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THE SPECTRUM OF THE SHELL OF PLEIONE*

OTTO STRUVE AND P. SWINGS

ABSTRACT

The absorption spectrum of the shell of Pleione, which made its appearance in 1938, has a radial velocity of +10.3 km/sec. It shows sharp cores of the Balmer lines as far as H_{31}. *Mg* II 4481 and *Si* II 4128, 4131 are weak, probably because of the dilution of the exciting radiation. The lines of *Ni* II, *Fe* II, and *Cr* II are relatively strong; those of *Ti* II and *Mn* II are very weak; *Fe* I, *Mg* I, and *Sr* II are present. The lines of *Fe* II give an excitation temperature of about 17,000°. The ionization is greater than in the shell of 17 Leporis, but not all intensities are accounted for by the ionization theory.

The dilution factor is of the order of 0.1. From the state of ionization the electron pressure, estimated to be of the order of 0.5 bar in 17 Leporis, is probably appreciably higher in Pleione. Geometrical considerations suggest a value of $P_e = 0.1$ bar. The shells of stars like Pleione are not unlike the reversing layers of normal supergiants. But the stars inside these shells belong to the main sequence. The shells form a spectral sequence which runs parallel to the normal stellar sequence from the early B's to the late A's. The ionization of the shells is lower than that of the corresponding stars.

1. Pleione (28 Tauri=BS 1180, $\alpha=3^h43^m.2$, $\delta=+23°50'$ [1900]) is a member of the Pleiades cluster. Its Harvard spectral type is B8p, and its visual apparent magnitude is 5.18. The proper motion ($\Delta\alpha=+0''.016$ and $\Delta\delta=-0''.049$) and the radial velocity (+10 km/sec) agree with those of other cluster members. Adopting for the Pleiades a parallax of $0''.006$, or a distance of 170 parsecs, the visual absolute magnitude of Pleione is −1.0. It, therefore, belongs to the main sequence, as do the other early-type members of the Pleiades. It is reasonable to suppose that the radiation of Pleione resembles that of a black body; then if its color index is −0.05, we compute for the radius

$$\log_{10} R = 0.82I - 0.20M_v + 0.51 = 0.7$$

$$R = 5R_\odot$$

2. From December 28, 1888, when the first spectrographic observation[1] was secured at Harvard, until February 2, 1903, when H. W. Jung recorded the presence of double reversals of the hydrogen lines, emission features were prominent in the spectrum of Pleione. In November and December, 1905, E. B. Frost[2] noticed at the Yerkes Observatory that all emission lines had disappeared. Between 1905 and 1924 numerous spectrograms taken at the Yerkes Observatory show strong absorption lines of *H*, with marked Stark-effect wings and with a pronounced rounding-off at the centers of the contours, suggestive of rapid axial rotation. The usual *He* I lines λ 4472, λ 4026, etc., were exceedingly broad and shallow, indicating an equatorial line-of-sight component of the rotational velocity of about 300 km/sec. The line *Mg* II 4481 was so weak and broad that its existence could not be definitely established. Our spectrograms, with their relatively high dispersion of 30 A/mm, are not suitable for determining the spectral class of this object.

In October, 1938, McLaughlin[3] and Orren Mohler[4] independently announced the reappearance of emission lines in Pleione. McLaughlin also discovered narrow absorption cores in the *H* lines, as far as $H\eta$, and a large number of weak, narrow lines of *Fe* II,

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[1] A description of the spectral changes was given by R. H. Curtiss, *Pub. Obs. U. of Michigan,* **3,** 19, 1923.

[2] *Ap. J.,* **23,** 268, 1906.

[3] *Ap. J.,* **88,** 622, 1938.

[4] *Ap. J.,* **88,** 623, 1938.

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Ti II, *Sc* II, *Cr* II, *Ni* II, and perhaps *V* II. He states that *He* I 3819 was conspicuous and was wider than the metallic lines. The lines of *Si* II and *Mg* II 4481 were possibly wider than those of the metals.

3. From photoelectric observations made at Harvard in 1935, 1936, and 1937, Calder[5] believes that the brightness of Pleione had gradually decreased by about one-sixth of a magnitude, and more recently E. G. Williams[6] finds a reddening corresponding to an increase in the color index of 0.08 mag.

