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SPECTROPHOTOMETRIC INVESTIGATIONS OF SOME O- AND B-TYPE STARS CONNECTED WITH THE ORION NEBULA*

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ABSTRACT

Photometric and spectrophotometric measures of a number of early-type stars connected with the Orion nebula are given for the wave-lengths between 4000 and 9000 A. The results show that most of the stars are affected by strong selective absorption which increases rapidly from 9000 to 6000 A to a nearly constant value for the shorter wave-lengths between 6000 and 4000 A. If we assume that the absorption is due to dust particles, a preliminary discussion based on available theoretical data indicates that the diameters of the particles are of the order of $150 m\mu$. The present limitations of such an analysis are discussed.

It was pointed out in the preceding *Contribution* that the abnormal features of the puzzling Trapezium cluster could be explained by the assumption that in the close neighborhood of the exciting stars the Orion nebula is more transparent than farther out. This explanation requires that the exciting stars should be situated within the nebula. Consequently, one would expect their light to be modified in reaching us through the nebula. The definite color excess of ϑ_1 Orionis[1] leaves no doubt that such is the case.

In order to obtain more detailed data on the optical properties of the Orion nebula, we have undertaken a spectrophotometric investigation of a few of the brightest O- and B-type stars in the central region of the nebula. Since it is essential for a sound physical interpretation of the data to investigate the intensity distribution over a range of wave-lengths as large as possible, we have extended our measures over the interval from λ 4000 to λ 9000. Two different methods have been used: spectrophotometric measurements for the region from λ 4000 to λ 6500 and photometric measures within selected larger intervals of wave-length between λ 5000 and λ 9000. The data obtained from the two series thus overlap for about 1000 A.

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[1] Cf. Stebbins and Huffer, *Pub. Washburn Obs.*, **15**, 5, 1934.

I. PHOTOMETRIC MEASURES WITHIN SELECTED INTERVALS BETWEEN λ 5000 AND λ 9000

To obtain the deviations of the Orion stars from black-body radiation between λ 5000 and λ 9000, we have compared them photometrically with a normal star of nearly the same spectral type for a number of spectral regions. The observations were made with the 60-inch reflector. The comparison star was in all cases HD 36960, visual magnitude 4.67, spectral type B1s, which, according to Stebbins and Huffer,[1] has a normal color. It is of convenient brightness for comparisons with the stars under investigation and situated so close to them that corrections for differential extinction were unnecessary. Since the Orion stars of our list vary in spectral type from O7 to B1, the measured deviations from black-body radiation for the earlier types should be minimum values, and corrections may be computed if necessary. For the present we have neglected these rather small corrections, in view of the considerable uncertainties affecting the upper part of the stellar temperature-scale.

To produce a photometric scale on each plate, the comparison star was successively exposed with full aperture, through a 40-inch diaphragm, a 32-inch diaphragm, and a wire-gauze screen, the reduction in intensity being 1.12, 1.96, and 3.06 mags., respectively. The stars to be investigated were then placed close to the series of scale images and exposed for the same length of time as the scale images, either with full aperture or through one of the diaphragms.[2] Thus the difference in magnitude between each star and the comparison star could be easily evaluated. All the measurements were made with a thermoelectric photometer. The spectral regions selected for these measures are given in Table 1.

Table 2 contains the measured magnitude differences between the Orion stars and HD 36960. The designations of the Trapezium stars (ϑ_1) are those given in Aitken's catalogue of double stars. Because of unfavorable weather conditions during the last season, some of the figures in Table 2 are based on measures of a single plate only. Serious errors are unlikely, however, since all the data

[2] The exposure times ranged from 10 sec. for the yellow and red regions to 60 sec. for the infrared plates. By using short exposure times and selecting the proper filters, we were able to suppress completely even the bright nebulosity around the Trapezium.

collected in Table 2 were obtained under perfect observing conditions. The mean error of a single observation derived from comparisons for which more than one plate was available is ±0.06 mag.

