Revista Mexicana de Astronomía y Astrofísica, Volumen 2, Agosto 1977

THE LAW OF INTERSTELLAR EXTINCTION

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Received 1976 November 30

RESUMEN

Se ha usado la fotometría de banda intermedia de 13-colores, publicada recientemente por Johnson y Mitchell, para investigar la ley de extinción interestelar en varias regiones del cielo. Esta ley tiene valores diferentes en estas regiones, lo que debe indicar que hay diferencias físicas en el material interestelar que produce la extinción en las diversas regiones estudiadas. Sin embargo, un valor de $R = A_V/E(B\text{-}V) = 3.24 \pm 0.2$ (p.e.), quizás sea satisfactorio para estudios estadísticos en nuestra galaxia. De nuevo se ha encontrado que el valor de R en la región de la nebulosa de Orión es mucho más grande que en otras partes del cielo. Parece posible además que en aquellas regiones con estrellas O embebidas en nebulosas, R tiene valores grandes.

ABSTRACT

The new 13-color medium-narrow band photometry published by Johnson and Mitchell has been used to investigate the law of interstellar extinction in several regions of the sky. The extinction laws in these regions are different, and must indicate that there are physical differences of the interstellar material which produces the extinction in the several regions studied. Nevertheless, a value of $R = A_V/E(B\text{-}V) = 3.24 \pm 0.2$ (p.e.) probably is satisfactory for statistical investigations in our Galaxy. The value of R in the region of the Orion Nebula has again been found, to be much higher; and it seems likely that high values of R will be found in regions where O-type stars are imbedded in nebulae.

Key words: INTERSTELLAR: REDDENING — EXTINCTION — PHOTOMETRY.

I. THE LAW OF INTERSTELLAR EXTINCTION

During the past 20 years, I have made a number of studies of the law of interstellar extinction. My most recent publication on this subject appeared in 1968 (Johnson 1968). It was written before I realized how much emission was being produced by the circumstellar shells of some high-luminosity reddened stars; as a result, the far-infrared curves for some celestial regions are distorted there. Furthermore, that study was based entirely upon the broad-band UBVRIJKL photometry, and details of the interstellar extinction curves were smoothed out by these broad-band filters.

The recent publication (Johnson and Mitchell 1975) of 13-color medium-narrow band photometry of the stars brighter than fifth visual magnitude makes it possible to re-examine in more detail the law of interstellar extinction in various regions of the sky. Furthermore, my recently-obtained spectra of the two brightest stars of the Orion Trapezium (Johnson 1977) make possible new and important interpretations regarding the interstellar extinction in the region of the Orion Nebula.

II. THE EXTINCTION LAWS IN VARIOUS DIRECTIONS

It was possible to select from the data list of 13-color photometry published by Johnson and Mitchell (1975) a fairly large number of stars for several regions of the sky, stars for which the interstellar

