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THE PROBLEMS OF THE A-TYPE STARS.

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ONE of the most baffling problems in stellar spectroscopy, which the theory of ionization has failed to solve, is summarized by Morgan (1) in these words :—" It seems safe to conclude that there is some physical factor other than temperature and surface gravity concerned in the production of the spectra of the A stars . . ." There exists an enormous literature on the peculiarities of the A stars, and some years ago it was customary to distinguish between " silicon stars " (τ^9Eri), " strontium stars " (73 Dra), " manganese stars (α And), etc. In recent years these designations have largely disappeared from the literature, probably because it was assumed that the theory of ionization had explained the intensities of the elements in the A-type stars. This is, however, not the case, and it is important that the departures of the observations from the theory should not be glossed over. As a matter of fact, the failure of the modern theory to account for the weakness of *Ca* II K in the A2 star 78 Virginis and for the great strength of this line in the A2 star μ Orionis (1) constitutes a serious obstacle to our progress in astrophysics.

The principal phenomena which require explanation are :—

(1) The *Ca* II line K, whose intensity is often used to determine the type (or temperature) of a star is sometimes incompatible with the intensities of other lines such as *Mg* II, *Fe* II, *Si* II, *Ti* II, *Cr* II, etc. This phenomenon has been described by Morgan and others. It suggests that in some A stars *Ca* II is greatly weakened.

(2) There are numerous other inconsistencies between such elements as *Si* II, *Sr* II, *Mn* II, *Cr* II, *Fe* II, *Ti* II, *Ni* II. The ionization potentials of these ions are known, and it is a simple task to compare the observed ratios of intensities of pairs of these elements with predictions based upon the ionization theory.

(3) There are distinct groups of anomalous stars in which the lines of certain ions are greatly enhanced. For

example, in some A stars *Si* II is abnormally strong, while in others *Mn* II or *Sr* II may be exceptionally strong.

(4) There appear to be, according to Morgan, many A stars whose line intensities undergo periodic variations. The classical representative of this group is α^2 Canum Venaticorum, but there are several other bright stars whose line intensities show similar changes. Most of them are abnormal in other respects: Some, like α^2 CVn, have variable *Eu* II lines which in certain phases are almost phenomenally strong. Others, like ϵ UMa, have variable lines of *Ca* II, or, like 73 Draconis, variable lines of *Cr* II.

It has been customary in the past to escape the problems of the A stars by attributing properties (1), (2), and (3) to differences in the abundances of certain elements, while property (4) was usually thought of as representing a type of pulsation similar to that observed in Cepheid variables (2). It is almost certain that these escapist ideas have done more harm than good. There are few elements which show two stages of ionization, and it is difficult to test directly whether differences in abundance or in ionization are primarily responsible for (1), (2), and (3). Whatever information there is strongly suggests that while in some cases differences in abundance do play an important role (υ Sgr), the majority of the observed anomalies cannot be caused by them.

Similarly, it is not possible to attribute (4) to Cepheid-like pulsations. In α CVn the radial velocity of the star, as determined from strong lines of *Si* II and *Fe* II, does not vary more than by about 1 km/sec. The light changes by perhaps 0·03 mag. In a normal Cepheid the velocity varies in a range of some 40 km/sec and the light undergoes variations of the order of one magnitude. Yet, the changes in the line intensities of α CVn are enormously more conspicuous than those of a normal Cepheid. In this connection, it appears from Coudé spectrograms taken at the McDonald Observatory that the range in equivalent width of the strongest lines of *Eu* II is much greater even than that determined by Tai (3), who adopts for $S = \frac{1 - x_1}{1 - x_2}$ the value of 3. On our plates the strongest *Eu* II lines cannot be identified with certainty when near minimum, and S is at least 10 (4). Tai made as good a case as he could for the ionization theory. Our results suggest that the physical conditions must change even more drastically if we wish to interpret the changes in line intensities to ordinary changes in temperature and pressure.

Moreover, the ionization theory encounters other difficulties. Tai uses *Eu* II and adjusts T and P in such a way as to satisfy the changes in line intensities of *Ti* II and *Fe* II. But he finds that although his theory assigns *Ca* II, *Sr* II and other elements of low ionization to group A of lines which vary in the same sense as *Eu* II, it predicts a larger variation in intensity than that observed. The discrepancy in the case of *Sr* II, with an ionization potential of 11·0 volts, as compared with 11·2 volts for *Eu* II, is particularly striking. The lines 4078 and 4215 change only very little in intensity. In fact, λ 4215 changes so little that even its class (A or B) remains uncertain. The discrepancy between *Eu* II and *Sr* II is much more important than the agreement between *Eu* II and *Ti* II. It can be stated without ambiguity that the elementary theory of ionization fails to explain the variations in line intensities. This does not mean that the temperature and pressure remain constant. There may be a small residual effect which corresponds to an enhancement of lines of higher ionization potential when the lines of *Eu* II are weak. But the effect is much more complicated than the simple theory predicts.

