BROADBAND STRUCTURE IN THE INTERSTELLAR EXTINCTION CURVE*

D. S. HAYES, G. E. MAVKO, R. R. RADICK, and K. H. REX
Rensselaer Polytechnic Institute, U.S.A.

and

J. M. GREENBERG
State University of New York at Albany, N.Y., U.S.A.

Abstract. We have analysed observations of the interstellar extinction in the range 3400 Å–11 000 Å. The observations have high photometric accuracy and wavelength resolution, and allow a detailed examination of broadband structure as well as the general shape of the wavelength dependence of the extinction curve. The broadband structure has a characteristic size of several hundred ångströms, and may be as important as the diffuse bands in indicating the physical nature of the grains.

We describe our preliminary theoretical interpretation of this broadband structure, and the new observation which it predicts.

1. Introduction

In this paper we report a preliminary observational and theoretical analysis of broadband structure in the interstellar reddening curve in the range 3500–11000 Å. By 'broadband', we mean observations with a wavelength resolution on the order of 100 Å. There are two 'features' in the interstellar extinction curve which we will discuss: (a) The 'knee' in the interstellar extinction curve, taken to be at $1/\lambda = 2.25\ \mu^{-1}$ or $2.30\ \mu^{-1}$ in various published accounts (Whitford, 1958; Nandy, 1964; Underhill and Walker, 1966, 1967; Harris, 1969) and (b) a broad, shallow feature centered on $1/\lambda = 1.8\ \mu^{-1}$.

The 'knee' in the interstellar extinction curve is an apparent sharp break in the slope of the interstellar extinction curve in the blue region of the spectrum. The interstellar extinction curve has been described as having the appearance of two intersecting straight lines by some observers (Whitford, 1958; Nandy, 1964; Harris 1969; Underhill and Walker, 1966, 1967). This 'knee' has been attributed to graphite (Wickramasinghe, 1967) because the index of refraction of graphite has a change in slope a short distance to the blue of the position of the knee, as determined by Nandy (1964).

The broad shallow feature centered on $1/\lambda = 1.8\ \mu^{-1}$ was noticed by Whiteoak (1966) and Walker (1967), and was discovered independently by one of us (DSH) in 1967. Seen in 'emission', it has not been noticed by other observers because of its extreme width (~ 2000 Å) and shallowness ($0\overset{m}{.}05$ for 1^m total reddening between $1/\lambda = 2.09$ and $1.136\ \mu^{-1}$). It is most probably a feature connected with the grains, because of its great width. One would not expect such a broad feature to be caused by an independent constituent of the interstellar medium, especially in 'emission'.

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In this paper we will show that the 'knee' in the interstellar extinction curve is explained in a straightforward way by a change in the curvature of the theoretical extinction curve in this region. The wavelength of this curvature change is related only to the size distribution of the grains. Thus, there will be no need to invoke graphite to explain the 'knee'.

The feature at $1/\lambda = 1.8\ \mu^{-1}$, however, must be explained by a change in the index of refraction of some component of the interstellar medium. A plausible model of this feature is that it is part of a double dispersion curve resulting from two broad absorptions centered on 4170 and 6670 Å. The most important consequence of this model is that it predicts that structure should also be seen in the wavelength dependence of the interstellar polarization.

2. The Observed Features

Because of the relative shallowness of these features compared to the general slope of the extinction curve, they are difficult to see in an ordinary graph of the interstellar extinction vs λ or $1/\lambda$. We have chosen the graph of the residuals after a straight line is subtracted from the measured extinction curves. In Figure 1 are shown data for a mean extinction curve derived from spectrophotometric measurements of 28 O-type stars. The data are those of Whiteoak (1966). The extinction curves for the individual stars have been derived by subtracting off the mean energy distribution of seven stars

