AN ANALYSIS OF THE SHAPES OF ULTRAVIOLET EXTINCTION CURVES. IV. EXTINCTION WITHOUT STANDARDS

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ABSTRACT

In this paper we present a new method for deriving UV through IR extinction curves, based on the use of stellar atmosphere models to provide estimates of the intrinsic (i.e., unreddened) stellar spectral energy distributions (SEDs), rather than unreddened (or lightly reddened) standard stars. We show that this “extinction without standards” technique greatly increases the accuracy of the derived extinction curves and allows realistic estimations of the uncertainties. An additional benefit of the technique is that it simultaneously determines the fundamental properties of the reddened stars themselves, making the procedure valuable for both stellar and interstellar studies. Given the physical limitations of the models we currently employ, the technique is limited to main-sequence and mildly evolved B stars. However, in principle, it can be adapted to any class of star for which accurate model SEDs are available and for which the signatures of interstellar reddening can be distinguished from those of the stellar parameters. We demonstrate how the extinction without standards curves make it possible to (1) study the uniformity of curves in localized spatial regions with unprecedented precision, (2) determine the relationships between different aspects of curve morphology, (3) produce high-quality extinction curves from low color excess sight lines, and (4) derive reliable extinction curves for mid to late B stars, thereby increasing spatial coverage and allowing the study of extinction in open clusters and associations dominated by such stars. The application of this technique to the available database of UV through IR SEDs, and to future observations, will provide valuable constraints on the nature of interstellar grains and on the processes that modify them, and it will enhance our ability to remove the multiwavelength effects of extinction from astronomical energy distributions.

Key words: dust, extinction — methods: data analysis — stars: abundances — stars: atmospheres

1. INTRODUCTION

A detailed determination of the wavelength dependence of interstellar extinction, i.e., the absorption and scattering of light by dust grains, is important for two very different reasons. First, since it is a product of the optical properties of dust grains, extinction provides critical diagnostic information about interstellar grain populations (including size distribution, grain structure, and composition), providing guidance for interstellar grain models. Second, the accuracy to which the intrinsic spectral energy distributions (SEDs) of most astronomical objects can be determined depends on how well the effects of extinction can be removed from observations. In both cases, a fundamental issue is how accurately the wavelength dependence of extinction can be measured. Consequently, it is essential to have a firm grasp of how measurement errors can affect the determination of this wavelength dependence.

This paper is the culmination of a series of “techniques” papers published over the past 5 years (Fitzpatrick & Massa 1999, 2005; Massa & Fitzpatrick 2000; hereafter FM99, FM05, and MF00, respectively) whose aim has been to develop a technique to simultaneously determine the wavelength dependence of extinction (to higher accuracy than previously possible) and the physical properties of a reddened star. It represents a continuation of our earlier series on the properties of UV extinction (Fitzpatrick & Massa 1986, 1988, 1990, hereafter FM90) and provides a detailed description of a new technique for deriving interstellar extinction curves that does not rely on observations of standard stars, virtually eliminates the effects of “mismatch” error, and yields an accurate assessment of the uncertainties. This “extinction without standards” technique opens the door to a new class of extinction studies, including regions heretofore inaccessible. For example, errors in the traditional “pair method” approach to extinction strongly limit our ability to study extinction in two important regimes. The first is low–$E(B - V)$ sight lines, with which one might hope to relate extinction properties to the environmental properties of specific physical regions. The second is extinction derived from mid to late B stars. These stars are plentiful and often constitute the bulk of the stars available for extinction measurements in intrinsically interesting regions, such as the Pleiades. We demonstrate how the extinction without standards approach overcomes both of these problems and present examples of each. Some first results from this program were illustrated by Fitzpatrick (2004; hereafter F04). In addition to the extinction results, we demonstrate that our approach simultaneously provides accurate stellar parameters that are also astrophysically interesting.