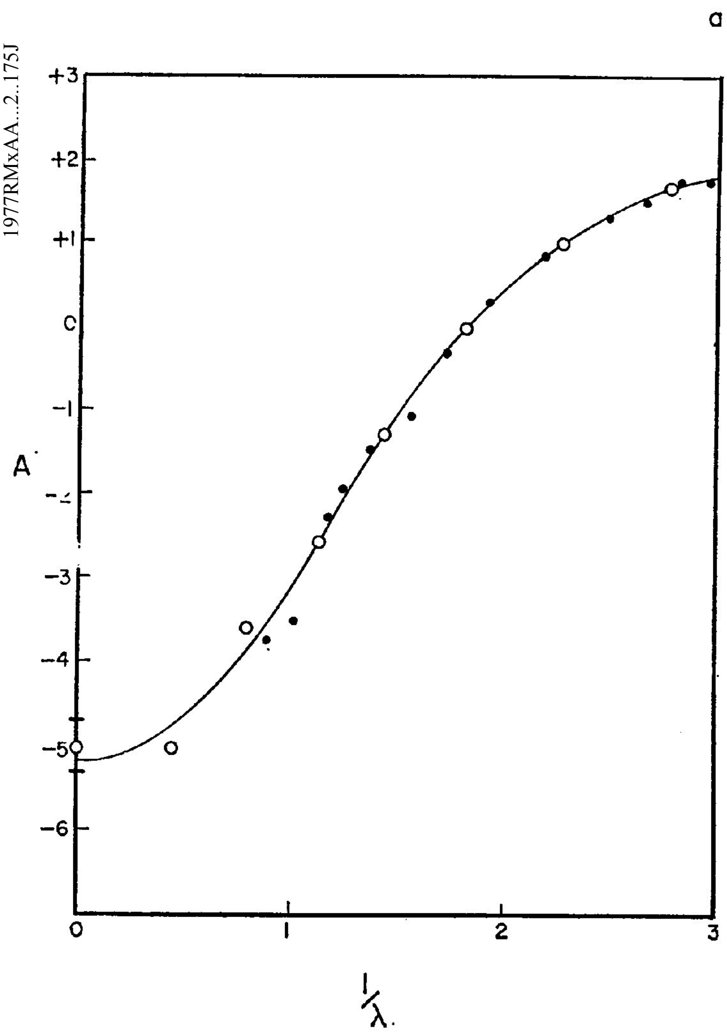

FIG. 1. The observed extinction law (normalized to E(B−V) = 1.0) for the Orion Sword region.

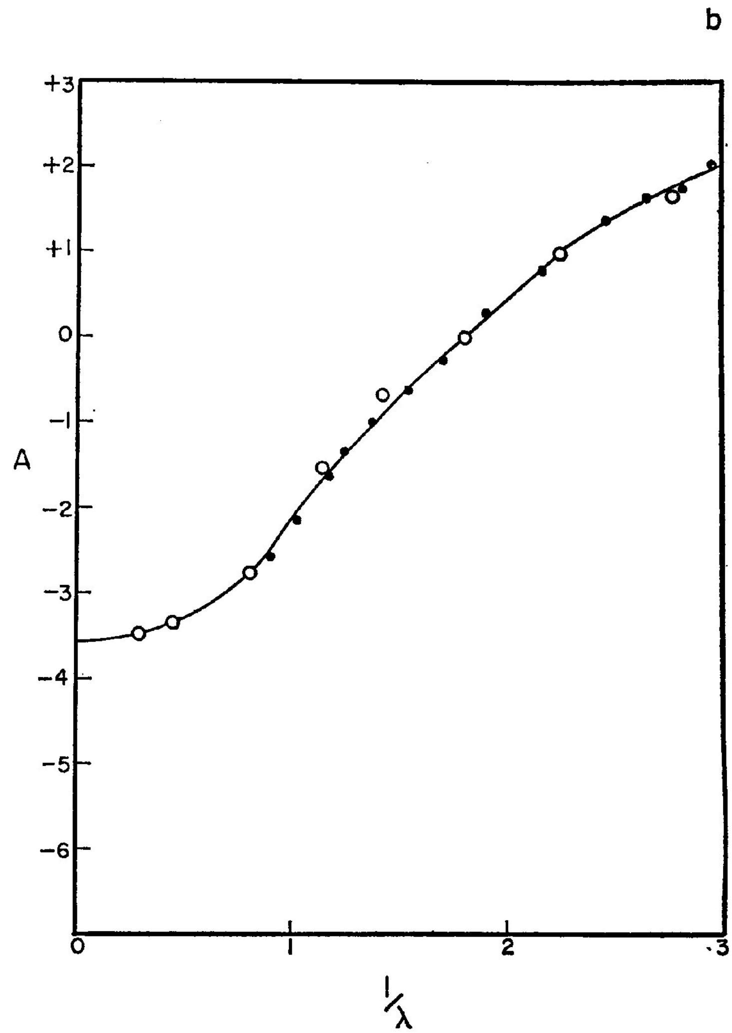

FIG. 2. The observed extinction law for Scorpius.

reddening varies from negligible to moderately high. These celestial regions are:

a. Orion Sword (Orion Nebula region)
b. Scorpius
c. Cygnus
d. Cepheus
e. Ophiucus
f. Perseus

The data are good, covering a rather wide range in reddening for all regions except the Orion Sword. In this region, the reddening depends largely upon observations of only a few Orion Nebula stars, principally θ^1 and θ^2 Ori.

