

THE SPECTRUM VARIABLES OF TYPE A

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I. INTRODUCTION

In the atmosphere of the second-magnitude A0p star α^2 Canum Venaticorum, unknown physical processes produce a wonderful and complex sequence of changes recurring with a period of 5.47 days. Figure 1, from the work of Babcock and Burd,¹ shows

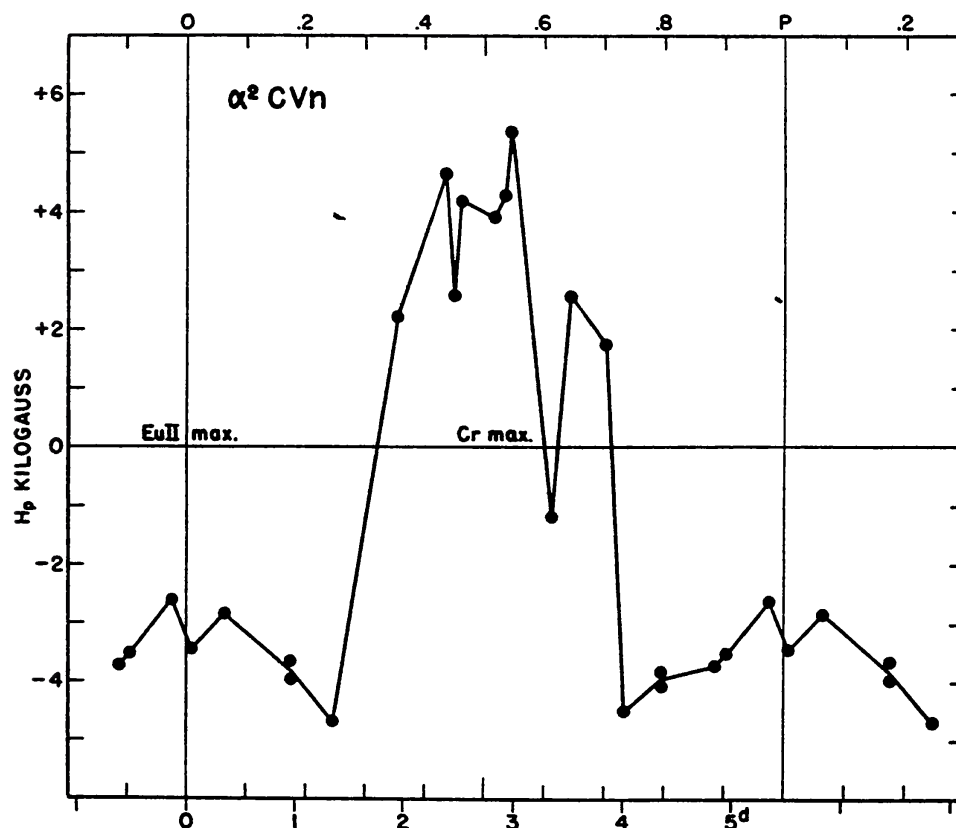
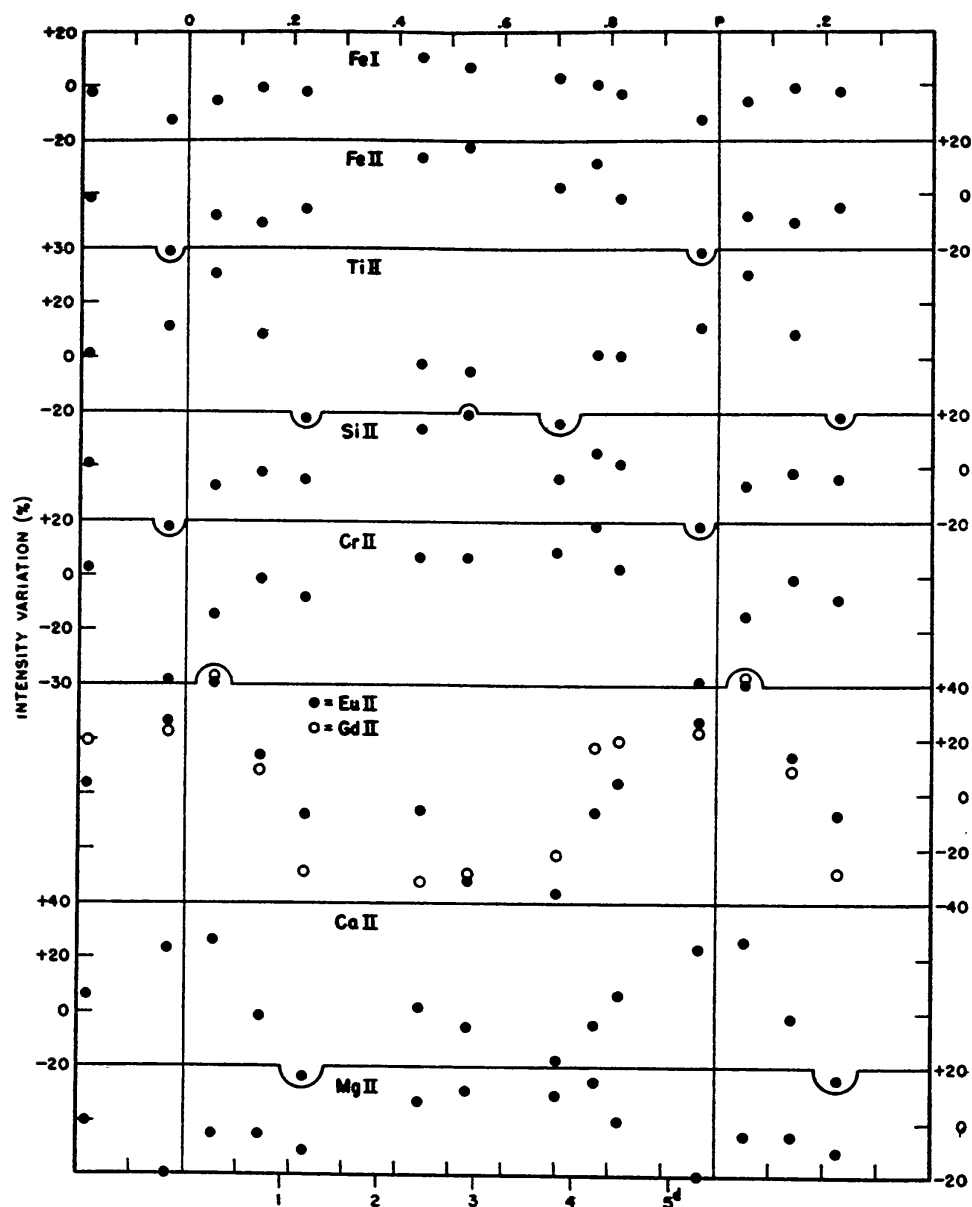


FIG. 1.—The magnetic field of α^2 Canum Venaticorum.
(Reproduced from the *Astrophysical Journal*)

that the stellar atmosphere supports a general magnetic field that appears to vary from about -4000 gauss at the phase $\Phi = 0^{\circ}0$ to $+5000$ gauss at phase $\Phi = 0^{\circ}5$. Figure 2, which has been com-

FIG. 2.—Spectrum variation in α^2 Canum Venaticorum.

piled from a recent paper by G. R. and E. M. Burbidge,² illustrates the spectrum variations that accompany the magnetic changes. At $\Phi = 0^{\circ}0$, lines of Eu II and other rare-earth elements are at maximum strength, far stronger, in fact, than in the spectrum of any normal star; these lines then decrease about 70 percent in intensity to a minimum near $\Phi = 0^{\circ}5$. Lines of Cr II, on the other hand, are at minimum strength at $\Phi = 0^{\circ}0$, while lines of other

elements change their strength according to still other laws. Complex radial-velocity variations also occur in this remarkable object; these are illustrated in Figure 3, from Babcock and Burd's paper.