TABLE 1

SPECTRAL REGIONS OBSERVED

Plate	Filter	Region	Mean Wave-Length
Agfa isochrom.......	Wratten No. 15	5100–5800	5400
Eastman IC.........	Wratten No. 23	5800–6600	6200
Eastman IC.........	Wratten No. 29	6200–6600	6400
Eastman 144U.......	Wratten No. 29	6800–7400	7100
Eastman IR*........	Wratten No. 88	7300–8400	7900
Eastman IP*........	Wratten No. 88	8200–9200	8800

* The infrared-sensitive R and P plates were hypersensitized.

TABLE 2

ORION STAR *minus* HD 36960

λ	ϑ_1 ORIONIS				ϑ_2 $5^m.17$, O9	HD 37042 $6^m.53$, B1	HD 37061* $6^m.8$, B1	HD 37018* $4^m.65$, B2
	A $6^m.84$, B1	B $7^m.93$, B6	C $5^m.36$, O7	D $6^m.85$, B1				
5400.....	$+2^m.40$	$+3^m.00$	$+0^m.39$	$+2^m.10$	$+0^m.37$	$+1^m.85$	$+2^m.29$	$-0^m.38$
6200.....	1.73	2.86	+ .19	1.71	+ .26	1.60	2.30	....
6400.....	1.36	2.94	+ .02	1.40	+ .21	1.51	1.95	.26
7100.....	1.70	....	+ .02	1.54	+ .02	1.53	1.69	.26
7900.....	1.35	2.59	− .40	1.28	....	....	1.45	.17
8800.....	+1.08	+2.01	−0.26	+0.97	−0.01	+1.07	+1.33	−0.24

* HD 37061 is the central star of NGC 1982, HD 37018 of NGC 1977. Although the magnitude of HD 37061 is given in the *B.D.* and the *Henry Draper Catalogue* as 9.1, the foregoing value is correct (cf. also Hubble, *Mt. W. Contr.*, No. 241, Table IV, 1922). Probably the star is variable.

II. SPECTROPHOTOMETRIC MEASURES BETWEEN λ 4000 AND λ 6500

The spectrophotometric data were obtained with a two-prism spectrograph[3] attached at the cassegrain focus of the 60-inch reflector. Since in this spectrograph the distance between the collimator mirror and the first prism is greater than the focal length of the collimator, an image of the telescope mirror is formed in front

[3] *Pub. A.S.P.*, **48**, 277, 1936.

of the first prism. Diaphragms containing twelve holes with different diameters were inserted in this place to obtain spectra with equal exposure times but with different intensities of light. Four different diaphragms have been used, which reduced the intensity by 1.1, 2.1, 3.0 and 4.0 mags., respectively. The spectra were taken with a slit of 0.2 mm. width, so that the entire star image was used, and widened by trailing the star image on the slit. Agfa Supersensitive Panchromatic film was used.

Each film was calibrated with a series of five spectra of the comparison star, taken with full aperture and the four diaphragms. Two spectra of each star which was to be measured were taken with two consecutive diaphragms. This procedure allowed measurements for all wave-lengths between 6500 and 4000 A on the linear part of the calibration-curve, in spite of the varying color sensitivity of the film. Lengthwise microphotometer tracings of the spectra were used for measuring. With the aid of calibration-curves, drawn separately for each wave-length, the differences between the magnitude of the Orion star and of the comparison star were derived at wave-length intervals of 250 A.

The results of these observations are given in Table 3. The star HD36959, visual magnitude 5.58, spectral class B1, has been used as comparison star for the spectrophotometric measurements. Since it seemed of interest to find whether the absorption effects observed in the Orion stars differ from those of stars which are affected by general space absorption, we have performed similar measurements for a few stars in the Perseus region which, according to Stebbins and Huffer, show marked color excesses. Results for these stars are given in the last three columns of Table 3. The star HD11241, visual magnitude 5.49, spectral class B3, served as comparison star for the Perseus stars.

