Publications of the Astronomical Society of the Pacific

Vol. 105 **1993 November** **No. 693**

Publications of the Astronomical Society of the Pacific
105: 1209–1221, 1993 November

The Interstellar Extinction Curve[1]

J. KREŁOWSKI[2] AND J. PAPAJ

Institute of Astronomy, N. Copernicus University, Chopina 12/18, 87-100 Toruń, Poland
Electronic mail: jacek@astri.torun.edu.pl, japap@pltumk11.bitnet

Received 1993 May 5; accepted 1993 September 3

ABSTRACT. The history of the study of interstellar extinction is briefly discussed. The methods used to determine the extinction law are presented and compared, and the main difficulties involving the application of certain methods are shown. This paper emphasizes the necessity of investigating single-cloud extinction curves instead of ill-defined long-distance means.

1. INTRODUCTION

1.1 Historical Remarks

The first documented observation of extinction effects (appearing in the form of dark regions) is that of Sir William Herschel who in 1784 observed a section of the sky containing no stars. The nature of such dark spots remained a mystery through many years, even as late as the publication of the famous *Atlas of the Selected Regions of the Milky Way* by E. Barnard in 1919 and 1927, which proved the existence of many dark regions in the sky differing in size (from a few degrees to only an arcminute) and shape (from almost circular to completely irregular). Astronomers of the 1920's and 1930's finally concluded that the "voids" observed in the stellar background are due to the presence of some irregularly distributed diffuse matter (at least not condensed into stars) which causes *extinction*, preventing stellar photons from reaching the observer. The extinction is the sum of two physical processes: *absorption* and *scattering.*

Soon after this realization that interstellar space is populated with dark clouds of diffuse matter, questions arose as to their sizes, densities, and distances. The first attempt to estimate these cloud parameters was made by Wolf (1923). His method was based on star counts up to some apparent magnitude m outside and inside a dark region.

Wolf's method is based on the assumption that all stars can be characterized by the same absolute brightness which is, of course, not true. Pannekoek (1920) proposed to apply a distribution function of absolute magnitudes to the star counts. Quite similar, although more sophisticated, were the approaches proposed by Bok (1931, 1937). His method involved star counts in concentric shells around some chosen points, e.g., the apparent centers of dark clouds. Malmquist (1939, 1943, 1944) developed the method of using spectral types and luminosity classes to determine individual distances of stars as well as their intrinsic stellar parameters, and hence the extinction for individual stars instead of averages for large samples. Individual extinctions could be later averaged for samples such as star clusters where a rough homogeneity of the local interstellar medium may be expected.

1.2 Reddening

The interstellar extinction of starlight is the most indicative phenomenon revealing the presence of diffuse dark matter in the Galaxy. One of the most straightforward conclusions that may be inferred just from a visual inspection of the POSS charts is that extinction is selective: being greater in the blue than in the red spectral range. This is why the word *reddening* is often considered synonymous to *extinction.* The most popular measure of extinction (reddening) is the color excess

$$E_{B-V}=A_B-A_V=(B-V)-(B-V)_0,$$

where $(B-V)_0$ denotes the intrinsic value for the color index of the star under consideration, whereas A_B and A_V are the total extinctions in the photometric B (4400 Å) and V (5500 Å) bands, respectively. As follows from the above formula, the color excess may be determined even when the total extinction is not known in any of the photometric bands. As a rule, color excess grows with increasing absolute extinction.

Following the papers of Kapteyn (1909) and Trumpler (1930a), the existence of differential absorption was definitely established. Trumpler (1930b) proved that extinction depends on the wavelength approximately as λ^{-1}. This is why extinction curves are still plotted as a function of reciprocal wavelength following Trumpler's rule.

The interstellar medium may contain hardly more than a few atoms per cm^3 on average (the well-known Oort

[1]Invited review paper.
[2]Visiting Fulbright Scholar at the Department of Astronomy, University of Texas at Austin, Robert Lee Moore Hall 16.314, Austin, TX 78712.

limit; Oort 1932). The only form of such low-density material which can cause continuous absorption or scattering in the visual wavelength range is dust. Solid particles, both by absorbing and scattering light, cause the observed reddening due to their large surface area despite their low mass (consisting mostly of heavy elements—the total mass of dust cannot be larger than 1% of any cloud).

The physical structure of interstellar grains will not be discussed in this paper; it suffices to mention that they are quite evidently inhomogeneous chemically and nonspherical—rather complicated compounds of minerals and organic matter as suggested by the collections of interplanetary dust particles (see, e.g., McDonnell 1988).

1.3 Structure of the Interstellar Medium

Extinction is a rather spectacular phenomenon when it occurs in huge complexes of stars and interstellar matter such as OB associations. The massive complexes do not, however, contain the bulk of the mass of interstellar matter. Struve found as early as 1847 that the apparent number of stars per unit volume drops with distance from the Sun. To correct for this strange effect, it became necessary to introduce extinction as large as 1 mag per kpc. The results of Kapteyn (1904)—1.6 mag, also those of Schalen (1929) and Bok (1931), were in line with Struve's result.

These extinctions per kpc are, of course, averages; the interstellar medium is far from homogeneous. High-resolution observations of spectral lines of interstellar gases (e.g., of sodium D_1 and D_2 or ionized calcium H and K) clearly proved that observations of interstellar matter towards any significantly reddened star typically involve a couple of intervening clouds of different radial velocities (see, e.g., Hobbs 1969). As a result, the question arises as to how opaque is the "average cloud." It has been assumed that an average cloud in the diffuse interstellar medium is characterized by a total extinction of roughly $A_V=0.2$ mag (Allen 1963).

Extinction effects are now most often observed in the mostly featureless spectra of hot OB stars which makes it easy to recognize interstellar effects against the background. Moreover, such stars are intrinsically bright, especially in the extraterrestrial UV which allows the determination of extinction curves in the most interesting range of the 2200 Å bump (see Sec. 2). High intrinsic brightness also allows the observations of distant, heavily reddened objects. The OB stars are, however, young objects, recently formed from clouds of interstellar matter and they are usually still closely associated with remnants of these dense clouds. Some of the early-type stars appear to have circumstellar disks formed from the parent matter or shed by the stars themselves due to high rotational speeds. Distant stellar aggregates may be reddened additionally by the diffuse interstellar clouds situated along the lines of sight towards them. It is therefore necessary to bear in mind that any observed hot star may be obscured simultaneously by several clouds of differing origins and history. Thus, such line-of-sight mean effects of several clouds can involve contributions of very different environments; a separation of extinction effects formed in different clouds is not possible.

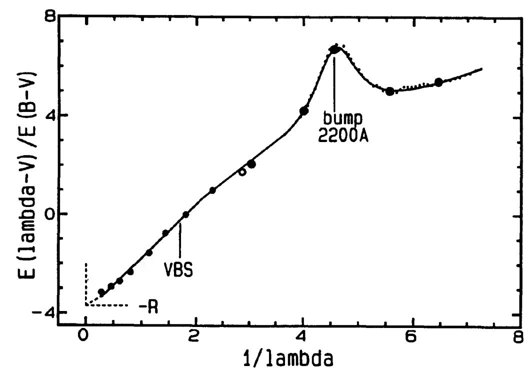

FIG. 1—Typical extinction curve plotted in the usual coordinates. Note the lack of spectral features, except for the 2200 Å bump. The curve cuts the ordinate axis at the point $-R$. The position of the VBS is also indicated.

It is of importance to mention that the extinction curve can be investigated in the range from far ultraviolet to far infrared only in the cases of not very dense clouds. Dense clouds (sites of the most recent star-formation processes) are so opaque that no objects can be observed through them, especially in the far UV, where the extinction is highest. Perhaps the optical properties of very dense clouds resemble those of globules or elephant trunks seen inside OB associations; perhaps their remnants may be observed in the form of circumstellar disks, formed together with young stars. This review is, however, restricted to the description of the observable extinction curves. Moreover the present review does not deal with the extinction in galaxies other than our Milky Way System. The reader may find a recent review of this problem in the paper by Fitzpatrick (1989).