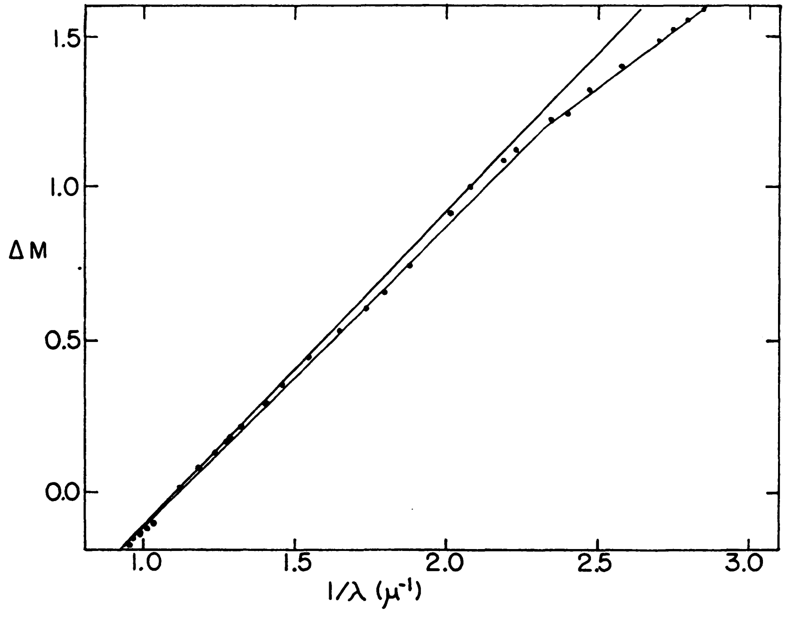

Fig. 1. The mean reddening curve for twenty-eight O-type stars. Also shown are two straight lines intersecting at $2.3\ \mu^{-1}$, exhibiting a common interpretation of the observations, and the reference straight line, passing through $2.19\ \mu^{-1}$ and $1.136\ \mu^{-1}$.

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of small reddening. Whiteoak compared the reddened stars with model atmospheres, a procedure which can be successful only if the absolute calibration of stellar energy distributions is correct, within the error of the observations. The Oke (1964) calibration, even with the modifications introduced by Whiteoak, was sufficiently in

TABLE I

The 'unreddened' stars

		B	$m_{2.09}-m_{1.136}$
ι Ori	O9 III	0.12	−1.01
υ Ori	B0 V	0.18	−1.07
ζ Ori	O9.5 Ib	0.13	−0.95
δ Ori	O9.5 II	0.15	−0.97
σ Ori	O9.5 V	0.18	−0.99
15 Mon	O7	0.15	−1.03
10 Lac	O9 V	0.13	−1.00
mean		0.15	−1.00

TABLE II

The 'reddened' stars

	B	$m_{2.09}-m_{1.136}$	$E(m_{2.09}-m_{1.136})$	D
HD 13268	0.09	−0.31	+0.69	0.09
17520	0.13	0.11	1.11	0.07
17505	0.09	0.30	1.30	0.05
14947	0.06	0.42	1.42	0.05
16429	0.11	0.83	1.83	0.04
15570	0.05	1.00	2.00	0.04
46966	0.14	−0.62	0.38	—
47129	0.11	−0.37	0.63	0.03
46150	0.11	−0.21	0.79	0.04
46149	0.13	−0.14	0.86	0.04
46223	0.07	0.00	1.00	0.04
46573	0.07	0.21	1.21	0.05
188209	0.11	−0.72	0.28	—
193322	0.16	−0.36	0.64	0.04
191978	0.15	−0.27	0.73	0.06
190864	0.06	−0.13	0.87	0.04
192281	0.06	0.22	1.22	0.06
193443	0.12	0.21	1.21	0.07
HDE 228368	0.08	0.49	1.49	0.04
228854	0.08	0.98	1.98	0.06
HD 194334	0.05	1.20	2.20	0.05
BD+40°4227	0.09	2.23	3.23	0.04
HD 218915	0.11	−0.52	0.48	—
209975	0.10	−0.37	0.63	0.06
210839	0.08	−0.04	0.96	0.08
BD+60°2522	0.06	0.43	1.43	0.03
HD 216898	0.15	0.57	1.57	0.05
217086	0.13	0.82	1.82	0.05

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error (Hayes, 1970; Oke and Schild, 1970) that Whiteoak's comparison of the wavelength dependence of extinction for different regions (his Figure 3) only shows the error in the absolute calibration scaled by the relative mean reddening for each region. The same calibration error partially vitiates the work of Underhill and Walker (1966, 1967) which also referred the reddened stars to model atmospheres.