4. The following spectrographic observations have been secured at the Yerkes and McDonald Observatories:

1938	Dec. 16	$1^{h}\ 8^{m}$	U.T. at Yerkes	λλ 3900–5000	disp. 30 A/mm at λ 4500
1940	Sept. 13	9 7	U.T. at Yerkes	λλ 3900–5000	disp. 30 A/mm at λ 4500
1940	Nov. 3	11 22	U.T. at Yerkes	λλ 3900–5000	disp. 30 A/mm at λ 4500
1940	Nov. 12	9 45	U.T. at McDonald	λλ 3100–4900	disp. 40 A/mm at λ 3933
1940	Dec. 8	0 37	U.T. at Yerkes	λλ 3900–5000	disp. 30 A/mm at λ 4500
1941	Jan. 7	4 20	U.T. at McDonald	λλ 6000–6600	disp. 180 A/mm at *Hα*
1941	Jan. 7	5 2	U.T. at McDonald	λλ 3100–4900	disp. 40 A/mm at λ 3900

During the last two years the general appearance of the spectrum has remained the same. The metallic lines are strong and fairly sharp. The sharp absorption cores of *H* are strong and are visible to H_{31}. It is clear that the correlation between the number of Balmer absorption lines and absolute magnitude, which exists among normal stars,[7] breaks down completely in the case of Pleione. We are evidently concerned not with a normal reversing layer but with a tenuous shell at a considerable distance from the reversing layer. Several other objects of this class are known, but in no other case have we any reliable information concerning the absolute magnitude and the radius of the star.

5. The radial velocity of the shell of Pleione is found to be +10.3 km/sec. This agrees closely with the value of 10.0 ± 1.3 km/sec found from measurements of the broad lines[8] prior to the origin of the shell. The sharp cores of *H* and the narrow lines of *Cr* II, *Ti* II, *Ni* II and *Fe* II give substantially the same velocity. The shell does not expand, as it does in 17 Leporis or P Cygni, but remains stationary, as in γ Cassiopeiae.

6. We proceed with a detailed description of the spectrum. The shell may best be compared with α Cygni (cA2) and 4 Lacertae (cB8)—both normal supergiants. Most of the metallic lines and the cores of the hydrogen lines are much weaker in Pleione than in α Cygni.

H.—Hβ shows a weak double emission line, with the violet component slightly the stronger. *Hα* is a fairly strong double emission line. The sharp absorption cores are superposed over broad wings which resemble those observed prior to 1938. They may now be slightly narrower, but in any case weakening of the underlying B8 spectrum by the continuous spectrum of the shell is in this case negligible. Small-dispersion spectrograms by Morgan and Miss Sherman bring out the broad wings conspicuously. The discontinuity in the energy distribution near the Balmer limit is much less conspicuous than in α Cygni. It is less abrupt and resembles that observed in main-sequence stars. This phenomenon is caused by the broad wings of the underlying hydrogen lines.

He I.—The broad lines of the B8 star, λλ 4472, 4026 (2^3P-n^3D), 4388 (2^1P-n^1D), etc., are heavily blended with metallic lines. The same is true of λ 3820 (2^3P-6^3D). Our spectrograms show no clear indication of any of the sharp lines which arise from

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[5] *Harvard Obs. Ann.*, **105**, 453, 1937.

[6] *Observatory*, **62**, 301, 1939.

[7] Unsöld and Struve, *Ap. J.*, **91**, 365, 1940.

[8] J. H. Moore, *Pub. Lick Obs.*, **18**, 28, 1932 (star HD 23862).

metastable levels and which are observed in the shells of ζ Tauri, φ Persei, γ Cassiopeiae, etc. The excitation temperature must be too low to produce sufficient populations in levels whose excitation potentials are of the order of 20 volts.

Mg II.—The line λ 4481 is present, and its estimated rotational broadening is about 150 km/sec—one-half of the broadening shown by the normal B8 lines. This line is too weak in comparison with the lines of *Fe* II, etc., but it is now stronger than it was prior to 1938. The enhancement after 1938 is a phenomenon not heretofore recorded. It is probable that the line is produced in relatively low layers of the shell. This effect suggests stratification in the shell.

Si II.—The lines λ 4128, λ 4131 ($3^2D-4^2F^0$) are very weak and broad. They originate from ordinary levels, and the dilution of radiation in the shell accounts for this effect. The lines λλ 3854, 3856, 3863 ($sp^2\,{}^2D-4^2P^0$) are also very weak. Although the level $sp^2\,{}^2D$ is not metastable, the transition probability from it to the ground level 3^2P^0 should be smaller than that from 3^2D to 3^2P^0. The fact that dilution in Pleione and also in 17 Leporis tends to weaken the violet group of *Si* II lines cannot be reconciled if the corresponding transition probability is more than about 100 times smaller than that of $3^2D \rightarrow 3^2P^0$. It is difficult from the existing evidence on *Mg* II and *Si* II to estimate the dilution factor. The fact that *Mg* II 4481 is present in the lower layers suggests roughly that $W = 0.1$ and $r = 1.5R$, where R is the radius of the star. We note that if this shell were opaque for continuous radiation and if the effective temperature were the same as that of the B8 star the apparent magnitude would have increased by 1.0 mag. The observations have shown a very small decrease.

