Section I

Dust in the Diffuse Interstellar Medium

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MEASUREMENTS OF INTERSTELLAR EXTINCTION

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ABSTRACT. The results of interstellar extinction measurements from the near IR to the far-UV are reviewed. The average interstellar extinction curve for the diffuse cloud medium exhibits a nearly linear rise (in $1/\lambda$) from 1 μm^{-1} to the 2.25 μm^{-1} "knee" in extinction where the slope changes. In the UV there is a pronounced extinction bump near 4.6 μm^{-1} (2175 Å) followed by a broad minimum and a steep rise in extinction to the shortest wavelengths for which measurements exist. For wavelengths shortward of about 5500 Å, the interstellar extinction curve exhibits considerable variation in shape from one sight line to another. In addition to strength variations, the width (FWHM) of the 2175 Å extinction bump has been observed to vary by more than a factor of two from 360 to 770 Å with the average width being 480 Å. In contrast, the central position of the feature only varies from 2110 Å to 2195 Å with the average central position being 2175 Å. The most extreme variations in extinction are found at far-UV wavelengths where $E(\lambda - V)/E(B - V)$ has been found to range from 3 to 12.5 at 1250 Å. In the last few years significant progress has been made in determining various empirical relationships among extinction parameters in the different wavelength regimes and in determining how extinction curve shape changes are influenced by the interstellar environment in which the dust resides. Those relationships are discussed.

1. INTRODUCTION

The extinction produced by interstellar dust refers to the combined effects of the scattering and absorption of electromagnetic radiation by dust along sight lines through interstellar space. Since extinction is generally measured toward stars, the sight lines extend from the earth to the star and have an angular extent equal to the infinitesimal solid angle subtended by the star. The well-defined sight line over which the scattering and absorption occurs greatly simplifies the theoretical interpretation of extinction measurements. Accurate measurements of the wavelength dependence of extinction therefore provide fundamental information about the physical and chemical nature of interstellar dust.

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The ultimate goals of extinction measurements are to help determine the sizes and chemical compositions of interstellar grains and to help to understand how the dust/gas phase chemistry operates. These properties are not uniquely determined by extinction measurements alone. Nevertheless, extinction measurements frequently provide very important clues as to which solids might be present. Also, very important constraints frequently result from the lack of extinction features which help to exclude some of the many materials which could exist in interstellar space. An additional motivation for understanding the detailed behavior of extinction is that astronomers frequently encounter situations where it is desirable to correct the flux distributions of reddened objects for its effects.

This is a review of interstellar extinction measurements from near-IR (NIR) to far-UV wavelengths for Milky Way dust. While our review emphasizes recent results, there is considerable overlap with other recent reviews of the properties of interstellar dust [e.g. Mathis (1987, 1988); Witt, 1988]. Many of the topics which we have not included in our review (e.g. dust models, polarization, the diffuse interstellar bands, the very broad structure in the visual extinction, the various IR extinction features, circumstellar extinction and extragalactic dust) are considered in the other reviews found in this symposium volume. Since other papers presented at this symposium will discuss interpretations in terms of grain models, this review concentrates on the observational results upon which the models must be judged.

The organization of this review is as follows: In § 2 we discuss the practical aspects of producing extinction measurements and how to assess their reliability. In § 3 we review recent observations of interstellar extinction in the NIR through far-UV. In § 4 we summarize the observational relationships between different aspects of extinction parameters, and between extinction parameters and other observables. Finally, in § 5 we discuss some research areas which we believe will be very productive in the near future.

2. PRODUCING EXTINCTION PARAMETERS AND CURVES

The spectrum of a reddened star expressed in magnitudes can be written as:

$$m(\lambda) = M(\lambda) + A(\lambda) + DM, \tag{1}$$

where $m(\lambda)$ and $M(\lambda)$ are, respectively, the apparent and absolute magnitudes of the star at wavelength, λ, $A(\lambda)$ is the total extinction, and $DM = 5\log d(\mathrm{pc}) - 5$ is the distance modulus of the star. Since DM is independent of λ, colors are used to eliminate it, with the $\lambda - V$ color being traditionally employed. Thus, one normally deals with observed colors of the form:

$$m(\lambda - V) = M(\lambda - V) + E(\lambda - V), \tag{2}$$

where $m(\lambda - V) = m(\lambda) - m(V)$ and $M(\lambda - V) = M(\lambda) - M(V)$ refer to the observed and intrinsic colors between λ and the photoelectric V band ($\lambda \approx 5500$ Å) and $E(\lambda - V) = A(\lambda) - A(V)$ is the standard color excess between λ and V. It is frequently useful to employ optical depth units rather than astronomical magnitudes. These can be expressed as $\tau(\lambda) = A(\lambda)/1.086$ and $\tau(\lambda)—\tau(V) = E(\lambda - V)/1.086$. There are two basic approaches for extracting the extinction information contained in Equation (2). These are from plots of $E(\lambda - V)$ versus $E(\lambda' - V)$ and from individual curves illustrating the wavelength dependence of extinction. Which approach is employed is usually dictated by the sample size and the number of observed wavelength points. The interpretation of either approach relies upon our ability to determine whether variability seen from one line-of-sight to another is the result of observational uncertainties or of genuine differences in the properties of the scattering and absorbing material. Because we can only understand our results as well as we understand the errors which affect them, we begin with a discussion of the errors affecting extinction data.

2.1. ERRORS AND SAMPLE BIAS

The sources of error can be separated into two broad categories: errors incurred in the observing process and errors in the analysis. Both types of error are often systematic in wavelength and in total extinction.

Some of the major sources of observational errors include: photometric errors (due to Poisson statistics, sky subtraction errors, atmospheric extinction corrections, etc.), scattered light contamination from dust near the star and instrumental instabilities or degradations. Some of these errors may introduce characteristic spectral signatures into the observations. For example, the wavelength dependence of the degradation of the spectrometers aboard the second Orbiting Astronomical Observatory (OAO-2) and the International Ultraviolet Explorer (IUE) Satellites are known to produce structure which can influence the appearance of the 2175 Å extinction bump in uncorrected data (Savage, 1975; Bohlin and Grillmair, 1988) while IUE detector saturation problems have, on occasion, lead to the reporting of erroneous extinction features near 2800 Å (Karim, Hoyle and Wickramasinghe, 1983).