DISCUSSION OF THE RESULTS

The results are grouped in Figures 1–3 according to the apparent types of the curves, the difference between the magnitude of the star and the magnitude of the comparison star being plotted against the reciprocal of the wave-length. In these figures the spectrophotometric measurements have been reduced to HD 36960 as comparison star.[4]

ϑ_1 and ϑ_2 Orionis are considered as the exciting stars of the Orion nebula NGC 1976. ϑ_1 shows pronounced reddening, whereas the color-curve of ϑ_2 is almost normal. From this we may conclude that ϑ_1 is imbedded deeply in the nebulosity, whereas ϑ_2 is situated close to the front of the nebula but still inside.[5] The very strong reddening

TABLE 3

ORION STAR *minus* HD 36959, PERSEUS STAR *minus* HD 11241

λ	Orion						Perseus		
	ϑ_1 (C)	ϑ_1 (D)	ϑ_1 (A)	ϑ_2	HD 37042	HD 37061	HD 14134	HD 14143	HD 14818
	O7 5^m36	B1 6^m85	B1 6^m84	O9 5^m17	B1 6^m53	B1 6^m8*	B2 6^m66	B1 6^m66	B1 6^m24
4000...	+0.6	+2.2	+2.3	+0.6	+2.9	+2.9	+1.95	+2.0	+1.35
4250...	.7	2.25	2.3	.6	2.8	2.7	1.85	1.9	1.2
4500...	.6	2.05	2.2	.55	2.8	2.5	1.7	1.8	1.1
4750...	.55	2.05	2.0	.6	2.9	2.2	1.6	1.6	1.1
5000...	.5	2.0	2.0	.55	2.9	2.2	1.4	1.5	1.0
5250...	.6	2.0	2.1	.55	2.9	2.2	1.3	1.35	0.9
5500...	.55	2.0	2.0	.45	2.8	2.1	1.2	1.25	0.85
5750...	.45	1.85	1.95	.4	2.8	2.0	1.0	1.1	0.75
6000...	.4	1.75	1.9	.4	2.75	2.0	1.0	1.05	0.75
6250...	.4	1.7	1.9	.4	2.65	1.9	1.0	1.0	0.75
6500...	+0.3	+1.6	+1.8	+0.4	+2.6	+1.8	+0.8	+0.7	+0.6

* Although the magnitude of this star is given in the *B.D.* and the *Henry Draper Catalogue* as 9.1, the foregoing value is correct (cf. also Hubble, *Mt. W. Contr.*, No. 241, Table IV, 1922). Probably the star is variable.

of HD 37061, the exciting star of the detached nebulosity NGC 1982 northeast of the great nebula, suggests a position within or behind the nebulosity. The selective absorption is almost certainly due to the same dust particles to which we must attribute the continuous emission in the spectrum of the Orion nebula.

Further observations will be necessary to decide which details of

4 HD 36959 compared to HD 36960 showed no difference of color between 9000 and 5000 A.

5 The photometric measures in Table 2 show that the central star of NGC 1977, HD 37018, is free from selective absorption and therefore probably situated in front of the nebula.

the color-curves are real; for example, the weak maximum in the neighborhood of 5200 A in Figure 1. There can be no doubt, however, that the observed inflexions are real features of the color-curves. Such details can only be explained by proper selection of the