Fe II.—All strong lines are present, and nearly all come from metastable levels. There seems to be a pronounced excitation effect, which cannot be explained by differences in the curves of growth of α Cygni and Pleione:

λ 3468	$c^2G_{3\frac{1}{2}}-z^2G^0_{3\frac{1}{2}}$	E.P. 4.1 volts	strong in Pleione
λ 3493	$c^2G_{4\frac{1}{2}}-z^2G^0_{4\frac{1}{2}}$	E.P. 4.1 volts	strong in Pleione
λ 3296	$a^4D_{1\frac{1}{2}}-z^6D^0_{1\frac{1}{2}}$	E.P. 1.1 volts	weak in Pleione

Other lines show the same behavior. If we assume for α Cygni $T' = 8000°$, we find the excitation temperature of Pleione from

$$\log \frac{n_{rs}}{n'_{rs}} - \log \frac{n_{rt}}{n'_{rt}} = 5040\ (E_{rs} - E_{rt}) \left(\frac{1}{T'} - \frac{1}{T}\right) .$$

The left side of the equation is estimated to be about log 10. Hence $T = 17{,}000°$, which is in sufficient agreement with the spectral type of the exciting star. The result is of low precision, but the important thing here is to ascertain that the excitation conditions in shells are in accord with the theory of dilution and that no hitherto unknown effects appreciably influence the populations of the various levels.

Lines of *Fe* II which start from ordinary levels are rather weak but are probably present:

λ 3906	$c^2F_{2\frac{1}{2}}-x^2G^0_{3\frac{1}{2}}$	E.P. 5.5 volts	present in Pleione
λ 4003	$d^2D_{2\frac{1}{2}}-x^2F^0_{3\frac{1}{2}}$	E.P. 5.9 volts	blended with *Fe* II $b^4P_{\frac{1}{2}}-z^4P^0_{1\frac{1}{2}}$, fairly strong

It is not yet known on theoretical grounds whether these lines should be weakened when the dilution factor is of the order of 0.1. Although the lower levels, c^2F and d^2D, are not metastable, they can combine only with several odd quartet and sextet levels,

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which lie within about 1 volt from these two even levels.[9] The corresponding probabilities are undoubtedly rather low, so that it should not surprise us that the lines are actually present. Their weakness in 17 Leporis[10] may well be due to the low excitation temperature of the star.

Ti II.—The lines of *Ti* II are greatly weakened with respect to *α* Cygni, and there is an indication that low-level lines—like λ 3388 ($a^4F_{3\frac{1}{2}}-z^4G^0_{3\frac{1}{2}}$), E.P. = 0.0 v.—are weakened more than high-level lines—like λ 4172 ($b^2F_{2\frac{1}{2}}-x^2D^0_{1\frac{1}{2}}$), E.P. = 2.6 v. It is certain that the low-level lines are relatively much weaker than in 17 Leporis,[11] where they are probably enhanced with respect to *α* Cygni. All lines come from metastable levels.

Cr II.—All lines come from metastable levels and are relatively strong. There is no definite indication of the excitation effect.

Fe I.—Several lines, such as λλ 4404 ($a^3F_3-z^5G^0_4$), 4071, 4045 ($a^3F-y^3F^0$) are present but are weak. All arise from metastable levels.

Ca I.—λ 4227 is absent.

Ca II.—H and K ($4^2S-4^2P^0$) are strong and sharp. These lines were absent prior to 1938. λ 3706 and λ 3737 ($4^2P^0-5^2S$) are present. The former is blended with a faint line of *Ti* II, which is weakened in Pleione; the latter is blended with a strong line of *Fe* I, which may be serious. Unless the indentification of λ 3706 with *Ca* II is erroneous, its occurrence as a sharp line in Pleione is definitely contrary to the theory of dilution: level $4^2P^0_{\frac{1}{2}}$ is the upper level of *Ca* H. The B8 star is relatively deficient in radiation falling in the wing of Hϵ, and the corresponding depopulation of state $4^2P_{\frac{1}{2}}$ should be conspicuous. There is no explanation for the anomaly.