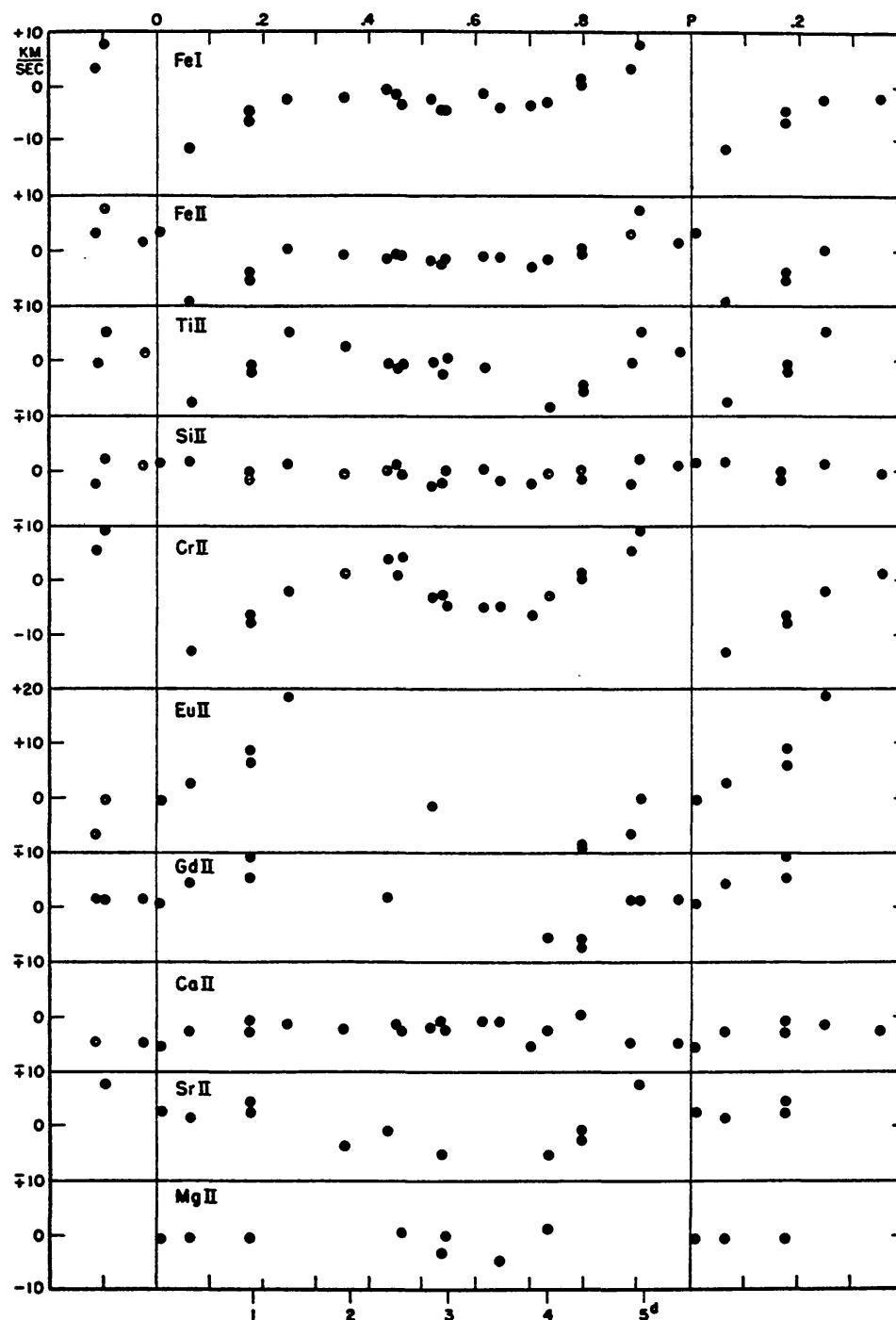


FIG. 3.—Radial velocities in α^2 Canum Venaticorum.
(Reproduced from the *Astrophysical Journal*)

These observations of α^2 Canum Venaticorum, and also those of other similar stars which we shall discuss below, at once suggest a whole array of intriguing astrophysical problems. What is the chemical composition of the atmosphere of this unusual star? Why does it differ from that of the atmospheres of normal stars, and why does it appear to vary? What is the meaning of the radial-velocity variations observed, and of the small variations in light and color? What is the geometry of the magnetic field, and what its origin? How is the magnetic field related to the abundance anomalies? And how, if at all, can these phenomena be fitted into the current picture of the evolution of stars?

At the present time, we are not able to give satisfactory answers to any of these questions. However, it has been quite clear ever since 1907, when Belopolsky first established the period of α^2 Canum Venaticorum, that we cannot suppose the system to be a spectroscopic binary, with some lines originating in one star and some in a companion. It is also clear that we cannot explain the spectrum variations in terms of changes in ionization and excitation in an atmosphere with constant, although abnormal, abundances. In 1939, Tai drew attention to the fact that if the temperature were to rise from 9000° to $10,000^\circ$ while the pressure doubled, then the concentration of Eu II would triple while that of Cr II would diminish threefold.³ But Tai's theory implied large intensity variations in the lines of other ions, notably Sr II, which are not observed. Most important of all, it required that the concentration of Eu III vary 180° out of phase with that of Eu II. But subsequent observations by Swings in the far ultraviolet have shown that the lines of Eu III vary synchronously with those of Eu II.⁴

In the light of present knowledge, we need no longer try to account for the observed intensity variations by changes in the physical conditions of a gas of constant chemical composition. For the observation of a rapidly variable magnetic field makes it clear that the observed spectroscopic changes do not primarily reflect physical changes in a given mass of gas. The gas that constitutes the visible reversing layer at phase $\Phi = 0^{\text{P}}0$ is not the same gas that does so at phase $\Phi = 0^{\text{P}}5$. This important conclusion follows from the fact that, as a consequence of the large

size and high electrical conductivity of a stellar atmosphere, the magnetic lines of force are virtually "frozen into" the gas. In the absence of differential gas motions, the magnetic field can change only very slowly when it is measured at a point fixed in the gas.