In § 2 we provide a broad overview of the basic problem of measuring an extinction curve and compare the merits of curves derived by the pair method and curves derived by using stellar atmosphere models. In § 3 we describe our new model-based technique in detail and list the basic ingredients needed to determine an extinction curve using this approach. In § 4 we describe the data used in the current study. In § 5 we provide a number of sample extinction curves derived using model atmospheres. We also demonstrate the high precision of the new curves and the reliability of the error analysis employed. Finally, in § 6 we describe some of the scientific advantages of this new technique and our plans to exploit them.

2. MEASURING EXTINCTION

To understand how interstellar extinction is measured and to appreciate how different measurement techniques can affect the
outcome, we begin with the intrinsic elements of an uncalibrated observation of an SED of a reddened star obtained at the Earth, \( f_\lambda \). This can be expressed as

\[
f_\lambda = F_\lambda r_\lambda \theta_\lambda^2 10^{-0.4 A_\lambda},
\]

(1)

where \( F_\lambda \) is the intrinsic surface flux of the star at wavelength \( \lambda \), \( r_\lambda \) is the response function of the instrument, \( \theta_\lambda \equiv (R/d)_\lambda^2 \) is the angular radius of the star (where \( d \) is the stellar distance and \( R \) is the stellar radius), and \( A_\lambda \) is the absolute attenuation of the stellar flux by intervening dust (i.e., the total extinction) at \( \lambda \). Alternatively, the observed SED can be expressed in terms of magnitudes \( m_\lambda \) by

\[
m_\lambda = -2.5 \log F_\lambda \theta_\lambda^2 + A_\lambda + C_\lambda \quad \text{or} \quad m_\lambda = M_\lambda + 5 \log d - 5 + A_\lambda + C_\lambda,
\]

(2)

(3)

where \( C_\lambda = -2.5 \log r_\lambda \) is a term that transforms between the observed magnitude system and absolute flux units and \( M_\lambda \) is the traditional definition of the absolute magnitude of the star at \( \lambda \).

The difficulty in measuring the total extinction \( A_\lambda \) can be seen by rearranging these equations to solve for the extinction term. Equation (1) yields

\[
A_\lambda = 2.5 \log \left( \frac{r_\lambda \theta_\lambda^2 F_\lambda}{F_\lambda} \right),
\]

(4)

while equation (3) yields

\[
A_\lambda = m_\lambda - M_\lambda - 5 \log d + 5 + C_\lambda.
\]

(5)

In either case, a true measurement of \( A_\lambda \) would require calibrated SED observations, knowledge of the intrinsic SED of the star, and measurements of both the stellar distance and radius, or their ratio \( \theta_\lambda \). Unfortunately, there are no early-type stars for which both of these latter quantities are known to sufficient accuracy to allow a meaningful measurement of \( A_\lambda \). As a result, indirect methods must be employed, and \( A_\lambda \) is always a derived quantity, subject to assumptions.

In virtually all extinction studies, the actual measured quantity is a “color excess” that describes the extinction at a wavelength \( \lambda \) relative to that at a fiducial wavelength. The traditional approach is to adopt the \( V \) band as the fiducial, since \( V \) magnitudes are widely available, accurately calibrated, and typically of high quality. This color excess can be expressed as either

\[
E(\lambda - V) \equiv A_\lambda - A_V = 2.5 \log \left( \frac{r_\lambda F_\lambda}{r_\lambda F_V} \right),
\]

(6)

as based on equation (4), or

\[
E(\lambda - V) \equiv A_\lambda - A_V = (m_\lambda - m_V) - (M_\lambda - M_V) + (C_\lambda - C_V)
\]

\[
= m(\lambda - V) - M(\lambda - V) + C(\lambda - V),
\]

(7)

as based on equation (5). Thus, the determination of the color excess requires only the measurement of the observed SED and a knowledge of the shape of the intrinsic SED. There are two basic approaches to determining color excesses, based on the use of either unreddened stars or stellar atmosphere models to represent the intrinsic SEDs of reddened stars. These two techniques, and the issue of the normalization of extinction curves, are discussed in the three subsections to follow.

