NO. 28. HELIUM LINES IN EARLY TYPE STARS: SYSTEMATIC EFFECTS AND POSSIBLE CAUSES OF THE TRUMPLER SHIFT*

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ABSTRACT

The Trumpler Red Shift in clusters is discussed. Reference is made to the production of He^3 in hot stars; the presence of He^3 in the surface layers of a hot star could affect radial velocity measurements.

Early measurements of radial velocities of O stars in a number of galactic clusters showed a systematic effect in the sense that these stars appeared to be traveling away from the sun faster than stars of later type in the same cluster. Trumpler (1935) attributed this to a gravitational effect proportional to M/R, where M and R are the mass and radius of the star, respectively; on this basis he derived very large masses (no longer accepted as real) for the O stars.

The O stars are statistically infrequent objects, and their distribution over the sky is patchy. Most O stars are concentrated in a few regions (generally as members of O associations or clusters), so that analytical studies of the total data on O star radial velocities are of relatively small value and easily affected by systematic motions. However, it is interesting that a residual K-term of about 5-6 km/sec for the stars of types O and B appears in the analyses of Campbell and Moore (1928) and Smart and Green (1936); see also Becker (1950), Weaver (1955). It is unlikely that the systematic differences in the measured radial velocities, at least of the cluster stars, are real, and the author of the present paper considers that analysis of the individual line positions in the O star spectra themselves should be made.

The explanation of the spurious Doppler effect found by Trumpler and others may lie in the interpretation of phenomena which are special to O-B stars and enhanced in the hotter stars. Anomalies in the hydrogen and helium lines therefore suggest themselves.

Radial velocities ρ in the Perseus Arm have been investigated by Dr. H. Abt (Abt and Bautz, unpublished), who finds

$$\bar{\rho} = \bar{\rho}_{21\ \mathrm{cm}} + 7.4\ \mathrm{km/sec} \qquad (1)$$

for stars in h and χ Persei. A survey of the group of associations, II Cephei, which appears to form part of the same arm of the galaxy, showed a similar effect among 45 O-B stars,

$$\bar{\rho} = \bar{\rho}_{21\ \mathrm{cm}} + 8.6\ \mathrm{km/sec}. \qquad (2)$$

However, the difference $\bar{\rho} - \bar{\rho}_{21\ \mathrm{cm}}$ appears to be important chiefly among stars of variable velocity, which are probably binary systems. In a sample of 21 stars (63 spectra) for which effects from orbital motions can be expected to cancel out,

$$\bar{\rho} = \bar{\rho}_{21\ \mathrm{cm}} + 15\ \mathrm{km/sec}, \qquad (3)$$

$\bar{\rho} - \bar{\rho}_{21\ \mathrm{cm}}$ being negligible in the case of 24 other stars of the group.

Abt's results are not quite parallel to Trumpler's, since the Trumpler effect is confined to the O type spectra and the Perseus Arm stars were nearly all B type, only about six O stars being included. Abt (*loc. cit.*) discusses the possibility of distortion from gaseous streams surrounding members of close binary systems and draws attention to Hardie's (1950) revision of earlier work on U Cephei in this connection. However, a change in the γ velocity for

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U Cep over seven years is increased from 13 to 22 km/sec in Hardie's results, so that there are some unresolved mysteries remaining in this star. Abt's main conclusion is that O-B radial velocities should be regarded with caution in statistical studies, particularly of galactic structure.

The distortion of the hydrogen line profiles in many binary systems has been well shown by the work of Struve and others. It remains to be seen whether such distortions have contributed to the Trumpler effect.

The present author wishes to investigate the possible presence of the isotope He^3 in O stars. So far as is known, this possibility has not been examined for O type cluster stars, but since the average isotopic shift $He^3 - He^4$ for helium lines appearing in O-B spectra is about 15 km/sec, as is shown below, it is tempting to explore the possibility further. The He^3 shift has no relation to Abt's results, since the lines he measured were primarily H_γ to H_{11}, and 4026A, 4120A and 4471A of helium, for which the mean isotopic shift is too small to account for the differences in equations (1)-(3).

Dr. R. M. Petrie's researches on wavelength standards for radial velocity determinations from B type spectra (Petrie, 1953) are of interest. Petrie's careful investigation correlated radial velocities measured from individual lines with those assigned to the same star by methods other than direct spectroscopic measures; for example, several of his standards were binaries, where a check can be made on the γ velocity of the pair. For the majority of lines finally adopted as suitable standards it was possible to accept laboratory wavelengths. It is noteworthy that the majority of the He I lines were rejected, chiefly on the grounds of large scatter, or "substantial positive residual." This scatter or residual could be caused by the presence of at least some He^3 in the atmospheres of some stars, although 4388A, which has an isotopic shift of 0.27A, was retained by Petrie as a standard wavelength. There is thus a strong argument against the presence of He^3 in Petrie's standards. This has been confirmed by measures of helium line positions for three of the standards (55 Cyg, ρ Leo and ζ Per; Kraft, personal communication), which show no isotopic shift. Kraft also reports the absence of He^3 in 10 Lacertae. His results were confirmed by measures made by the present author. The spectral range covered was from 4800A to 6700A at a dispersion of about 13.5 A/mm. Since this interval includes six He lines, with possible isotopic shifts ranging from 0.5A for 6678A to 0.05A for 5875A, very favorable conditions for the detection of He^3, if present, were afforded and the negative result can be considered well established, although only one plate was measured for each of the four stars.