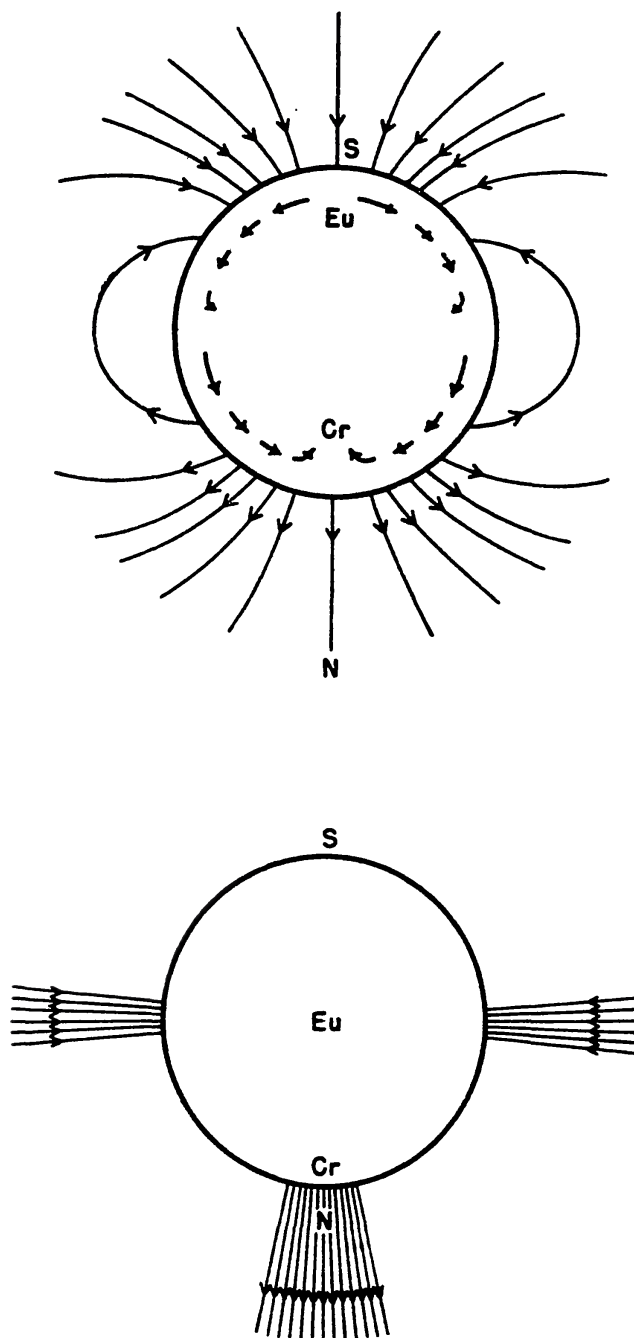


FIG. 4.—Deformation of a dipole magnetic field by gravity oscillations (schematic).

If there are no appreciable differential motions, the relatively rapid changes we observe can be understood only by supposing that we view, successively, physically distinct parts of the stellar atmosphere, each with its own distinctive and highly permanent local magnetic field. On the other hand, if the magnetic field is actually deformed, so that rapid changes occur at a point fixed in the gas, then the differential gas motions must be so large that in this case, too, we view different parts of the atmosphere at different phases.

Two main types of models are now being considered to describe the variations observed in stars like α^2 Canum Venaticorum. Following the pioneer investigation of Schwarzschild,⁵ a number of workers have studied the hydromagnetic oscillations of a star. These are oscillations that involve differential motions of the gas. Since the magnetic field is frozen into the gas, the differential motions entail an elastic distortion of the lines of force. An extreme case of such an oscillation is illustrated in Figure 4. The equilibrium field is that of a dipole, but differential gas motions near the surface, mainly in the horizontal direction, carry all the lines of force of the southern hemisphere to the equator, and all those of the northern hemisphere to the north pole. The motions then reverse to produce the opposite configuration. Sweet has recently shown that such an oscillation, as seen in integrated light by an observer in the equatorial plane, would appear as a reversing magnetic field.⁶ However, the amplitude of the observed field would amount to less than 5 percent of H_p , the polar field of the undistorted dipole.

In an alternative type of model, one envisages a star in rigid rotation, with no appreciable differential motions of the gas. The lines of force then move rigidly with the gas, and the magnetic variations are supposed to result simply from the changing aspect of the star as it rotates. It is necessary to suppose that the axis of rotation does not lie in the line of sight, and that the magnetic field is not symmetrical around the axis of rotation. Figure 5 illustrates a simple configuration in which the field has an axis that is inclined to the poles of rotation. As the star rotates, the line of sight sweeps out the small circle Q_1Q_2 , and the observed field varies with the magnetic latitude of the subsolar point $\odot$.

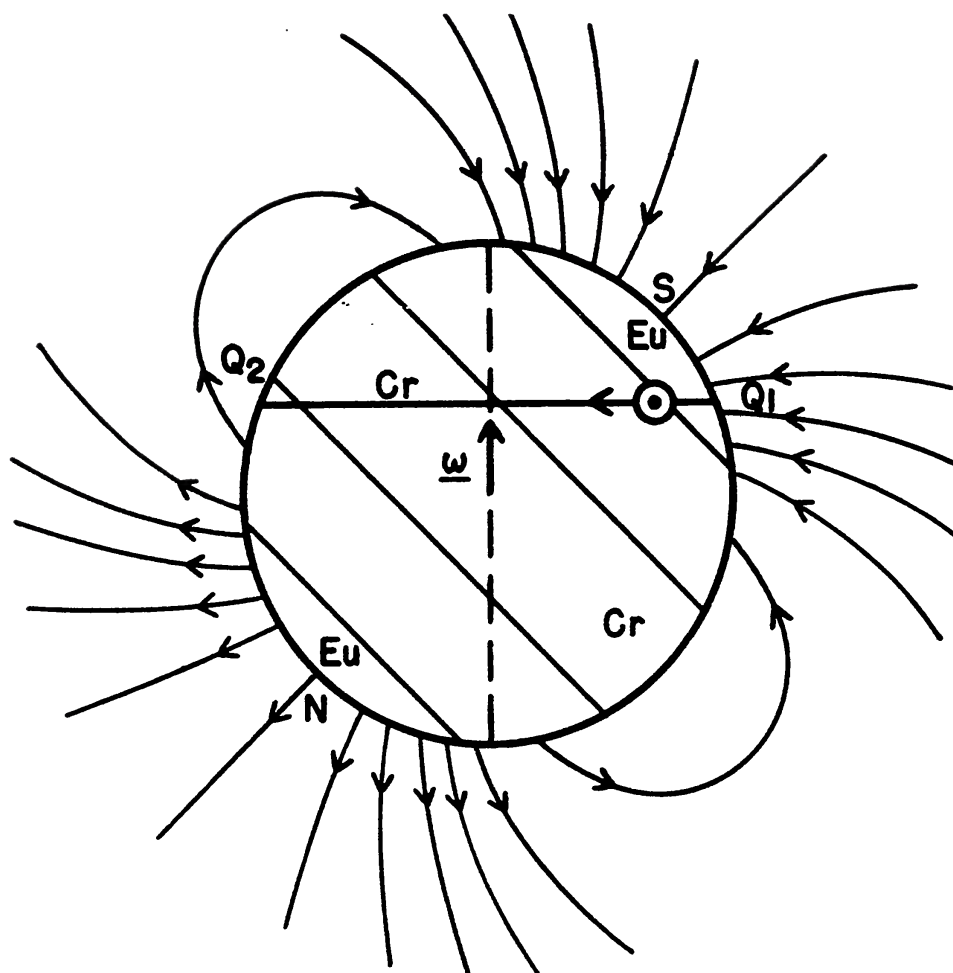


FIG. 5.—An oblique rotator, with the axis of a dipole magnetic field inclined to the rotational axis.