2. EXTINCTION LAW

2.1 General Form, the Data Available

The *extinction curve*—the dependence of extinction on wavelength—is typically determined (and plotted) in the form of ratios of consecutive color excesses relative to E_{B-V}; i.e., $E_{\lambda-V}/E_{B-V}$ vs. $1/\lambda$ (see Fig. 1). This figure reveals the typical features of the extinction curve: the nearly linear growth with λ^{-1} from the far infrared ($\lambda>2$ μm) to the top of the 2200 Å bump, the bump itself and the far-UV branch representing the growth of extinction at these wavelengths. The extinction curve is sometimes presented in the form of A_λ/A_V vs. λ^{-1}. Astrophysicists are still searching for the best way of presenting it—see Chlewicki (1989) and the two recent reviews by Mathis (1987, 1990). We use here the traditional form since color excesses can be determined with a much better precision than total extinction. Also the risk of bias toward certain interpretations is smaller in this case, as discussed by Chlewicki (1989).

The whole spectral range divides naturally into three regions as defined by the extinction curve. The first observations of extinction were confined to visual wavelengths

(3000–7000 Å). In this range, as mentioned above, the extinction curve closely resembles a straight line segment, growing towards its blue edge. Such a "curve" is rather featureless (Savage and Mathis 1979) and thus it is very difficult to determine any specific physical parameters of dust particles based solely on its shape. The only spectral feature of the extinction curve found in the visual spectral range is a very shallow feature, the so-called very broad structure, whose existence is difficult to demonstrate in individual cases based on the existing data (Wampler 1966; Breger 1976; Ardeberg and Virdefors 1980), as shown by Krełowski et al. (1986). The depth of the feature, which extends roughly from 4000 to 7000 Å, can be measured photometrically, however, and it seems to correlate with extinction effects in the far UV (Reimann and Friedemann 1991).

Observations of extinction were first extended towards the extraterrestrial ultraviolet by Stecher (1965). Since that time, several astronomical spectroscopic satellites have provided many spectra of early-type stars and photometric data in the range hidden from ground-based observatories. The first survey of Bless and Savage (1972) presented several curves which differed especially in the shape of the 2200 Å extinction "bump" and in the UV portion of the curve with $\lambda \leqslant 1800$ Å. These differences were confirmed later in many original papers as well as in the atlases of Aiello et al. (1988), Fitzpatrick and Massa (1990), and Papaj et al. (1991). The data treated in the reviews were acquired with several satellites: *OAO-2* (spectral range from 1050 to 3600 Å; limiting magnitude ~5), *TD-1* (spectral range from 2540 to 1360 Å; limiting magnitude ~6) and *IUE* (spectral range from 3300 to 1200 Å; limiting magnitude ~12). *IUE* is still operating, so we may expect additional data in the future. In addition the five-band photometry (centered at 1550, 1800, 2200, 2500, and 3300 Å) conducted with the aid of the *ANS* satellite, may be used for rough estimates of the extinction law, especially towards fainter objects.

Through the last few decades many photometric observations have been made and cataloged (Gezari et al. 1984) in the far-infrared windows, permitting extension of the observed range up to 10 μm or even farther. These data help determine the extinction law close to $1/\lambda = 0$, as illustrated in Fig. 1.

The extinction curve certainly contains information about chemical composition, crystalline structure, and other properties of the interstellar dust particles. This information is, however, extremely difficult to extract and thus the structure and composition of interstellar dust grains is still a matter of debate.

2.2 Methods of Extinction Curve Determination

2.2.1 The Pair Method

An extinction curve for a reddened star may be determined by comparing its flux distribution with that of an unreddened of the same spectral type and luminosity class. Figure 2 shows the comparison of a blackbody distribution for $T = 20{,}000$ K (0) with the same continuum modified by the Savage and Mathis (1979) mean curve for $E_{B-V} = 0.20$. Is it possible to use a slightly reddened star as a standard? No. Although such a method is quite popular (see, e.g., Massa et al. 1983), distant stars (as we have mentioned above) are usually obscured by several interstellar clouds. Their optical parameters may be quite different. The greater the observed reddening, the greater the probability that we have to deal with an extinction averaged over a few different clouds. On the other hand, a slightly reddened star is quite likely to be obscured by only one cloud (this problem has already been addressed by Witt et al. 1984). Thus the extinction law towards the standard may be different from that of the star under consideration. The dereddening of such slightly reddened stars using an average extinction curve (used in certain projects as a method of determining standards) is ill advised for the same reason. Slightly reddened stars are not acceptable as spectrophotometric standards.

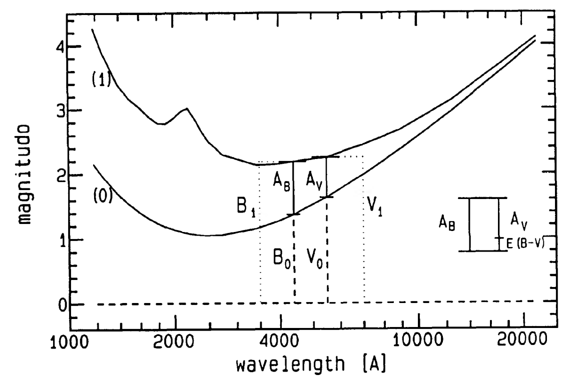

FIG. 2—The modification of the Planck (0) curve ($T = 20{,}000$ K) by the extinction curve proposed by Seaton (1979). Note the general growth of extinction towards the far UV.

The possible differences between optical properties of individual clouds, already noted by Bless and Savage (1972), emphasize the importance of the studying of single, isolated clouds. Only these kinds of environments may be considered fairly homogeneous; extinction curves derived from observations of such objects may have general physical applicability. Long-distance, ill-defined averages may be useful only for dereddening distant objects or for comparing general properties of the interstellar medium of our Galaxy to those in other galaxies. The difficulty with determining single-cloud extinction curves is that the optical depths of isolated clouds are usually very low. In such cases, the extinction effects are very difficult to determine precisely—observational errors are often comparable with the final results. This fact forces us to select our spectrophotometric standards very carefully (see Sec. 2.2.2). The problems of the selection of standards as well as other sources of errors are discussed extensively by Chlewicki (1989).

2.2.2 Color–Color Method

This method is based on the following concept. Let us consider a set of stars of the same spectrum and luminosity

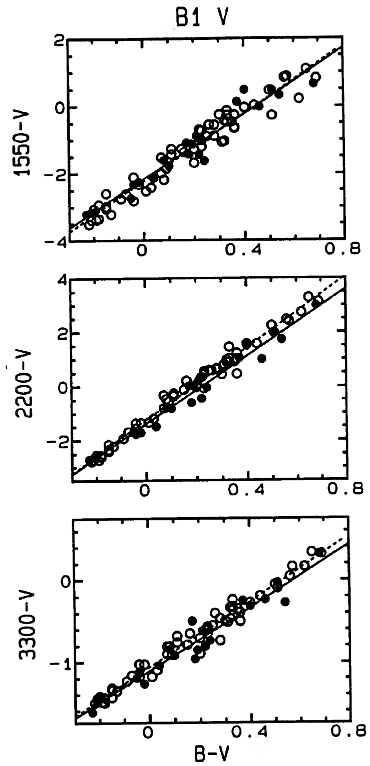

FIG. 3—Examples of three two-color diagrams involving three *ANS* bands for a sample of B1 V stars. Open circles—normal B stars, dots—Be objects. Note the identical intrinsic flux distributions in both subsamples [the relations are identical for intrinsic $(B-V)$'s].

class (Sp/L). In the absence of extinction a plot of a given color $\lambda-V$ vs. $(B-V)$ should reduce to a single point. If extinction is present, the relation becomes linear (as shown in Fig. 3) and can be expressed in the form:

$$\lambda-V=a*(B-V)+b.$$

Substituting the intrinsic $(B-V)_0$ into the formula we should obtain the intrinsic color index $(\lambda-V)_0$. By introducing the reddening explicitly into the equation we can rewrite the formula as

$$\lambda-V=a*[(B-V)_0+E_{B-V}]+b=(\lambda-V)_0+E_{\lambda-V},$$

which reduces to

$$E_{\lambda-V}=a*E_{B-V}.$$

Therefore, we can derive the mean extinction curve of a sample from the slopes of its two-color relations. This method has been applied by Krełowski and Strobel (1987) to indicate the different extinction laws in the Sco OB2 and Per OB1 associations. The disadvantage of this method is the lack of stellar aggregates which may offer us large enough samples of the same Sp/L, since only inside such aggregates can the interstellar medium be considered as sufficiently homogeneous.