The extinction laws computed for these six regions, normalized to E(B-V) = 1.0, are shown in Figures 1-6. The open circles represent the data from UBVRIJKL photometry (Johnson 1968), while the filled circles represent data computed from the recent 13-color photometry (Johnson and Mitchell 1975). The circles with error-bars in Figures 1, 3 and 6 represent values of A_V (the visual magnitude extinction) computed by the variable extinction method (Johnson 1968).

The close agreement between the broad-band UBVRIJKL (circles) and the 13-color points (filled circles) should be noted, because this agreement of the 13-color data with the older data confirms the general shapes of the various extinction curves. Specifically the peculiarly different laws in Orion (Figure 1) and Scorpius (Figure 2) are well confirmed by the 13-color photometry. In the majority of cases, the reddened stars used for the UBVR-IJKL color-excesses are not the same stars that were used for the 13-color color-excesses (Two points in the Orion curve, those for the 63 and 99 filters,

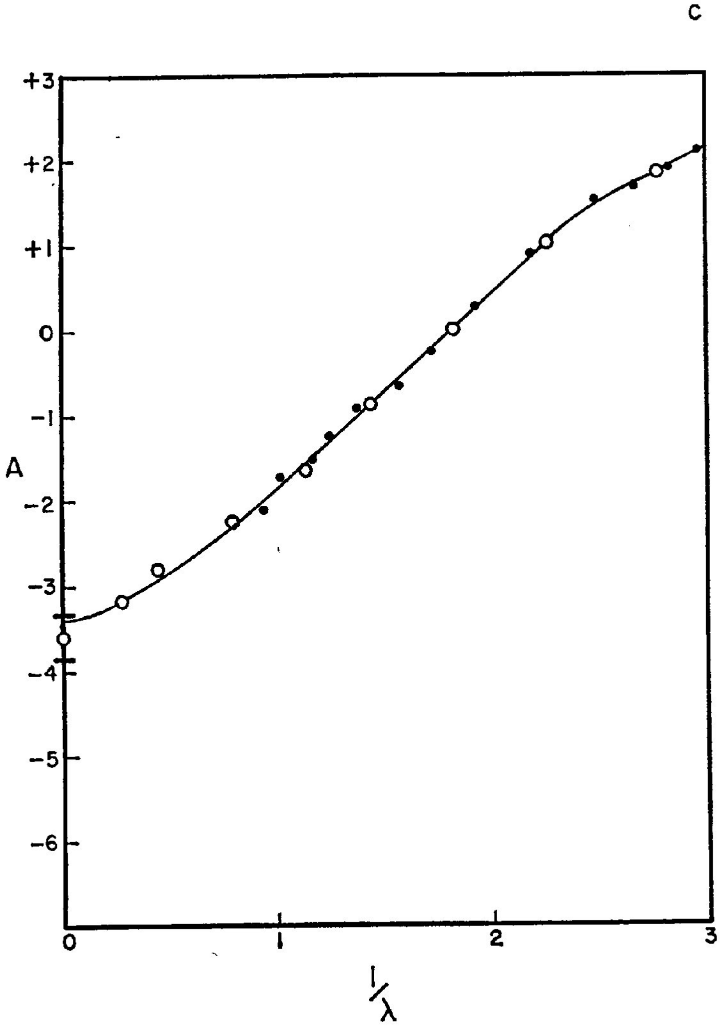

FIG. 3. The observed extinction law for Cygnus.

differ significantly from the remainder of the points. These differ because of the very strong Hα and λ 9530 Å nebular emission lines which fall within these two filters' pass-bands).