To account for the spectrum variations that are observed to accompany the magnetic changes, it is necessary to suppose, on either of these models, that there is a separation of elements according to the intensity of the magnetic field, and possibly even according to sign. Actually, neither model, in its present state of development, seems able to account for all the observations at hand, and perhaps ultimately we shall conclude that elements of both theories must be incorporated in the definitive theory of the spectrum variables.

II. THE PECULIAR A STARS

The spectrum variation in α^2 Canum Venaticorum was first announced by Ludendorff in 1906, but nine years earlier Miss

Maury had already called attention to certain peculiarities in its spectrum. She noted the abnormal weakness of the K line of Ca II, and the unusual strength of Si II λ 4128 and 4131. These spectroscopic peculiarities of α^2 Canum Venaticorum have since proved to be typical of a large number of A-type stars. In the *Henry Draper Catalogue*, Miss Cannon noted peculiarities in the spectra of 110 of the 6300 A0 stars. In most of these peculiar A stars, lines of Si II or Sr II are abnormally strong, and in many the K line is weak. Subsequent work by Miss Walther showed that similar peculiarities occur in the spectra of roughly 13 per cent of all stars in the range of types B8 to F0.⁷

In the Hertzsprung-Russell diagram, these peculiar A stars appear to define a coarse sequence that lies about a magnitude above the main sequence. The hottest objects in the group are prone to show enhancement of the Mn II lines; as the excitation diminishes, the stars tend to show, in turn, abnormally strong lines of Si II, Eu II, Cr II, and Sr II. The colors of the peculiar A stars are invariably too blue for their *Henry Draper Catalogue* types; the average A0p star, for example, seems to have the luminosity and color of a B8V star. In their distribution over the sky and in their motions, the peculiar A stars are not distinguishable from the normal A stars of Baade's Population I. They are known to occur in some open clusters, and are commonly found in binary systems with normal or metallic-line stars. Since the peculiar A stars associate so intimately with the normal stars that they closely resemble in gross characteristics, there is no reason to expect that they are essentially different in internal structure, composition, or origin. On the other hand, there is some indication that they occur most frequently in clusters that have no B-type stars. In the clusters where they do occur, they are therefore among the brightest stars. These observations suggest that a peculiar A star may develop its characteristic peculiarities only as it starts to evolve off the main sequence.

Roughly 10 percent of the peculiar A stars show conspicuous variations in the strength of certain absorption lines. Similar intensity variations, and smaller ones, may still have gone undetected in many of the known peculiar A stars. However, there are certainly some well-observed peculiar A stars in which no

spectrum variation now occurs—at least, none of the order of magnitude observed in α^2 Canum Venaticorum. No criterion is known for concluding, from a single spectrogram of a peculiar A star, whether or not it will prove to be a spectrum variable. Among the known spectrum variables, there are a few cases where the observations of line strength suggest that the variation may not be recurrent. In most well-observed cases, however, the variation is found to be definitely periodic. Such periods are known for 13 stars; they range from 0.52 day for HR 5313 to 20.27 days for 73 Draconis, with HR 7575 having the much longer period of 226 days.

Among these 13 spectrum variables, the five with the longest periods are known from the work of H. W. Babcock to have variable magnetic fields. The fields are frequently strong enough to give Zeeman patterns for some lines that are wide compared with the Doppler width. Such a line may be appreciably intensified in a strong magnetic field. The maximum possible intensification factor is $n/2$, where n is the number of Zeeman components, in case the line falls on the flat part of the curve of growth. In light from the whole stellar disk, the intensification will be less than this limit. Nevertheless, for a line like Eu II λ 4205, with 21 widely spaced Zeeman components, the magnetic intensification may be quite large. There is some correlation between the observed intensity variations in α^2 Canum Venaticorum and the computed magnetic intensifications, but in some cases the observed intensity variation appreciably exceeds the maximum possible magnetic intensification. In any case, magnetic intensification cannot depend on the sign of the field. While it must contribute to the observed spectrum variations, it obviously cannot be the major cause of them.

Babcock's observations for Zeeman effect are made with a double analyzer for circularly polarized light placed before the slit of the spectrograph. This produces two analyzed spectra side by side on the plate. Into one of these spectra goes all light circularly polarized in one sense; into the other goes all light circularly polarized in the opposite sense. In "magnetic" stars, most lines in one spectrum are slightly shifted relative to their counterparts in the other. On the assumption that this displacement

represents the average Zeeman effect over one magnetic hemisphere of a star with a dipole magnetic field, Babcock has shown that near $\lambda 4500$ the relative displacement in angstroms of the two lines will be

$$\Delta\lambda = 5.75 \times 10^{-6} H_p Z.$$

Here H_p is the polar field in gauss, and Z is a measure of the width of the Zeeman pattern that depends only on the properties of the atom producing the line. All Babcock's results for H_p are derived from the measured displacements by means of this relation. Besides the assumption on the character and aspect of the field, the relation presupposes certain other reasonable assumptions about the surface brightness over the disk, etc.

In the spectra of eight periodic spectrum variables, the lines are too wide for the ready detection of the Zeeman effect. For these objects, and for many other broad-line peculiar A stars, we have no evidence bearing on the existence of a magnetic field. Among all the peculiar A stars that have sharp lines, however, *no case has been noted where evidence of a general field fails to appear*. In view of the general spectroscopic similarities between the broad-line peculiar A stars and the sharp-line ones, it is reasonable to conclude that all these objects are characterized by general magnetic fields.

There is at least one peculiar A star (HR 6326) that is a periodic magnetic variable but does not show any marked spectrum variation. For one other star (HR 9080) the period has been established from photometric observations by Provin. This gives us a total of 15 peculiar A stars with known periods. Table I lists these stars. The magnetic fields are taken from the paper of Babcock and Cowling.⁸ Most of the photometric data are by Provin;⁹ an asterisk in the last column indicates that the light is variable, but with unknown, though small, amplitude. The photometric range for HR 5313 depends upon unpublished work by R. Hardie.

