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THE EXTINCTION LAW IN THE ORION NEBULA

Rafael Costero and Manuel Peimbert

SUMARIO

Se obtiene una ley de extinción promedio para cuatro regiones de la Nebulosa de Orión a partir de la comparación de cálculos teóricos con observaciones ópticas de líneas en emisión y observaciones del continuo en radiofrecuencias. Esta ley es definitivamente anormal y a partir de ella se encuentra $R = 5.5 \pm 0.7$. Al normalizar los valores de los excesos de color de las estrellas situadas en la Nebulosa de Orión al de E_{B-R} de la ley promedio, se encuentra que los excesos de color en U, V, I y J se ajustan a la ley promedio; sin embargo en K y L se encuentran excesos de emisión muy considerables después de corregir por extinción. Estos excesos posiblemente se deban a rerradiación producida por el polvo interestelar y a procesos atómicos de emisión, que ocurren en la vecindad de las estrellas.

ABSTRACT

An average extinction law for the Orion Nebula is obtained by comparing emission line optical observations and continuum radio observations with theoretical computations for four regions in the Nebula. The derived law is abnormal and yields an $R = 5.5 \pm 0.7$. Normalizing the E_{B-R} values of stars in the Orion Nebula to our extinction law it is found that the agreement is good in the U, V, I, and J excesses, but not for K and L which show significant additional emission. Possibly this emission is due to dust reradiation and to nebular free-free and emission line radiation produced near the stars.

I. *Introduction*

In the first extensive study on the regional variation of the reddening law, Stebbins and Whitford (1943, 1945) concluded that the extinction curve between λλ3530 and 10300 Å was about the same everywhere except in the direction of the Trapezium stars. The abnormal behavior of the interstellar extinction in the Orion Nebula aggregate was first noticed by Baade and Minkowski (1937); it has been confirmed by means of multicolor photoelectric photometry and the variable extinction method (Sharpless 1952; Johnson and Borgman 1963; Johnson 1965, 1968; and Lee 1968).

Current theories of recombination-line radiation and free-free radio continuum emission accurately predict the ratio of unreddened Balmer and Paschen-line to radio continuum fluxes originated in emission nebulae (Osterbrock and Stockhausen 1960, 1961; Menon 1962; Terzian 1965). In consequence, by comparing between observed and theoretical fluxes, it is possible to obtain the total extinction at those line wavelengths.

In the Orion Nebula, the total extinction at different hydrogen-line wavelengths has been deduced by Méndez (1967), Gebel (1968), Schmitter (1970), and Werner, Pipher, Terzian, and Houck (1969). Méndez and Gebel also obtained the ratio of total to selective extinction, A_V/E_{B-V}; their results yielded values of R close to those obtained before by the variable extinction method, but considerably smaller than those derived from multicolor photometry.

In § II the average reddening law between λλ3500 Å and 1.95 cm and the total extinction at Hβ is obtained for four regions in the Orion Nebula; the average reddening law is compared to the normal law and the observations of stars in the nebula are corrected for extinction. In § III the R values for each region are derived, the possibility of regional variations of the extinction law in the Orion Nebula is considered, and a new total to selective extinction ratio R_H is defined. The conclusions are presented in § IV.

II. *Reddening Curve and Total Extinctions*

The photoelectric line intensity measurements by Peimbert and Costero (1969) of four regions in the Orion Nebula (Ori I, II, III and IV) and the radio map at λ1.95 cm by Schraml and Mezger (1969) are compared with theoretical line intensities predicted from the radio fluxes to derive an average reddening curve and the total extinctions.

In Table 1 the flux at a given wavelength relative to the flux at Hβ, F(λ)/F(Hβ), observed by Peimbert and Costero (1969) are presented together with the absolute fluxes in Hβ, F(Hβ), given in erg cm^{-2} sec^{-1}; the latter values are slightly different from those of the original paper since the value used for the scanner dispersion is 16 Å/mm instead of the 15 Å/mm assumed previously.

