (Middlehurst and Aller 1968). If 70 percent of the galactic mass has passed through it since the Sun formed, then the youngest stars should show Eu enrichments by about a factor of 14 over solar values, contrary to observation.

Michaud (1970) considered the effects of radiative diffusion on the atmospheres on A-type stars. If the atmosphere has no circulation currents faster than 10^{-3} cm s^{-1} then diffusive processes can be important. The radiation force can be transferred to a given element by photoionization (continuum absorption), line absorption, and autoionization. For the stars under consideration, there is little flux below the Lyman limit. Photoionization will occur for those levels whose ionization potentials are less than 13.6 eV. Furthermore the abundance anomalies are expected to be functions of the effective temperature.

Line absorption can support the overabundances of elements heavier than the iron peak, while the light metals and iron-peak elements have to be supported by continuum absorption in order to have large overabundances. Silicon can have large overabundances if it has broad autoionization levels. The abundant, light, un-ionized elements, which have no properly placed continua and which do not have enough lines to be supported by them, should be most underabundant. Ionization will slow down the settling process. Unfortunately, Michaud has not considered the effects of line blanketing in the rocket-ultraviolet due to large elemental overabundances, especially those of the rare earths. Because of the differences with the observations (see table 7), the theory in its present form is at best incomplete.

Havnes and Conti (1971) suggest that the abundance anomalies result from a magnetic accretion process. The rotating stellar magnetic fields of the Ap stars selectively capture atoms from the ionized interstellar medium. Atoms of the heavier elements have relatively small charge-to-mass ratios. Hence they penetrate close to the star where a further ionization may take place. When this occurs, the ion is captured by the field and describes a periodic orbit as it spirals along a magnetic-field line. The ion gradually diffuses from the field to the surface. The elemental abundances are initially concentrated at the magnetic poles. The relatively slow rotation of the magnetic stars results from the interaction of the magnetic field with the ionized interstellar gas.

This theory naturally results in spectrum-variable production. One-quarter of the sharpest-lined cool Ap stars are known to be spectrum variables (Preston 1970, 1971*a*). Havnes and Conti point out that elemental diffusion goes preferentially over the surface rather than deeper into the star because of the larger diffusion velocities at smaller optical depths. The older magnetic stars would then have the most uniform distribution of the elements on the surface, the longest rotational periods, and perhaps the greatest abundances. But from the results we have seen, it appears that some of the spectrum variables may have the largest elemental abundances.

A commonly accepted theory of the origin of the magnetic field suggests that it originates with star formation (Mestel 1967). The massive clouds in spiral arms are those associated with this process (Field 1970). Hence, at birth the magnetic stars may have already begun to accumulate their anomalous abundances.

This hypothesis provides a simple conceptual framework within which to explain the abundance anomalies, and it does explain why magnetic stars are slow rotators. Although it does not explain all the features of the abundance anomalies, it is more in accord with observation than the other theories of Ap stars.

Thus, there is no completely satisfactory theory of Ap stars. Some authors have attempted to combine aspects of various theories in an ad hoc manner (see, e.g., Guthrie 1971). Detailed consideration of the diffusive processes on stellar surfaces is necessary for both Michaud's and Havnes and Conti's theories. In addition, if such processes occur, the assumption that the stellar atmosphere has a uniform composition is no longer true, and the effects of abundance gradients may have to be considered. Furthermore, the similarity of the dependence of the Fe abundance on effective temperature for both the cool Ap and Am stars suggests a theory based on atmospheric and atomic properties, if the cause of the Am abundance anomalies is a subsurface elemental separation zone. However, there is no relation between the values of the ionization potentials and the abundance anomalies which might be expected with such a theory. But this may mean that the values of the continuum fluxes at the wavelengths of the absorption edges have been affected by the great overabundances. Nevertheless, the details of the reconciliation of any theory of abundance anomalies in Ap stars with the results of this study are beyond the scope of this discussion.

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APPENDIX

SOME COOL Ap STAR ABUNDANCE RULES

From the examination of the overabundance values for each star, the following conclusions can be drawn: The Cr and Mn overabundances are always greater than those of Si, Ti, and Fe. The Cr overabundance is greater than that of Mn, except for three stars where the overabundance difference is less than 0.3 dex. The Si overabundance is less than that of Fe except for two stars in which they are equal, and less than that of Gd and Eu. The Sr overabundance is greater than that of Y except for two stars. Yttrium is less overabundant than Cr, Mn, Eu, and Gd. The Eu overabundance is always greater than that of Nd, while Gd is more overabundant than Nd except for two stars.

For the Ap program stars, the following inequalities regarding absolute abundances can be derived by use of figure 2, and by examination of a few stellar abundances for those elements with several good determinations:

$$\mathrm{Ti} > \mathrm{Y, Ce, U};$$

$$\mathrm{Cr, Fe} > \mathrm{Ca, Ti};$$

$$\mathrm{Mg, Si, Cr, Fe} > \mathrm{Ni, Sr, Eu};$$

$$\mathrm{Mg, Si, Cr, Fe, Ni} > \mathrm{Nd};$$

$$\mathrm{Mg, Si, Ca, Cr, Mn, Fe, Co, Ni} > \mathrm{Sc, V, Y, Ce, Gd, U}.$$

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