Earlier values of radial velocities of B stars, obtained as mean values over a number of lines, including those of helium, led to a statistical *K*-effect of about 2 km/sec, which has now been practically eliminated by the adoption of improved wavelength standards. With regard to the O stars, Petrie (1953) states:

> "The question of wave-length standards for O-type spectra has been deferred for the present. Statistically speaking, the O stars are not very important in radial velocity programs, but they are of considerable interest in problems of star clusters."

Generally speaking, the O type spectra are poor in absorption lines. Many, such as the Of, stars show emission lines (e.g., of N III and He II in λ Cephei and HD 210839; see Underhill, 1960), produced in an extended atmosphere. In the present paper, consideration of such stars, as well as those broad-line stars where photospheric currents such as turbulence or rotation may be of importance, is omitted. The following discussion is intended to be restricted to main sequence sharp-line O stars showing only an absorption spectrum.

Helium lines in sharp-line stellar spectra could be subject to the following types of disturbance, which would tend to render them unreliable as radial velocity criteria.

1) *Stark effect.* The behavior of helium in electric fields up to 100 kv/cm was investigated by Foster and Douglas (1939), and theoretical analyses of the Stark effect for helium have been made by Holtsmark,[1] Krogdahl (1945, 1947, 1949), and more recently by Griem, Baranger, Kolb, and Oertel (1962). Second-order Stark effect (generally a slight shift to the red accompanied by broadening and asymmetry of the line profile due to perturbations of the initial and final states involved in the transition) predominates in He I. Violet shifts at higher field strengths ($\sim$ 40 kv/cm) were noted by Foster and Douglas for the 2^1P-5^1F and 2^1P-5^1G components of 4387A of He I. The isotopic shift $He^3 - He^4$ of the 2^1P^0-5^1D line is given in Table 1. Petrie retained 4387A as a B star standard wavelength. In general, the Stark effect can be expected to cause a shift of

[1] Holtsmark's and other early work is discussed in White (1934).

TABLE 1
CALCULATED ISOTOPIC SHIFTS (He^3-He^4)

Transition	λ (A)	Δν (cm⁻¹)	Δλ (A)	Equivalent Radial Velocity V (km/sec)
2^3P-3^3S	7065	−0.059	+.03	+1
4	4713	0.376	.08	5
5	4120	0.512	.09	7
6	3867	0.584	.09	7
7	3732	0.634	.09	7
8	3652	0.652	.09	7
2^3P-3^3D	5875	0.181	.06	3
	4471	0.426	.09	6
	4026	0.539	.09	7
	3819	0.599	.09	7
	3705	0.636	.09	7
	3634	0.659	.09	7
2^1P-3^1S	7281	0.987	.52	21
	5047	1.260	.32	19
	4437	1.382	.27	18
	4168	1.447	.25	18
	4023	1.485	.24	18
	3935	1.510	.23	17
2^1P-3^1D	6678	1.043	.47	21
	4921	1.282	.31	19
	4387	1.393	.27	18
	4143	1.453	.25	18
	4009	1.490	.24	18
	3926	1.513	.23	18
2^1S-3^1P	5016	−0.729	+.18	+11

For all lines of He II, the isotopic shift Δν (He^3-He^4) would correspond to an apparent velocity of recession, V, equal to + 13.5 km/sec.

not more than 1-2 km/sec to the red.[2] In 10 Lacertae, the shift due to Stark effect appears to be negligible for the helium lines.

2) *Pressure effects.* Increase of pressure will produce a broadening and red shift similar to the Stark effect (Lenz, 1933; Lindholm, 1941, 1945), but in sharp-line stars, the effect on the line positions would be negligible.

3) *Isotope effects.* Isotopic shifts in the sense He^3-He^4 are given for a number of lines of He I in Table 1. Column 2 shows data taken from Fred, Tomkins, Brody, and Hamermesh (1951). Columns 3 and 4 are derived from their data. For He II the isotopic change in wavelength for He^3 relative to He^4 is equivalent in all cases to a Doppler shift of + 13.5 km/sec.

Thus, on the basis of an atmospheric content of helium composed of pure He^3, the total red-shift contributions from these causes may include up to about 2 km/sec gravitational shift, a shift due to Stark effect of not more than 1-2 km/sec with about 20 km/sec isotopic shift at maximum. A systematic apparent velocity of recession of about 15-18 km/sec relative to stars of later type moving with the same actual radial velocity could then be expected to show in Trumpler's measures if the standard of reference for the helium lines were taken to be the wavelength of He^4, if the helium lines were used for assessment of the radial velocities, and if He^3 were in fact an appreciable atmospheric constituent. For comparison, Table 2 is reproduced from Trumpler (1935). Tables 3 and 4 show, for stars of NGC 6530 and 6611, more of Trumpler's measures (as quoted by Walker, 1957, 1961). Here also, most O type stars show a substantial red shift relative to later types, though the cluster velocity is difficult to define from the data.