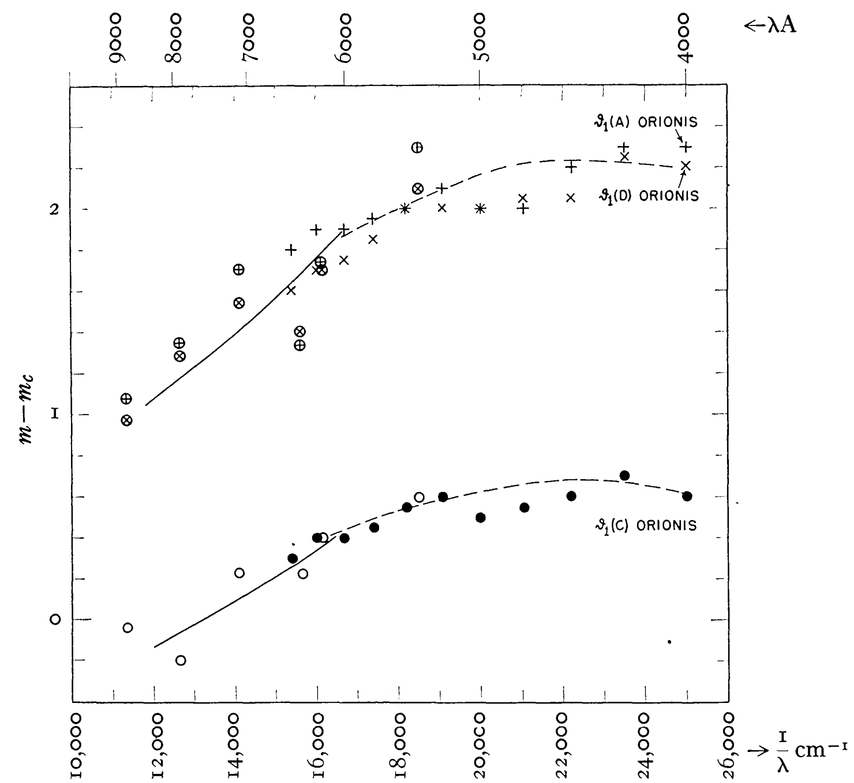

FIG. 1*a*.—ϑ_1(A) Orionis, B1, mag. 6.4: Plus signs, spectrophotometric data; the same within circles, photometric data.

ϑ_1(C) Orionis, O7, mag. 5.36: Dots, spectrophotometric data; circles, photometric data, the latter corrected by +0.25 mag. in order to obtain the best accordance with the spectrometric values.

ϑ_1(D) Orionis, B1, mag. 6.5: Crosses, spectrophotometric; crosses within circles, photometric data.

optical constants of the interstellar particles. Their complete analysis finally will lead to a determination of these constants. Meanwhile, since the computations by Schalén[6] show that the general trend of the absorption-curves does not depend greatly on the

[6] *Upsala Medd.*, No. 64, 1936.

choice of the optical constants, a tentative analysis of the observed curves may be undertaken with the aid of available computed absorption-curves if details are neglected.

The opacity produced by dust is due to pure absorption and to scattering of light. The total optical depth is given by $\tau = \tau' + \tau''$,

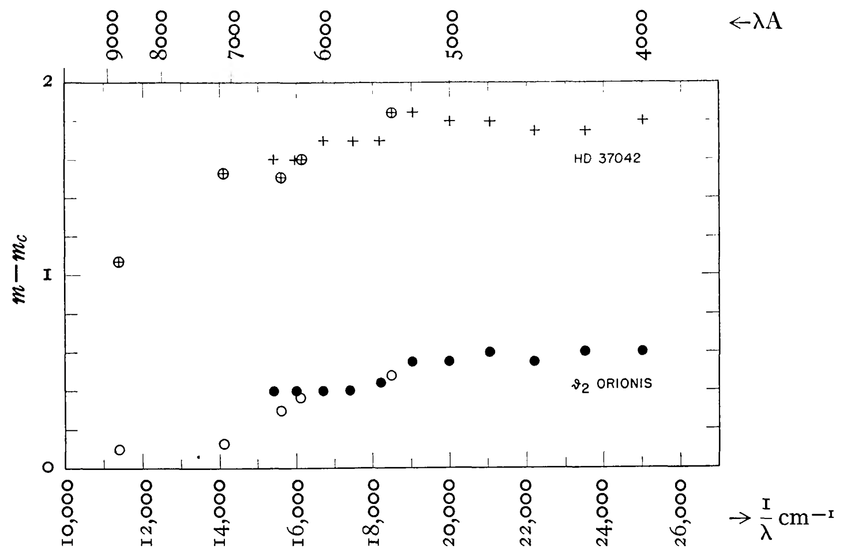

FIG. 1*b*.—HD 37042, B1, mag. 6.31: Plus signs, spectrophotometric data; the same within circles, photometric data.