The relative emission coefficients $j(\lambda)/j(H\beta)$ presented in Table 1 were obtained by interpolating the theoretical computations for Case B by Pengelly (1964); the values for the electron temperature adopted for each region were obtained from Peimbert and Costero (1969). Pengelly's

TABLE 1

Orion Line Intensities and Extinction

Region		Ori I (T_e = 7950 °K; N_i/N_p = 1.103)*				Ori II (T_e = 7400 °K; N_i/N_p = 1.096)			
Wave-length	*Identi-fication*	*log** $F(\lambda)/F(H\beta)$	*log*** $j(\lambda)/j(H\beta)$	$E(\lambda,H\beta)$ *(mag)*	*log* $I(\lambda)/I(H\beta)$	*log* $F(\lambda)/F(H\beta)$	*log* $j(\lambda)/j(H\beta)$	$E(\lambda,H\beta)$ *(mag)*	*log* $I(\lambda)/I(H\beta)$
3835	H9	−1.22	−1.14	+0.20	−1.14	−1.25	−1.14	+0.28	−1.16
4102	Hδ	−0.64	−0.60	+0.10	−0.59	−0.65	−0.60	+0.13	−0.59
4340	Hγ	−0.37	−0.34	+0.08	−0.33	−0.38	−0.34	+0.10	−0.34
4861	Hβ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6563	Hα	+0.61	+0.47	−0.35	+0.48	+0.60	+0.47	−0.33	+0.46
9229	P9	−1.23	−1.58	−0.88	−1.57	−1.23	−1.58	−0.88	−1.61
10049	P7	−0.86	−1.24	−0.95	−1.23	−0.85	−1.24	−0.98	−1.27
10938	P6	−0.60	−1.03	−1.08	−0.99	−0.66	−1.03	−0.93	−1.10
1.95 cm	free-free			−1.15				−1.30	
log $F(H\beta)$#				−9.17				−9.22	
$\langle T_A \rangle$†				13.95				13.51	
log $I(H\beta)$##				−8.71				−8.70	
$C(H\beta)$††				0.46				0.52	

Region		Ori III (T_e = 6850 °K; N_i/N_p = 1.078)				Ori IV (T_e = 5900 °K; N_i/N_p = 1.009)			
Wave-length	*Identi-fication*	*log* $F(\lambda)/F(H\beta)$	*log* $j(\lambda)/j(H\beta)$	$E(\lambda,H\beta)$ *(mag)*	*log* $I(\lambda)/I(H\beta)$	*log* $F(\lambda)/F(H\beta)$	*log* $j(\lambda)/j(H\beta)$	$E(\lambda,H\beta)$ *(mag)*	*log* $I(\lambda)/I(H\beta)$
3835	H9	−1.21	−1.14	+0.18	−1.14	—	−1.15	—	—
4102	Hδ	−0.64	−0.60	+0.10	−0.59	−0.68	−0.60	+0.20	−0.63
4340	Hγ	−0.35	−0.34	+0.03	−0.31	−0.38	−0.34	+0.10	−0.34
4861	Hβ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6563	Hα	+0.57	+0.47	−0.25	+0.45	+0.62	+0.48	−0.35	+0.49
9229	P9	−1.23	−1.58	−0.88	−1.55	—	−1.57	—	—
10049	P7	−0.88	−1.24	−0.90	−1.23	—	−1.23	—	—
10938	P6	−0.67	−1.02	−0.88	−1.04	—	−1.01	—	—
1.95 cm	free-free			−1.10				−1.15	
log $F(H\beta)$				−9.45				−10.52	
$\langle T_A \rangle$				6.35				0.643	
log $I(H\beta)$				−9.01				−10.06	
$C(H\beta)$				0.44				0.46	

* From Peimbert and Costero (1969). ** From Pengelly (1964). # $F(H\beta)$ is the observed flux in erg cm^{-2} sec^{-1}. † $\langle T_A \rangle$ is the average antenna temperature, deduced from Schraml and Mezger (1969). ## $I(H\beta)$ is the unreddened flux in erg cm^{-2} sec^{-1}. †† $C(H\beta)$ is the Hβ reddening logarithmic correction.

computations were based on the assumption that the population of the nl states in hydrogen atoms is determined only by radiative processes. This assumption is valid for $n < 10$ for typical densities in gaseous nebulae.