Sc II.—λ 4246 and λ 4375 are fairly strong but are much weaker than in 17 Leporis.

Sr II.—The ultimate lines λ 4078, λ 4215 are present but are weak.

Ni II.—These lines are greatly enhanced in Pleione.

Mg I.—The lines λ 3832, λ 3838 ($3^3P^0-3^3D$) are present. Although state $3^3P^0_1$ is not metastable, the transition probability $3^3P^0_1 \rightarrow 3^1S_0$ is small, and the occurrence of λ 3832 is not surprising.

V II.—All strong lines are present. A relatively strong line, otherwise unaccounted for, at λ 4529.05 may belong to *V* II 4528.51 ($a^3D_3-z^3F^0_4$), in which case the spectrum would be even more enhanced in Pleione than *Ni* II. The line λ 4005.7 ($a^3G_5-z^3G^0_5$) is also relatively strong, but λ 3545, λ 3557 ($a^3F-z^3D^0_2$), though present, are not as greatly enhanced as are the lines of *Ni* II. It is more probable that λ 4529.05 is an unidentified line.

Mn II.—All lines are greatly weakened in Pleione.

S II.—An otherwise unidentified line at λ 4250.4 is probably not *S* II 4249.94 (as in *α* Cygni), and several other relatively strong lines of *S* II, λ 4162, λ 4153, show rather unsatisfactory coincidences. The fact that these lines originate from normal levels renders the identification doubtful.

A strong, sharp line was observed at λ 3748.5, in the immediate vicinity of H_{12}. This line is present in *α* Cygni, but Struve and Wyse found only relatively unimportant contributors to the line. It is probably a strong line of *Fe* II observed by Dobbie at λ 3748.49.

7. The results of the preceding section may be summarized by listing the elements in the order of decreasing intensity ratio: Pleione/*α* Cygni (Table 1).

It is instructive to compare this table with a similar table for 17 Leporis.[12] The weakness of *Si* II and *Mg* II in both stars is accounted for by dilution. The great weakening in Pleione of *Ti* II and *Mn* II and the relative strengthening of *Ni* II and *Fe* II, show that the state of ionization of the shell in Pleione is higher than in 17 Leporis. But the place

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[9] Dobbie, *Ann. Sol. Phys. Obs. Cambridge*, **5**, Part 1, 8, 1938.

[10] *Ap. J.*, **90**, 732, 1939.

[11] *Ibid.*, p. 730.

[12] *Ibid.*, p. 734.

of *V* II is not consistent with the change of ionization, and the presence of *Fe* I and *Sr* II is abnormal.

TABLE 1

Element	*Ni* II	*Fe* II	*Fe* II	*Cr* II	*Sc* II	*V* II	*Mg* I
I.P.	18.2	16.5	16.5	16.6	12.8	14.7	7.6
Average E.P.	3	4	1	2–3	0–0.3	1	2.7
Element	*Fe* I	*Sr* II	*Ti* II	*Mn* II	*Si* II	*Mg* II	....
I.P.	7.8	11.0	13.6	15.7	16.3	15.0	....
Average E.P.	0–1	0	1	1.8	7–10	9	....

The material is quite insufficient to determine the ionization. But we can at least compute the quantity

$$\log\frac{n_{r+1}}{n_r}+\log\frac{P_e}{W}=-I_r\frac{5040}{T}+\frac{5}{2}\log T-0.48+\log\frac{2u_{r+1}}{u_r}$$

for several typical elements, such as *Ni* II and *Mn* II. We shall disregard the partition functions.

TABLE 2

Star	17 Leporis	Pleione
T	10,000°	17,000°
I_r (*Ni* II)	18.2 volts	18.2 volts
I_t (*Mn* II)	15.7 volts	15.7 volts
$\left(\log\frac{n_{r+1}}{n_r}+\log\frac{P_e}{W}\right)_{Mn\,\text{II}}$	+1.61	+5.44
$\left(\log\frac{n_{t+1}}{n_t}+\log\frac{P_e}{W}\right)_{Ni\,\text{II}}$	+0.36	+4.70

In order that the ionization be not excessive we must assume that in 17 Leporis P_e/W is of the order of 10 bar. Since[13] $0.01 < W < 0.1$, we find, approximately, $P_e = 0.5$ bar, or $n_e = P_e/kT = 3 \times 10.^{11}$ This is very similar to the electron density of the solar chromosphere. In the case of Pleione the higher temperature gives rise to a much higher degree of ionization. If $P_e = 0.5$ and $W = 0.1$, we have

$$\left(\log\frac{n_{r+1}}{n_r}\right)_{Mn\,\text{II}}=+4.7$$

and

$$\left(\log\frac{n_{r+1}}{n_r}\right)_{Ni\,\text{II}}=+4.0\,.$$

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[13] *Ibid.*, p. 727.