There are also several sources of analysis errors. For example, a standard star used to determine the extinction may contain unknown peculiarities. This error can be recognized if the extinction properties of all the stars compared to one standard have a common peculiarity. The mismatch of spectral details between the reddened and standard star used to determine the extinction parameters is frequently the dominant source of error affecting extinction measurements. This error shows up as scatter near the origin in plots of one color excess versus another, and may exhibit itself as spurious fine structure in extinction curves. Because no two stars are ever truly alike, the best one can hope to do is to minimize the mismatch effect by carefully selecting reddened and standard stars, and to randomize the residual effects by increasing the sample size. In the ultraviolet, it has been determined that normal main sequence B stars are particularly useful because the effects of the continuum mismatch for these stars tend to be self-cancelling (Massa, Savage, and Fitzpatrick, 1983).

It is possible to quantify the effects of the various sources of error and to produce estimates for their magnitudes. The approach is to simply estimate the variance of each kind of error on each quantity entering the measurements (Massa, Savage, and Fitzpatrick, 1983; Carnochan, 1986; Massa, 1987). The reliability of these estimates can be validated by observing the extinction to several stars in a single cluster in which there is no reason to suspect that conditions may differ greatly from one line-of-sight to another and then to determine whether the observed variance matches the predicted variance. Massa and Fitzpatrick (1986) have performed this exercise to identify which of a set of clusters seemed to be affected by a single extinction curve.

They then used these results to determine the measurement errors of additional parameters, such as the width of the 2175 Å extinction bump, for which *a priori* error estimates are difficult to determine.

There are a few general problems which plague all extinction measurements. One is the intrinsic sample bias of a magnitude-limited sample. In all such surveys, the most reddened stars are necessarily the most luminous. This bias, recognized by Kapteyn (1909), causes the effects of the luminosity differences on stellar continua to be intertwined with the effects of extinction. Another problem is that there are very few lines-of-sight which sample a single environment. This fact always complicates the interpretations of extinction measurements, and forces us frequently to rely on statistical interpretations. A related problem is that extinction properties derived from long pathlengths are biased toward the most highly absorbing material along the line-of-sight. Finally, from visual to shorter wavelengths, it is not generally possible to sample the densest concentrations of dust. Therefore, most of the extinction information available refers to dust in diffuse interstellar clouds or in the outer layers of dense clouds.

2.2. INTRINSIC VARIABILITY

If different lines-of-sight contain dust with different absorption and scattering characteristics, then the measured extinction curves will be intrinsically different from one line-of-sight to another. This effect is particularly easy to identify in plots of one color excess versus another. If the photometric errors are relatively independent of extinction, the extinction variation causes the data points to fan out from the origin into a "wedge"-shaped domain. The scatter at zero excess is just the mismatch error. The boundaries of the wedge may reflect the extremes in the range of extinction affecting the data, but this need not be the case. The reason is that there may not be a line-of-sight which is affected exclusively by dust having one extreme of extinction or the other. Furthermore, a wedge-shaped distribution of points only indicates more than one form of extinction. There may, in fact, be several distinct components affecting the data and only principle component analysis can determine the actual number (see Massa, 1980; Nicolet, 1987). Nevertheless, wedge-shaped boundaries on a color excess plot indicate that there is no universal extinction "law" for the two extinction parameters under consideration. Figure 1 is a plot of the (1500 Å) $- V$ color excess measured by the Netherlands Astronomical Satellite (ANS) (Savage *et al.*, 1985) versus the 2175 Å bump excess. Because most stars have very smooth intrinsic continua across the 2175 Å feature, the mismatch scatter at the origin is almost exclusively in the measures of the (1500 Å)-V excess, reflecting the range of intrinsic (1500 Å)-V colors within a spectral class. Notice that the points fan out and become less centrally concentrated at higher excesses. This clearly demonstrates how poorly the bump and the level of the far-UV extinction are coupled (Greenberg and Chlewicki, 1983).

3. RESULTS OF EXTINCTION MEASUREMENTS

In this section, we review recent extinction measurements in the NIR, visual and UV. For each wavelength range we report the form of the mean curve and discuss whether large scale deviations from this mean are common.

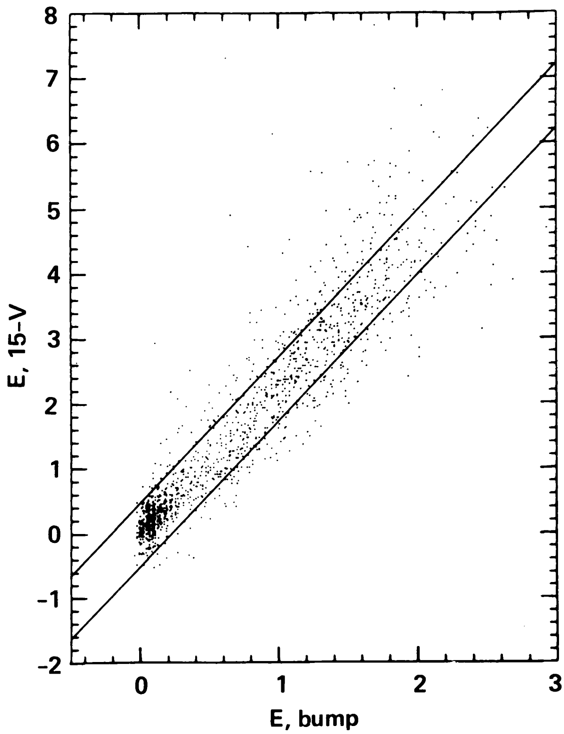

Fig. 1. Correlation between the (1500 Å)-V color excess, E(15-V), and E(bump), a measure of the strength of the 2175 Å extinction bump based on ANS satellite data. Near the origin, the scatter in E(15-V) reveals the stellar mismatch errors. The two solid lines which bracket the mismatch errors reveal that at large extinction, the data fan out into a "wedge"-shaped region which clearly reveals that extinction at 1500 Å and in the bump are poorly coupled. This figure is from Savage *et al.* (1985) through the courtesy of the Astrophysical Journal.