The differential extinction between two wavelengths, λ_1 and λ_2, when self-absorption is negligible, is given by

$$E(\lambda_1, \lambda_2) = 2.5 \log \left[\frac{j(\lambda_1)/j(\lambda_2)}{F(\lambda_1)/F(\lambda_2)} \right] . \tag{1}$$

From equation (1), the emission coefficient values, and the observed flux ratios, the differential extinctions were derived and are also presented in Table 1.

To derive the total extinction $A(\mathrm{H}\beta)$, the observed flux, $F(\mathrm{H}\beta)$, is compared to the radio flux at $\lambda 1.95$ cm. From Pengelly (1964) the emission coefficient for Hβ in the 5000 to 10000 °K temperature range is given by

$$j(\mathrm{H}\beta) = 2.52 \times 10^{-22} N_e N_p T_e^{-0.827} ; \tag{2}$$

where $j(\mathrm{H}\beta)$ is given in erg cm^{-3} sec^{-1}, and N_e and N_p are the electron and proton densities in cm^{-3}. The emission coefficient for the free-free continuum radiation in the radio-frequency interval ν, $\nu + d\nu$ (Oster 1961) can be expressed as

$$j(\nu)d\nu = 8.65 \times 10^{-38} N_e N_i T_e^{-0.5} (7.695 + 1.5 \log T_e - \log \nu) d\nu , \tag{3}$$

where $j(\nu)$ is given in erg cm^{-3} sec^{-1} Hz^{-1}, and N_i is the number of ions per cm^3. The N_i/N_p ratios listed in Table 1 were taken from Peimbert and Costero (1969).

To obtain the flux from radio observations the brightness temperature, given by

$$T_b = T_A/\eta_B , \tag{4}$$

is used; T_A is the antenna temperature and η_B is the beam efficiency. The average antenna temperatures presented in Table 1 were obtained from the observations at $\lambda 1.95$ cm by Schraml and Mezger (1969); the average was taken over the solid angle corresponding to the optical observations (see Peimbert and Costero 1969) and η_B was taken to be 0.48. The low values of T_b imply that the nebula is optically thin to free-free radiation at $\lambda 1.95$ cm and consequently that equation (1) can be used. The observed radio flux, $F(\nu)$ given in erg cm^{-2} sec^{-1} Hz^{-1}, is not affected by dust extinction and therefore is equal to the intrinsic radio flux, $I(\nu)$, which is given by

$$I(\nu)d\nu = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/kT_b) - 1} \Omega \, d\nu ; \tag{5}$$

where Ω is the solid angle; for $h\nu/kT_b \ll 1$

$$I(\nu)d\nu \approx (2kT_b/\lambda^2) \, \Omega \, d\nu . \tag{6}$$

The total extinction at Hβ in magnitudes is then defined by

$$A(\mathrm{H}\beta) = E(\mathrm{H}\beta, 1.95) = -2.5 \log \left[\frac{j(1.95)/j(\mathrm{H}\beta)}{F(1.95)/F(\mathrm{H}\beta)} \right] . \tag{7}$$

The total logarithmic extinction $C(\mathrm{H}\beta) = 0.4 \, A(\mathrm{H}\beta)$, was obtained from equations (2), (3), (4), (5) and (7) and is presented in Table 1. It should be noted that the use of equation (6) would have yielded higher values of $I(\nu)$ than those derived from the exact equation (5), by factors of 1.01, 1.01, 1.03, and 1.33 in Ori I, II, III, and IV, respectively.

The wavelength dependence of $f(\lambda)$, the ratio of the differential extinction relative to Hβ, to the total absorption at Hβ, defined by

$$f(\lambda) = \frac{E(\lambda, \mathrm{H}\beta)}{A(\mathrm{H}\beta)} ; \tag{8}$$

has been plotted in Figure 1 for the four regions observed in Orion. A smooth curve was adjusted to the observations with the condition that it crossed through $f(\mathrm{H}\beta)$ and $f(\infty)$; this curve has been drawn in Figure 1 as a solid line. The average extinction law for the four regions considered in the

Orion Nebula, $\langle f(\lambda)\rangle$, has been obtained and is presented in Table 2. In Figure 1 the dashed line represents the Normal Extinction Law (Seaton 1960).