ϑ_1 Orionis, O9, mag. 5.17: Dots, spectrophotometric; circles, photometric data, the latter corrected by +0.1 mag. in order to obtain the best accordance with the spectrometric values.

where τ' and τ'' are, respectively, the optical depth due to absorption and to scattering. We may write

$$\left.\begin{aligned} \tau' &= \frac{\pi}{2} N d^2 \tau_1(a) , & \tau'' &= \frac{\pi}{2} N d^2 \tau_2(a) , \\ \tau &= \frac{\pi}{2} N d^2 \tau_0(a) , & \tau_0(a) &= \tau_1(a) + \tau_2(a) , \end{aligned}\right\} \tag{1}$$

where N is the total number of particles in the line of sight over an area of 1 cm², λ the wave-length, d the diameter of the particles, and $a = \pi d/\lambda$. τ_0, τ_1, and τ_2 are functions of a and of the optical constants of the material of which the particles are composed. Two different sets of theoretical data for $\tau_0(a)$ are available which cover a spectral range of sufficient extension to render the analysis significant.

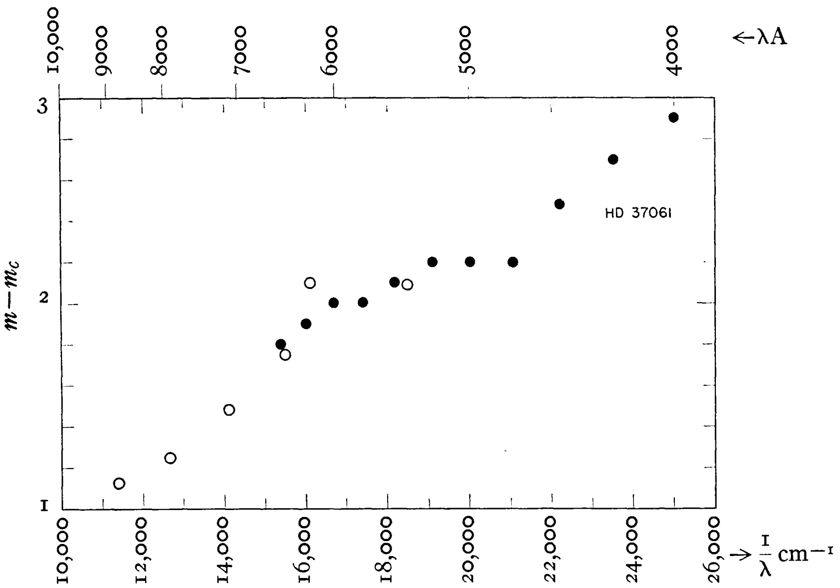

FIG. 2.—HD 37061, B1p, mag. 6.8: Dots, spectrophotometric; circles, photometric data, the latter corrected by −0.20 mag.