3.1. THE NIR

NIR extinction measurements are particularly useful for two reasons. First, because extinction is very weak in the NIR, it is possible to sample much more deeply embedded dust than at shorter wavelengths. Second, NIR measurements allow one to estimate the total extinction along the line-of-sight by means of the "color difference method". This approach takes advantage of the fact that extinction decreases at longer wavelengths. As a result, without being too bold, it is possible to extrapolate extinction curves to zero extinction at infinite wavelength. The result of this extrapolation is normally presented as the ratio of total-to-selective extinction, $R = A(V)/E(B-V)$.

Particular care must be taken in selecting stars to study NIR extinction. For example, the winds of OB supergiants can affect their NIR colors (Barlow and Cohen, 1977). Fortunately, these stars are not normally used for extinction mea-

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surements at other wavelengths because supergiant classes are so broad and the effects of luminosity on the spectra so great that mismatch errors are quite large. The Be phenomena can affect the NIR colors of main sequence B stars, but normally such stars have undergone episodes of strong line emission in the past and can be identified and avoided. Also, for stars associated with hot emitting dust (e. g. stars in HII regions such as θ Ori and Herschel 36), great care must be taken to avoid the contamination of the extinction measurements by the thermal dust emission (Cardelli and Clayton, 1988).

Numerous studies of NIR extinction have been carried out and many of the earlier results are summarized by Koornneef (1983) who gives, in his Table 5, a recommended average NIR extinction curve for diffuse cloud dust. The value $R = 3.1$ listed by Koornneef for the average sight line agrees within the errors of about ± 0.05 with other recent determinations (e.g. Rieke and Lebofsky, 1985). It has been determined that at wavelengths longer than V, and except in dark clouds, the wavelength dependence of the NIR extinction curve is invariant (Jones and Hyland, 1980; Smith, 1987; Tapia *et al.*, 1988; Whittet, 1988). It is now widely accepted that most of the differences in R values obtained by the color difference method applied along various lines-of-sight is caused by departures from the standard curve at wavelengths shortward of V. There is, however, one caveat. Because dust absorbs so poorly in the NIR, large column densities of dust must be traversed before appreciable extinction occurs. Consequently, the diffuse lines-of-sight used to determine the curve shape may represent a mean of several curves from a number of distinct regions which have been weighted toward the curve of the most strongly extincting material.

A considerable amount of important NIR extinction work is in progress, especially observations of open clusters and associations (Chini and Krugel, 1983; Leitherer and Wolf, 1984; Tapia *et al.*, 1984; Tapia *et al.*, 1988; Roth, 1988). Although this work continues to suggest little or no variation in extinction for wavelengths longer than V, the extinction variations shortward of V are substantial and observations of these variations provide very important clues about processes which modify grains.

3.2. THE VISUAL

Two large data bases for studying visual extinction exist. One is filter photometry and the other spectrophotometry. When color excesses are derived from filter photometry and combined with spectroscopic distance estimates, the results can be extremely useful for discerning the three-dimensional structure of dust in the Milky Way. For example, the maps of FitzGerald (1968), Neckel and Klare (1970), and Lucke (1978) illustrate well the patchy distribution of dust in the local region of the Milky Way. With special care, these color excess maps can be made with an accuracy of better than 0.01 magnitudes (Knude, 1984). A statistical analysis of the degree of patchiness of reddening data provides interesting information on the typical sizes and optical thicknesses of interstellar clouds (Davidson, Claflin and Haisch, 1987).

Intrinsic variability in the shape of visual extinction curves is very difficult to assess from filter photometry, and spectrophotometry is required to address this question. Unfortunately, very little spectrophotometric extinction work has been done with modern detectors which are capable of producing spectra having very high

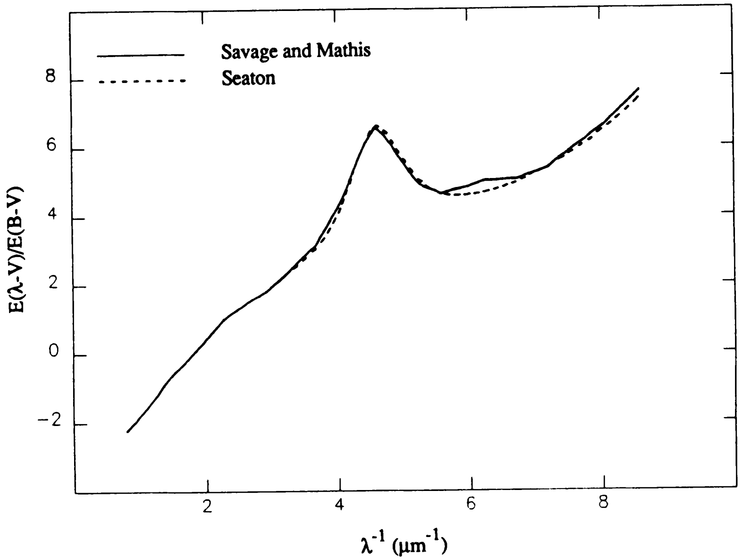

Fig. 2. Two average interstellar extinction curves are illustrated in a plot of $E(\lambda - V)/E(B - V)$ versus λ^{-1} in μm^{-1}. The curves are from Savage and Mathis (1979) and Seaton (1979). The Savage and Mathis curve contains a spurious artifact near $\lambda^{-1} = 6.3\ \mu m^{-1}$ which is the result of a luminosity mismatch error in the average TD-1 satellite survey data used to produce the average curve.

signal-to-noise characteristics. As a result, most of the analyses are based upon older scanner measurements. The mean curve derived 30 years ago by Whitford (1958) remains as good as any, as has been verified by Ardeberg and Virdefors (1982). This latter reference is particularly valuable because it compares the new results of the authors with most of the earlier visual extinction measurements obtained from both narrow-band and from broad-band data. The visual extinction curve is well represented by two linear curves (in $1/\lambda$) which join at approximately 2.25 μm^{-1}.