For our 'unreddened' star, we have used the mean energy distribution of seven stars with little reddening. They are listed in Table I, along with their spectral types, Balmer discontinuities, and color $m(\lambda_1)-m(\lambda_2)$ where $1/\lambda_1 = 2.09\ \mu^{-1}$ (4785 Å) and $1/\lambda_2 = 1.136\ \mu^{-1}$ (8800 Å). Also given are the data for the 'mean unreddened star'. In this range of spectral types (O5–B0), there is little change in the slope of the continuum. In the wavelengths used by Whiteoak for this observations, only the Balmer discontinuity will show a significant change with spectral type or luminosity class, and we have applied corrections to our reddening curves for the difference in Balmer discontinuity between the mean unreddened star and each reddened star. Table II gives a list of all the reddened stars used, with their Balmer discontinuities, colors and color excesses for the wavelength points corresponding to $1/\lambda = 2.09\ \mu^{-1}$ and $1.136\ \mu^{-1}$.

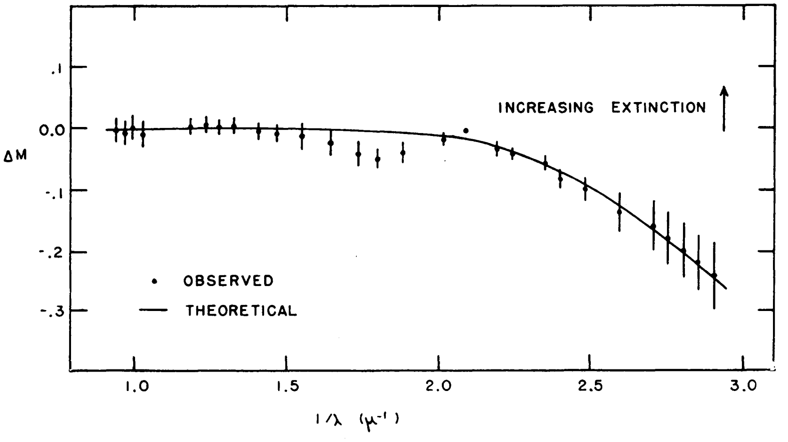

Fig. 2. The extinction residuals, after the reference straight line is subtracted from the mean extinction curve. Also shown is a theoretical curve.

The individual extinction curves are normalized to 1 mag. reddening between $1/\lambda =$ 2.09 and $1.136\ \mu^{-1}$, and then averaged and plotted against $1/\lambda$. The average curve is shown in Figure 1, along with our reference straight line, passing through the normalization points. Also shown are the two straight lines which best describe the interpretation often found in the literature. They show the 'knee' at their intersection at about $2.30\ \mu^{-1}$. The residuals produced when the reference straight line is subtracted from the extinction curve are shown in Figure 2. The residuals allow a closer look at the 'knee' in the interstellar extinction law. It should be evident, from Figure 2, that since Nandy drew his straight lines in such a way as to average over the feature at $1.8\ \mu^{-1}$, he has arrived at a value of the wavelength of the 'knee' which is too far to

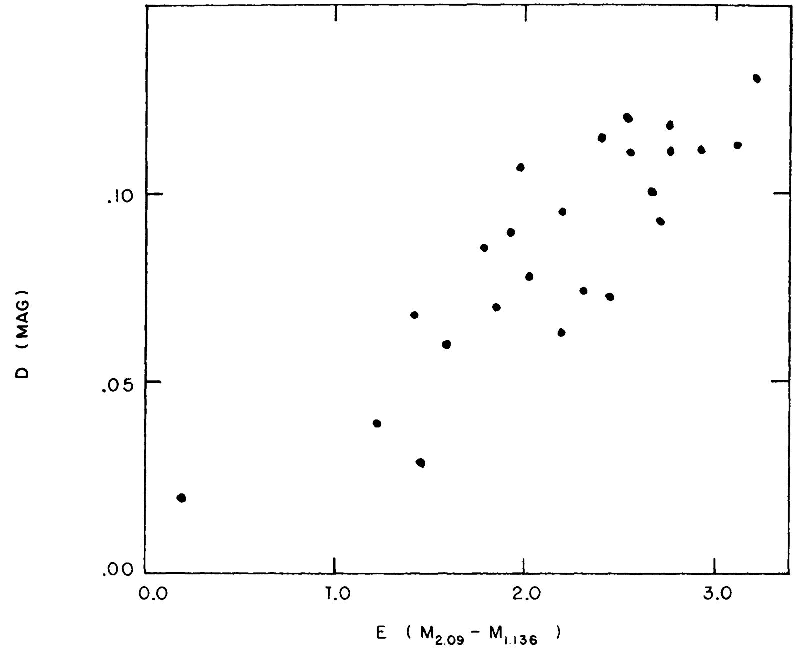

Fig. 3. The central depth of the 1.8 μ^{-1} 'feature', plotted against $E(m_{2.09}-m_{1.136})$.

the blue. If one must assign a value to the position of the 'knee', it must be placed, not at 2.30 μ^{-1}, but at about 2.09 μ^{-1}:

Figure 2 also clearly shows the broad, shallow feature peaking at about $1/\lambda = 1.8$ μ^{-1}.