He^3 has been shown conclusively to be present in 3 Centauri A (spectral type about B5 III-IV) by Sargent and Jugaku (1961). It may be noted that the lines of the spectrum of this star are extremely sharp (also that other peculiarities exist besides the helium anomaly). In other B stars, such as γ Peg and HR 2154, He^3 is not present in the surface layers.

The proton-proton reaction produces He^3 as an end product at temperatures $\sim 8 \times 10^6$ °K since at such temperatures the final reaction

$$He^3 + He^3 \rightarrow He^4 + 2H$$

can not take place. A process such as thermal diffusion would then be necessary to bring the He^3 to the surface. Little account has been taken of the zone at temperatures near 8×10^6 °K in considering energy production since its contribution in this respect would be negligible; products, such as He^3, of nuclear reactions taking place in this zone, if diffused slowly outward, could play a part in modifying the surface composition of the hottest stars over the lifetime of these stars, and provided convection or other currents do not carry the material inward too quickly (the lifetime of He^3 in the deeper interior being short), some such mechanism as the above may have contributed to the O star velocity residual. Besides the lines of helium and hydrogen, lines of O, C, Si, and N appear in O star spectra. These are unaffected by Stark shifts, and also relatively insensitive to isotopic effects, though they would be shifted

[2]The appearance of the forbidden 4469.9A component in the wing of the permitted 4471A (2^3P-4^3D) line was noted many years ago in stellar spectra by Struve, but always at the zero static field position. To match the observed stellar intensity, an appreciable static field would be required. Mrs. Krogdahl (*loc. cit.*) has shown that a zero displacement of the 4470A component is to be expected in stellar fields where the broadening is produced by interatomic fields.

TABLE 2
RADIAL VELOCITIES OF CLUSTER O STARS AND OF RELATED CLUSTERS*

Cluster (NGC No.)	Star	Sp. Cl.	$V_{St.}$ (km/sec)	Comparison Stars $V_{Cl.}$ (km/sec)	Comparison Stars No. of Stars	$V_{St.}-V_{Cl.}$
2244	9		+ 48	+ 34.6	6	(+ 13)
	15	06	+ 41.0			+ 6.4 ± 2.0
	8	09	+ 41.6			+ 7.0 ± 2.0
2264	60	07	+ 33.1	+ 19.3	11	+ 13.8 ± 1.4
2353	1		+ 35	+ 19.7	5	(+ 15)
2362	1	08.5	+ 43.2	+ 34.5	7	+ 8.7 ± 2.1
6871	2	09	− 13.5	− 21.3	3	+ 7.8 ± 3.1
	5	B0	− 7.7			+ 13.6 ± 2.9
7380	1	09	− 40.0	− 43.2	4	+ 3.2 ± 3.5

* From Trumpler (1935)

TABLE 3
NGC 6530: DATA FROM WALKER (1957)

Walker No.	Star	Sp.	V (km/sec)	Remarks (Walker)
2	HD 164536	B3	− 11	HD Sp. Class
7	9 Sgr	05	+ 9	non-member?
42		B3n	− 19.0 ± 2.3	
56		B3nne	− 8.4	vel. variable
60		B3nne	+ 4.3 ± 4.1	vel. prob. variable
65	HD 164906	B0nne	− 3.1 ± 5.9	vel. variable
66		B2ne	− 12.0 ± 2.9	H_β, H_γ emission
76		B2n	− 18.8 ± 2.9	
80		B2n	− 10.9 ± 4.4	vel. variable
93		B2nn	− 14.6 ± 2.1	
100	HD 164947	B3	+ 6.1 ± 2.8*	non-member?
118	HD 165052	07n	+ 3	non-member?

* Brighter component

TABLE 4
NGC 6611: DATA FROM WALKER (1961)

Walker No.	Sp.	V	Remarks (Walker)
166	09	+ 1.1	
197	08	+ 6.2*	HD 168075. Wilson:§ $V = +27$ km/sec
246	09	+ 6.0	
254	B2	+ 3.8	
280	B0nn	+ 1.7†	
351	Ble	− 2.9	
367	B0	+ 4.8‡	
401	08	+ 12.1	HD 168137. Wilson:§ $V = +26$ km/sec

* Probably variable
† Double lines?
‡ Variable
§ Wilson (1953)

by any radial currents in the star's outer layers. Provided no such currents (or negligible currents only) exist, the lines of the heavier elements can be used to obtain a standard of reference for assessment of special factors affecting the positions of the helium lines.

Since definitive published data are not available to answer the question of the individual line shifts in the cluster stars, a new investigation of the Trumpler stars is now being undertaken.

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