It is well established that a few features of the visual extinction curve are variable from place to place. One of these is the ratio of slopes on either side of the 2.25 μm^{-1} "knee" (Nandy, 1964; Whiteoak, 1966; Anderson, 1970). There also appears to be very broad structure in the curve, whose relative strength may vary (Hayes *et al.*, 1973; Schild, 1977; Walker *et al.*, 1980; Krełowski, Maszkowski and Strobel, 1986).

3.3. THE UV

The first complete UV extinction curve was produced by Stecher (1965). The first large study of UV extinction properties was with data from OAO-2 by Bless and Savage (1972). Subsequent work has employed photometry from the Dutch ANS satellite and spectrophotometry from the TD-1 and IUE satellites. Catalogs of UV extinction parameters and curves have been compiled by Savage *et al.* (1985);

Friedmann and Roder (1987); and Aiello *et al.* (1988).

Several mean UV extinction curves have been derived (see Figure 2), and those most commonly used are by Savage and Mathis (1979) and Seaton (1979). Both are similar, except that the Savage and Mathis curve contains an artifact near 6.3 μm^{-1}. This feature results from the magnitude limited survey observations of the TD-1 satellite data used to determine the curve. The feature is at the location of the *C*IV 1550 Å stellar wind line which is stronger in more luminous stars, and shows up in the mean curve.

The UV extinction curve contains several morphological features which are apparent in Figure 2. They are: the overall linear rise into the UV, the 2175 Å extinction bump, and the far-UV curvature which is independent of the linear rise, i. e., some curves have strong curvature and low overall UV extinction, while others are strong in both respects. There is also a noticeable absence of fine structure which narrows the field of candidates for the absorbing material considerably. At this symposium, Carnochan (1989) claimed from an analysis of TD-1 satellite data the detection of a second but much weaker bump peaking near 1700 Å (i. e., $\lambda^{-1} = 5.88\ \mu m^{-1}$). This feature is not apparent in the curves based on IUE measurements (in particular see Figures 1 and 2 in Fitzpatrick and Massa, 1988).

Variability of the shape of UV extinction curves from one line-of-sight to another was first revealed by the OAO-2 results of Bless and Savage (1972). However, at that time it was not known whether the variability was widespread or confined to a few peculiar regions. Many examples of "anomalous" extinction were produced in the following years (Walker *et al.*, 1980; Bohlin and Savage, 1981; de Boer, 1983) and it is now well established that the strong variability of UV extinction is a common phenomena (Massa, 1980; Kester, 1981; Meyer and Savage, 1981; Massa, Savage, and Fitzpatrick, 1983; Greenberg and Chlewicki, 1983; Witt, Bohlin and Stecher, 1984; Kiszkurno *et al.*, 1984; Carnochan, 1986; Nicolet, 1987; Massa, 1987). Figure 3 displays a set of extinction curves from Witt, Bohlin and Stecher (1984) which covers most of the range in UV extinction normally encountered. At the shortest UV wavelengths, the range of extinction is enormous. For example in the Milky Way, $E(\lambda - V)/\ E(B - V)$ at $\lambda = 1250$ Å has been observed to range from 3 for σ Sco (Bless and Savage, 1972) to 12.5 for HD 62542 (Cardelli and Savage, 1988).

It is important to study the behavior of extinction in localized regions. Such observations can reveal clues about how the dust responds to a specific set of conditions, and the length scales over which significant observational differences in the curve shapes can occur. A large number of regions containing open clusters and molecular clouds have been studied (Wu, Gilra and van Duinen, 1980; Morales *et al.*, 1980*a* and 1980*b*; Snow and Seab, 1980; Massa and Conti, 1981; Meyer and Savage, 1981; Witt, Bohlin and Stecher, 1981; Aiello *et al.*, 1982; Morgan, McLachlan, and Nandy, 1982; Hecht *et al.*, 1982; Panek, 1983; Krełowski and Strobel, 1983; Massa and Savage, 1984; Franco, Magazzu, and Stalio, 1985; Rosenzweig and Morrison, 1986; Clayton and Fitzpatrick, 1987; Torres, 1987; Krełowski and Strobel, 1987; Torres and Massa, 1988). One surprising result from this work is that, in the diffuse interstellar medium, the shape of UV extinction curves is frequently uniform over relatively large areas of the sky measuring about 10x10 degrees which corresponds to linear extents of about 100x100 pc at the typical distances involved. This result can be interpreted in one of two ways. One is that grains exposed to diffuse interstellar conditions are quickly reset to a fixed state. The other is that low den-