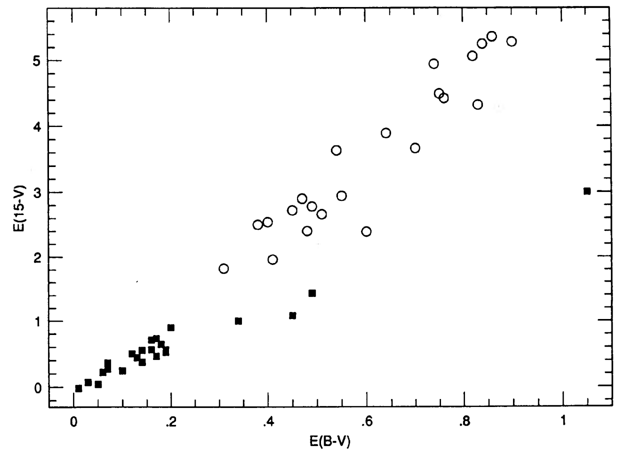

FIG. 4—The relations of pairs of color excesses for objects taken from two stellar aggregates (Sco OB2—squares, per OB1—open circles). The relations, first applied by Krełowski and Strobel (1983), facilitate the calculation of average extinction curves for the considered OB associations.

2.2.3 Excess–Excess Method

This method is also useful for homogeneous samples (stellar aggregates); averaging can make the results more precise. The method involves determinations of individual color excesses from photometric or spectrophotometric data for stars of the same aggregate and correlating the calculated $E_{\lambda-V}$ excesses with E_{B-V}. The linear relations between any pair of color excesses lead to the mean extinction curve for the whole aggregate as done, e.g., by Krełowski and Strobel (1983) and illustrated in Fig. 4. It is necessary to assume that the extinction law towards all stars of the same cluster is very similar. The source of uncertainty in this approach is mostly the lack of good spectrophotometric standards. The method may be advised for deriving extinction curves in stellar aggregates which do not offer large enough samples of the same Sp/L to allow using the method described in Sec. 2.2.2.

2.3 Determination of Standards

The importance of precise determinations of intrinsic flux distributions in stellar spectra to derive extinction curves was emphasized above (see Sec. 2.2.1). The selected standard must be of well-determined spectral type and, moreover, free of any extinction. Such objects are in fact very scarce. Keep in mind, too, that the most common measure of the amount of interstellar matter along a line of sight—E_{B-V}—may be slightly uncertain. The lack of unreddened objects among OB stars makes the determination of intrinsic $(B-V)$'s rather difficult. The existing intrinsic color systems published by Johnson (1963), Fitz-Gerald (1970), Heintze (1973), Flower (1977), and Schmidt-Kaler (1982) allow differences up to 0.04 mag in certain spectral types. Such differences are not very important when E_{B-V}'s are large, but if an extinction curve of a slightly reddened object is to be normalized (i.e., divided by a small value of E_{B-V}), this uncertainty may introduce relatively big errors. Another source of uncertainty is the possibility that every star may be erroneously classified, which is especially important among very hot stars since the effective temperature grows very rapidly with *Sp/L*.

To avoid the above difficulties, Papaj et al. (1990) replaced real stars in the role of spectrophotometric standards by "mean unreddened flux distributions" (also called "artificial standards") in the following way: measured ($\lambda-2740$ Å) colors (2740 Å is the wavelength of the "red" edge of *TD-1* spectra) for samples of stars of the same *Sp/L* were correlated with measured $(B-V)$'s in order to find their mean, unreddened values. This method for determining intrinsic colors was applied first by Gałęcki et al. (1983) and proved to be very useful (following the formulae given in Sec. 2.2.2). It assumes that among a sample of identically classified stars the only phenomenon which can alter their colors is extinction. Those colors usually correlate very tightly, allowing precise straight-line fits representing mean relations between color excesses in different wavelengths. This method allows us to include even heavily reddened stars in the procedure of standard determination, and this expands the size of our potential sample. We assume that an average over a large sample is really the average spectrum of a certain type. The accuracy of such a procedure was already illustrated (see Sec. 2.2.2). Deviations from the mean relation may be caused by errors in spectral classification (if not very large can be minimized in the averaging procedure; strongly deviating points can be analyzed on an individual basis); errors in data recording procedures (described for the *TD-1* data by Papaj et al. (1990); differences in extinction law from cloud to cloud (the slopes of mean relations between colors representing some mean reddening curve); or other errors; these are of relatively minor importance as they produce only the usually observed scatter which should be minimized in the averaging procedure.

The *TD-1* spectra offer us a potential check of the correctness of the *Sp/L* match: the strength of the C IV feature at 1550 Å which is sensitive to effective temperature ($T_{\rm eff}$); see Panek and Savage (1976) and the "metallic" bands centered around 1900 and 2100 Å (which are more sensitive to the luminosity class). These spectral features disappear in the smoothing procedure applied by Nandy et al. (1976), so unfortunately one cannot use their standards to check the *Sp/L* match. The gradient of the spectrum grows rather rapidly with temperature among the hot OB stars; one spectral subclass changes the effective temperature by a few thousand degrees. Therefore the extinction law in the UV is very sensitive to the correct match of $T_{\rm eff}$. When deriving extinction curves with the aid of a well-matched standard, we should observe no depression between 2740 and 2540 Å [see Fig. 5(b)], which is typical for too cool standards, and smooth extinction around the C IV feature (1550 Å). The precision of the latter check is up to half a spectral subtype as illustrated in Fig. 5(a).

It is interesting to note that, in a way, extinction helps us to eliminate its own effect. Extinction effects are especially strong in the 2200 Å bump area. When the chosen intrinsic $(B-V)_0$ is not correct, the bump appears in the "dereddened" spectrum in the form of residual absorption

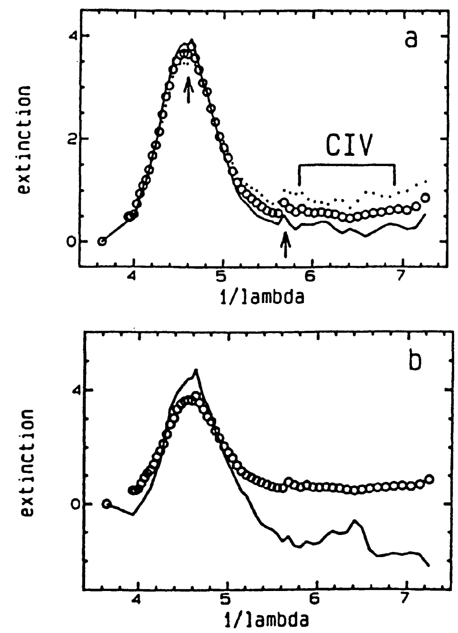

FIG. 5—The *Sp/L* match check after an extinction curve is calculated. The spectrum of β^1 Sco (solid and dotted lines) was compared with standards of B0 V and B1 V spectral type (upper frame). The C IV lines at $\lambda^{-1}\sim 6.45$ μm form either "emission" or "absorption" features in the resultant curves. Apparently the mean curve (featureless in the range of C IV) is the proper one and thus the star must be of B0.5 V spectral type. Frame (b) demonstrates the result of the application of intentionally wrong standard—B3 V. Note the strong C IV residuum and the depression blueward of the normalization point.

or even emission. The same "emission" is observed in some of the Nandy et al. (1976) standards (e.g., B0 III) as the result of dereddening slightly reddened spectra with the aid of the "mean interstellar extinction law" (Fig. 6). The best choice of $(B-V)_0$ is logically the one which makes the bump disappear completely. This criterion was applied by Papaj et al. in choosing their final versions of the "artificial standard energy distributions" of early-type stars and the intrinsic values of $B-V$ colors. The published intrinsic $(B-V)$'s of early-type stars differ slightly from source to source. The 2200 Å bump "ironing out" check may help to

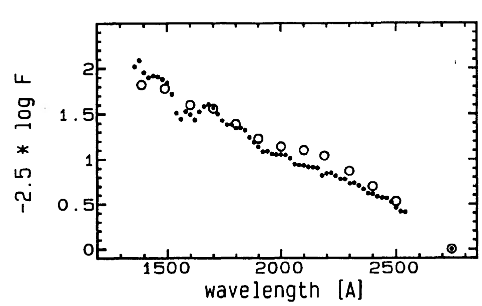

FIG. 6—The "artificial standard" of B0 III compared with that of Nandy et al. (1975); the latter was determined by means of dereddening a slightly reddened spectrum using the mean extinction curve. The "emission" in the range of the 2200 Å bump reveals that this dereddening went too far.

choose correct intrinsic colors. The precise values of the latter, attributed to certain spectral types and luminosity classes, are of basic importance when determining extinction curves from spectra of slightly reddened stars. Bless and Savage (1972) and others have shown that individual cases may differ seriously from the mean law. The method described above may be summarized as dereddening an average star of given *Sp/L* using the mean extinction law found for a sample of stars of the same spectral type and luminosity class. Smoothing all possible discrepancies, the method gives us the flux distribution in the spectrum which is, on average, classified as a given *Sp/L*.