Beyond this agreement and confirmation, the 13-color photometry makes it possible to see much more detail in the individual curves. The well-known straight-line extinction law first found by Whitford (1958) can be seen in several of the figures, as can be seen the "break" between two straight lines at approximately $1/\lambda = 2.4\,\mu m^{-1}$. I think, however, that the second "break" at $1/\lambda \simeq 1.2\,\mu m^{-1}$, and the long-wavelength straight-line section which appears in Figures 4 and 6 had not been seen previously. From the extrapolation of the photometric curves, the values of $R = A_V/E(B\text{-}V)$, for the several regions are listed in Table 1. The mean value of R, excluding the Orion Sword region, is 3.24.

TABLE 1

$R = A_V/E(B\text{-}V)$ FOR SEVERAL CELESTIAL REGIONS

Region	Code	R
Orion Sword	a	5.2
Scorpius	b	3.6
Cygnus	c	3.4
Cepheus	d	3.0
Ophiucus	e	3.2
Perseus	f	3.0

The extinction curves for these six regions have been collected in Figure 7, with the zero-points of all ordinates set to A = 0. With the exception of the Orion Sword region, all regions have a law which, between $1/\lambda \simeq 1.2\,\mu m^{-1}$ and $1/\lambda \cong 2.4\,\mu m^{-1}$, is a straight line; furthermore, these straight line sections all appear to have essentially the same slope; i.e., the

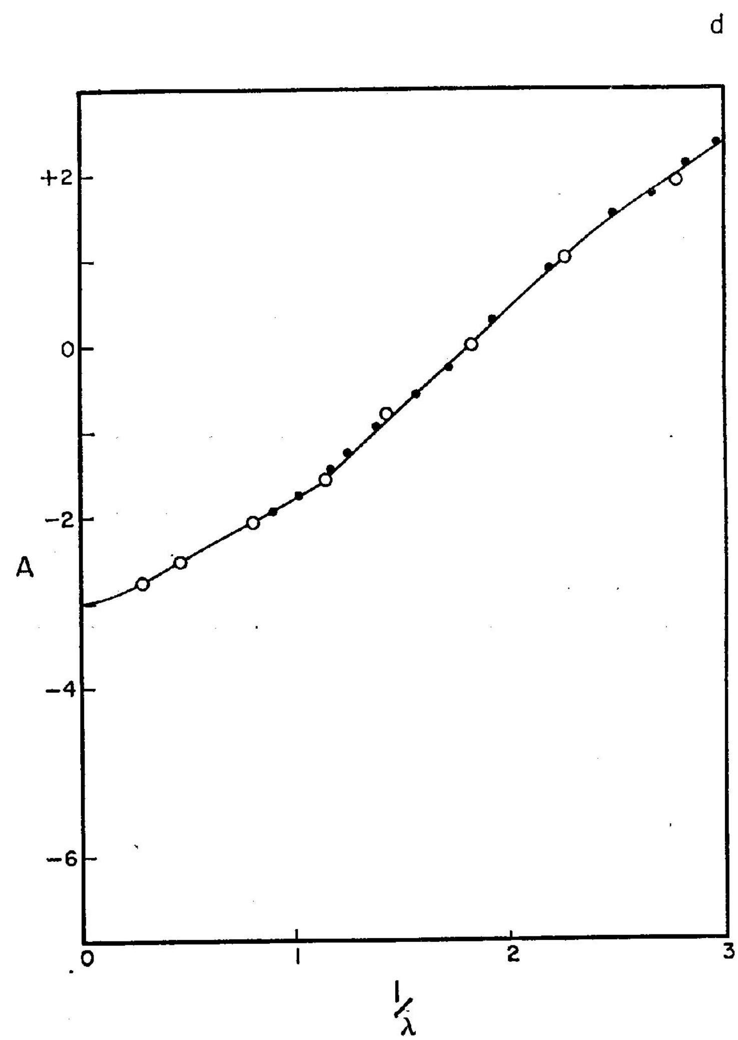

FIG. 4. The observed extinction law for Cepheus.