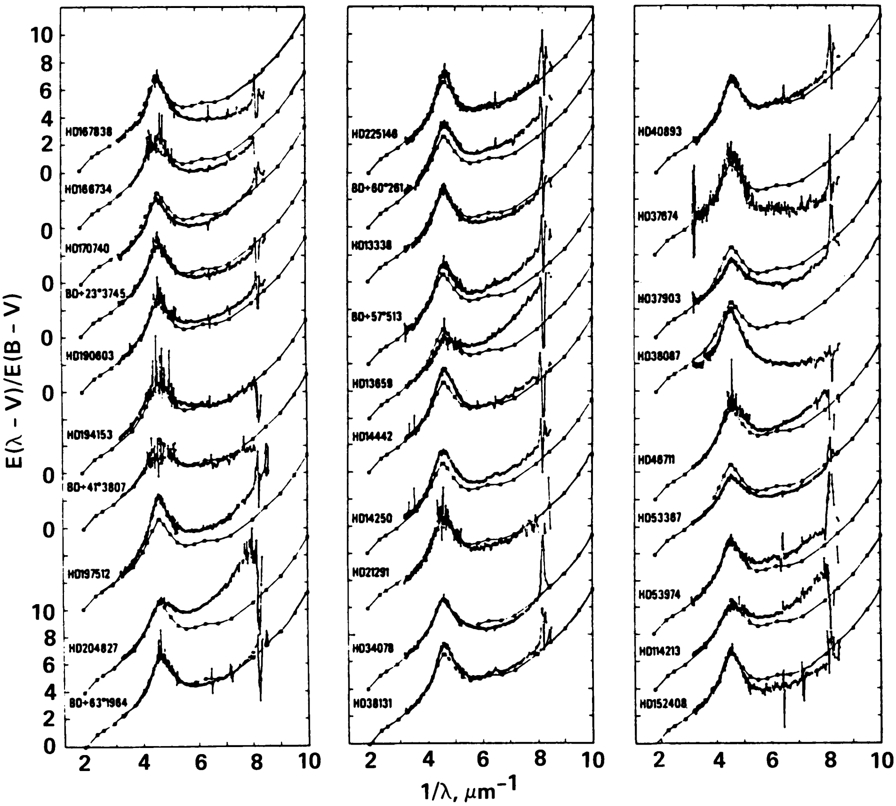

Fig. 3. Ultraviolet extinction curves for 29 Stars from Witt, Bohlin, and Stecker (1984). The curves, which are normalized to $E(B-V) = 1.0$, are compared to the average extinction curve of Savage and Mathis (1979) which is illustrated with the solid line passing through the filled-in squares. The extreme range in UV extinction is well illustrated for HD 204827 which has very large far-UV extinction and for HD 38087 which has small far-UV extinction. Structure in the observed extinction curves near 6.5 and 8.2 μm^{-1} is produced by stellar CIV l 1550 Å mismatch and by the interstellar HI Lyman a 1216 Å line. The figure is through the courtesy of the Astrophysical Journal.

sity lines-of-sight intersect large numbers of clouds with very low reddening or wisps whose individual curves may vary wildly. But, because no single cloud dominates the absorption and a wide range of clouds are sampled, the resulting curve is quite similar to a mean curve. The many interesting empirical relationships determined from the work referenced above are summarized in § 4.

3.4. THE 2175 Å EXTINCTION BUMP AND CURVE PARAMETERIZATION

The shape of the 2175 Å extinction bump is highly symmetric, and its similarity to a Lorentzian was pointed out by Savage (1975). Seaton (1979) showed that the bump is fitted to high accuracy by a Lorentzian profile. More recently, Fitzpatrick and Massa (1986) have advocated the use of a "Drude" profile. This is actually the full form of the solution to scattering by a forced, damped harmonic oscillator (Jackson, 1962). It fits the bump slightly better than a Lorentzian, but its main advantage is that it is directly related to simple characterizations of the optical properties of solids (Bohren and Huffman, 1983). Some advantages of adopting a parameterization scheme for the bump are that it makes it possible to quantify its width and central position. An additional argument, which applies to all aspects of extinction curves, is that if an appropriate analytical representation for the curves can be found, then the results of extinction measurements can be reproduced to high accuracy by a simple analytic formula and a few coefficients which are easily tabulated.

Fitzpatrick and Massa (1986), found that the bump has an average width and peak position of 480 Å and 2175 Å, respectively. However, they also noted that the bump width and central position can vary from one line-of-sight to another by ±25% and ±0.08%, respectively. Figure 4 shows two profiles at the extreme ends of the width range of their sample. When Cardelli and Savage's (1988) measurements of two extremely unusual bumps are included, the observed variation in the width and peak position increases to +62% and -3% from the average. Figure 5 is a plot of the observed bump widths versus their peak positions. The lack of a trend in these data goes counter to the predictions of classical Mie scattering and absorption by pure graphite grains (Fitzpatrick and Massa, 1986).

Although the 2175 Å feature has been seen in the circumstellar dust surrounding recently formed stars (Sitko, Savage, and Meade, 1981), it has not been detected in ejected circumstellar shells where the dust has recently condensed. In fact, for the various cases studied, the results are either no bump (e.g. α Sco, Snow *et al.*, 1987) or bumps at longer wavelengths (e.g. 2500 Å for Abell 30, Greenstein, 1981; 2400 to 2500 Å for R CrB and RY Sgr, Hecht *et al.*, 1984). In the cases of the planetary nebula Abell 30 and the carbon stars R CrB and RY Sgr, it has been proposed that amorphous carbon has formed in the carbon rich circumstellar environments. Whether or not a dust component that has maximum extinction near 2400 to 2500 Å can evolve into a component with maximum extinction near 2175 Å remains an open question. It would be valuable to search for additional candidate objects to continue the study of the extinction produced by recently formed circumstellar dust. Unfortunately, the most favorable objects are various types of cool stars and these are exceedingly difficult to study in the UV.

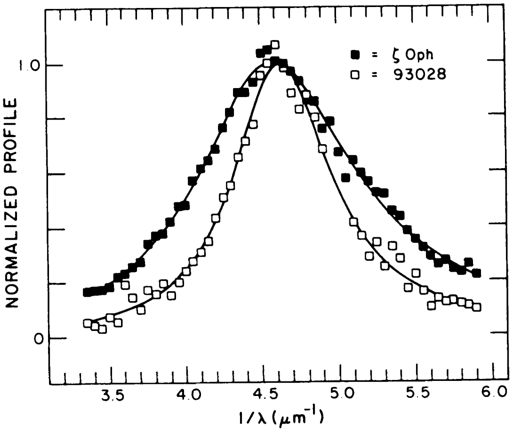

Fig. 4. Normalized profiles for the broadest and narrowest 2175 Å extinction bumps in the extinction study of Fitzpatrick and Massa (1986). The filled symbols are the data for ζ Oph while the open symbols are for HD 93028. The solid lines represent the analytical Drude profile fit to the observations. In the two cases illustrated, the FWHM of the bump ranges from $\gamma(\lambda^{-1}) = 1.251$ to 0.768 which corresponds to 597 Å and 359 Å, respectively. The figure is through the courtesy of the Astrophysical Journal.

