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THE INTERPRETATION OF THE SPECTRUM OF HD 190073*

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ABSTRACT

The hypothesis proposed by Beals for the interpretation of the complex contours of lines of *H* and *Ca* II in HD 190073 is discussed in the light of recent observations made at the McDonald Observatory. The absorption lines designated by Beals as A_2 and A_3 and the emission of *Ca* II and *H* probably originate in a shell whose radius is several times larger than the radius of the star. The absence of A_1 near the center of the emission in *Ca* II H suggests that this sharp line is produced at a lower level, where the velocity of expansion is negligible. The central reversals of the *H* lines, on the other hand, may come from an upper layer of the shell where the atoms have become decelerated. In this case the absorbing layer must lie immediately above an optically thick emitting shell, so that it will act somewhat like a reversing layer and not like a detached shell at great distances from the emitting regions.

In a recent paper C. S. Beals[1] has made an attempt to explain the unusual contours of the *H* lines and of the line *Ca* II K in the spectrum of HD 190073. The observational features of this remarkable object have been described by Merrill,[2] Beals,[3] and the present writers.[4] The *H* lines show broad underlying absorption lines corresponding roughly to type A. Superposed over these normal lines are bright lines, which sometimes are accompanied by strong violet absorption borders of the P Cygni type. The emission lines frequently show reversals, which are not quite central. The *Ca* II line K shows a relatively weak, but fairly broad, emission in the normal position of the line. A fairly strong central absorption is designated by Beals as A_1. On the violet side of the emission line is a strong double absorption line, the two components of which are designated as A_2 and A_3. There are numerous other emission lines, especially in the region of confluence of the strong higher members of the normal, Stark-broadened *H* lines and on the violet side of the Balmer limit. The spectrum undergoes slow changes. Most conspicuous is the disappearance of the P Cygni absorption of the *H* lines, which was first observed by Merrill. Our observations at the McDonald Observatory showed conspicuous P Cygni-type absorption lines in 1939 and less conspicuous ones in November, 1941. A plate taken July 8, 1942, shows ordinary Be-type bright lines, which are visible to $H\delta$ but cannot be seen clearly at $H\zeta$. There are no conspicuous changes in the rest of the spectrum, except that the narrow space of continuous spectrum (or of emission) between A_2 and A_3 undergoes slight oscillations in position. In 1939 it was displaced toward the violet side of the center between the outer edges of A_2 and A_3. In 1941 it was displaced toward the red. In 1942 it was still slightly displaced toward the red. The star is particularly interesting because, according to Merrill, the *Na* I lines are bright. They do not show conspicuous absorption components like the lines of *Ca* II.

The stellar lines of *Mg* II and *Si* II are fairly sharp, and the star does not show appreciable rotational broadening. The star is clearly not related to the ordinary Be stars, in which axial rotation has an important bearing upon the origin of the nebulous shell. Nor is the star a supergiant, like α Cygni, where expanding shells are frequently observed. HD 190073 belongs to the small group of stars of the main sequence which possess absorbing and emitting shells. The interpretation proposed by Beals is therefore of great

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1 *J.R.A.S. Canada*, **36**, 145 and 201, 1942; *Pub. A.A.S.*, **10**, 222, 1942.

2 *Ap. J.*, **77**, 51, 1933.

3 *Pub. A.S.P.*, **51**, 219, 1939.

4 *Ap. J.*, **91**, 594, 1940; *Pub. A.S.P.*, **54**, 11, 1942; *Pub. A.A.S.*, **10**, 238, 1942.

interest, and we shall discuss it in the light of our observations made at the McDonald Observatory.

In a convincing manner Beals has demonstrated that the P Cygni structure of the *H* lines arises in an expanding shell above a nonexpanding reversing layer. This agrees with our conclusions from the ultraviolet emission lines, which are not weakened by the strong Balmer continuous absorption or by the wings of the broad Balmer lines.

By a procedure which differs materially from that which we have used in other similar cases, Beals concludes that the P Cygni absorption lines and the emission lines of *H* originate at a height of about $r = 10\ R_*$, while the *Ca* II emission originates at $r = 3.4\ R_*$ and the most displaced *Ca* II absorption component at $r = 5.6\ R_*$. These values are derived upon the assumption that the velocity of A_3, namely, -320 km/sec, corresponds to the velocity of escape at that distance r where A_3 is formed. As to order of magnitude, these values given by Beals agree with those which we have derived for other P Cygni-type stars. The spectrum of HD 190073 shows undisplaced absorption lines of *Mg* II 4481 and *Si* II 4128, 4131, which probably originate in the A-type reversing layer. There are no emission lines of *Mg* II and *Si* II or any violet-displaced absorption components which would correspond to A_2 and A_3. If we had observed in a normal stellar spectrum a *Ca* II line of the intensity of A_2 or A_3, we should certainly have expected to observe fairly strong lines of *Mg* II and *Si* II. The conclusion is therefore justified that the dilution of radiation in the shell is appreciable, though its amount cannot be ascertained. We conclude that our interpretation of the spectrum is consistent with that of Beals.