2.1. The Pair Method

The first approach is the “pair method.” A pair-method curve is constructed by comparing the fluxes of a reddened star and an (ideally) identical unreddened standard star. Essentially, the absolute magnitudes in equation (7) are replaced by the observed magnitudes of the standard star and the curve is usually expressed in the form

\[
k(\lambda - V) \equiv \frac{E(\lambda - V)}{E(B - V)} = \frac{m(\lambda - V) - m(\lambda - V)_0}{(B - V) - (B - V)_0},
\]

(8)

where the color excesses \( E(\lambda - V) \) are normalized by \( E(B - V) \) and the subscripted quantities refer to unreddened indices for the standard star. (The issue of normalization is discussed below.) When the two stars are observed using the same instrument, this method has the advantage that calibration terms cancel, eliminating any dependence on the absolute flux calibration, \( r_\lambda \) or \( C_\lambda \).

There are, however, two disadvantages to this technique. The first is that the grid of unreddened standard stars is necessarily limited, so some mismatch in the SEDs of the reddened and unreddened stars, termed “mismatch error,” is inevitable. The second is that there are very few truly unreddened early-type stars, so usually the “unreddened” standard must be corrected for some small amount of extinction whose exact magnitude and wavelength dependence are uncertain. This creates an error that can propagate into the resulting extinction curves.

Massa et al. (1983) presented a detailed study of the uncertainties affecting pair method extinction curves and showed that mismatch effects dominate the error budget. If one uses a single unreddened spectral standard for each spectral class and assumes that all spectral classifications are perfect, then as a result of spectral binning, mismatch errors will be equal to or less than half of a spectral class. Figure 1 shows how such mismatches can affect extinction curves derived from main-sequence B stars. In each of the four groups of curves in Figure 1, the true shape of an extinction curve affecting a B1, B2, B5, or B9 star is indicated by the solid curve. The extinction curves that would be derived via the pair method in the presence of a \( \pm 1 \) spectral class mismatch error are shown by the dash-dotted curves for the case of \( E(B - V) = 0.15 \) and by the dashed curves for \( E(B - V) = 0.30 \) mag. (The derived curves fall below the true curve in the UV and above the true curve in the IR when the standard star is cooler than the reddened star, and vice versa.) In practice, spectral classifications are not perfect and the available unreddened standard stars do not necessarily lie in the middle of the range of properties within a single spectral class. Both these effects exacerbate the spectral mismatch problem, and thus the uncertainties shown in Figure 1 are likely closer to typical errors, rather than extremes.

Although it may appear from Figure 1 that a discontinuity at the Balmer jump at \( \lambda^{-1} \approx 2.7 \mu m^{-1} \) would provide an obvious indicator of the presence of spectral mismatch in an extinction curve, this is almost never practical. The spectrophotometric data available for constructing extinction curves are generally limited to UV wavelengths (\( \lambda^{-1} > 3.3 \mu m^{-1} \)), which are highlighted in Figure 1. Typically, the only data available in the optical and near-UV are photometric indices that straddle the Balmer jump, such as the Johnson \( U - B \) color, and these cannot be used to distinguish the effects of mismatch from intrinsic curve shape.

Mismatch error clearly can have a profound effect on the shapes of curves derived from stars with low color excesses, particularly in the mid to late B spectral range and most particularly in the UV spectral region. In fact, it is mismatch error that provides the low temperature cutoff to the spectral range of stars.
from which useful UV extinction measurements can be made. Mismatch also severely limits extinction studies based on stars hotter and/or more luminous than the main-sequence B stars. For the O stars, very few unreddened standard stars exist and extreme mismatching of spectral types is often necessary to derive a curve, although, since the intrinsic UV through optical SEDs of the O stars are not well known, it is not clear how large an effect this introduces in the derived curves. The use of luminous, evolved stars for extinction studies is particularly problematic, since unreddened standards are rare and the sensitivity of the intrinsic SEDs to both temperature and surface gravity can lead to very severe mismatch errors in the resultant curves (although see the discussion in Cardelli et al. [1992] for results in the early B spectral range).