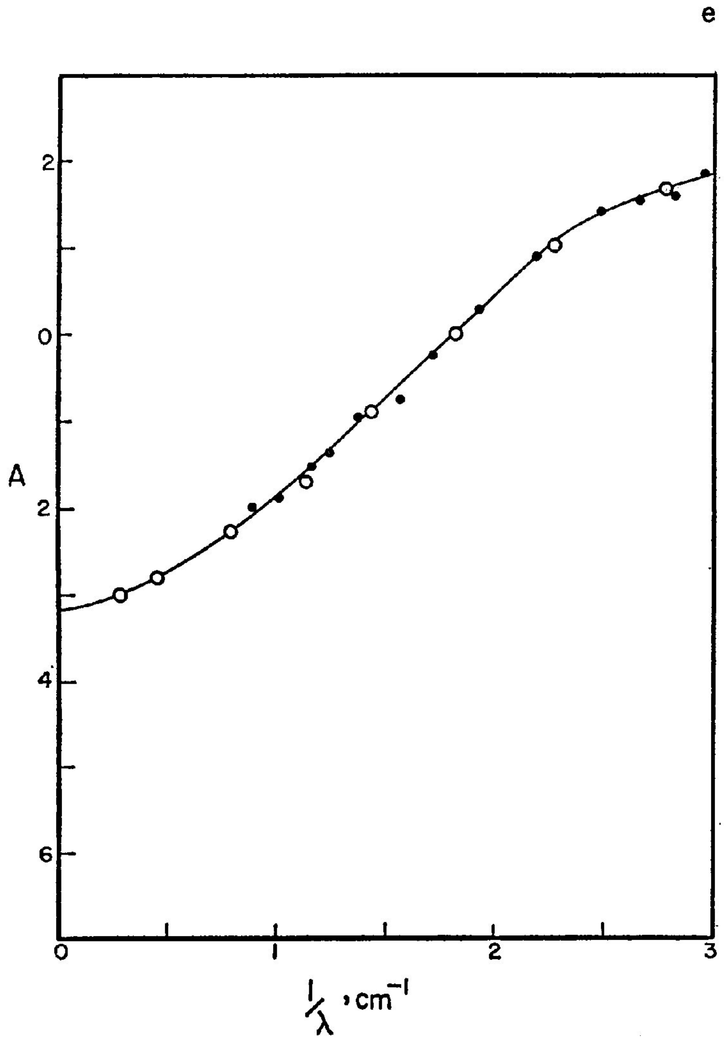

FIG. 5. The observed extinction law for Ophiucus.