Perhaps of even greater interest is the origin of the undisplaced absorption line A_1 of *Ca* II. From his discussion of the *H* lines Beals has concluded that the approximately central reversals of these lines can best be explained as absorption by atoms which after "leaving the stellar surface are subjected to a positive outward acceleration which subsequently changes sign and becomes negative, reducing the velocity to relatively small values at great distances from the star." By assuming that the velocity of A_3 (-320 km/sec) corresponds to the velocity of escape at a point where the accelerating force, not otherwise specified, is suddenly cut off, Beals estimates for A_1 a height $r = 1000\ R_*$. He does not give a numerical estimate for the reversals of the *H* lines but suggests that the height is of the same order.[5] Incidentally, he agrees with Merrill that the line A_1 cannot be of interstellar origin. The absence of similar lines of *Na* I is a convincing argument.

It must be emphasized that the estimate of $r = 1000\ R_*$, which Beals gives for the reversals of the emission lines, rests upon the assumption that the accelerating force is cut off in the vicinity of $r = 10\ R_*$. It is therefore desirable to test the estimate $r = 1000\ R_*$ by other methods. If we understand the hypothesis of Beals correctly, we must suppose that for calcium, as well as for hydrogen, all observable emission is produced within about $r = 10\ R_*$. Between this distance and the much larger distance $r = 1000\ R_*$ the atoms are rapidly decelerated by the gravitational field of the star. In this region they are not believed to contribute materially to the observed features of the spectrum. Only at very great distances the atoms have become sufficiently decelerated to produce the absorption line A_1, near the normal wave length of the line. Evidently this picture involves the consideration of a more or less detached absorbing shell at $r = 1000\ R_*$, whose optical thickness within the line is small. It should also be noted that the observed emission at *Ca* II K is fairly weak. Hence the optical thickness of the emitting shell, which Beals estimates at $r = 3.4\ R_*$, is small.

If we can disregard all cyclical processes and assume that the entire absorbed energy is re-emitted in the same frequency, then, on general grounds, the measured energy emitted in the shell is exactly equal to the energy absorbed in the line. Hence, if there is no expansion or rotation, the emission line will be just sufficient to fill in the absorption line. This picture should hold in the case of *Ca* II, where the lower level is the ground

[5] *J.R.A.S. Canada*, **36**, 211, 1942.

state and the upper level is connected with it by a very strong transition. If cycles are present, they must, in the case of *Ca* II, tend to increase the emission relative to the absorption. It is, therefore, difficult to see how the absorption line A_1 can be formed at great distances from the photosphere without a corresponding amount of emission. We can verify this conclusion by computation.

Since the volume of the shell projected upon the apparent disk of the star, or eclipsed by it, is very small, the total energy, in ergs, radiated by the shell in all directions is approximately

$$4\pi r^2 H N_2 h\nu_{12} A_{21}\ , \tag{1}$$

where H is the thickness of the shell, and N_2 is the number of atoms in the upper level of the particular transition which we are considering. According to Beals, the radius of the star is

$$R_* = 2.1\odot \approx 10^{11}\ \text{cm}\ ,$$

and its distance is

$$D_* = 280\ \text{parsecs} \approx 10^{21}\ \text{cm}\ .$$

The radius of the shell is $r = 1000\, R_* = 10^{14}$ cm, and its angular diameter is therefore of the order of 0.″01. All the light given by equation (1) will enter the slit of the spectrograph, and the source can be treated as a point.