That the 1.8 μ^{-1} feature is definitely interstellar is shown by its close correlation with the total reddening, as shown in Figure 3. We have defined the strength of the feature by the central depth, D, in magnitudes, of a smooth curve drawn through the residuals. The central depth is measured at 1.8 μ^{-1} where the peak is almost always found. The zero level is at 2.09 μ^{-1} and 1.732 μ^{-1}. The total reddening is measured by the color excess defined by the points at 2.09 μ^{-1} and 1.136 μ^{-1} as given in Table II. The value of D, for each star is also given in Table II. Although the central depth shows large scatter (as would be expected, since the largest value is only $0\overset{m}{.}07$, and the observational accuracy is about $0\overset{m}{.}02$), the linear correlation is obvious. This means that this feature is closely associated with whatever causes the reddening, although it does not prove that it is caused by some characteristic of the interstellar grains, themselves.

3. Theoretical Interpretation

Also shown in Figure 2 is a theoretical curve. It has been derived from a simple analytic approximation to the wavelength dependence of scattering from spherical par-

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ticles with a constant real index of refraction of $1.33-0.00i$ and a Gaussian size distribution $n(a) = A \exp[-(a/a_0)^2]$, with an a_0 of 0.23 μ (Greenberg, 1973). The theory for perfectly aligned infinite cylinders seen broadside produces the same curve in this region, if the index of refraction is constant. Thus, the 'knee' in the extinction curve is a normal consequence of the existence of the interstellar medium of a distribution of dust particles with sizes resulting in a change of curvature in the curve at about this wavelength, and one need not look for changes in the index of refraction to explain it. We should comment here that even Nandy's value of the 'knee' lay too far to the red of the change in the index of refraction of graphite (for which, see Wickramasinghe and Guillaume, 1965) for the graphite to be a plausable cause of the knee. Incidentally, our conclusion does not rule out the existence of a distribution of smaller sizes, as is presumably needed to fit the ultraviolet extinction data. Therefore, the 'knee', such as it is, does not give evidence about the composition of the grains. Apparently, it *does* give evidence on the size distribution of the grains.

We have made a preliminary attempt to construct a plausible model of the cause of the broadband structure in the extinction curve, as evidenced by the 1.8 μ^{-1} peak. Since this peak is seen in 'emission', we must consider broad absorption bands in neighboring regions. It is evident that such absorption bands will be very broad (several hundred to a thousand ångströms), so it seems likely that they are caused by an impurity in the grains which cause the interstellar extinction, itself. Following Greenberg and Stoeckly (1970), we predict that structure will also be produced in the wavelength dependence of the interstellar polarization, and that the observed existence or absence of such broadband polarization structure will be evidence for or against this model

In order to better define the structure to be fitted in the extinction law, we must find the residuals from a smooth 'continuum' extinction law, instead of from a straight line, as in Figure 2. We have defined the smooth continuum by a theoretical curve similar to that shown in Figure 2. It is also based upon a model of perfectly aligned infinite cylinders, but with a size distribution of the radii of a the cylinders given by $n(a) = \exp[-5(a/a_0)^3]$ where a_0 is taken to be 0.225 μ. The index of refraction is here taken to be $1.66-0.01i$. The residuals which result when this curve is subtracted from the observed extinction curve are shown in Figure 4. It is clear that the peak at 1.8 μ^{-1} is not an isolated feature, but part of a complex structure extending over the entire range of observation. One should therefore include observations extending into the UV and IR. The examination of the UV and IR extinction data which already exists has been started, but is not complete at this date.