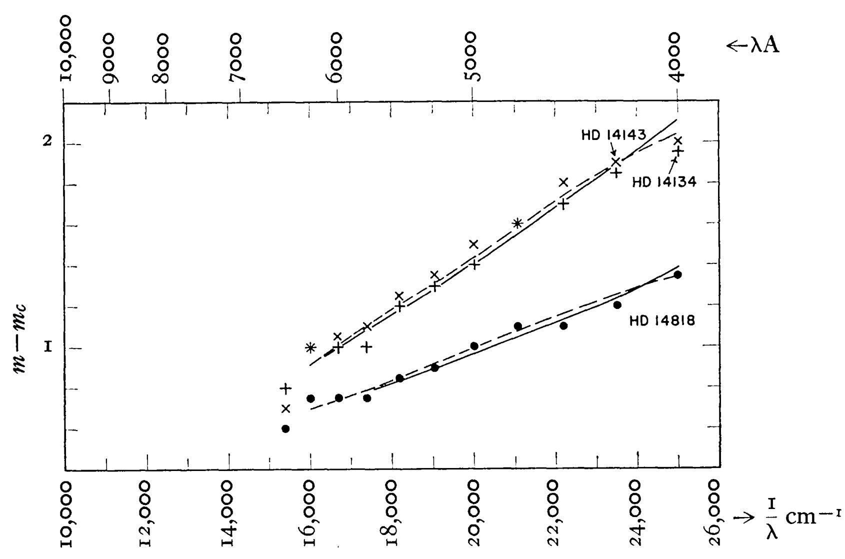

FIG. 3.—Spectrophotometric data: HD 14134, B2s, 6.66: plus signs; HD 14143, B1s, 6.66: crosses; HD 14818, B1s, 6.24: dots.

Schalén[6] has computed values of τ_0 for the interval 3850–6200 A, using as optical constants the values measured by Meier[7] for iron. These values are considerably smaller than those obtained for iron by any other observer. As a matter of fact, the measurements of Meier were carried out on thin layers of iron which had been produced by Biernacki[8] by the evaporation method. In accordance with the vacuum technique of that time, the evaporation took place in a comparatively small vessel and in an atmosphere of hydrogen at 10^{-3} mm Hg pressure. It is hardly to be expected that layers produced under such conditions consist of pure iron. Indeed, they showed an unusual magnetic behavior which led Biernacki himself to suspect a large proportion of impurities. It thus appears that the optical constants used by Schalén are not the constants for pure iron but for iron containing, most likely, a large proportion of hydrogen in addition to impurities from residual gases, such as air and hydrocarbons. This mixture of different elements may, however, well be a better model for interstellar dust than pure iron.

Values of τ_1 for the spectral range 5000–7000 A and one value of τ_2 for 6500 A for carbon particles of $175 m\mu$ diameter may be derived from computations by Senftleben and Benedict.[9] As the optical constants of carbon remain practically unchanged throughout the spectral range to be considered, these values may be used to compute τ_1 for any particle size and for that part of the spectrum where $1.10 > a > 0.73$. The theory of diffraction indicates that for this range of a, τ_1 should be approximately proportional to a. The values of τ_1 are indeed represented by $\tau_1 = 0.67a$, with an average deviation of 1 per cent. It thus seems safe to assume that τ_2 is proportional to a^4, as required by theory. From the value of τ_2 for the wave-length 6500 A and the particle diameter 175 $m\mu$, τ_2 then becomes $\tau_2 = 0.183a^4$. As τ_2 is small relative to τ_1, the errors arising in τ from the assumption made in the computation of τ_2 will also be small.

Values of d and N may now be determined by fitting computed curves to the observations in the following way. Let m_{ph}, $m_{0,ph}$, and $m_{c,ph}$ be, respectively, the observed photographic magnitude

[7] *Ann. d. Phys.*, **31**, 1017, 1910.

[8] *Ibid.*, **16**, 943, 1905.

[9] *Ibid.*, **60**, 297, 1919.

of a star obscured by dust, the photographic magnitude of the same star without obscuration, and the photographic magnitude of an unobscured comparison star. Further, let $m_0(\lambda)$ be the magnitude of the unobscured star for any wave-length λ. We may then write

$$m_0(\lambda) = m_{0,\ ph} + J_0(\lambda) . \tag{2}$$

$J_0(\lambda)$ may be called the color function of the star; and, if λ_v is the effective wave-length for visual magnitudes, $J_0(\lambda_v)$ will be the color index of the star. Similarly,

$$m_c(\lambda) = m_{c,\ ph} + J_c(\lambda) . \tag{3}$$

If $i_0(\lambda)$ is the intensity of the light entering the dust cloud and $i(\lambda)$ the intensity of the emerging light, we have

$$i(\lambda) = i_0(\lambda)e^{-\tau(\lambda)} ,$$

and

$$m(\lambda) = m_0(\lambda) + 1.086\,\tau(\lambda) . \tag{4}$$

Substituting $m_0(\lambda)$ from (2) into (4), we find

$$m(\lambda) = m_{0,\ ph} + J_0(\lambda) + 1.086\,\tau(\lambda) . \tag{5}$$

Finally, subtracting (3) from (5), we obtain for the observed difference of magnitudes

$$\left.\begin{aligned} \Delta(\lambda) &= m(\lambda) - m_c(\lambda) , \\ &= m_{0,\ ph} - m_{c,\ ph} + J_0(\lambda) - J_c(\lambda) + 1.086\,\tau(\lambda) . \end{aligned}\right\} \tag{6}$$