2.4 Total-to-Selective Extinction Ratio

The extinction curve illustrated in Fig. 1 does not give us absolute extinction values (as star counts do), but only relative ones. To "translate" the curve into absolute extinctions, necessary to deredden real stars, one has to determine at least one value of the absolute extinction, e.g., in the V band. A widely adopted parameter is the total-to-selective extinction ratio

$$R=A_V/E_{B-V},$$

where A_V represents the total extinction. In a plot such as that in Fig. 1, the absolute value of R is represented by the point in which the curve intersects the ordinate axis (i.e., for $1/\lambda=0$). The extinction for infinite wavelength should be zero by definition. Let's mention, however, a serious difficulty faced in the infrared. When considering the radiative transfer equation in the ultraviolet or visual wavelength ranges we may neglect the re-emission term due to the low temperature of interstellar grains. In the infrared it can easily be a much too simplistic approximation. Thus, even while the applied standards are absolutely correct, the resultant extinction may be seriously contaminated by emission originating in dust grains due to the energy from all other spectral ranges absorbed by these grains. No reliable method of separating dust emission from the extinction determinations have yet been invented.

2.4.1 Variable Extinction Method

One of the first methods to measure the R was the so-called "variable extinction method" which is applied to star clusters or associations. If we assume the observed extinction to originate within a stellar aggregate, then the apparent and absolute magnitude of any star are linked by the familiar relation

$$m-M=5\log r+RE_{B-V}-5.$$

Suppose the aggregate is distant enough that all the stars can be assumed to have the same distance. In this case, by plotting the distance modulus versus the color excess we obtain a straight line with slope R and intercept $5\log r-5$. This method was applied by Johnson (1968) to determine the R value for several star clusters.

Thus, the variable extinction method is valid only in cases of distant star clusters which are not obscured by any interstellar clouds along the line of sight. Nature rarely provides us with such ideal circumstances and thus the R values determined in this way are usually very uncertain.

2.4.2 Extrapolation Methods

One may try to estimate R for an individual object. Suppose we found an extinction curve like that in Fig. 1, including the infrared bands (using the pair method). We can extrapolate the curve to $1/\lambda=0$ and derive R.

Difficulty arises from the extrapolation of the curve. When the wavelength is large in comparison to the grain size, the curve should behave like λ^{-4}. In the far infrared this condition is certainly fulfilled. On the other hand, in practice we are forced to make a fourth-order polynomial fit to just a few points (the infrared photometry).

The method may be also applied to some homogeneous samples (stellar aggregates) and the averaging procedure can make the results more precise. However, the radiation of circumstellar shells may contribute strongly to the observed infrared colors of some cluster members, affecting the resulting R values. Such difficulties were faced by Johnson and Borgman (1963) while comparing extinction curves in Cygnus and Orion clusters. The unusually high R value suggested in their paper may result from circumstellar dust radiation. In cases of numerous stellar aggregates, representing large samples of the same *Sp/L*, we may use the color–color method (independent of uncertain standards) as applied by Krełowski and Strobel (1987) to Per OB1 and Sco OB2.

2.4.3 Star Counts

The most direct determination of R involves star counts in two colors: B and V. As illustrated by Fig. 2, with absolute values of extinction in these two bands, we may calculate both A_V and E_{B-V}. It is, of course, possible to make such counts within rather small fields on the sky, determining the absolute extinctions A_B and A_V. This method was described by Schalen (1975). The disadvantage of the method is the possibility that even along the same line of sight we may expect the presence of quite different clouds (Westerlund and Krełowski 1988).

We conclude this section with the following general remark. All existing methods aiming at the determination of a correct value of the total-to-selective extinction ratio are uncertain to some degree. The generally accepted average value of R lies somewhere between 3.0 and 3.2. However, different authors find widely differing values. None of them can be applicable in every case.

2.5 Far-Ultraviolet Segment of Extinction Curve Versus *R*

Cardelli et al. (1989) used a varying R value to parametrize the whole extinction curve. R was determined by extrapolating near-infrared extinction to infinite wavelength. Their Fig. 1 shows the observed extinction laws along many lines of sight, plotted against R^{-1} for several values of λ. The ratio A_λ/A_V correlates quite tightly with R^{-1}, even down to UV wavelengths. They have published a set of formulas allowing one to calculate the whole ex-

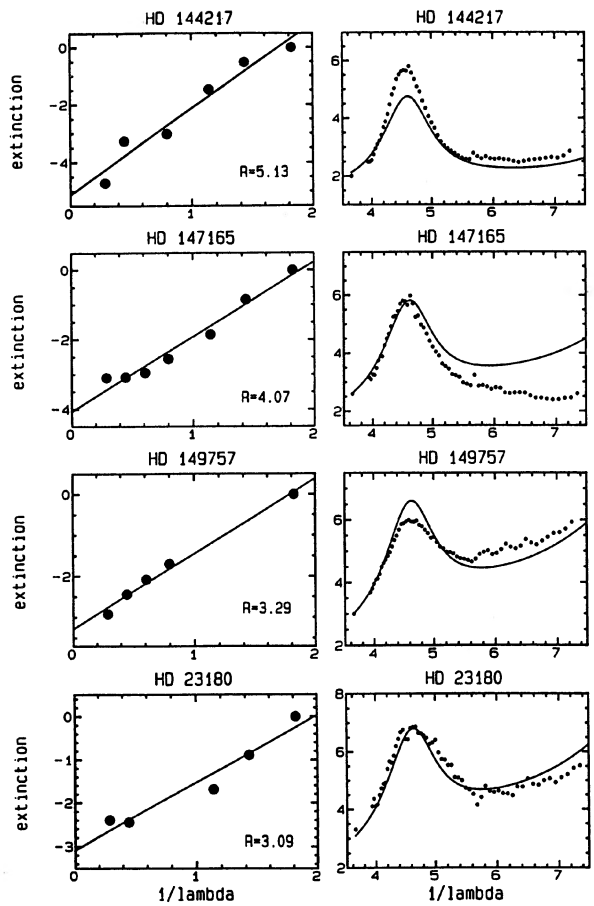

FIG. 7—The comparison of the UV extinction curves calculated in accordance with the Cardelli et al. 1989 formulae (solid lines) with those determined observationally (small dots). The left frames show the way in which the R values have been determined.

tinction curve when R is determined. The existence of an interrelation between different kinds of grains (infrared-to-visual extinction is believed to be caused by rather large-size dust particles, whereas the far-UV growth is by very fine ones) puts a strong constraint on the size distribution of dust particles. Most probably, the relation reflects the diffuse interstellar clouds which contribute strongly to the extinction of distant objects.

The above procedure cannot be, however, advised in any individual case. Cardelli et al. (1989), as well as Mathis (1990), themselves mentioned evident deviations from the extinctions calculated using their formulas. One of the reasons we should expect such deviations is illustrated in Fig. 7, which presents a comparison of calculated and observationally determined extinction curves for four bright stars for which the observations are of especially high quality (confirmed by several independent sources). For each star, the effect of extrapolating its individual curve to infinite wavelength is shown. This is just a linear fit, rather than the method used by Cardelli et al., which involves the mean-infrared extinction curve of Rieke and Lebofsky (1985), a weighted average of older measurements, as a guide. The mean curve of Rieke and Lebofsky can hardly be assumed as a universal "law"—the measurements it is based on are taken from different sources and derived from scarce samples of stars. The elimination of possible circumstellar infrared radiation was never done with a proper precision. Similarities to theoretically derived curves cannot make it more certain—theoretical curves depend critically on the assumed dust models and size distributions which are both free parameters of any fit. The plots of Fig. 7 illustrate how uncertain are the observationally determined values of R (for fainter stars, the IR photometric data are much more scarce). The ultraviolet segments of the curves show evident misfits either in the bump or in the far-UV branch. Only in one case (HD 23180) does the observational ultraviolet extinction curve coincide with the one calculated from the formulas of Cardelli et al. (1989). The stars involved are nearby, relatively heavily reddened objects and this is probably why the formula describing the general interstellar medium does not apply fully in any of the cases.