TABLE 2

Normalized Extinction Law in Orion

λ (Å)	1/λ (μ^{-1})	$\langle f(\lambda)\rangle$ (Orion)	$f(\lambda)$ (Normal)*
3500	2.86	+0.23	+0.42
4000	2.50	+0.14	+0.24
4500	2.22	+0.06	+0.10
4861	2.06	0.00	0.00
5000	2.00	−0.02	−0.04
6000	1.67	−0.17	−0.26
7000	1.43	−0.36	−0.45
8000	1.25	−0.56	−0.60
9000	1.11	−0.71	−0.73
10000	1.00	−0.80	−0.81
11000	0.91	−0.85	−0.85
20000	0.50	—	−0.97
∞	0.00	−1.00	−1.00

* From Seaton's (1960) Table 9.

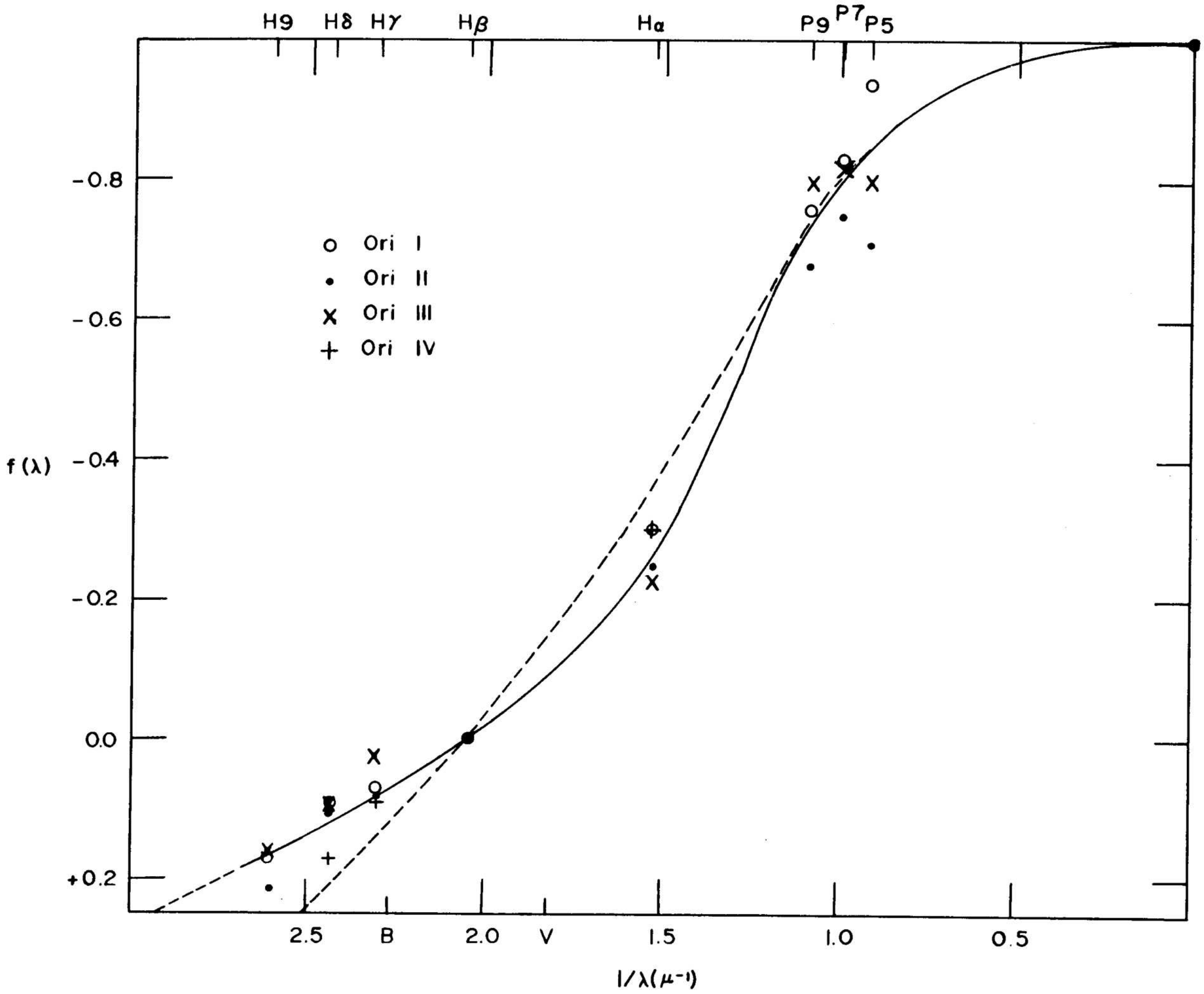

Fig. 1.—*Total extinctions normalized at $f(H\beta) = 0$, $f(\infty) = -1$, obtained from nebular free-free to bound-bound emission ratios; the solid line is the average extinction law for the four observed regions; the dashed line is the Normal Extinction Law.*

The unreddened relative intensities, $I(\lambda)/I(\mathrm{H}\beta)$ given in Table 1 were obtained from

$$\log I(\lambda)/I(\mathrm{H}\beta) = \log F(\lambda)/F(\mathrm{H}\beta) + C(\mathrm{H}\beta)\,\langle f(\lambda)\rangle \ . \qquad (9)$$

The logarithmic relative intensities obtained with the average extinction law are slightly different to those given by Peimbert and Costero (1969), the latter were derived by means of Johnson and Borgman's (1963) extinction law for the Trapezium stars. The differences are smaller than 0.01 in the λλ3727 to 5000 Å range and increase up to 0.05 in the neighborhood of Hα.

In Figures 2 and 3 $\langle f(\lambda)\rangle$ is compared with the extinction values derived from stellar observations by Lee (1968), where the stellar E_{B-R}'s have been normalized to $\langle f(B)\rangle - \langle f(R)\rangle$. After normalization the agreement is good at *U, V, I,* and *J*; however there are pronounced deviations in *K* and *L*. The differences in the *K* and *L* values imply significant emission excesses at these wavelengths.

There are at least six possible explanations for the additional emission in *K* and *L:* a) an incorrect extinction law, however it is doubtful on the basis of the good agreement obtained in the *U—J* range; b) late type bright star companions of the O and B stars, which is unlikely since in this case the companions would contribute also to the *I* and *J* intensities; c) anomalous stellar emission; d) dust reradiation; e) free-free radiation in the stellar vicinity; and f) emission line radiation in the stellar neighborhood. It is difficult to evaluate possibilities d, e, and f, due to the inhomogeneities in the Nebula as well as the sky subtracting practice for the stellar observations, which in some cases is done measuring sky deep in the Nebula —where the infrared interstellar radiation might be significant— and without reporting differences between sky inside and outside the Nebula.