The difference of color due to the difference in temperature of the two stars is $E(\lambda) = J_0(\lambda) - J_c(\lambda)$. If only stars of the same or very similar spectral classes are compared, $E(\lambda)$ is small and may be neglected for a first approximation. Using observed values of Δ for three different wave-lengths, λ_1, λ_2, λ_3, we derive from (6)

$$\frac{\Delta(\lambda_1) - \Delta(\lambda_2)}{\Delta(\lambda_1) - \Delta(\lambda_3)} = \frac{\tau_0\left(\dfrac{d}{\lambda_1}\right) - \tau_0\left(\dfrac{d}{\lambda_2}\right)}{\tau_0\left(\dfrac{d}{\lambda_1}\right) - \tau_0\left(\dfrac{d}{\lambda_3}\right)} \tag{7a}$$

and

$$\Delta(\lambda_1) - \Delta(\lambda_2) = 1.086 \frac{\pi}{2} N d^2 \left[\tau_0 \left(\frac{d}{\lambda_1} \right) - \tau_0 \left(\frac{d}{\lambda_2} \right) \right] . \qquad (7b)$$

Values of d and N can be determined from (7*a*) and (7*b*) if the theoretically computed values of τ_0 as a function of d/λ are used. τ can then be computed for any wave-length, and, with the aid of (4), the total obscuration $m(\lambda) - m_0(\lambda)$ for any wave-length can be determined.

The broken curves in Figures 1 and 3 give the best fit for iron, the dotted curves for carbon. The resulting values of d, N, and Nd^3 are given in the third, fourth, and fifth columns of Table 4. The sixth column gives the total masses M in grams per square centimeter in front of the star and the last column the total obscuration $m - m_0$ for the wave-length 4000 A. The agreement between the two sets of data obtained for iron and carbon is satisfactory, especially so far as the diameters of the particles and the values for the total obscuration are concerned. Apparently it is safe to conclude that the particles obscuring the stars in the central part of the great nebula in Orion are larger than those obscuring the stars in Perseus. The values obtained for these latter stars are in general agreement with those derived by Schalén[6] from similar measurements on stars in Cygnus and Cepheus by Trumpler,[10] and by Struve, Keenan, and Hynek.[11]

No satisfactory representation can be obtained for the star HD 37061 (Fig. 2). This color-curve shows a pronounced inflexion and is of a type entirely different from any of the theoretical curves for iron in the range 4000–6200 A. The values for carbon can be fitted either to the range 6400–9000 A or to the range 4000–5600 A, but the respective values of the constants differ widely. This result shows clearly that reliable conclusions on the properties of interstellar dust can be obtained only if an extended spectral range is used. Results based on small parts of the spectrum, such as the usual color index, are likely to be entirely misleading.

Difficulties of this type are not surprising. It is rather more surprising that they do not appear in all cases. The observed absorp-

[10] *Pub. A.S.P.*, **42**, 267, 1930. [11] *Ap. J.*, **79**, 1, 1934.

tion is certainly not due to particles of uniform size. The shape of the absorption-curve will therefore depend not only on the optical constants of the particles but also on the frequency of particles of different size. In such a case it will generally not be possible to represent the observations by a theoretical curve computed for one particular size; only when the majority of all particles give absorption-curves which are similar to one another can this be done. This condition is automatically fulfilled for all particle sizes in the spectral range $a < 1$, if the optical constants do not vary with wave-