The assumption a single parameter to characterize the whole wavelength range seems rather simplistic. In his comment to the Fig. 7, Mathis (private communication) raised the problem of the shape of the extinction curve in the far-IR range, which is most probably nonlinear. However, even with a well-known analytic formula describing this segment of the extinction curve, a fit of a curve to a few data points must be considered as very uncertain method of extrapolation. Cardelli et al. (1989) also applied weights to their photometric data points and considered that the M and L filters were possibly influenced by grain radiation. Such a weighting procedure is more or less qualitative and depends strongly on one's experience. Thus we may expect different R values derived from the same data by different authors. A much more extensive study of the relations between extinctions at different wavelengths is clearly necessary.

3. THE EXISTING SURVEYS OF EXTINCTION LAW

3.1 Spectroscopic Surveys

The rapidly growing body of data acquired from astronomical satellites ironically has made it easier to survey extinction curves in UV than in the optical wavelength range. Such surveys, based on homogeneous sets of data from the same instrument, offer us a great deal of information about the properties of interstellar dust grains. The ultraviolet range appears to be more sensitive to possible changes of conditions inside different clouds. Three extensive surveys of extinction curves, drawing on data from the *TD-1* and *IUE* satellites, are presently available in the literature. They are: Aiello et al. (1988), Fitzpatrick and Massa (1990), and Papaj et al. (1991). The first survey uses *IUE* spectra of stars which are moderately to heavily reddened (E_{B-V} from 0.3 to 1.0 mag) applying spectra from the older *OAO-2* satellite as unreddened standards. The survey of Fitzpatrick and Massa uses only the *IUE* spectra and covers the range of reddenings similar to that

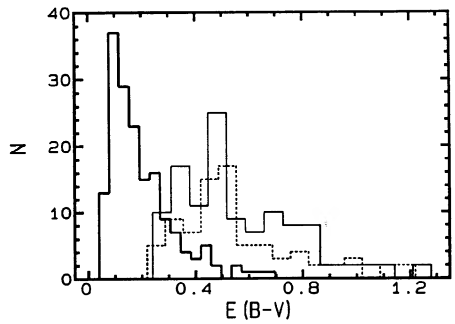

FIG. 8—A histogram comparing the reddening in the samples presented in the three published atlases of extinction curves. Note the lack of slightly reddened stars in the atlases of Aiello et al. (dotted line) and of Fitzpatrick and Massa (thin solid line). The third atlas (of Papaj et al.) contains more low E_{B-V}'s which may represent stars obscured by single clouds.

of Aiello et al. (1988). The last survey is based on the old *TD-1* data from which the "artificial standards" were derived (Papaj et al. 1990) and applied to reddened stars. The color excesses range from a few hundredths to about 0.5 mag; in most of cases the sample stars of Papaj et al. are much less reddened than those of Aiello et al. (1988) or Fitzpatrick and Massa (1990), given the brighter limiting magnitude of the *TD-1* instrument—see Fig. 8.

The resultant curves, produced by these surveys, vary substantially from object to object but can be grouped into "families" (apparently caused by similar clouds) as discussed, e.g., by Papaj (1990); for the very "peculiar" curves see also Sitko et al. (1981). These surveys also emphasize that only a few actual extinction curves resemble the mean curve determined by Savage and Mathis (1979). The results of Papaj et al. seem to be quite different from those of Aiello et al. (1988)—the latter extinction curves do not deviate as much from the "Galactic mean." However, for the six stars common in both samples (HDs): 37367, 48434, 53974, 147933, 154445, and 209339), the extinction curves are clearly similar in both atlases. The same is true for HDs: 37367, 147933, 149757, 154445, and 193322, the stars common in the samples of Fitzpatrick and Massa (1990) and Papaj et al. (1991). Let's emphasize once again that while these stars fall in the "slightly reddened" range in the two older surveys, they are situated in the range of "high reddening" in the most recent survey. The three sets are thus complementary in practice. Remember that strong extinction effects suffer usually much less the noise contained in the spectra and standard energy distribution inaccuracies which makes the results much less sensitive to any of the possible errors. It is also rather clear that high reddenings are usually "composite cases"—the extinction originates in several clouds and so the extinction curves deviate much less from what is determined as the average Galactic extinction curve. However, the concept of the latter, presented, e.g., in the pioneer papers of Savage and Mathis (1979) or Seaton (1979) is to be considered now as basically incorrect, since in practically every case the published extinction curves are averaged from the sample of relatively nearby stars. Such a sample may be not representative for the Galaxy as a whole. However, this "mean curve" was first determined before deep sky surveys in the UV were available. An "average Galactic interstellar extinction curve" should be derived from spectra of distant objects only—distant enough to be obscured by representative samples of all possible kinds of interstellar clouds (Krełowski 1990).

3.2 *IUE* Satellite and Natural Standards

The surveys of Aiello et al. (1988) and Fitzpatrick and Massa (1990) prove that extinction curves in the ultraviolet can differ significantly from star to star. Using real stars as standards (Aiello et al. used spectra acquired with the *OAO-2* satellite for this purpose), they focused their attention on heavily reddened stars. Some of these curves show particularly large discrepancies from the Savage and Mathis average. Such discrepancies are typically observed within nearby aggregates (like Sco OB2 in the old survey of Bless and Savage 1972, or the Orion Nebula in the recent one of Fitzpatrick and Massa). These curves apparently originate not in the diffuse interstellar clouds (their total optical depth towards such nearby aggregates is negligible), but rather in remnants of the giant parent clouds—the original material for the specific aggregates. Such remnants, responsible for the local extinction, differ considerably in their optical properties from diffuse interstellar clouds, as might be expected. The very dense and cold phase of a cloud contraction facilitates grain growth, producing different sizes, shapes, and probably chemical compositions of the dust. The radiation of newly formed stars may in turn cause many chemical reactions in the grain mantles—also affecting their optical properties and changing the shapes of the extinction curves. The evident difference between extinction curves observed in nearby aggregates may suggest other chemical compositions or contraction histories for different giant molecular clouds.

3.3 *TD-1* Satellite, Artificial Standards, and Low Reddenings

The atlas of Papaj et al. (1991) includes the extinction curves of many lightly reddened stars sufficiently bright to be recorded with a sufficient S/N ratio. It is, however, not a complete survey of the sky to a certain limited magnitude, but this particular set of satellite data is closed and cannot be supplemented in the future. However the material presented in this Atlas allows at least one important conclusion: *different interstellar clouds are populated by grains of different properties.* Their chemical compositions, crystalline structures, sizes, and shapes may differ from cloud to cloud. Some of the determined extinction curves clearly fall into well-separated categories, forming "families." The plots of three different "families" of extinction curves, derived from stars which may be believed to be obscured by single clouds (based on high-resolution profiles of interstellar lines), are shown in Fig. 9. Thus extinction curves formed in different media may be compared at some level, to help interpret properties of dust particles. It is however, necessary to observe many lightly reddened

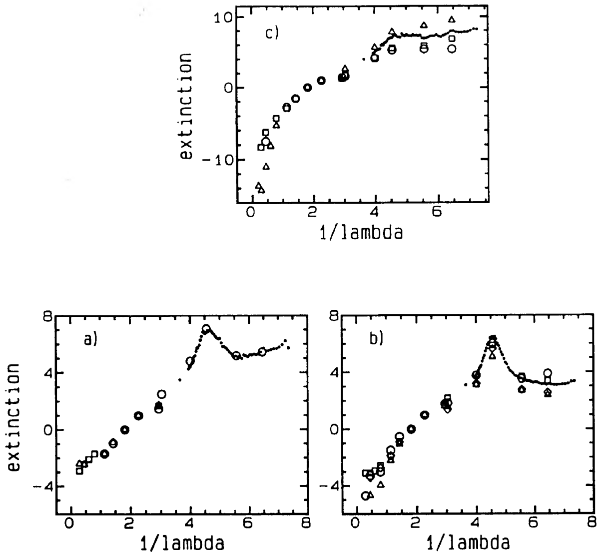

FIG. 9—Three families of extinction curves found in the atlas of Papaj et al., representing probably three different types of interstellar (or circumstellar) clouds. Note the strong discrepancy from the typical curve of Fig. 1 in the case of Be stars (c). Big symbols—photometric measurements; small dots—*TD-1* spectra.