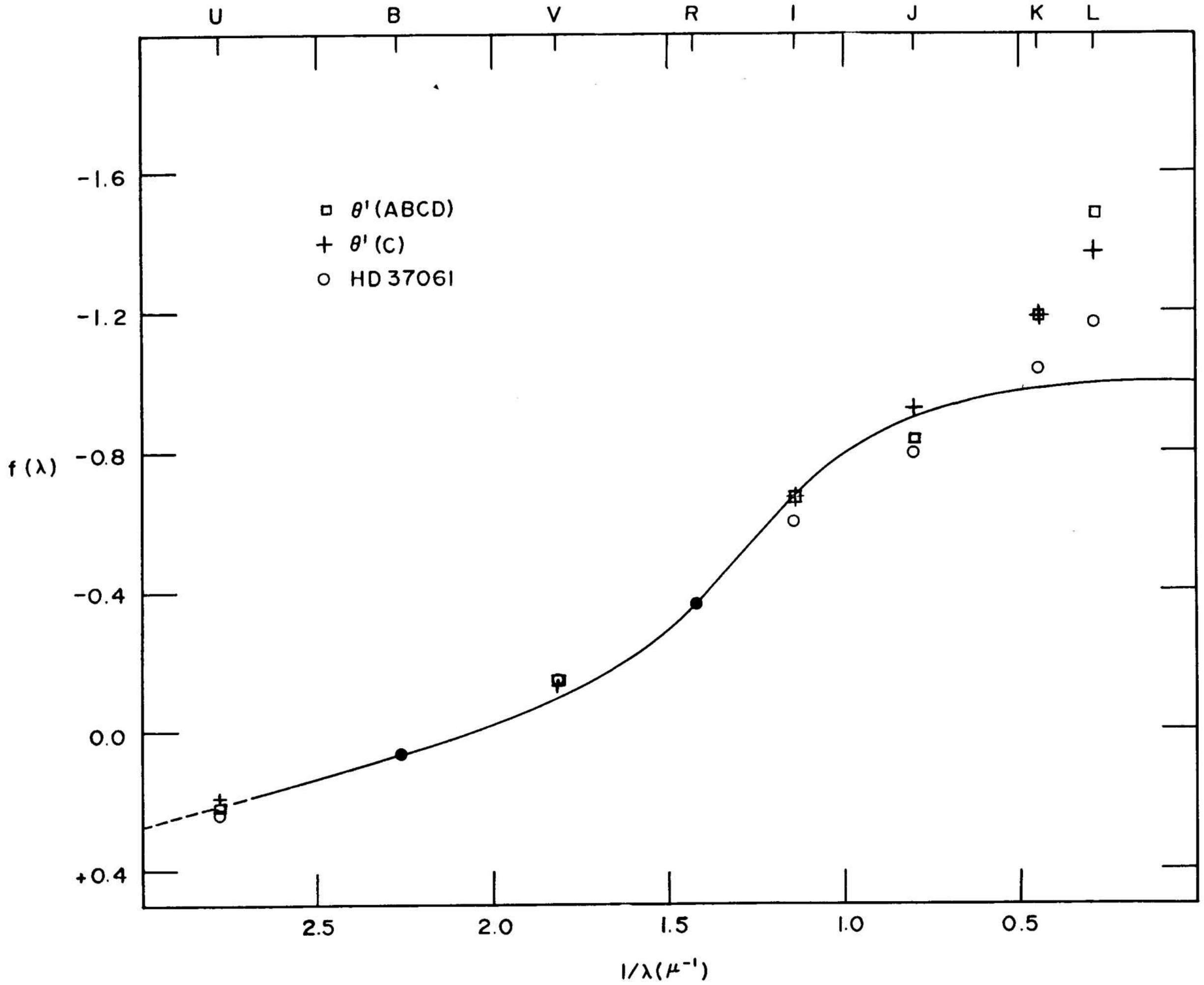

Fig. 2.—*Comparison between the average nebular extinction law (solid line) and the stellar color excesses obtained by Lee (1968) for θ' Ori (A, B, C, D), θ' Ori (C), and HD 37061; the stellar excesses are normalized to ⟨f(B)⟩ — ⟨f(R)⟩.*