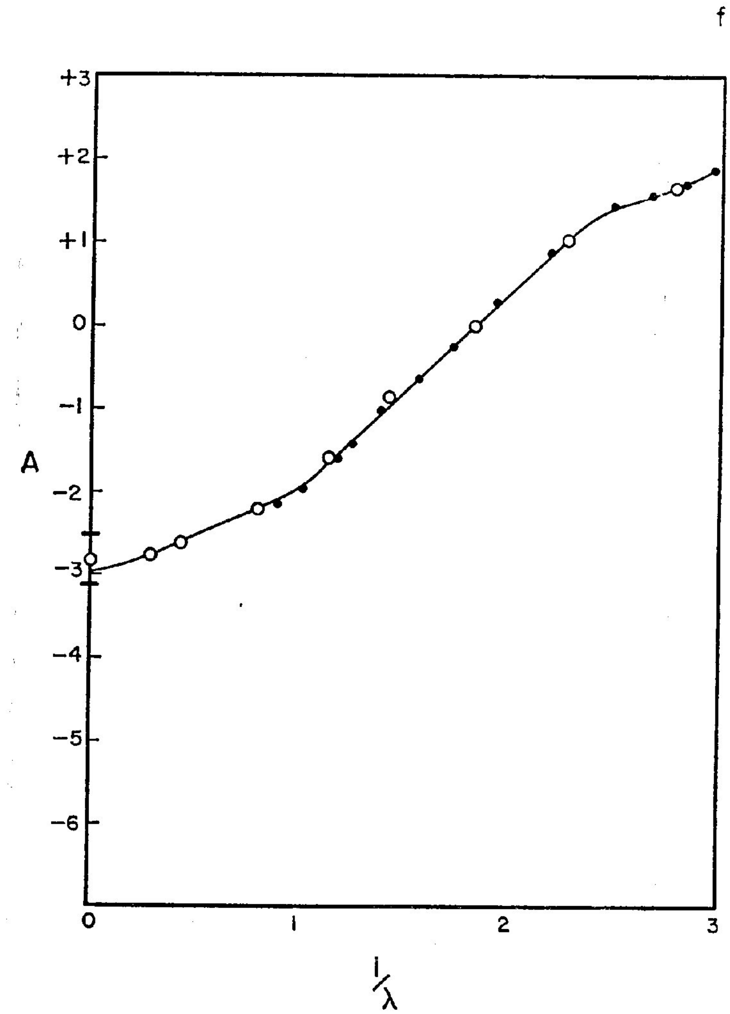

FIG. 6. The observed extinction law for Perseus.

extinction curves are parallel in this portion. On the blue side of the "break" at 2.4 μm^{-1}, and on the red side of the 1.2 μm^{-1} "break" the extinction laws of the several regions are quite different. Thus, while the extinction laws between 1.2 and 2.4 μm^{-1} appear to be very similar, they differ significantly in the value of $A_V = 3.24 \pm 0.2$ for the 5 regions. The kinds of particles and their size distributions are not identical.

III. THE ORION SWORD REGION

Curve "a" in Figure 7, for the Orion Sword region, differs very strongly from the others. Not only is the extinction, *normalized to* $E(B\text{-}V) = 1.0$, much greater than for the others, but the general shape of the curve is quite different. This difference in shape for the Orion Trapezium was noticed long ago by Stebbins and Whitford (1948). They speculated that the excess infrared radiation might be caused by cool, late-type companions of the Trapezium stars, but came to the conclusion that no plausible combination of cool-stars they had observed would produce a satisfactory fit to their colors.

I have recently observed at a resolution of 3.85 cm^{-1} the spectra of the two brightest stars of the Orion Trapezium. These spectra are published in the *Atlas of Stellar Spectra, I,* (Johnson 1977), along with a representative sample of cool, late-type stars. Examination of these spectra, and comparison with the late-type spectra in the *Atlas,* demonstrates conclusively that the excess infrared radiation does not come from cool stars; there is not the slightest trace of the spectral features of late-type stars

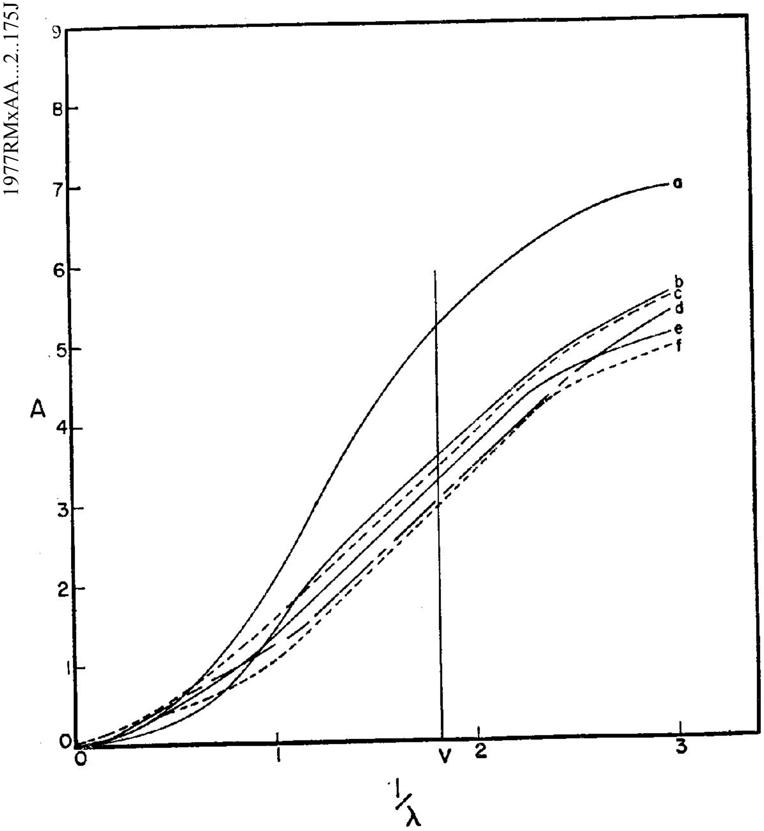

FIG. 7. The observed extinction laws for the six regions, with the ordinates set to zero for A = 0. The vertical line marked "V" designates the effective position of the V filter.