Table I excludes some 25 other peculiar A stars in which Babcock has found general magnetic fields, as well as a number of known spectrum variables, and a few magnetic stars of very different spectral types (M, Be). These objects are omitted because

TABLE I
PECULIAR A STARS OF KNOWN PERIOD

No.	Star	HD		P (days)	Principal Variable Lines	Magnetic Field H_p (kilogauss)	Photometric Range
		No.	m_v				
1	HR 5313	124224	4.9	0.52	Si II, He I, λ 4201	Unknown	0.085
2	56 Ari	19832	5.6	0.73	Si II, He I, λ 4201	Unknown	0.06
3	21 Com	108945	5.4	1.03	Ca II, Sr II	Unknown	*
4	χ Ser	140160	5.3	1.60	Ca II, Sr II	Unknown	0.02
5	ι Cas	15089	4.6	1.74	Ca II, Sr II	Unknown	0.02
6	HR 1732	34452	5.4	2.47	He I, λ 4201	Unknown	*
7	HR 9080	224801	6.2	3.74	Unknown	+7.5	0.03
8	ADS 16252(B)†	—	10.2	3.77	Cr II, Eu II	Unknown	Unknown
9	ϵ U Ma	112185	1.7	5.09	Ca II, Cr II	Unknown	0.025
10	α^2 CVn	112413	2.9	5.47	Cr II, Eu II	+5.0 to -4.0	0.030
11	HR 6326	153882	6.2	6.00	None	+4.5 to -5.0	*
12	—	71866	6.7	6.8	Eu II	Reversing	Unknown
13	HR 5355	125248	5.7	9.30	Cr II, Eu II	+7.0 to -6.0	0.053
14	73 Dra	196502	5.2	20.27	Ca II, Eu II	-1.2 to -2.3	0.02
15	HR 7575	188041-2	5.6	F0p, A 226	Eu II	+1.2 to +4.8	Unknown

† Data taken from G. H. Herbig, *Ap. J.*, 106, 112, 1947. The spectrum variable is probably an optical companion to ADS 16252(A), which is the eclipsing binary ZZ Cephei.

we do not yet know their periods. Indeed, Babcock's observations indicate that many of the magnetic variables, and especially those of later types—near F0—are either irregular or, at most, only roughly cyclic. But for some of the stars that are included in Table I, we know little more than the periods. In many cases the period has been established from estimates of line strengths on spectrograms of relatively low dispersion. These results suffice to show only the gross features of the variation; detailed measurements of the kind that are available for α^2 Canum Venaticorum exist for only two or three other stars. In many cases, the spectra are rich in lines, or the lines are very wide. Blending difficulties therefore preclude detailed studies.

Even in the best known stars, the results of different observers are sometimes in very poor agreement. The prototype, α^2 Canum Venaticorum, is notorious in this respect. As Struve has pointed out, Ludendorff, who discovered the spectrum variation in this star, noted intensity changes especially in “precisely those lines that vary little,” according to modern observations.¹⁰ Belopolsky divided the lines into three groups: A and B lines, which vary 180° out of phase; and C lines, which vary little or not at all. Modern observers have agreed that most lines of the rare-earth elements fall in group A, together with most lines of Ti II and the K line of Ca II; and that most lines of Cr II and Fe II fall in group B. But there is still rather serious disagreement over the amount of the intensity changes. The Burbidges define the ratio of the maximum to the minimum equivalent width of a line as its amplification factor, F . For Eu II λ 4130 their measures give $F=4$; Tai also found $F=4$. But Struve adopts $F>10$. Actually, F appears to vary appreciably from line to line of an element. Some of these variations must be accidental, due to photometric errors and the effects of unknown blends. Some, however, can probably be related to the width and multiplicity of the Zeeman pattern, as we have seen above. Mean values have been used in the preparation of Figure 2. Curves similar to these have recently been prepared at this observatory for the 9.5-day spectrum and magnetic variable HR 5355. They indicate that, in the mean, the lines of Eu II, Gd II, and Ce II in this star vary strictly in phase with each other, and with the same amplification

factor. The lines of Cr I, Cr II, and Sr II also vary together in the mean, but 180° out of phase with the lines of the ionized rare-earth elements.

Belopolsky reported strong and variable emission lines in α^2 Canum Venaticorum in 1928; Miss Anger also found variable emission lines to be present. More recently, neither Struve nor Babcock observed any strong emission features in this star. There are also large discrepancies among the various radial-velocity observers. In 1919, Kiess gave a velocity curve for Eu II $\lambda 4205$ that ranged from -20 to $+15$ km/sec, but in 1932, Miss Farnsworth's results indicated a velocity curve for this line that runs from 0 to $+30$ km/sec. More recently, velocity curves for Eu II by Struve and Swings¹¹ on the one hand, and Babcock and Burd¹ on the other, agree in giving the range as about -10 to $+20$ km/sec. But differences that are significant, though small, occur between their curves for Cr II and other elements. Different photometric observers also disagree concerning the light and color variations of this star.⁹

It is quite possible that some of these discrepancies between observers reflect secular changes.² Unpublished McDonald Observatory velocities for HR 5355 indicate a definite change in the γ -axis of the velocity curves over a four-year interval. The spectrum variations also may change slowly with time; in several peculiar stars for which large intensity changes were reported some years ago, no variation can be detected now.

There are also other observations that indicate irregularities from cycle to cycle. The mean periods appear not to change over many years, but occasionally the curve giving H_p or line strength as a function of phase will be temporarily advanced or retarded. This effect is probably responsible for the deep notch in the magnetic curve for α^2 Canum Venaticorum (Fig. 1); in one cycle, the field diminished somewhat earlier than usual. The larger H_p that directly follows in phase was actually observed in a different cycle, two years earlier. A number of observers have noted still another kind of irregularity: within a single cycle, very abrupt changes sometimes seem to occur in the intensities and profiles of some lines. The suspected variations appear on spectrograms exposed in rapid succession, and separated only by an insignifi-

cant fraction of the period. In extreme cases, the time scale of these effects is of the order of a minute. Unpublished observations of 56 Arietis by Code, with a photoelectric spectrum-scanner, tend to confirm the reality of abrupt line-intensity changes. However, these very rapid changes have not yet been securely established, and they may be illusory.

As to the more leisurely periodic line-intensity variations in the stars of Table I, few generalizations can be drawn. The intensity curves are generally decidedly anharmonic, and the phase relations between the curves of different elements are complicated and differ from star to star. In α^2 Canum Venaticorum, Fe II reaches a pronounced minimum at Eu II maximum; in HR 5355, Fe II maximum coincides with Eu II maximum. In both stars, however, Ti II and Ca II show a *double wave*, with maximum intensities at Eu II maximum and again near Cr II maximum. In ι Cassiopeiae and 21 Comae Berenices, Ca II reaches maximum strength about 0^p1 after Sr II maximum; in χ Serpentis, these two ions vary 180° out of phase. In this last star, a small group of lines, appreciably narrower than all others in the spectrum and probably due to La II, come to a sharp maximum midway between Sr II maximum and Ca II maximum. Figure 6, from intensity estimates on plates of low dispersion, illustrates the spectrum variation in 56 Arietis; especially notable is the double wave in He I.

An axially symmetric oblique rotator like that of Figure 5, with different elements separated according to the strength of the magnetic field, cannot give effects of this kind. Such a model would produce a spectrum variation that is symmetrical about the phase when the magnetic pole transits the central meridian of the disk. Further, Babcock has shown that, for the case of an oblique dipole field, the magnetic curve must have certain geometrical properties that are not observed.