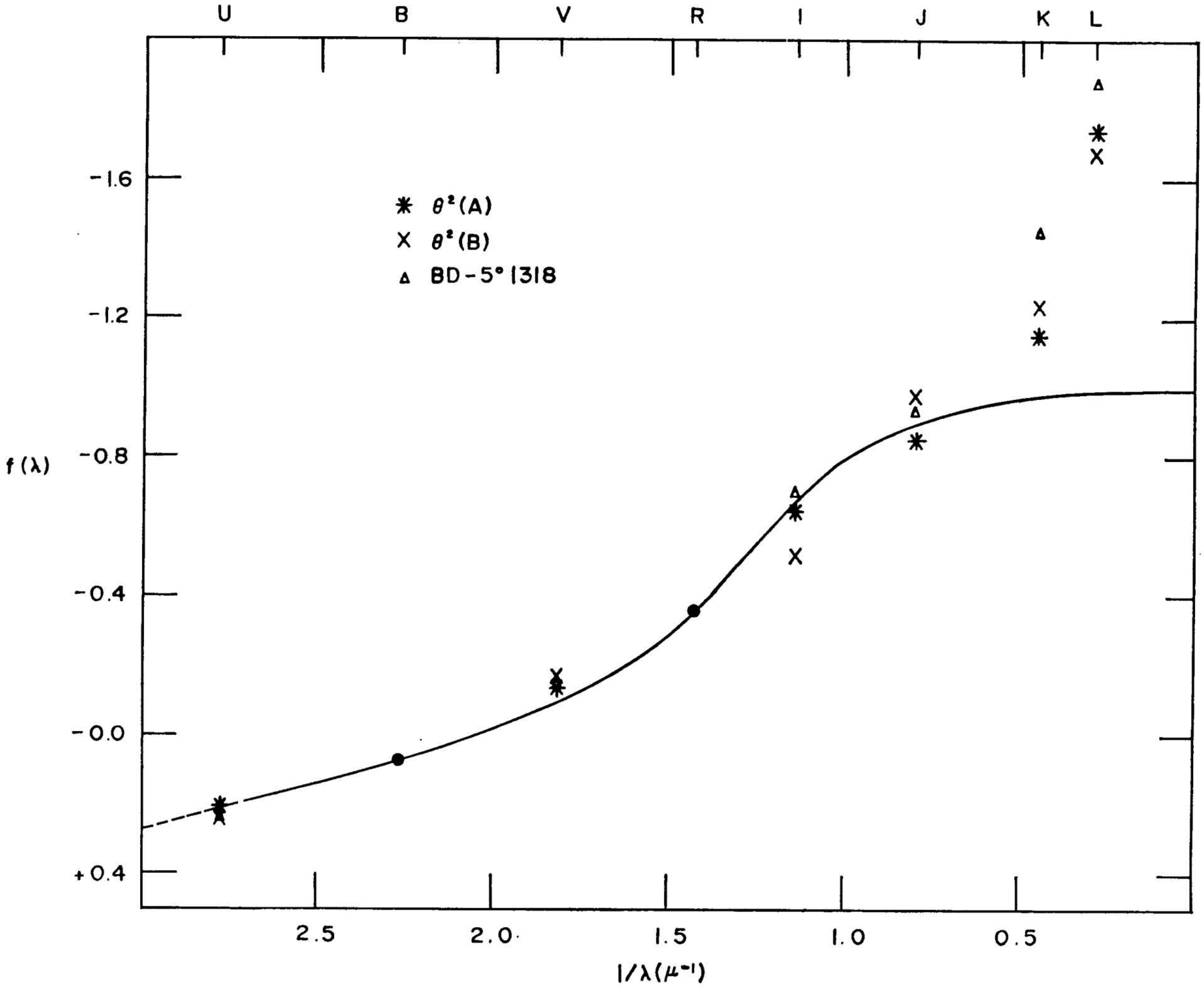

Fig. 3.—*Same as Figure 2 for* θ^2 *Ori (A),* θ^2 *Ori (B), and BD —5°1318.*

The comparison of the stellar and nebular reddening laws is strictly valid only when the extinction takes place between the nebula and the observer (external); but if a fraction of the extinction occurs inside the nebula (internal) the total extinction determined from nebular emission lines would be underestimated (see Mathis 1970). However the effect of internal dust extinction on the reddening law is small since a good agreement is obtained between the stellar and nebular extinction laws in the $U-J$ range.

III. *Values of R and* R_H

An average value of the total to selective extinction, $\langle R \rangle = A_V/E_{B-V}$, for the four points can be obtained from Figure 1 and is given by

$$\langle R \rangle = \frac{1 + \langle f(V) \rangle}{\langle f(B) \rangle - \langle f(V) \rangle} = 5.5 \pm 0.7 \; ; \qquad (10)$$

the probable error was estimated by assuming an 0.13 mag. error in $A\,(\mathrm{H}\beta)$, which is equivalent to an 0.02 mag. error in E_{B-V}. The effect of internal dust extinction on the total to selective extinction ratios is to increase them, therefore if this effect is important the real value of $\langle R \rangle$ would be smaller and the discrepancies on K and L would be even larger; however since the nebular and stellar reddening laws are very similar in the $U-J$ range, it is unlikely that the internal dust extinction considerably changes the value of R.

It is also possible to derive R for each region by obtaining individual extinction laws; therefore we constructed a curve for each region similar to that in Figure 1; each $f(\lambda)$ yields the best fit for $f(\mathrm{H}9)$, $f(\mathrm{H}\delta)$ and $f(\mathrm{H}\gamma)$, and intersects $f(\mathrm{H}\beta) = 0$, $f(\mathrm{H}\alpha)$ and $f(\infty) = -1$.