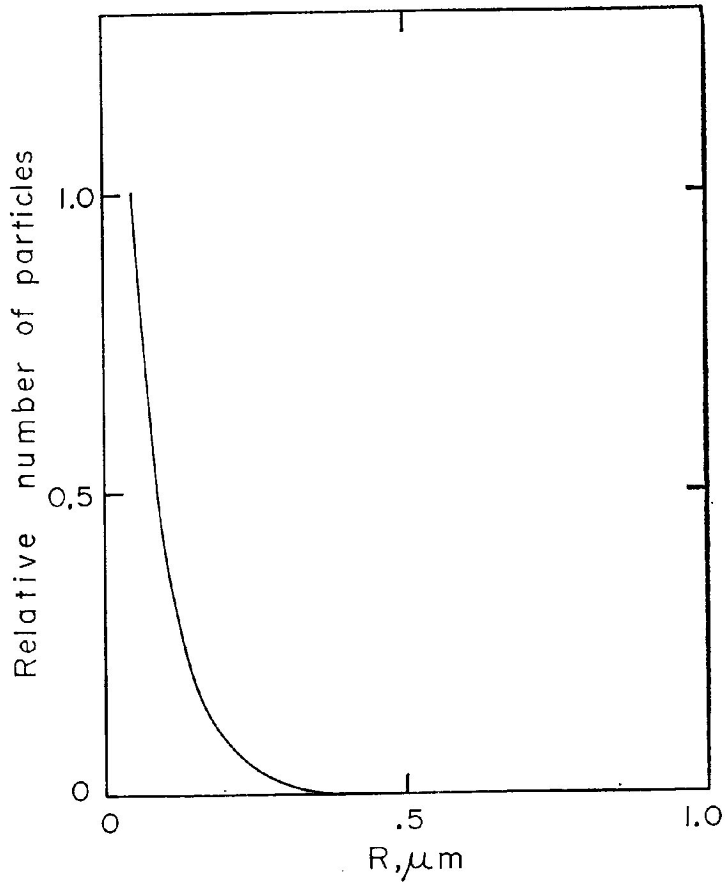

FIG. 8. The relative distribution of particle sizes in Cygnus.

in the spectra of the trapezium stars, even out beyond 10000 Å.

Other interesting information can be derived from the spectra in the *Atlas*. In Table 2 are listed the equivalent widths of the members of the Paschen series which are measurable in the spectra of the two Trapezium stars and in ζ Orionis. The equivalent widths of the lowest members of the Paschen series of the three stars have about the same equivalent widths, indicating that their spectral types are similar (θ^1 C Ori: O6; θ^1 D Ori : B1?; ζ Ori : O9.5 Ib). However, the lines of the trapezium stars are much broader than those of ζ Orionis and they become invisible much more quickly as we proceed toward the Paschen continuum. The Paschen lines of the Trapezium stars cannot be measured beyond P 14, while they can be measured so far as P 19 in ζ Orionis. These two facts indicate that the Trapezium stars have much lower luminosity than the O9.5 Ib supergiant, ζ Ori, although probably not as faint as class V, judging from preliminary measures of the Paschen lines in ζ Oph (O9.5 V) and α Vir (B2 V).

Of more interest concerning the interstellar extinction law in Orion is the fact that the Paschen lines of the Trapezium stars are not specially weak (for P 7-P 11) compared with those of ζ Orionis; this would seem to preclude a continuous emission source as the source of the infrared excess, because such emission would tend to fill in the Paschen lines, making them too weak. It appears that the peculiar extinction curve for the Orion Sword cannot be disputed on these grounds.

The very large departure of the Orion Sword curve from the others in Figure 7 is caused largely by the normalization to E(B−V) = 1.0; normalization at V−K would make the curve lie amongst the others. No change in normalization, however, can account for the well-established difference in shape between the Orion Sword law and the others.