Arguments of this kind clearly require that we abandon the simple oblique-rotator model of Figure 5. However, there is no reason to insist on axial symmetry in an oblique rotator. If we are willing to envisage a more complicated kind of surface field, consisting of large but irregularly placed magnetic areas and associated abundance irregularities, then an oblique-rotator model

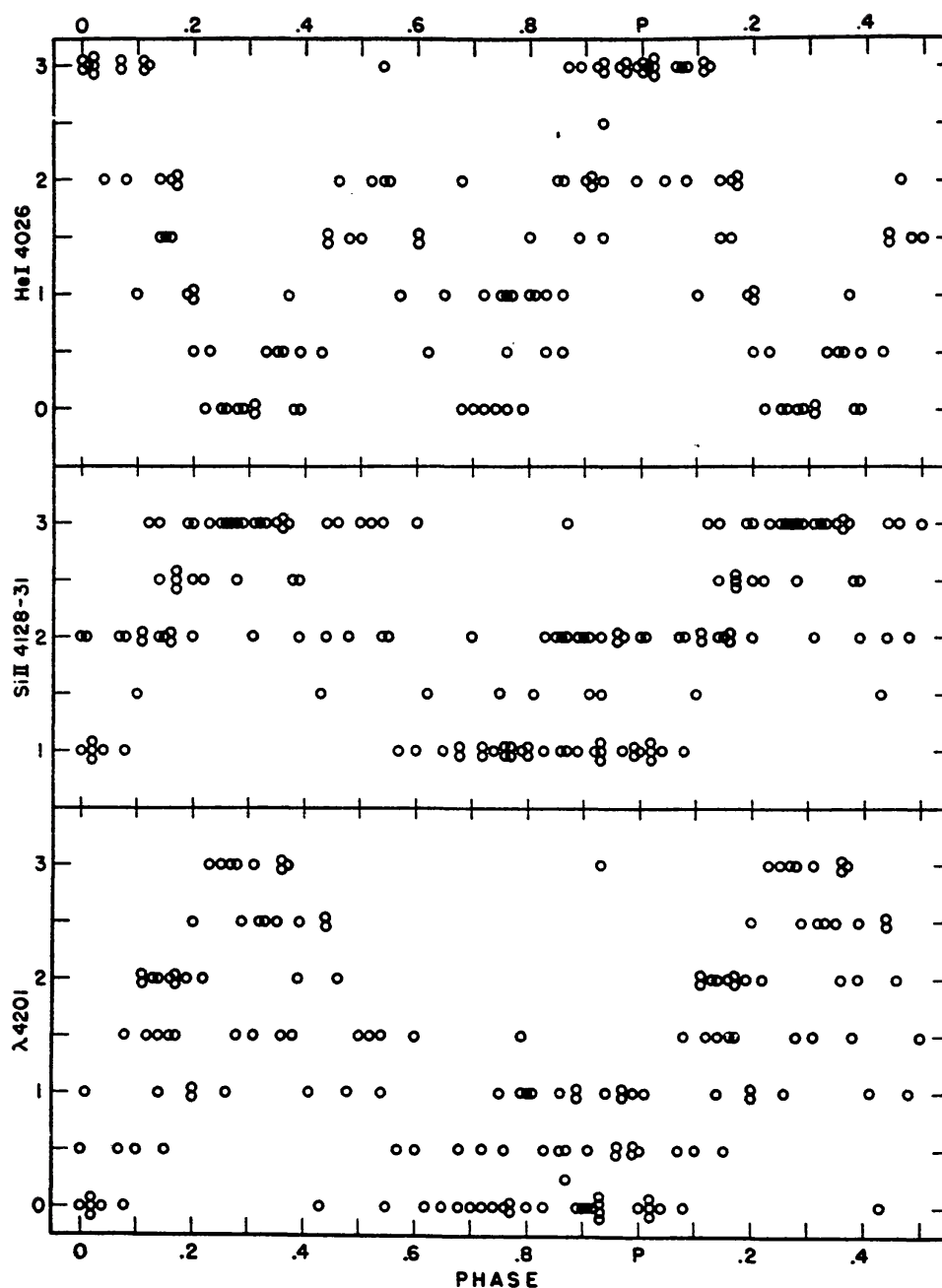


FIG. 6.—Spectrum variation in 56 Arietis ($P = 0.73$ day). The intensities are expressed in arbitrary units.

may still be able to account for many of the observations. A peculiar A star that does not show a conspicuous spectrum variation might then be explained in any of three ways: as an object viewed nearly along the rotational axis, as a star with anomalous

areas that are symmetrical about the rotational axis, or as a star with a large number of small anomalous areas.

I have advanced the argument that the line widths of relatively nonvariable lines in the periodic stars of Table I strongly support the theory that the observed periods are simply the periods of rotation. There is, in fact, a very strong correlation between period and line width, in the sense that the widths are nearly inversely proportional to the periods. This relation is illustrated for four spectrum variables and a sharp-line comparison star in Plate I. For selected lines in the spectra of nine of the known periodic peculiar A stars, I have shown that the profiles can be quantitatively explained on the assumption that they are broadened by rotation with the observed periods, the stars being assumed to be viewed nearly in the equatorial plane. I have not actually measured the contours of lines in the remaining six stars of Table I, but from an inspection of their coude spectra it is clear that none of these objects can seriously deviate from the results of the other nine.

If the spectrum variation of Eu II lines is caused by the transit across the stellar disk of a large permanent "rare-earth patch," we should be able to discern the motion of this patch in the Eu II radial velocities. For an A0 star, the equatorial velocity of rotation, in km/sec, is related to the period in days very nearly as $V = 100/P$. Since $P = 5.47$ days for α^2 Canum Venaticorum, we should therefore measure a differential velocity of approach of about 18 km/sec as the rare-earth patch rounds the approaching limb of the star, and a like velocity of recession as it rounds the receding limb. At Eu II maximum, with the patch transiting the central meridian, the differential velocity should vanish. Figures 2 and 3 show that the observations do, in fact, agree reasonably well with these predictions for Eu II and Gd II. For most of the other ions, however, the picture is less simple. It is still true in most cases that variable lines indicate velocities of approach before maximum strength, and of recession after maximum. These effects are particularly large in the two very-short-period spectrum variables 56 Arietis and HR 5313, where the observed differential velocities are much larger than in α^2 Canum Venaticorum.¹² But in a number of cases the detailed explanation

of the intensity and velocity curves seems to require at least two separate patches for each atom or ion—cf. He I in 56 Arietis (Fig. 6). Even this may not suffice, for some ions, like Si II in α^2 Canum Venaticorum, show an intensity variation but little or no velocity variation. Moreover, in HR 5355 Babcock finds evidence for some velocity variations that seem too abrupt to be attributed to the motion of a patch across the disk.¹³ The magnetic curve for α^2 Canum Venaticorum presents a similar difficulty; the extreme values of H_p in Figure 1 were observed within a single cycle and are separated by only 0^p19.

We may note several additional pieces of evidence that the observed hemisphere is indeed nonhomogeneous, if not actually marked by large, permanent patches. In several of the magnetic variables, Babcock has noted significant differences in the effective field indicated by different ions at the same phase. Thus, in α^2 Canum Venaticorum, the notch at $\Phi = 0^p612$ represents a plate on which Babcock and Burd found $H_p = -70 \pm 270$ gauss from Fe II, and -3150 ± 470 gauss from Cr II. Again, in HR 5355, the magnetic curves for the rare-earth elements and Cr differ systematically from those for Fe and Ti.

Another effect that seems to indicate nonhomogeneity of the disk has been found by Babcock in several magnetic variables near the phases where the field appears to change sign. In this so-called “cross-over effect,” lines of some ions are systematically wider and shallower in one of his analyzed spectra than in the other. As Babcock has pointed out, this effect can arise through a combination of differential Doppler and Zeeman shifts, if the radial velocity and the line-of-sight component H_z of the magnetic field vary together across the stellar disk.¹³ The sign of the effect is such that the mean observed field always changes toward the direction of H_z in the approaching region. Antipodal magnetic areas of opposite polarity on an oblique rotator would produce an effect of this kind.