4. RELATIONSHIPS AMONG EXTINCTION PARAMETERS

4.1. FUNCTIONAL RELATIONSHIPS

A variety of relationships between different characteristics of extinction curves have been uncovered. For example, Massa (1980) and Nicolet (1987) have shown that over the TD-1 satellite wavelength range from 2740 to 1360 Å, all UV extinction curves obtained from lines-of-sight free of dense clouds can be expressed as linear combinations of two functional forms, or components. An example of a correlation between portions of extinction curves which are widely separated in wavelength is given by Roth (1988). He finds that R and the level of the far-UV extinction normalized to $E(B-V)$ are correlated for lines-of-sight toward the open cluster Tr 37.

Additional relationships have been determined for the coefficients derived from parametric representations of extinction curves from a wide range of environments. Carnochan (1986) found that the slope and intercept terms in a parameterization scheme for UV extinction curves are functionally related. By this, we mean that, to within the observational errors, the slope and intercept terms can be treated as a single linear function whose slope-to-intercept ratio is fixed and for which a multiplicative scale factor is the only unknown.

Fitzpatrick and Massa (1988) verified this relationship, and also found that the far-UV curvature (i.e., the departure of the curve from a linear form in the far-UV) can be represented by a single functional form. In their parameterization scheme, UV extinction curves are represented by six parameters describing: the strength, central position and width of the bump, the strength of the far-UV curvature, and the slope and intercept of the linear contribution (because the latter two are functionally related, only five terms are actually needed). Figure 6 demonstrates the quality of their fits. Fitzpatrick and Massa also found that the strength of

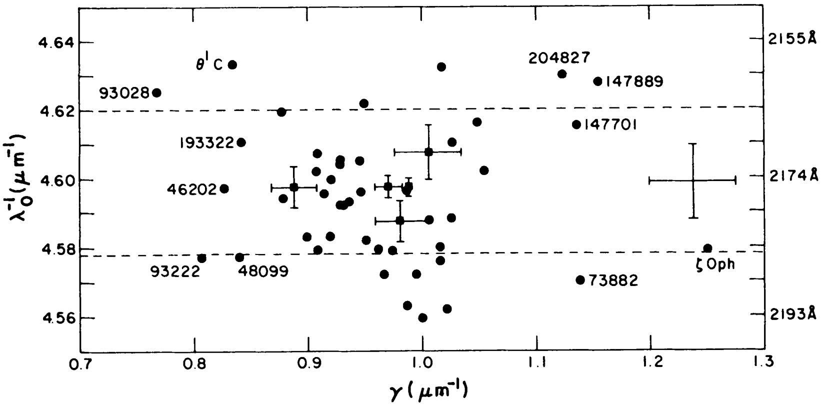

Fig. 5. Plot of the 2175 Å extinction bump width, γ (FWHM in μm^{-1}), versus the bump peak position λ_0^{-1} (μm^{-1}) as determined from analytical fits of Drude functions to the observations analysed by Fitzpatrick and Massa (1986). The observed variation of bump width and peak position is much larger than the representative errors in the measurements which are inferred from an analysis of many stars in clusters. No correlation between the bump width and position is apparent. In the case of graphite, classical Mie scattering and absorption calculations predict that broader bumps are associated with larger grains for which the peak extinction falls at larger wavelengths. The figure is through the courtesy of the Astrophysical Journal.

the curvature term and the width of the 2175 Å bump are correlated. This result, shown in Figure 7, is somewhat surprising because the strength of the curvature term depends upon the choice of normalization, while the width of the bump is independent of normalization.

More recently, Cardelli, Clayton and Mathis (1988) found an analytical expression which can represent the general trend of extinction curves from the NIR to the UV using the observed value of R as the only free parameter. Figure 8 demonstrates how well this one parameter family can represent several extreme examples of extinction curves. This result has great significance for the astronomer interested in correcting astronomical data for the presence of dust since an estimate of R can often be obtained from NIR ground based photometry.

4.2. ENVIRONMENTAL RELATIONSHIPS

In addition to mathematical relationships among various morphological properties of extinction curves, correlations have been uncovered which relate the properties of extinction curves to specific environmental characteristics of the regions where the absorbing material resides. In many ways, these correlations are physically more meaningful, since they may help to uncover how dust grains respond to specific interstellar conditions.

A well known environmental relationship is that the value of R increases in the denser regions of clouds (see Carrasco, Strom, and Strom, 1973; Whittet, 1974). Furthermore, Whittet and van Breda (1975) found that R approaches an asymptotic

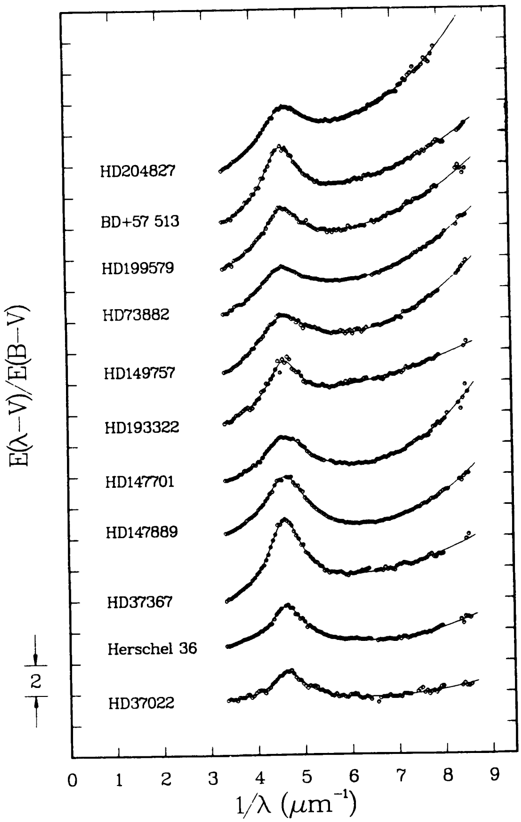

Fig. 6. The solid lines illustrate parameterized fits of analytical functions to the observed extinction data for eleven stars. The function consists of three parts: a Drude profile, a linear (in λ^{-1}) extinction term, and a far-UV curvature term. The analytic function fits the data very well and allows the complete UV extinction curve to be described by a small number of parameters. The figure is from Fitzpatrick and Massa (1988) through the courtesy of the Astrophysical Journal.