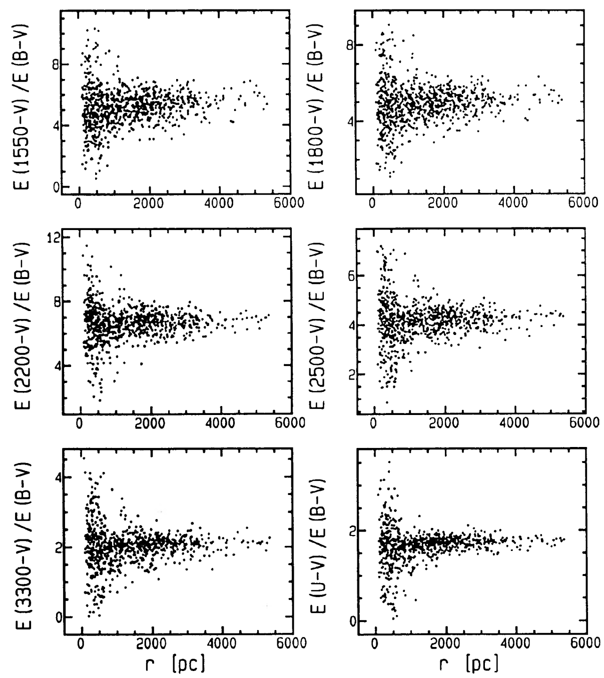

FIG. 10—The averaging of the color excess ratios with growing distance. The average to which the points converge at great distances may be considered as a value representing the mean Galactic extinction curve.

stars in the vacuum ultraviolet, presumably together with high-resolution spectroscopy of interstellar gases to determine the structure of the interstellar medium towards any object under consideration.

3.4 *ANS* Photometry, Deep Sky Survey, Galactic Average

Soon after the shape of the extinction curve had been determined by Stecher (1965) in the extraterrestrial ultraviolet, revealing the famous 2200 Å "bump," the goal of many researchers was to find a typical or average curve which could be applied to every object in the Galaxy. The observed differences between extinction laws in single interstellar clouds give rise to doubts about the validity of the concept of a mean Galactic extinction curve. If the local discrepancies are too large, the mean curve cannot be applied in an individual case. The mean extinction curves existing in the literature (Savage and Mathis 1979; Seaton 1979) are averaged over relatively small samples of rather nearby stars, typically involving local or even circumstellar components. Remnants of the parent clouds of OB stellar associations as well as circumstellar shells may differ considerably from diffuse interstellar clouds, as shown in Sec. 3.1. The extinction effects of the latter should dominate in spectra of very distant (over 2 kpc) stars, which are scarce in the samples of Savage and Mathis or Seaton.

The only extensive deep sky survey of early-type stars in the vacuum ultraviolet is the catalog of *ANS* photometry (Wesselius et al. 1982). The existing material allows us to determine intrinsic UV color indices as described in Sec. 2.2. The intrinsic colors determined in this way lead to color excesses for about 1000 stars situated at different distances (up to 6 kpc) from the Sun. Krełowski and Papaj (1992) calculated the above color excesses together with the approximate stellar distances determined from spectroscopic parallaxes. Recall that the determinations of extinction curves act as a check on the existing spectral classifications (See Sec. 2.2), so the distances used here are probably fairly reliable. Moreover, the statistically meaningful samples of 1000 stars must smooth possible scatter caused by random distance errors.

UV color excess plotted versus distance gives the result shown in Fig. 10. The greatest scatter is observed among the nearby (brightest) stars and cannot be attributed to photometric or classification errors, which should be small for these objects. Thus, the only possible explanation of the effect is that the nearby stars are obscured mostly by single clouds which differ considerably in their optical properties, supporting the arguments in previous sections. With increasing distance the data clearly converge to one average which may be properly called the "average Galactic extinction curve." Increasing the sample of stars cannot change this result. Furthermore, note that the ratio of atomic hydrogen column density to E_{B-V} behaves in the same fashion as a function of distance (de Boer et al. 1987). We also emphasize that the average extinction for nearby stars is the same as for distant ones—only the scatter is much greater. This newly determined "mean Galactic extinction curve" differs from those of Savage and Mathis, (1979) and Seaton (1979) mostly in the far-UV range, i.e., shortward of the 2200 Å bump. This fact is in accordance with the conclusions of Witt et al. (1984), who mentioned that the far-UV extinction observed in diffuse interstellar clouds is stronger in relation to E_{B-V} than the average of Savage and Mathis (1979). The new plot is higher in this range which may be interpreted as the increasing influence of small dust particles when the observed extinction involves more and more diffuse clouds along the line of sight. The former "mean curves" were determined from relatively small samples, excluding many distant objects too faint to be observed with *OAO-2* or *TD-1*. The mean curve of Krełowski and Papaj (1992) can be used, however, only for comparison of the general properties of interstellar matter in our Galaxy and other galaxies, as well as for the dereddening of very distant objects (where the scatter becomes reasonably small). It is not to be used for dereddening of any nearby object—these must be considered on an individual basis.

The above considerations lead to the conclusion that the mean extinction law as well as other mean relations may be used only with extreme caution. Practically any two parameters of the interstellar medium correlate to some degree. General relations may be helpful when considering processes which take place in the interstellar medium, but are useless when applied to individual objects. The extinction law can change from one sightline to another either due to some physical processes which alter the grain size distribution or due to another combination of a few types of interstellar clouds. It is enough to have 3–4 types of interstellar clouds to produce every conceivable shape of extinction curve, assuming those clouds can differ not only with optical properties of their grains but also with their total masses and sizes. A spectral classification of dark interstellar clouds is clearly necessary—it may show us whether optical properties of clouds change more or less continuously or rather suddenly after a kind of threshold is crossed.

4. PARAMETRIZATION OF THE EXTINCTION CURVE

The great variety of extinction curves deduced from the surveys described in Sec. 3.1 makes necessary the determination of some objective criteria to facilitate the discussion of similarities and differences between individual extinction curves. Another reason for establishing such criteria is the investigation of relations between the shape of the extinction curve and some other parameters of interstellar clouds, such as intensities of atomic and/or molecular lines, as well as the unidentified diffuse interstellar bands. Undoubtedly, the interrelationships give the only way to understand fully the physical conditions inside interstellar clouds.

Moreover, one of the reasons for determining extinction curves is to give a simple, straightforward recipe for dereddening stars, which is interesting for astronomers dealing with stellar spectra who wish to use the extinction curve only for deriving "true" stellar continua from the raw data. The above requirements lead to a parametrization of existing interstellar extinction curves, i.e., to their presentation in the form of mathematical formulas, containing several parameters which are to be determined in any individual case.

The first attempts to parametrize the extinction curve in the extraterrestrial ultraviolet are those of Savage (1975). He found the Lorenz profile to be a good approximation for the prominent 2200 Å feature. Seaton (1979) used the same profile to approximate his mean extinction curve. However, using a combination of the Lorentz function with polynomials of first and second degree, he introduced many independent parameters. Carnochan (1986), analyzing the spectra of *TD-1* satellite, reduced the number of the necessary parameters to three using also the Lorentz profile. Another function has been proposed by Fitzpatrick and Massa (1986). They divided the spectral range into two parts, using a different function in each of them. The far-UV term (shortward of 3000 Å) of their function is the following:

$$F_D(\lambda^{-1};a_1,a_2,A,\lambda_0,\gamma) = a_1+a_2\lambda^{-1}+\frac{A}{[\lambda^{-1}-(\lambda_0^{-1})^2/\lambda^{-1}]^2+\gamma^2}. \quad (1)$$

The above so-called "Drude profile" allows one to approximate the observational data more precisely than the Lorentz one. Also, the physical interpretation of the derived parameters is more straightforward. Fitzpatrick and Massa (1988) introduced an additional higher-order term to facilitate the fitting. Subsequently Cardelli et al. (1989) introduced the following formula:

$$\frac{A_\lambda}{A_V}=a(\lambda^{-1})+\frac{b(\lambda^{-1})}{\mathbf{R}}, \quad (2)$$

in which $a(\lambda^{-1})$ and $b(\lambda^{-1})$ are the two terms, empirically determined, for different spectral ranges. It is in accordance with their attempt to parametrize extinction curves using just one parameter, the total-to-selective extinction ratio, as described in Sec. 2.5. Formula (2) depends strongly on the precision of the **R** value determination and cannot be advised as a dereddening tool for individual cases, which may be quite discrepant, as mentioned in Sec. 2.5.