A hydromagnetic oscillation could also produce the cross-over effect and also, with sufficient elaboration, probably account for certain aspects of the radial-velocity variations that have been observed in some stars. The relatively abrupt variations observed at some phases could probably be more easily explained in terms

of a pulsation than by a rigid rotator. On the other hand, the pulsation theory suffers from some severe difficulties of its own. In the absence of a magnetic field, the fundamental mode of radial pulsation in an A0 star will have a period of only about 3 hours. To obtain periods as long as those observed in the peculiar A stars, Cowling has considered oscillations in which the motion is mainly horizontal.¹⁴ In these so-called "gravity oscillations," the gravitational forces are sufficiently diluted to yield the relatively long periods observed. The electromagnetic forces play virtually no role in determining the period. But while gravity oscillations of the correct periods exist, they are not the fundamental modes, and it is not known why they should be preferentially excited.

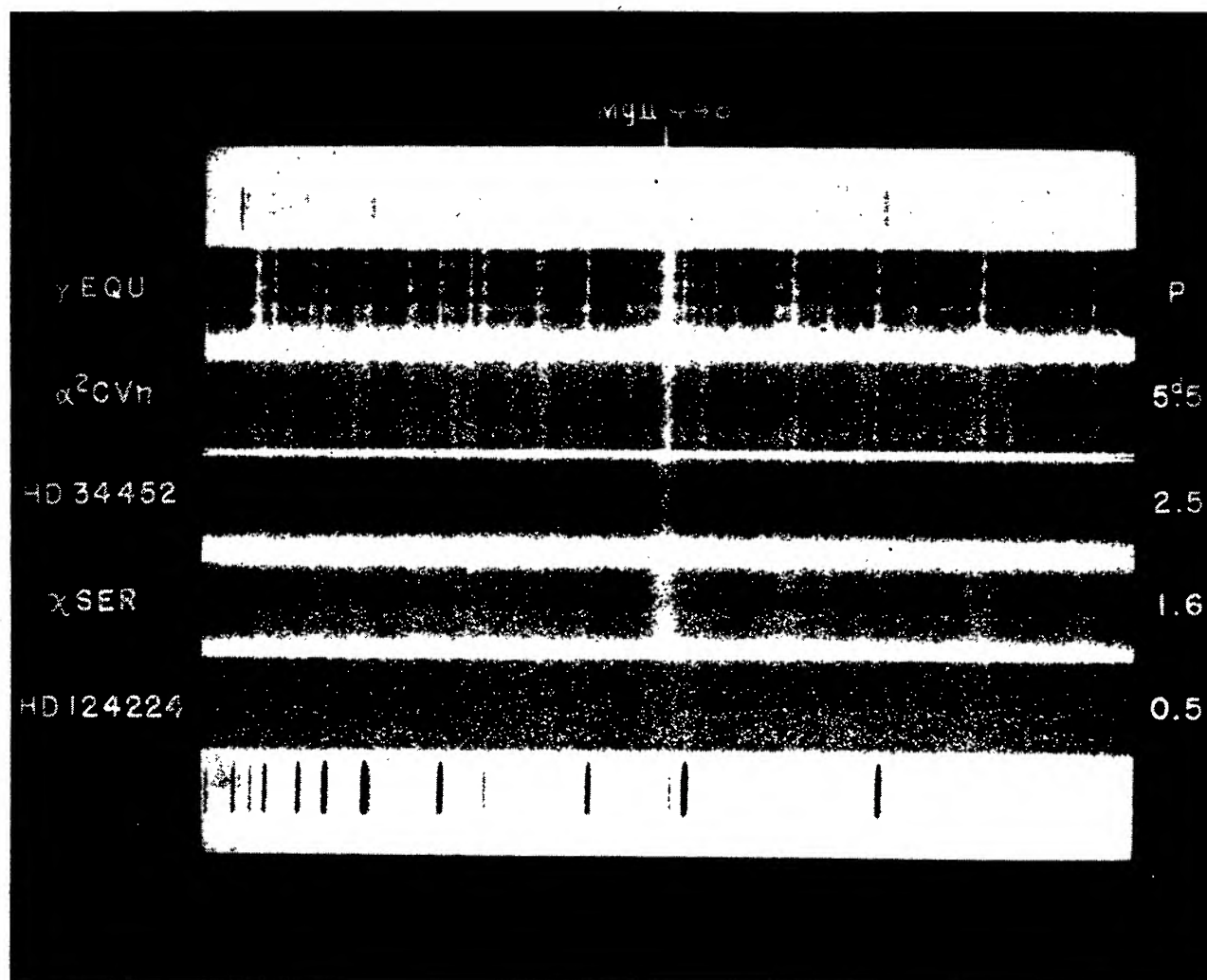
There is the additional problem of accounting for the observed field reversals in some stars. The observed field can be reversed only by extremely large distortions of the true field, and then only in especially favorable aspects. In his recent study of this problem, Sweet has shown that, for a large class of field geometries, field reversal would be much less common than is actually observed, and that the nonreversing fields should show much larger effective fields than are observed.⁶

The period-line width relation represents yet another difficulty for the pulsation theory. Differential radial velocities over the disk appear to be required for the explanation of the observed line widths in the spectrum variables of shorter period. If pulsations are responsible for the line widths, the period-line width relation requires that these have the same amplitude in all the periodic stars; namely, the radius of an A0 star. Moreover, standing waves of the kind that have so far been considered will not suffice, for they require that all differential motions vanish twice during each cycle.

III. THE ABUNDANCE ANOMALIES

Abundance determinations in peculiar A stars have been attempted by several investigators, but usually from spectrograms of relatively low dispersion. The earlier work has now been largely supplanted by the recent studies of the Burbidges.^{2,15} They have discussed 4.8 Å/mm spectrograms of α^2 Canum Venaticorum, and 18 Å/mm spectrograms of HR5597 = HD133029.

PLATE I



The period-line width relation in spectrum variables. The original dispersion of the spectrograms was 4.5 Å/mm. The star γ Equulei is a peculiar A star with a variable magnetic field, but it is not a spectrum variable.

Their abundances relative to those of a standard star have been obtained by a curve-of-growth analysis. The abundances are summarized in Table II.