The ionization is so strong that it is difficult to understand how any lines of *Ni* II or *Mn* II can remain in sight. Adopting a third ionization potential of 30 volts, we find that

$$\log \frac{n_{r+2}}{n_{r+1}} = +0.5 ,$$

so that lines of the doubly ionized ions should be observed. We certainly have no strong lines of *Fe* III, and it is extremely doubtful that the ionization is anything like as high as our computations have suggested. Perhaps the exciting temperature of Pleione is lower than $T = 17{,}000°$, and perhaps the electron temperature T_e is not equal to T, as we had tacitly assumed. Even so, it is difficult to see how the density of the shell of Pleione can fail to exceed that of 17 Leporis by a factor of 10, at least. Perhaps we can speak of the former as a dwarf shell and of the latter as a giant shell. Another possible source of error is in our estimate of W. If for Pleione $W < 0.01$, then the third ionization would be relatively unimportant, and a reasonable adjustment of pressure and dilution would satisfy the observations.

There remains the question of whether a pressure of the order of $P_e = 0.5$ bar is consistent with the geometrical dimensions of the shells. Because of the width of *Mg* II 4481 it is probable that the shell has an appreciable thickness. In the case of Pleione the average radius of the shell is about $r = 1.5R = 7.5R_\odot$. The metallic lines in Pleione are approximately of the same intensity as in a main-sequence star of corresponding spectral type. This suggests that the numbers of atoms and electrons per square centimeter are also the same in the shell and in such a reversing layer. Computation then shows that the pressures are roughly in the ratio

$$\frac{\text{pressure of reversing layer}}{\text{pressure of shell}} = 10^3 .$$

The average pressure in the reversing layer of a normal main-sequence star is about 100 bar. Hence, geometrical considerations lead to a pressure in the shell of 0.1 bar, which is in sufficient agreement with the value suggested by the state of ionization.

The order of magnitude of P_e in shells, and their thicknesses, suggests structures which resemble the reversing layers of supergiant stars. For a red giant[14] the geometrical extent of the atmosphere is roughly two thousand times greater than that of the sun, or about 6×10^{10} cm $\sim 1R_\odot$. The pressures, on the other hand, are in the ratio of about 100 : 1, so that $P_e = 1$ bar in the giant. These considerations are crude and do not clarify individual differences such as those between Pleione and 17 Leporis. But they serve to give us a picture of a typical shell surrounding a main-sequence star.

It is significant that all known absorption shells form a more or less uniform spectral sequence, which runs parallel to the usual sequence, with the shell nearly always showing a lower degree of ionization than the exciting star. There is no obvious theoretical reason for this phenomenon; the chromosphere of the sun shows that the outer layers of a stellar atmosphere may well be highly ionized. But the chromosphere has not enough matter in it to be comparable to the shells of Pleione or 17 Leporis. The existence of a spectral sequence of shells means that the average pressures of the shells are of the same order or that they vary in a regular manner with the spectral type of the exciting star. Our comparison of Pleione and 17 Leporis suggests a ratio in pressure of at least 10, but we do not know whether or not this is a general effect.

A rather remarkable fact is the absence of any pronounced effects, in any of the shells

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[14] Unsöld, *Physik der Sternatmosphären*, p. 147, Berlin, 1938.

thus far observed, which may be attributed to departures of stellar energy-curves from black-body curves. Departures produced by continuous H absorption, similar to those discussed by Pannekoek,[15] should alter the ionization and the excitation of various atoms whose potentials lie on different sides of λ 911.

Another interesting circumstance is the pronounced tendency of shells to form around main-sequence stars of classes B3–B5. There is a close relationship between ordinary Be stars and stars surrounded by absorbing shells.

The question might be asked: What will happen to a star if the shell becomes very dense. We know that such shells exist and that there are all gradations, from shells which are almost transparent to continuous radiation to shells which are completely opaque. If the density of a shell is great, the continuous absorption must also be great, and the dilution must be negligible. If such a shell does not expand, the star will be a giant or a supergiant. But why some shells expand while others do not is not known. Nor have we the slightest idea how a stationary shell may be formed without a visible outburst of light.

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[15] *Ap. J.*, **84**, 488, 1936.