TABLE 4

COLLECTED RESULTS

Star	Element	d in $m\mu$	N per cm^2	$Nd^3 cm^3$ per cm^2	M g/cm^2	$m-m_0$ for $\lambda=4000$ A
ϑ_1(C) Orionis	Iron	130	$4.1 \cdot 10^9$	$0.90 \cdot 10^{-5}$	$3.7 \cdot 10^{-5}$	1.66
	Carbon	185	$3.4 \cdot 10^9$	$2.11 \cdot 10^{-5}$	$2.2 \cdot 10^{-5}$	1.78
ϑ_1 (A) Orionis, ϑ_1 (D) Orionis	Iron	130	$6.6 \cdot 10^9$	$1.45 \cdot 10^{-5}$	$5.9 \cdot 10^{-5}$	2.65
	Carbon	185	$4.7 \cdot 10^9$	$2.98 \cdot 10^{-5}$	$3.1 \cdot 10^{-5}$	2.60
HD 14134, Perseus, Hd 14143, Perseus	Iron	70	$2.8 \cdot 10^{10}$	$0.96 \cdot 10^{-5}$	$4.0 \cdot 10^{-5}$	2.17
	Carbon	62	$13.2 \cdot 10^{10}$	$3.20 \cdot 10^{-5}$	$3.4 \cdot 10^{-5}$	2.70
HD 14818, Perseus.	Iron	70	$1.6 \cdot 10^{10}$	$0.55 \cdot 10^{-5}$	$2.3 \cdot 10^{-5}$	1.28
	Carbon	62	$7.7 \cdot 10^{10}$	$1.9 \cdot 10^{-5}$	$2.0 \cdot 10^{-5}$	1.58

length. τ_1 will then be proportional to λ^{-1}, and τ_2 to λ^{-4}. For any distribution of particles with $d < \lambda/\pi$ the resulting τ will be a linear combination of the type $\alpha\lambda^{-1} + \beta\lambda^{-4}$, just as for one single particle size. This will, of course, still hold approximately when the optical constants vary slowly with the wave-length and when most, but not all, particles have diameters smaller than λ/π. An absorption-curve that can be represented by a single size may therefore reasonably be expected for a distribution with an average diameter of $70 m\mu$, such as that which results from the color-curve of the Perseus stars. For larger particles, the shape of the absorption-curve varies with the diameter. The fact that the absorption-curves from the Trapezium stars correspond approximately to a particle size of about $150 m\mu$, if not considered as fortuitous, demands a distribution of particle sizes with a very pronounced maximum.

At first sight it seems difficult to understand why interstellar dust is fairly homogeneous in the size of particles. On the other hand, there can be no doubt that the absorption-curves observed for the Orion stars differ from those for the Perseus stars, which correspond closely to the curves that have generally been obtained by other observers and apparently represent the most common type of absorption-curve. It is tempting to connect the unusual type of curve for the Orion stars with the greater transparency which has been observed for the central part of the great nebula in Orion. The link between these two observations is perhaps to be found in computations by Schoenberg and Jung.[12] These authors showed that in the neighborhood of early-type stars the radiation pressure exceeds greatly the gravitational attraction for particles of the size in question. The particles will therefore be removed from the neighborhood of the star, with a resulting dilution of the dust cloud and a diminution of the number of particles in the line of sight. This effect will be more pronounced for smaller particles, as the ratio of radiation pressure to gravity reaches a maximum for diameters of about $30 m\mu$ for O- and B-type stars. Thus it seems possible that the radiation of the central star renders the central part of the nebula more transparent by removing chiefly the smaller particles. The remaining distribution of particle sizes will have its maximum at a larger particle size than the original distribution. This maximum will be comparatively sharp only if the original distribution falls off rapidly toward larger diameters.

At present, the argument in favor of such an explanation cannot be considered convincing. It is necessary, and it is intended, to extend the measurements to a greater number of stars and, if possible, to a still greater spectral range. Furthermore, only after theoretical data covering the entire spectral range have been computed will it be possible to draw definite conclusions.

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[12] *A.N.*, **247**, 413, 1935.