TABLE II
ATOMIC ABUNDANCES (BY NUMBER) IN TWO PECULIAR A STARS

Element	Abundance Ratio		Element	Abundance Ratio	
	α^2 CVn	HR 5597		α^2 CVn	HR 5597
	γ Gem	α^2 CVn		Sun	α^2 CVn
Mg	0.4	3.5	Y	20:	—
Al	1.1	2.0	Zr	30	1.3
Si	10	2.5	Ba	0.9:	—
Ca	0.02	2.6	La	1020	0.2:
Sc	0.7	—	Ce	400	0.6
Ti	2.6	1.0	Pr	1070	0.6
V	1.3	2.3	Nd	250	0.6
Cr	5.2	1.8	Sm	410	0.6
Mn	16	1.0	Eu	1910	0.5
Fe	2.9	1.5	Gd	810	0.4
Ni	3.0	0.8	Dy	760	0.6
Sr	14	1.1			

Such abundance determinations always suffer from certain difficulties. Photometric errors may be important, and uncertainties due to blending are unavoidable in spectra as rich as these. Such effects become particularly invidious when, as is often the case, the only accessible lines of an interesting element are very weak. Ions dominate the spectra of these stars, and for these lines neither laboratory nor theoretical line strengths are available. Recourse has been had to stellar line strengths from Buscombe's work on the A0 IV star γ Geminorum for some ions, and to solar line strengths for others. The derived abundances are therefore subject to errors of the curves of growth adopted for these standard stars, as well as to errors of the curves adopted for the peculiar stars. For the latter, especially, it is dangerous to assume that all lines of all elements will fall on a single curve of growth that is computed on an approximate theory for a normal and homogeneous stellar atmosphere. Effects of magnetic intensification may cause other uncertainties.

The Burbidges have also had to contend with two additional

difficulties. For the elements Ce, Pr, Nd, Gd, and Dy, the second ionization potentials are still unknown. The authors have assumed a value of 11.5 e.v., which is the average for the other rare-earth elements. Since these do not differ much among themselves, it is unlikely that the assumed values are greatly in error. On the other hand, the ionization is such that about 80 percent of the rare-earth elements will be in the second state of ionization, which, in general, is not observed. A small error in the observed abundance of Gd II, for example, can therefore be magnified five times or more in the total abundance for Gd. Then, in α^2 Canum Venaticorum, the lines of most elements change with phase, as we have seen. The results of Table II are derived from mean line strengths, and therefore represent an average abundance over the cycle. However, for Ti, the abundance at $\Phi = 0^{\circ}0$ is 2.6 times the abundance at $\Phi = 0^{\circ}5$; for the rare-earth elements this factor may lie anywhere in the range 4.5 to 30!

With these difficulties in mind, the Burbidges have summarized their own abundance determinations in the following words:

"1. O is probably underabundant, although the factor could not be determined.

2. Ca is underabundant by a factor of about 30.

3. Si is overabundant by a factor of about 15.

4. The metallic group is overabundant by a factor of about 6; the effect is largest for Mn and Cr; the factor for Fe, which is the element contributing the major part of the metal peak, is only about 2, and this value is still subject to observational uncertainties.

5. Sr, Y, and Zr are overabundant by a factor of about 25.

6. La, Ce, Pr, Nd, Sm, Eu, Gd, and Dy have a mean excessive abundance ratio of the order of 600, while Ba is the only member of this group to have an apparently normal (i.e., solar) abundance.

7. Pb is probably overabundant by a factor of about 1500.

8. The presence of U cannot be ruled out. In addition, there are several unidentified lines in the spectra of these stars which may be attributable to other heavy elements."¹⁸

In addition to these conclusions, the Burbidges believe that at least some of the apparent abundance differences between α^2 Canum Venaticorum and HR 5597 are real. In particular the

rare-earth elements are only about half as abundant in the latter star as in the former.

Some of the abundance anomalies observed in the peculiar A stars are reminiscent of those in the S-type stars; in these, the rare-earth elements and other heavy elements also appear to be abnormally abundant. The S-type stars are red giants, and they may well contain hydrogen-exhausted central cores in which helium-burning takes place. Cameron has indicated that at the temperature ($T \sim 10^8^\circ$) and density ($\rho \sim 10^3$ gm/cm³) of such a core, nuclear reactions with neutrons will synthesize heavy nuclei from the relatively abundant metal nuclei of intermediate atomic weight.¹⁷

However, for the reasons that have been outlined in Section II, it seems probable that the peculiar A stars have originated relatively recently from matter with the normal cosmic abundances, and that the physical conditions in their interiors are not sufficiently extreme for the type of element synthesis that occurs in the cores of red giants. Accordingly, Fowler and the Burbidges have recently examined the possibility of explaining the anomalous abundances of a peculiar A star in terms of nuclear synthesis in the atmosphere itself.¹⁸ They find that two types of processes, one involving α -particle capture and the other neutron capture, may indeed lead to an enrichment of heavy elements in stellar atmospheres. In a general way, the operation of these reactions in a stellar atmosphere will give an order-of-magnitude agreement with the observed abundances of the heavy elements. However, the rare-earth nuclei that have magic-number isotopes are particularly stable against neutron capture and should be expected to build up to 10 or 100 times the abundance of the other rare-earth nuclei. The observed abundances do not reflect this effect. Eu, which appears to have the highest overabundance, has no magic-number isotope; Ba, with a nearly normal abundance, does have such an isotope. The observed overabundances of Sr, Y, and Zr, on the other hand, which also have magic-number isotopes, are of the expected order of magnitude.

For heavy-element synthesis by either the α -particle or neutron reactions, a process must be found for accelerating an appreciable number of nuclei to energies far greater than 1 electron

volt, which is the thermal energy appropriate to an A-star atmosphere. In particular, the former reactions will occur at the required rate only if, during the last half billion years, about 1 percent of all the nuclei down to a depth of 1000 km below the photosphere have, at one time or another, been accelerated to energies between 10 and 100 MEV. If thermal, these energies would correspond to $T \sim 10^{12^\circ}$! In addition, the spectrum of the energetic particles must be approximately of the form $f(E) \propto E^{-3}$. For the synthesis by the latter reactions, thermal energies of the order of 1 MEV are required; at one time or another, all parts of the atmosphere must have endured temperatures of about 10^{10° for at least a few hours.

As extreme as these conditions seem to be, it is possible that they may be produced by the strong and variable magnetic fields in these stellar atmospheres. The observed changes in the magnetic field imply the existence of strong electric fields that are coherent over distances of the order of a stellar radius. Depending on the state of motion of the gas, ions in it will be subject to large accelerations in these electric fields. There is still some controversy about these acceleration phenomena. It is uncertain whether only a few ions will be accelerated to very large energies, or whether all ions will be accelerated to moderate energies, or indeed, whether the gas will move bodily in such a way that virtually no ions will acquire highly superthermal energies. It would appear, however, that in some cases, at least, appreciable numbers of ions do reach highly superthermal energies. Phenomena of just this kind are actually observed in some solar flares, which are known to eject soft cosmic rays and other energetic ions.

Though the details of the proposed acceleration mechanisms still remain to be worked out, they seem to require local fields that exceed the observed average fields by one or two orders of magnitude. Moreover, the theory requires that H must change appreciably when it is measured in a reference frame that moves with the local gas velocity. In a perfectly rigid rotator, this would not occur. To reconcile the Fowler-Burbidge theory with an oblique-rotator type of model, it would therefore be necessary to suppose that actual deformations of the magnetic field do occur,

perhaps as the result of relatively small differential motions of semipermanent, neighboring magnetic areas. It is also necessary to suppose that the atmosphere of the star, with its anomalous abundances, is not continuously mixed into the interior. Since the hydrogen convection zone of an A-type star is likely to be a shallow one, and since the magnetic field itself may tend to inhibit mixing, it is not likely that mixing processes will be important in diluting the effects of the atmospheric synthesis of heavy elements.

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