In practice the emission of a shell is measured in terms of the radiation of the continuous spectrum of the star. This is

$$\pi R_*^2 c\, \rho_\nu d\nu\ , \tag{2}$$

where

$$\rho_\nu = \frac{8\pi h}{c^3}\, \frac{\nu^3}{e^{h\nu/kT}-1}\,; \qquad T = 10{,}000^\circ .$$

We choose for $d\nu$ the frequency interval $\delta\nu$, which corresponds to 1 A at the wave length considered. The measured quantity is, therefore,

$$x = \frac{4\pi r^2 N_2 H h\nu_{12} A_{21}}{\pi R_*^2 c\, \rho_\nu \delta\nu}\,.$$

Recalling that, approximately,

$$W = \frac{R_*^2}{4 r^2}\,,$$

we have

$$x = \frac{1}{W}\, \frac{N_2 H h\nu_{12} A_{21}}{c\, \rho_\nu \delta\nu} = \frac{1}{W}\, N_2 H\, \frac{h}{\lambda}\, A_{21}\, \frac{1}{\rho_\nu \delta\nu}\,. \tag{3}$$

The quantity N_2H is not directly known. But we observe the central reversal which we presume to be produced by the shell. For *Ca* II K this gives, in the case of Doppler broadening,

$$\text{E. W.} \approx 10^{-13} N_1 H\ . \tag{4}$$

For the line A_1 a reasonable estimate is E.W. = 1 A. Hence,

$$N_1 H = 10^{13}\,. \tag{5}$$

The corresponding value of N_2 is obtained from the Boltzmann relation modified by dilution,

$$N_2 H = N_1 H\, \frac{g_2}{g_1}\, W e^{-h\nu/kT} = 0.1\, W N_1 H = 10^{12} W\,. \tag{6}$$

Introducing into equation (3) this and the numerical values

$$h = 6.6 \times 10^{-27}\,, \qquad \lambda = 4 \times 10^{-5}\,, \qquad A_{21} = 10^{8}\,, \qquad \rho_\nu \delta\nu = 10^{-2}\,,$$

we find

$$x \approx 1\,. \tag{7}$$

This is precisely the amount of energy absorbed in the line by equation (4). Hence, if the atoms are at rest, the emission will fill in the absorption line and no central reversal will be observed. In order to maintain Beals's hypothesis we must assume that cycles are operating in the direction contrary to that in which they are set going by the dilution of radiation. Such cycles are not known at the present time.

The case is entirely different for H. Here we cannot assume, without further specification, that only two levels are concerned in the line production. If the second Balmer level is not metastable, then the population of it, as well as the population of the third, and higher, levels, is proportional to W. Hence, the factor $1/W$ in equation (3) does not cancel out, and x becomes roughly 10^6.

Without collisions the lifetime of the $2s$ level of H is 1/7 second. When collisions are present, the lifetime becomes shorter, so that for an electron density, $n_e = 10^{10}\ \text{cm}^{-3}$, the lifetime becomes 10^{-8} sec. If $W \ll \tau_3/\tau_2$, we can write, instead of equation (6),

$$N_3H = N_2H \frac{g_3}{g_2}\frac{\tau_3}{\tau_2} e^{-h\nu_{23}/KT}\,.$$

If, on the other hand, $W \geq \tau_3/\tau_2$, then expressions (6) and (7) remain essentially unaltered. In order that we may obtain, for H, $x = 10$, we must have for $W = 10^{-6}$,

$$\frac{\tau_3}{\tau_2} = 10^{-5}\,.$$

Since, approximately $\tau_3 = 10^{-8}$ sec, this requires that τ_2 must be of the order of 10^{-3} sec. The corresponding electron density[6] would be about $n_e = 10^6\ \text{cm}^{-3}$. There is no way to test this value. Observations give us only $N_2H = 10^{13}$. Remembering that in interstellar space $n_e = 3\ \text{cm}^{-3}$, it is quite plausible that the shell should have an electron density of 10^6. However, we are unable to prove this. We conclude that in the case of *Ca* II physical theory does not favor the hypothesis of an absorbing shell at great distances from the star which does not at the same time give rise to a strong emission line.[7]

The analysis by Beals is concerned for *Ca* II only with the line K. The line H is blended with $H\epsilon$ and is, therefore, more difficult to disentangle. However, our recent plate shows the Balmer lines free of P Cygni-type complications and is therefore useful for making a comparison between K and H. If the undisplaced line A_1 is produced much higher than any other spectroscopic feature of the star, it must superimpose itself with its normal intensity of $\frac{1}{2}$, as compared to K, upon the background produced by the sum of the intensities of the $H\epsilon$ wing and the *Ca* II emission. The central emission of $H\epsilon$ is presumably very weak, since it is not seen at $H\zeta$; but, even if it were present, the argument would still hold. In actual fact only an excessively weak indentation in the *Ca* II emission of H can be identified with the central reversal (Fig. 1). This is also confirmed by tracings from other plates and by the tracing published by Merrill. This faint feature has an area of probably not more than 0.1 of the area of the central reversal at K. It is presumably cut down by the very strong $H\epsilon$ line from the reversing layer or from the inner

[6] See eq. 10, *Proc. Natl. Acad.*, **25**, 72, 1939.