It seems to us, after a thorough study of the data, that the existing interpretations should be abandoned, and that a new solution of the problem of the A stars should be attempted along lines which are virtually thrust upon us by the results of our recent work on stellar shells, Wolf-Rayet stars, and planetary nebulæ.

It is very suggestive that the peculiarities occur precisely in that region of the sequence of stellar spectra where the Lyman lines and the Lyman continuous absorption cause a large redistribution of the energy in the continuous spectrum (5). How profoundly this redistribution affects the continuous spectrum of an A star may be inferred from the curve computed by Pannekoek (6) for a temperature $T_0=8480°$. The Lyman lines are neglected, but the continuum is allowed for. The redistribution is so significant that it must have a marked effect upon the ionization (and excitation) of those elements whose ionization potentials lie in the region of 12 volts.

What we have in mind is, of course, the effect of departures from thermodynamic equilibrium caused by the shape of the energy curves. In recent months we have independently been led to the conclusion that this physical dilution of radiation—as contrasted with the geometrical dilution observed in shells—plays an important role in a number of problems: the double maximum of the intensity distribution of the rotational lines of *CN* in the spectra of comets is caused by a depletion of the solar radiation in the appropriate frequencies through chance coincidences with strong Fraunhofer absorption lines (7). Similarly, in shells the intensities of emission or absorption lines of *H* depend upon the depletion of continuous radiation through Lyman absorption in the reversing layers (8). Numerous other cases of fluorescence excitation or ionization have been found to be anomalous because the exciting radiation is either depleted by absorption or is enhanced by emission in deeper layers.

Along these general lines a wide variety of otherwise unexplained observations can be interpreted, among which the following may be briefly mentioned (9) :—

(1) The enhancement of the emission lines of the singlet system of *He* I, relative to the triplets in many bright-line objects.

(2) The peculiar selectivities among the transitions of *N* II, *N* III, *N* IV, *C* II, *C* III, *Si* II, *Si* III, and other atoms, in Of- and P Cygni-stars.

(3) The influence of the ejection velocity (and other mechanical agents, such as axial rotation and turbulence) on the excitation in shells.

(4) The ionization conditions in nebulæ (and in the interstellar gas) excited by nuclei possessing emission or absorption lines.

(5) The nitrogen-flaring stages and the appearance of molecular bands in novæ.

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Consider now the remarkable weakening of the *Ca* II lines in certain A-type stars. Low abundance of calcium would, of course, explain the result, since in many stars *Ca* I is not strong enough to give conclusive evidence with regard to ionization. However, it is hardly reasonable to suppose that there are frequent departures from normal abundance among the A stars, when no such effect has been observed in the B's or in the late F's.

A related group of stars is that discovered by Titus and Morgan (10) in the Hyades. These stars "are all similar in the characteristic that the metallic arc lines are considerably stronger than normal; they are of the same strength as in a normal F star . . . . If the A stars had been classified by the intensity of the metallic arc lines, these objects would be classed as F stars with unusually weak K lines." We have obtained at the McDonald Observatory Cassegrain spectrograms of the six abnormal A stars, together with some 50 normal members of the Hyades. In all six stars the line *Ca* I 4226 is present and is of an intensity similar to that observed in a normal star of spectral type A 8 to F0. On the basis of *Ca* II, K, Titus and Morgan assign the following types :—

Smart No.	Sp. (Titus and Morgan).
12	A3*p*
14	A1*p*
23	A5*p*
31	A5*p*
42	A2*p*
67	A3*p*

It is probable that the weakening of *Ca* II is not accompanied by a similar weakening of *Ca* I, and that the effect cannot be caused by low abundance of calcium.

It is tempting to attribute the weakening of *Ca* II to excessive ionization. Ordinary thermal ionization cannot produce the desired effect, because *Ca* I remains normal and also because *Y* II with its ionization potential of 12·3 volts and *Sr* II with one of 11·0 volts fail to show changes which would correspond to those of *Ca* II, whose ionization potential is 11·8 volts. We must attribute the excessive ionization to an effect which is somehow localized near energies of 11·8 volts. Perhaps the fact that L_β falls at λ 1026 while the ionization limit of *Ca* II falls at λ 1044, has something to do with the problem. In a normal main-sequence star, without an appreciable hydrogen chromosphere, the strong absorption line of L_β will cut down the ionization of Ca^+, and therefore strengthen the line K. But in a star whose reversing layer is surrounded by a chromosphere L_β will be in emission, and this will tend to increase the ionization.