We will assume that the impurities in the grains responsible for this structure result in a limited number of broad absorptions. The frequency dependence of the complex index of refraction m is therefore given by the Clausius-Mossotti relation (in mks units):

$$\frac{m^2-1}{m^2+2} = \frac{m_0^2-1}{m_0^2+2} + \sum_{j=1}^{2} \left\{ \frac{N_j e^2}{12\pi^2 \varepsilon_0 m_e} \left[\frac{1}{\nu_{0,j}^2 - \nu^2 + i\nu\gamma_{1,j}} \right] \right\},$$

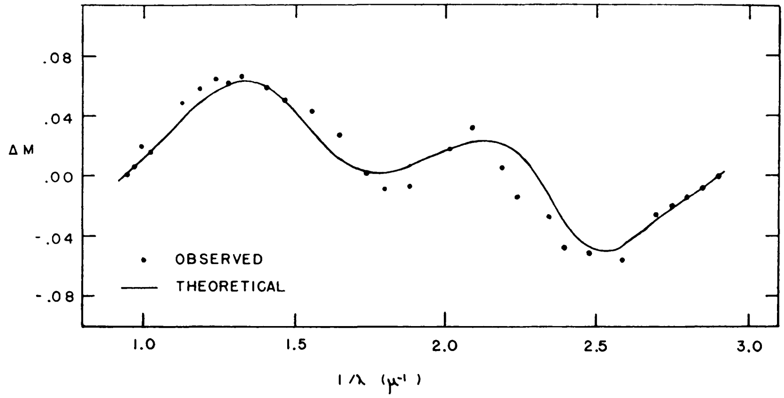

Fig. 4. The extinction residuals, after the reference 'continuum' curve is subtracted from the mean extinction curve. Also shown is a theoretical curve.

where we will attempt to find values of the natural frequencies ν_0, damping constants γ_1 and effective densities N of impurity atoms which will result in extinction residuals which fit the observations shown in Figure 4. This wavelength dependent index of refraction is then used to calculate the theoretical extinction curve for perfectly aligned infinite cylinders with the cubic size distribution given above.

TABLE III

Absorption band parameters used in Clausius-Mossotti relation

λ_0	ν_0	γ_1	$\Delta\lambda$	N
4170 Å	7.2×10^{14} s^{-1}	1.8×10^{14} s^{-1}	1000 Å	5.04×10^{25} m^{-3}
6670	4.5	2.1	2600	5.04

The theoretical curve is also shown in Figure 4. Table III lists the parameters of the Clausius-Mossotti relation for this curve, including the halfwidth, $\Delta\lambda$, for each absorption.

For this theoretical curve, we have taken $a_0 = 0.225\ \mu$, and the 'continuum' index of refraction m_0 to be $1.66 - 0.01i$.

All calculations of the scattering and absorption efficiencies were made with the computer code developed by Shah (1967).

The agreement between the theoretical residuals and the observed residuals shown in Figure 4 is on the order of the size of the measurement errors. Thus, until better observations are available, we will consider this physical model to be at least a plausible one, and examine its implications with respect to the wavelength dependence of the interstellar polarization. The theoretical normalized polarization is shown in Figure 5. There is clearly a measureable structure present. Work is now underway to try to confirm this feature observationally.

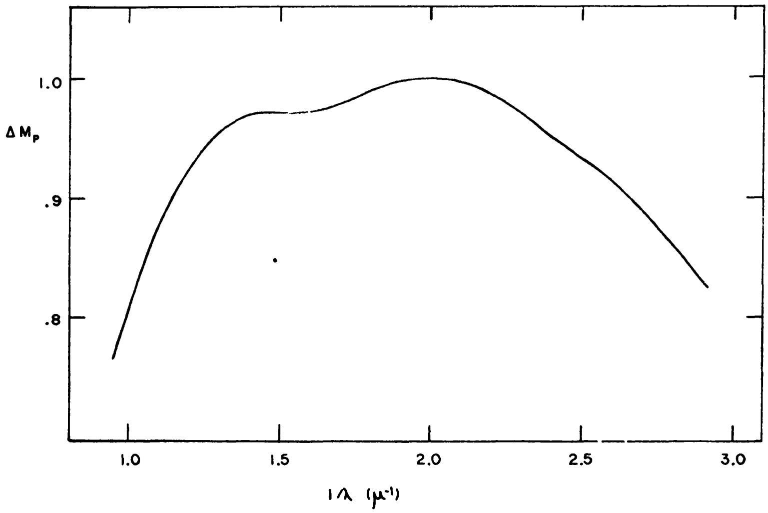

Fig. 5. The normalized polarization predicted for the theoretical model shown in Figure 4.

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