[7] The case of interstellar gas is, of course, different. The crucial point in the present discussion is that the shell appears as a point source.

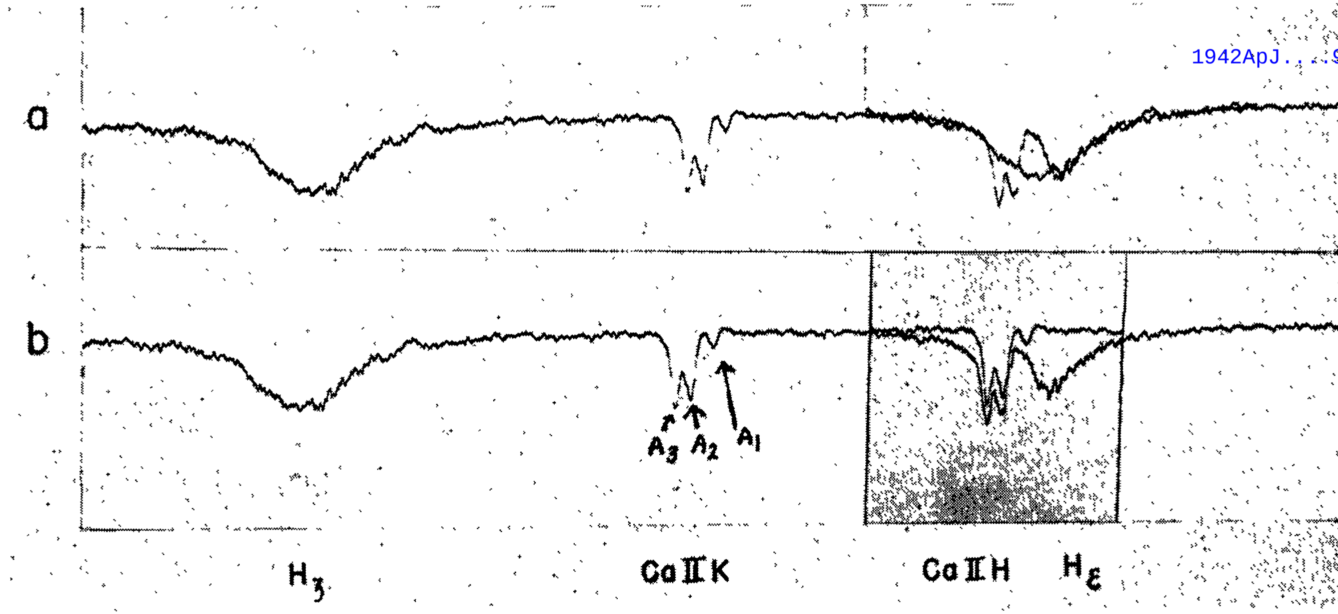

FIG. 1.—Tracing of spectrogram of HD 190073 obtained on July 8, 1942. (*a*) The tracing of H_ζ is superposed over that of H_ϵ. The red wings coincide. The emission and absorption of *Ca* II H show as departures from the curve representing H_ζ. (*b*) The tracing of *Ca* II K is superposed over that of *Ca* II H. The absorptions A_2 and A_3 coincide, but A_1 is very weak or absent in *Ca* II H, although it is strong in *Ca* II K.

shell. We are, therefore, inclined to attribute the line A_1 to a relatively low level, in spite of the difficulties mentioned by Beals.

This result does not invalidate the rest of Beals's discussion and in particular does not disprove his assumption that the accelerating force is reduced to zero (or to a small value) within the expanding shell. The central reversals of the H lines can, of course, not be attributed to the reversing layer. Hence the hypothesis proposed by Beals, namely, that they originate in a decelerated shell, merits careful consideration. For the H lines the emission is fairly strong, and we approach the case of a shell of considerable optical thickness. To make the hypothesis work, somewhat along the lines suggested by Rosseland,[8] it is only necessary to modify Beals's picture by supposing that the layers which are largely responsible for the broad emission line lie quite close—in fact, immediately below—the layer which is essentially responsible for the reversal. In that case the emission from the outer layer will not fill in the absorption (it acts like a reversing layer). According to this view, emission and absorption are thought to take place within the entire space occupied by the decelerated shell. To achieve this it is perhaps best to abandon the idea that the P Cygni absorption A_3 corresponds to the escape velocity at the appropriate distance r. There is no trouble in explaining the existence of decelerated expansion; and, by dropping the assumption, we can obtain a self-reversal at a much smaller distance from the star.

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[8] *Theoretical Astrophysics*, p. 294, Oxford, 1936.