It is difficult to arrive at a satisfactory theoretical evaluation of the effect. If we suppose that the continuous radiation in the ultraviolet region corresponds to a uniform temperature T, then the energy on the violet side of the Lyman limit is

$$E_{ul}=\frac{8\pi^2R^2k^4}{c^2h^3}T^4\int_{x_0}^{\infty}\frac{x^3}{e^x-1}dx,\quad x_0=\frac{h\nu_0}{kT}.$$

A fraction γ of this energy is converted into L_β. The energy normally available for the ionization of Ca^+ is essentially a strip of continuous spectrum between L_β and L_γ. On the violet side of L_γ other absorption lines follow in rapid succession. Moreover, the efficiency of ionization decreases (perhaps as ν^3) as we go farther away from the limit. If we set

$$E_{Ca^+}=\frac{8\pi^2R^2k^4}{c^2h^3}T^4\int_{x_1}^{x_2}\frac{x^3}{e^x-1}dx.$$

Where x_1 and x_2 correspond to λ 1026 and λ 973 respectively, we find, approximately :—

T.	E_{ul}/E_{Ca^+}.
10,000	0·4
12,000	0·6
15,000	0·0

But the energy curve beyond the Lyman limit is already depleted in the reversing layer. Moreover, only a fraction of the available energy will go into L_β, even if the opacity of the chromosphere for L_α is great. Perhaps an estimate of $\gamma=0·1$ will not be too far from the truth. On the other hand, E_{Ca^+} will be greatly reduced by the absorption wings of L_β and L_γ. It is rather difficult to estimate these. For T=10,000 the abundance of neutral *H* atoms exceeds that of excited atoms by a factor of 10^6. But the Stark effect $\Delta\nu$ in the Lyman lines is only about 0·4 times that of the Balmer lines. Converting this into $\Delta\lambda$, we find that the absorption coefficient is compressed

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in λ by a factor of perhaps 50. Hence, in an atmosphere of uniform pressure the Lyman lines should still be very much stronger than the corresponding Balmer lines. But the atmosphere is not uniform, and we have no way of telling, without lengthy computations, what the contours of L_β and L_γ are. We do, however, know that the Lyman jump corresponds in the A stars to a factor in intensity of about 30 (11). This must merge continuously into the region of discrete levels. Between L_β and L_γ the drop must, therefore, be somewhere between 0 and 30. We estimate that it may correspond to a factor of 10. It will, then, cancel the effect of γ, so that we are left with the original values of E_{ul}/E_{Ca^+}. This rough computation tells us that the proposed mechanism *may* account for the excessive ionization of Ca^+. Whether it actually does so cannot yet be decided. But we feel rather strongly that in view of the theoretical uncertainties involved in the computation (it will be recalled that Unsöld proposed a superexcitation of hydrogen in the Sun by a factor of $10^{5\cdot5}$) the observations should be used to derive information concerning the unobservable ultraviolet energy curve and not *vice versa*.

The proposed mechanism has many advantages. In the first place, we already know that there are stars with extended chromospheres and coronæ (12). In the second place we know that these structures are relatively unstable and are sometimes variable (bright H_α in α Cygni and β Orionis); this may account for the variability of the lines in α CVn. In the third place, the great opacity of the Lyman lines suggests a mechanism whereby relatively small differences in temperature and pressure may produce large differences in the ionization of some elements, without affecting the ionization of others. Comparisons between main-sequence stars and supergiants should be especially instructive. But the problem is complicated by the fact that the spectral classification is itself based upon the intensities of certain lines.

To return to the problem of α CVn, we have as yet no very convincing interpretation of the *Eu* II lines. These lines are at their maximum very much stronger than they are supposed to become anywhere in the spectral sequence. Since the ionization potential is 11·21 volts (13), corresponding to λ 1102, the ionization should normally be very complete ; *Eu* II should be weak, and *Eu* III strong. This agrees with the conclusions of Tai.

The spectrum of *Eu* II has been analysed by Russell, Albertson and Davis. Most of the lines which are present in the star originate from the ground-level $a^9\ S^0$ or from the low metastable level $a^7\ S^0$. There is, however, at least one strong line (and several weaker ones) which originate from the normal level $z^9\ P$. This line, λ 4355·09 ($z^9\ P_5$—$e^9\ S_4{}^0$; e.p. 3·2 v.) is effectively unblended, and it shows exactly the same strengthening as do λλ 4129, 4205, etc. The level $z^9\ P_5$ combines with the ground-level by giving the resonance line λ 3819·67. Since the high-level line of *Eu* II shares the variation of the resonance lines, we conclude that geometrical dilution is not important and that the excitations within the system of *Eu* II are normal.