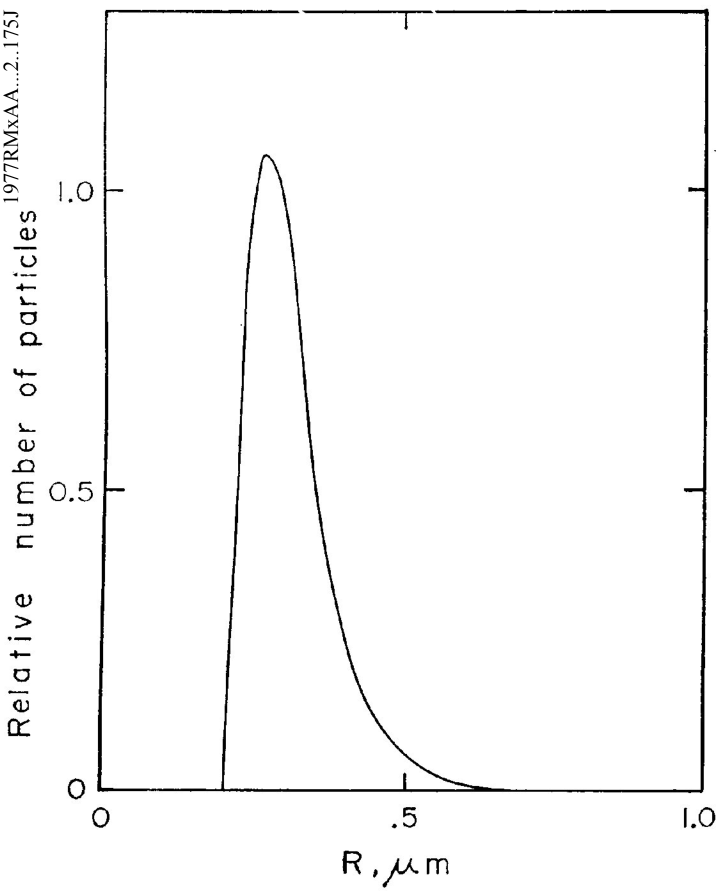

FIG. 9. The relative distribution of particle sizes in the Orion Nebula.

TABLE 2

EQUIVALENT WIDTHS OF PASCHEN LINES IN ORION STARS

	Equivalent widths, Å		
Line	θ^1 Ori A	θ^1 Ori B	ζ Ori
P 7	3.2	3.4	3.6
P 9	2.3	2.7	1.6
P 11	0.7	2.2	1.7
P 12	0.8	1.6	1.5
P 13	0.5	0.6	1.1
P 14	0.3	0.4	0.9
P 15	(not measurable)		0.6
P 16	"	"	0.6
P 17	"	"	0.3
P 18	"	"	0.2
P 19	"	"	0.2
P 20	(not measurable)		

This shape difference must be accounted by other means.

Long ago Baade and Minkowski (1937) suggested that the Trapezium stars might have modified the interstellar medium surrounding them by "blowing away" (by radiation pressure) the small particles of the Orion Nebula. The general shape of the Orion extinction curve agrees with this idea.

IV. SUMMARY

We have shown here that the interstellar extinction laws in several widely separated celestial regions are quite similar in some respects, but different in others. It does not seem likely that the physical characteristics of he interstellar medium can be everywhere identical, although it does appear that a value of $R = A_V/E(B-V) = 3.24$ may be a good approximation for statistical studies of stellar space distribution. We have reconfirmed the peculiar shape of the extinction law for the Orion Sword (Nebula) region, and we have shown that the observed infrared excess, relative to $E(B-V)$, cannot be caused by cool, late-type companions of the Trapezium stars, nor can it be caused by some sort of infrared continuous emission. The difference in the Orion law from those elsewhere most likely is due to ejection of the small particles from the Nebula by the radiation pressure from the O-type stars embedded in the nebula. It is very likely that this process has also occurred in other places where O-type stars are imbedded in nebulae, and that high ratios

$$[R = A_V/E(B\text{-}V)]$$

exist there also.

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