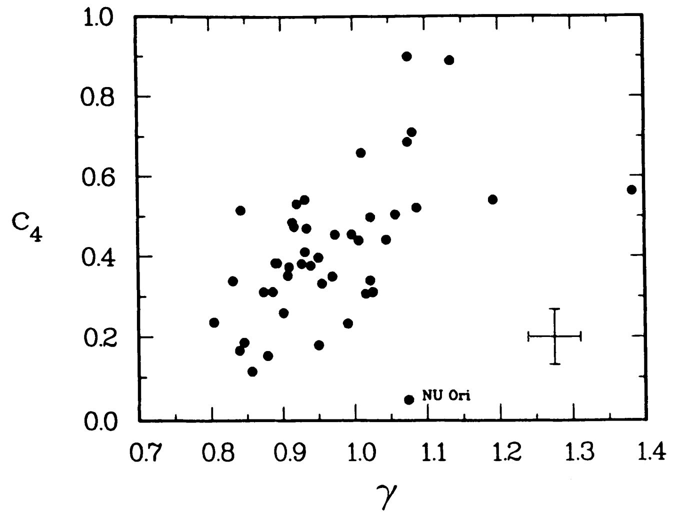

Fig. 7. Plot of the normalised strength of the far-UV curvature in extinction (C4 index) versus the width (FWHM) of the 2175 Å extinction bump, $\gamma(\mu m^{-1})$. Sight lines having wider bumps apparently have stronger than normal far-UV curvature. This figure is from Fitzpatrick and Massa (1988) through the courtesy of the Astrophysical Journal.

value in the ρ Oph cloud. These results are normally interpreted as indicating that dust grains in the denser regions of clouds have larger mean radii. However, Chini and Krugel (1983) have argued, on the basis of rather generalized grain models, that such a simple interpretation can be misleading because it does not consider the entire wavelength dependence of the extinction.

The observed correlation between R and cloud density implies that the variable extinction method is inherently in error. This is because the approach is based upon the notion that, as one penetrates a dense region, the ratio of selective-to-total extinction remains fixed. In light of the recent results which indicate that R is variable only because of deviations at B from a standard law, a modified version of the variable extinction method involving only wavelengths longward of V, such as $R' = A(V)/E(J-V)$, may be valid.

Other examples of environmental relationships are the correlation between the 2175 Å bump width and the mean line-of-sight density (Fitzpatrick and Massa, 1986; see Fig. 9), and the positive correlation between galactic altitude, $|z|$, and the strength of far-UV extinction (Kiszkurno-Koziej and Lequeux, 1987). While it is common to encounter low far-UV extinction in dense interstellar regions (Wu, Gilra, and van Duinen, 1980), there are counter examples (e. g. Cardelli, and Savage, 1988). Seab and Shull (1983) have noted the interesting result that the strength of the 2175 Å bump is enhanced for the dust near supernova remnants and have explained the result through a theory of the shock processing of grains. One must keep in mind that many of the extinction correlations that have so for been found apply only to the vicinity of a particular cloud or to a small number of regions studied and we must therefore be cautious in generalizing these results to the interstellar

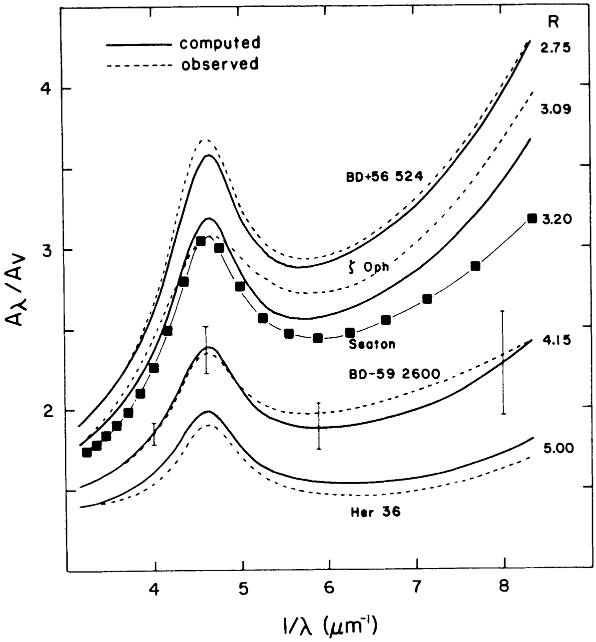

Fig. 8. The computed ratio of extinction A_λ/A_V for several values of R, plotted against λ^{-1} (μm^{-1}), compared to the observations. The computed extinction involves a function for which $R = A_V/E(B-V)$ is the only free parameter. The computed curves are a fair approximation of the actual extinction. The computed curve for $R = 3.2$ is nearly indistinguishable from the Seaton (1979) average curve which is shown as the solid squares. This figure is from Cardelli, Clayton and Mathis (1988) through the courtesy of the Astrophysical Journal.

medium as a whole.

4.3. RELATIONSHIP TO THE GAS PHASE

The most intimate tie between the gas and solid phase is the general correlation between $N(H) = N(HI) + 2N(H_2)$, the total hydrogen column density along the line-of-sight, and $E(B-V)$ (Bohlin, Savage, and Drake, 1978) with the result $N(H)/E(B-V) = 5.8\text{x}10^{21}$ atoms cm^{-2} mag^{-1}. This relation exhibits a variation of about a factor of 1.5. Some very dense regions have high $N(H)$-to-$E(B-V)$ ratios which have been interpreted by Jura (1980) as an indication that grains coagulate in dense clouds. The two most extreme cases are ρ Oph with $N(H)/E(B-V) = 1.0\text{x}10^{22}$ atoms cm^{-2} mag^{-1} (Shull and van Steenberg, 1985 for HI; Savage *et al.*, 1977 for H_2; also see de Boer *et al.*, 1986) and ν Ori (HD 37061) with $N(HI)/E(B-V) = 1.2\text{x}10^{22}$ atoms cm^{-2} mag^{-1} (Shull and van Steenberg, 1985 for HI). Note that the value for ρ Oph is a downward revision of the value originally derived by Bohlin, Savage, and Drake (1978) and that the value for ν Ori is a lower limit because H_2 data are unavailable.