From these individual curves $f(V)$ and $f(B)$ were estimated and R was computed for each region; the results are presented in Table 3. The probable errors were obtained by assuming an error of 0.25 mag. at $A(\mathrm{H}\beta)$, which is equivalent to an error of about 0.04 mag. in E_{B-V}. Previous determinations of R are also presented in Table 3; the variable extinction and the stellar multicolor photoelectric photometry methods have been discussed elsewhere (Sharpless 1963; and Johnson 1968). The R values assigned to Lee (1968) were derived from his monochromatic curves; Lee, based on possible interpretation for the abnormally large infrared excesses, concluded that $R \geqslant 5.5$ in the Trapezium region. Due to the large probable errors in the observations, it is difficult to determine whether or not there are significant differences in the extinction law for the four Orion regions. However, R near HD 37061 (Ori IV), determined from the free-free to bound-bound nebular method, is smaller than those close to the Trapezium (Ori I and II), and a similar difference between these regions is obtained from the stellar multicolor photometry method.

TABLE 3

Values of R in Orion

Region	*R*	R_H	*Method**	*Source*
Ori I	5.0 ± 1.2	3.3 ± 0.7	(1)	This paper
Ori II	5.8 ± 1.4	3.9 ± 0.9	(1)	This paper
Ori III	6.6 ± 1.6	4.7 ± 1.1	(1)	This paper
Ori IV	4.4 ± 1.1	3.3 ± 0.7	(1)	This paper
Neb. Center (0°25)	5.5 ± 4.9	3.6	(1)	Gebel (1968)
Neb. Center	4.7	—	(1)	Méndez (1967)
Sword	5.0 ± 0.3	—	(2)	Johnson (1968)
Sword	5.7	—	(2)	Johnson (1965)
Sword	6	—	(2)	Sharpless (1952)
Trapezium	7.7	—	(3)	Lee (1968)
HD 37061	5.3	—	(3)	
Trapezium	7.4 ± 0.3	—	(3)	Johnson and Borgman (1963)

* (1) Nebular free-free to bound-bound. (2) Variable extinction. (3) Stellar multicolor photoelectric photometry.

It is convenient to define a total to selective extinction ratio based on the emission lines observed to avoid interpolations and thus reduce the uncertainties. The two brightest Balmer lines are used for this purpose and the total to selective extinction ratio, R_H, is defined as

$$R_H = \frac{A(\mathrm{H}\beta)}{E(\mathrm{H}\beta, \mathrm{H}\alpha)} = \frac{f(\mathrm{H}\beta) - f(\infty)}{f(\mathrm{H}\beta) - f(\mathrm{H}\alpha)} = -\frac{1}{f(\mathrm{H}\alpha)} . \qquad (11)$$

The Normal Reddening Law yields $R_H = 2.7$, a value which is also considerably smaller than the R_H values derived for the four Orion regions listed in Table 3. The value of R_H assigned to Gebel (1968) was obtained from his data for a circle, centered in θ^1 Ori, 0°25 in diameter.

IV. *Conclusions*

The bound-bound to free-free nebular method to determine the reddening law has the advantages that the lines are practically monochromatic and that the contribution to the emission lines by mechanisms of continuum emission (starlight, dust scattered light, dust reradiation, and continuum atomic processes in the nebulae) can be easily subtracted. The main disadvantage is that if dust and gas are mixed in the nebula and produce a considerable fraction of the extinction, the dust and gas distributions, as well as the nature of the grains, would have to be known in order to be able to compare stellar and nebular extinction laws.

The value $\langle R \rangle = 5.5$ obtained here is definitely abnormal and is very similar to that derived from the variable extinction method, and considerably smaller than the values deduced from stellar multicolor photometry; consequently the excesses in K, L, M, and N should be considered carefully before deriving R values.

The large probable errors in our R values prevent us from determining if there are local variations in R, however, it is interesting to note that our value for Ori IV (M43) and that derived from Lee's observations for HD 37061 (the ionizing star of M43) are slightly smaller than the values for the Trapezium region.

From Figures 2 and 3 it is concluded that the excess found in K and L for the stars in the Orion Nebula region, is neither due to the reddening correction law nor to bright late type stellar companions. It is difficult to decide based on the infrared observations whether the anomalous emission is due to free-free and emission line radiation or to dust reradiation.

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