The choice of the best formula is just one of the problems to be faced when considering how many parameters and which data are required to describe uniquely an extinction curve. Another one is the question: which of the observational parameters and how many of them must be determined to allow the proper choice of extinction curve to deredden a given star? This problem was already addressed by Krełowski and Wegner (1989) from a purely empirical point of view, but the answer is still rather far from complete. The recent spectra of Snow suggests that, e.g., the intensity ratio of the two prominent diffuse interstellar bands, 5797 and 5780, may characterize the behavior of far-UV extinction. Parameters of this kind can be very useful since their determination is much easier than that of the whole extinction curve, which necessarily involves data from different instruments.

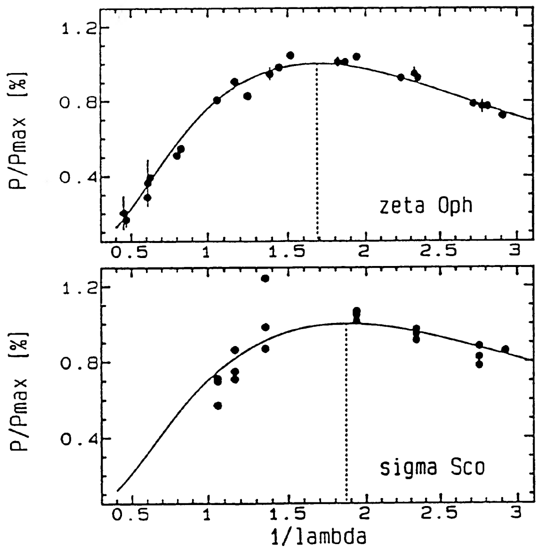

FIG. 11—The comparison of two well-determined polarization curves for two bright stars. Note the uncertainty in the wavelength of maximum polarization derived for both stars.

5. EXTINCTION VERSUS POLARIZATION

Interstellar polarization has been observed for many years and it is naturally related to extinction, as the only known form of matter in interstellar space which may be responsible for this phenomenon is dust. Thus the same grains cause both extinction and polarization. The polarization is also a selective process; its maximum is usually observed somewhere in the visual spectral range (Fig. 11). It was quite natural to try to use the polarization maximum wavelength as a parameter of the extinction curve (see, e.g., Mathis 1987).

The polarization is, however, a special absorption phenomenon occurring in interstellar space. All other interstellar absorptions, including both extinction and all discrete spectral features, get stronger and stronger when the beam crosses additional clouds. In the case of polarization the situation is different: a polarized beam, after crossing a cloud containing grains of some special alignment, may get unpolarized. Moreover, only nonspherical grains, contained in any cloud, may cause polarization, whereas all grains certainly contribute to extinction. The existing analyses of polarization do not include the considerations of the structure of the interstellar medium along any line of sight (as described in Sec. 1.3) which makes the conclusions uncertain.

As also seen from Fig. 11 which is based on bright, well-observed stars, a determination of the maximum of the polarization curve is difficult, as usually polarimetric measurements are only available in 4–5 bands.

We conclude that the maximum of polarization is the ill-advised parameter for determining extinction curves.

6. DISCUSSION

Extinction of the starlight is usually attributed to interstellar dust grains, as they are the only form of matter capable of producing such strong absorption and scattering effects despite the very low density of the interstellar medium. Quite recently polycyclic aromatic hydrocarbons (PAHs) have been proposed as the source of the far-UV rise of the extinction curve (Siebenmorgen and Krügel 1992) or as a possible broadening mechanism for the 2200 Å extinction bump (Salama and Allamandola 1992).

The variations of the extinction law, observed especially in the extraterrestrial ultraviolet, lead to the conclusion that distributions of sizes and/or shapes of dust particles may be specific to a cloud. It is usually assumed that the infrared and visual extinction is caused by relatively large dust grains (core-mantle or fluffy particles). Their extinction is supposed to become "gray" in the far UV when the particles are much bigger than the wavelength of radiation (Greenberg 1978). Thus, the only strong spectral feature observed in the extinction curve (the 2200 Å bump) is most probably caused by small carbon particles (Draine 1989) and perhaps this is why the shape of the bump is independent of E_{B-V}. The far-UV rise may be due to very small particles or, perhaps, to the PAHs. The proportions of these particles are apparently very similar in all diffuse interstellar clouds which leads to quite tight "mean relations" between different interstellar parameters. It was already emphasized by Chlewicki (1989) that extinction parameters are quite similar in all "diffuse" clouds, whereas they can be very specific in any dense cloud. However, precise criteria distinguishing "dense" and "diffuse" clouds are still to be formulated.

We have not discussed the possible dust models. The reader may find them in the papers of Greenberg (1989), Mathis (1989), and Williams (1989) presented during the panel discussion at the Symposium "Interstellar Dust." Let us just mention that our ideas concerning the dust composition and internal structure evolved enormously during the 1980's—from very simple, homogeneous or just core-mantle spheres or ellipsoidals to very complicated compounds of different minerals, organic residues, and ... vacuum. The grains are believed to be very porous and their densities very low.

The infrared absorption or emission features also attributed to the dust grains are not discussed here as well. They are discussed in several papers presented during the above mentioned IAU Symposium 135 and, more recently, by Allamandola et al. (1992). It is, however, very difficult to search for any relations between infrared and visual/ultraviolet spectral features. The infrared ones are usually observed only in very dense clouds which, as mentioned above, are too opaque to allow the determination of UV or visual segments of the extinction curve. As a result, the available information on short- and long-wavelength interstellar spectral features concern different clouds of, probably, quite different physical parameters.

7. CONCLUSIONS

Despite its long history as an astrophysical topic (1930–1993), the interstellar extinction is still a severe problem both for stellar astrophysicists who need a simple routine to correct for the interstellar effects in the stellar spectra, and those who try to understand the processes which are going on in interstellar clouds. This review shows how complicated the interstellar extinction is rather than offers final recipes for how to deal with the diffuse matter in our Galaxy. However, let's finish this paper with several conclusions, which the authors would like to emphasize to the astronomical community:

Although we know the general or typical shape of the extinction curve, we can hardly say that we know all possible forms of this important law—dense clouds may be expected to be sources of very "peculiar" (i.e., evidently different from average) extinction curves.

The only methods of the determination of extinction curve which can be advised now are: the pair method (Sec. 2.2.1) enforced in stellar aggregates by the excess–excess method (Sec. 2.2.3) and—in very large and well-observed aggregates—the color–color method (Sec. 2.2.2).

The proper observational determination of flux distributions in spectra of unreddened early-type stars is of basic importance; we advocate our method of constructing "artificial standards" (Sec. 2.3) as every individual unreddened object may be of different *Sp/L* than given in the literature or be slightly reddened.

The total-to-selective extinction ratio is the parameter which cannot be considered as well determined in any case; a reliable method of separating absorption and subsequent re-emission in the infrared spectral range is clearly necessary.

We expect that the bulk of the existing determinations of extinction curves should be redone—at the moment no reliable estimate of the uncertainties is possible.

The Galactic average extinction curve is the parameter characterizing the diffuse interstellar clouds; it is useless when dealing with dense remnants of OB association parent clouds; all mean relations are ill advised in individual cases.

A parametrization of the extinction curve may be useful both for dereddening and for investigating relations between grains and other interstellar material—how many independent parameters are to be determined is a problem that necessarily remains open.

The extinction curve is the continuous absorption spectrum of dark interstellar clouds; the behavior of this continuum seems to be closely related to that of discrete interstellar features (molecular lines, diffuse interstellar bands); perhaps it is possible to create criteria for choosing proper extinction curves from their easy-to-determine intensity ratios—this may be much better to use than the maximum of polarization curve.