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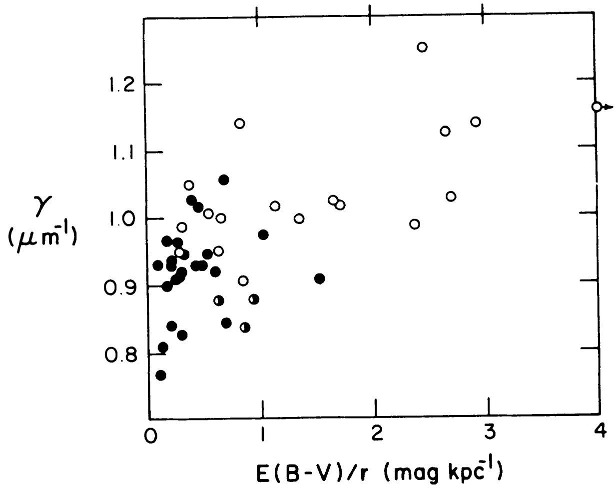

Fig. 9. A plot of the 2175 Å bump width, γ (λ^{-1}), versus $E(B-V)/r$, where r is the distance to each star. $E(B-V)/r$ is a crude indication of the line-of-sight dust density to each star. Data points for diffuse environments, star forming regions, and quiescent dense environments are indicated by filled, half-filled and open symbols, respectively. The broader bumps are found in the densest regions. This figure is from Fitzpatrick and Massa (1986) through the courtesy of the Astrophysical Journal.

An excellent, indirect way of studying the composition of interstellar dust is by determining what is missing from the gas phase. Such depletion studies, which are reviewed by Jenkins (1989), indicate that the interplay between dust and gas through gas accretion processes and dust destruction processes can be probed observationally, and that ultimately the depletion data should provide many clues about the physical and chemical processing of grain surfaces. Some of that processing may produce measurable modifications in the extinction characteristics of the interstellar dust. The results of searches for correlations between depletions and dust extinction parameters are discussed in Jenkins, Savage, and Spitzer (1986). Although a number of relations are revealed such as anticorrelations of $N(Fe)/N(H)$ with $N(H)/E(B-V)$ and with $E(\mathrm{Bump})/E(B-V)$, the interpretations of the anticorrelations are not straightforward.

A few observations have related molecular concentration and properties of the accompanying dust. Massa and Savage (1984) showed that the level of the far-UV extinction for lines-of-sight toward the Cep OB3 association did not depend upon the total amount of extinction along the line-of-sight, but rather on the relative molecular content (see Figure 10). For samples consisting of widely separated sight lines, Cardelli (1988) showed that the level of the far-UV extinction influences the presence of certain molecular species, a result possibly caused by variations in the photodissociation rates and by a lower H_2 formation efficiency on modified grains.

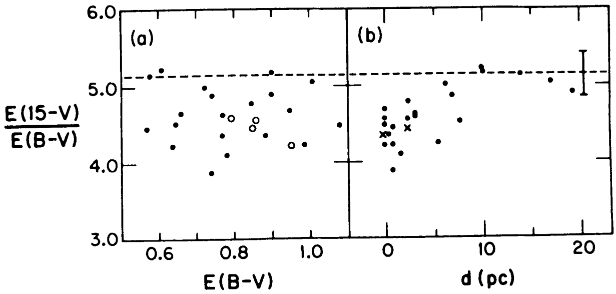

Fig. 10. Normalized level of 1500 Å extinction, $E(15-V)/E(B-V)$, versus $E(B-V)$ excess and versus distance, d(pc), away from the core of the Cep OB3 molecular cloud. The level of far-UV extinction is normal away from the core of the cloud but decreases systematically as the cloud core is approached. This figure is from Massa and Savage (1984) through the courtesy of the Astrophysical Journal.

5. FUTURE DIRECTIONS

In this section, we discuss a few areas of current research which, we believe, will be particularly productive in the near future.

One area stressed by Cardelli, Clayton and Mathis (1988), is that of obtaining additional NIR observations aimed at producing complete NIR-to-UV extinction curves. The NIR data allow curves to be normalized by $A(V)$ instead of $E(B-V)$. This facilitates model interpretations of both the gas and the dust because $E(B-V)$, being a slope, depends upon gradients in poorly defined optical properties and size distributions, while $A(V)$ depends only upon the general level of these quantities.

The connection between the presence and state of atomic and molecular species and the form of extinction curves also seems to have considerable potential for aiding our understanding of how dust and gas respond to one another's presence. This is a burgeoning area and considerably more work is needed. This is especially true since there are few cases where a single environment can be sampled. Consequently, a large number of lines-of-sight will have to be sampled before systematic trends may begin to emerge.

Finally, up to this point, nothing has been mentioned about the shortest wavelengths at which extinction can be measured, i. e., 3–60 Å X-rays. At these wavelengths, Rayleigh-Gans scattering theory is valid. In this regime, it is not only possible to measure extinction, but it is also possible to observe the halo into which the light has been scattered (Hakakawa, 1970). The additional information provided by the angular distribution of the scattered light has the potential to provide more information than conventional extinction measurements. It is impossible to take full advantage of this potential with instruments which have the spatial resolution and sensitivity of those flown to date. Nevertheless, the presence of scattering halos has been convincingly demonstrated with Einstein satellite data by Mauche and Gorenstein (1986). Their results indicate that AXAF may be able to contribute to the study of interstellar dust as well as those fields more normally considered in the realm of high energy astrophysics.

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