We are again, as in the case of *Ca* II, left with two possibilities : (*a*) an increase in the abundance of europium at certain phases, and (*b*) a suppression of double ionization by a local effect which does not sensibly affect atoms of other ionization potentials. Since we do not know the spectrum of *Eu* III and observe no lines of *Eu* I, the question of abundance remains unanswered. There are no conspicuous absorption features of *H* in the region required, namely, λ 1100. The ionization limit of *C* I is at 11·28 volts, and is probably of some importance. Another possibility is the resonance absorption line of *N* II at λ 1085. A variation in the *N* II line, which may sometimes be in emission, could perhaps produce a corresponding variation in the ionization of Eu^+. But the fact that to ionize nitrogen we require at least 14·5 volts does not encourage us to think the chromospheric emission line of *N* II can be strong. The presence of strong metallic lines around λ 1100, especially the numerous lines of *Fe* II (14) with lower level a^6D (ground term of *Fe* II), may be of importance, since in variable chromospheric conditions, the emission and absorption contributions of the various metallic lines relative to each other and to the Lyman features, may change considerably. At first sight, we should expect that a strong absorption feature at λ 1085 or at λ 1100 will almost equally affect the ionization of Sr^+ (i.p. 11·0 volts, or λ 1122) unless the continuous absorption coefficient varies much faster with λ than $1/\lambda^3$. In reality there is no large variation of *Sr* II 4077 and 4215. But there may also be compensating effects, even in a fairly narrow range of wave-lengths. At any rate, before we can discuss in detail the complex mechanism affecting the intensities of the rare-earth lines we require more information concerning the identifications of the hundreds of faint lines in α CVn which are as yet unidentified, and which share the variations of the *Eu* II lines.

We know that α CVn belongs to that group of A stars whose *Ca* II line K is abnormally weak. This is conspicuously shown in plate xvi. of *McDonald Observatory Contribution* No. 13 (15), where the star is compared with normal stars of classes B 8 to A 2. The hydrogen lines are also relatively weak, and the Balmer jump is small. *Fe* I is weak, while *Cr* II is strong. These peculiarities suggest that the problem of *Eu* II should be approached in the same manner in which we have dealt with the problem of *Ca* II.

In conclusion, it may be useful to point out that recent developments in stellar spectroscopy tend to emphasize the importance of the mechanisms by which atoms are excited and ionized. The long and exceptionally successful period of development characterized by the use of thermodynamic equilibrium is gradually being replaced by a new period in which emphasis is being placed upon departures from equilibrium conditions.

Yerkes Observatory,
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[2] C. P. Gaposchkin and S. Gaposchkin, *Variable Stars*, p. 177, 1938.

[3] *M. N.* **100**, 124, 1939.

[4] Incidentally, we find systematically much smaller equivalent widths than does Tai. Thus, *Eu* II 4129 has, at maximum, an equivalent width of 0·148 A and at minimum one of less than 0·014 A. Tai finds at maximum 0·3 A. and at minimum about 0·07 A. We also disagree with Tai in regard to a possible error in the period or to a secular decrease in the period. The formula of Miss Farnsworth satisfactorily predicts his own observations, as well as those obtained at the McDonald Observatory in 1941.

[5] The Lyman lines are, of course, strong at all temperatures at which ionization is unimportant. But for stars of later types the energies available in the shorter wave-lengths are insufficient to cause appreciable ionization of the ions under consideration, and the problem simply does not arise.

[6] *Ap. J.* **84**, 488, 1936.
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CORRESPONDENCE.

To the Editors of ' The Observatory '.

Short-lived Hα Prominences observed on the Sun's Disk.

GENTLEMEN,—

Dr. Hunter's ingenious model * reproduces so faithfully the general characteristics of the velocity-time curves in their later stages that there seems to be a high probability of his treatment being upon the right lines : once the initial impulsive force has spent itself the subsequent motion of the gas column is described under the action of solar gravity alone.

The velocity-time curves obtained at Sherborne indicate very clearly that the disappearance near the summit of the trajectory takes place at a velocity of about —20 km/sec on the ascent and the reappearance at +20 km/sec on the descent : it is therefore the velocity and not the height which is the variable concerned. It is true this velocity corresponds to a distance of 730 km below the top of the trajectory (assuming motion under solar gravity), but the distance integrals, quoted in my paper, show trajectories varying in height from 5000 to 50,000 km. Why, then, should the atoms become " invisible in Hα light " always at 730 km below the tops of their trajectories, a level which bears no relationship to conditions of temperature and pressure in the chromosphere ?

It seems to me that this difficulty may be resolved in a simpler way without any assumption of changes in

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* *The Observatory,* **64**, 201–204.