The authors are very grateful to Dr. L. Allamandola, Dr. J. Hesser, Dr. J. Matthews, and Dr. C. Sneden for reading and usefully commenting on the draft of this paper. The financial support of the Polish State Committee for Scientific Research under Grant 684/2/91 is acknowledged with thanks. One of us (J.K.) acknowledges the Fulbright Foundation financial support under Grant No. 16288.

REFERENCES

Aiello, S., Barsella, B., Chlewicki, G., Greenberg, J. M., Patriarchi, P., and Perinotto, M. 1988, A&AS, 73, 195
Allamandola, L. J., Sanford, S. A., Tielens, A. G. G. M., and Herbst, T. M. 1992, ApJ, 399, 134
Allen, C. W. 1963, Astrophysical Quantities (London, Athlone)
Ardeberg, A., and Virdefors, B. 1980, A&AS, 40, 307
Bless, R. C., and Savage, B. D. 1972, ApJ, 171, 293
Bok, B. J. 1931, Harvard Circ., 371
Bok, B. J. 1937, The Distribution of Stars in Space (Chicago, University Chicago Press)
Breger, M. 1976, ApJS, 32, 7
Cardelli, J. A., Clayton, G. C., and Mathis, J. S. 1989, ApJ, 345, 245
Carnochan, D. J. 1986, MNRAS, 219, 903
Chlewicki, G. 1989, in Evoluzione della polvere interstellare e questioni attinenti, ed. A. Bonetti, J. M. Greenberg, and S. Aiello (Amsterdam, North Holland), p. 53
de Boer, K. S., Jura, M. A., and Shull, J. M. 1987, in Exploring the Universe with IUE Satellite, Astrophys. Space Sci. Lib. (Dordrecht, Reidel), Vol. 129, p. 485
Draine, B. 1989, in Interstellar Dust, IAU Symp. 135, ed. L. J. Allamandola and A. G. G. M. Tielens (Dordrecht, Kluwer), p. 313
FitzGerald, M. P. 1970, A&A, 4, 234
Fitzpatrick, E. L. 1989, in Interstellar Dust, IAU Symp. 135, ed. L. J. Allamandola and A. G. G. M. Tielens (Dordrecht, Kluwer), p. 37
Fitzpatrick, E. L., and Massa, D. 1986, ApJ, 307, 286
Fitzpatrick, E. L., and Massa, D. 1988, ApJ, 328, 734
Fitzpatrick, E. L., and Massa, D. 1990, ApJS, 72, 163
Flower, P. J. 1977, A&A, 54, 31
Gałęki, Z., Graczyk, M., Janaszak, E., Kołos, R., Krełowski, J., and Strobel, A. 1983, A&A, 122, 207
Gezari, D. Y., Schmitz, M., and Mead, J. M. 1984, Catalog of Infrared Observations, NASA Ref. Publ. 1118
Greenberg, J. M. 1978, in Cosmic Dust, ed. J. A. M. McDonnell (Chichester, Wiley), p. 185
Greenberg, J. M. 1989, in Interstellar Dust, IAU Symp. 135, ed. L. J. Allamandola, and A. G. G. M. Tielens (Dordrecht, Kluwer), p. 345
Heintze, J. R. W. 1973, in Problems of Calibration of Absolute Magnitudes and Temperature of Stars, ed. B. Hauck and B. E. Westerlund (Dordrecht, Reidel), p. 231
Hobbs, L. M. 1969, ApJ, 157, 135
Johnson, H. L. 1963, in Basic Astronomical Data—Stars and Stellar Systems III, ed. K. A. Strand (Chicago, University of Chicago Press), p. 204
Johnson, H. L. 1968, in Nebulae and Interstellar Matter, Star and Stellar System VII, ed. B. M. Middlehurst and L. H. Aller (Chicago, University of Chicago Press), p. 167
Johnson, H. L., and Borgman, J. 1963, Bull. Astron. Inst. Netherlands, 17, 115
Kapteyn, J. C. 1904, AJ, 24, 115
Kapteyn, J. C. 1909, ApJ, 29, 46
Krełowski, J. 1990, in Nordic–Baltic Astronomy Meeting, ed. C.-I. Lagerkvist, D. Kiselman, and M. Lindgren (Uppsala, Uppsala Universitet Reprocentralen HSC), p. 153
Krełowski, J., Maszkowski, R., and Strobel, A. 1986, A&A, 166, 271
Krełowski, J., and Papaj, J. 1992, Acta Astron. 42, 211
Krełowski, J., and Strobel, A. 1983, A&A, 127, 271
Krełowski, J., and Strobel, A. 1987, A&A, 175, 186
Krełowski, J., and Wegner, W. 1989, Astron. Nach., 310, 281

Malmquist, K. G. 1939, Stockholm Obs. Ann., 13, No. 4
Malmquist, K. G. 1943, Uppsala Astron. Obs. Ann., 1, No. 7
Malmquist, K. G. 1944, Uppsala Astron. Obs. Ann., 1, No. 8
Massa, D., Savage, B. D., and Fitzpatrick, E. L. 1983, ApJ, 266, 662
Mathis, J. S. 1987, in Exploring the Universe with IUE Satellite, Astrophys. Space Sci. Lib. (Dordrecht, Reidel), Vol. 129, p. 517
Mathis, J. S. 1990, ARAA, 28, 37
Mathis, J. S. 1989, in Interstellar Dust, IAU Symp. 135, ed. L. J. Allamandola and A. G. G. M. Tielens (Dordrecht, Kluwer), p. 357
McDonnell, J. A. M. 1988, in Dust in the Universe, ed. M. E. Bailey and D. A. Williams (Cambridge, Cambridge University Press), p. 169
Nandy, K., Thompson, G. I., Jamar, C., Monfils, A., and Wilson, R. 1976, A&A, 51, 63
Oort, J. H. 1932, Bull. Astron. Inst. Netherlands, 6, 249
Panek, R. J., and Savage, B. D. 1976, ApJ, 206, 167
Pannekoek, A. 1920, Proc. Kon. Akad. v. Wetensch. Amsterdam, 23, 707
Papaj, J. 1990, in Nordic–Baltic Astronomy Meeting, ed. C.-I. Lagerkvist, D. Kiselman, and M. Lindgren (Uppsala, Uppsala Universitet Reprocentralen HSC), p. 237
Papaj, J., Wegner, W., and Krełowski, J. 1990, MNRAS, 246, 408
Papaj, J., Wegner, W., and Krełowski, J. 1991, MNRAS, 252, 403
Reiman, H.-G., and Friedemann, C. 1991, A&A, 242, 474
Rieke, G. H., and Lebofsky, M. J. 1985, ApJ, 288, 618
Salama, F., and Allamandola, L. J. 1992, ApJ, 395, 301
Savage, B. D. 1975, ApJ, 199, 92
Savage, B. D., and Mathis, J. S. 1979, ARAA, 17, 73
Schalen, C. 1929, Astron. Nach., 236, 249
Schalen, C. 1975, A&A, 42, 251
Schmidt-Kaler, T. 1982, in Landolt-Bornstein. Numerical Data and Functional Relationship in Science and Technology, New Series, ed. K. Schaifers and H. H. Voigt (Berlin, Springer), Group VI, Vol. 2, Subvol. b, p. 15
Seaton, M. J. 1979, MNRAS, 187, 73p
Siebenmorgen, R., and Krügel, E. 1992, A&A, 259, 614
Sitko, M. L., Savage, B. D., and Meade, M. R. 1981, ApJ, 246, 161
Stecher, T. P. 1965, ApJ, 142, 1683
Trumpler, R. J. 1930a, Lick Obs. Bull., 14, 154
Trumpler, R. J. 1930b, PASP, 42, 267
Wampler, E. J. 1966, ApJ, 144, 921
Westerlund, B. E., and Krełowski, J. 1988, A&A, 189, 221
Wesselius, P. R., van Duinen, R. J., de Jonge, A. R. W., Aalders, J. W. G., Luinge, W., and Wildeman, K. J. 1982, A&AS, 49, 427
Williams, D. 1989, in Interstellar Dust, IAU Symp. 135, ed. L. J. Allamandola and A. G. G. M. Tielens (Dordrecht, Kluwer), p. 367
Witt, A. N., Bohlin, R. C., and Stecher, T. P. 1984, ApJ, 279, 698
Wolf, M. 1923, Astron. Nach., 219, 109