2.2. Model Atmosphere Techniques

The second approach to deriving extinction curves is to model the intrinsic SED of the reddened star in order to isolate the effects of extinction. This technique was first used by Whiteoak (1966) to analyze optical spectrophotometry and has been applied in one form or another in many times since. We refer to it as extinction without standards, since it does not rely on a set of unreddened standard stars to determine the extinction curve. In this method, a model atmosphere of the reddened star is determined from its photometric or spectral properties. The advantage of this approach is that, in principle, a perfect, unreddened match can be determined for the intrinsic SED of the reddened star, eliminating the mismatch error that plagues pair-method curves.

The apparent disadvantages of the approach are not actual disadvantages but rather requirements, which can limit its accuracy and range of applicability. The first requirement is that a set of models must exist whose accuracy can be quantified and validated. The second is that the observations must contain adequate “reddening-free” information to accurately determine the intrinsic SED of a reddened star. The third is that the fluxes must be precisely calibrated, i.e., \( r_2 \) must be well determined.

We have been developing the necessary constituents of this method over the past 5 years. We began by demonstrating that the Kurucz (1991) ATLAS9 models provide faithful representations of the observed UV and optical SEDs of near-main-sequence B stars (FM99). We then showed that a combination of an observed UV SED and optical photometry provides adequate reddening-independent information to determine both the appropriate ATLAS9 model for a reddened star and a set of parameters (defined by FM90) that determine the shape of its interstellar extinction curve. Subsequently, we refined the calibration of the International Ultraviolet Explorer (IUE) data in order to improve the quality of the fits and the robustness of the physical information derived from them (MF00). Next, we verified the physical parameters derived from the models through applications of the models to eclipsing binary data, for which the results must agree with other constraints (see Fitzpatrick et al. 2003 and references therein). Finally, we used Hipparcos data of unreddened B stars to derive a consistent recalibration of optical and near-IR photometry (FM05) and, in the process, once again demonstrated the internal consistency of the models for near-main-sequence B stars. As a result of these efforts, we now have internally consistent \( r_2 \) for IUE and optical and near-IR photometry, and we are in a position to apply the results and to quantify the associated errors. These are the objectives of the current paper and are discussed fully in §3.

2.3. Normalizing the Curves

Once color excesses have been determined, we are faced with the problem of how to compare excesses derived for lines of sight with different amounts of extinction. After all, we are interested in the “shapes” of the curves, since these may reveal important clues about the size distribution and composition of the dust. This desire to compare shapes brings us to the normalization problem.

From a purely mathematical point of view, a straightforward approach would be to normalize the curves by their norm,

\[
E(\lambda - V) = \frac{E(\lambda - V)}{\sqrt{\sum E(\lambda - V)^2}}.
\]  

With appropriate weighting, this normalization could, on average, minimize the observational error in the normalization factor and reduce systematic effects. However, such a normalization would be sensitive to the strength of narrow features, such as the 2175 Å bump, and this could mask the overall agreement between curves over the majority of the wavelength range. A second approach is to search for some immutable feature of the curve and normalize by that. The idea behind this procedure is that if some aspect of all curves is always the same, then all curves can be normalized by the strength of this property and all the resulting curves will be directly comparable. This is the motivation for the \( A_\lambda \) normalization adopted by Cardelli et al. (1989). They assume that all extinction curves have a very similar (although not identical) form for \( \lambda \geq V \). However, there are problems with this normalization as well. In particular, as
pointed out above, $A_f$ is not a directly measured quantity but must be derived from IR photometry and requires assumptions about the shape of extinction curves at very long wavelengths. The shape of this extinction is often considered to have a universal form, but this has been demonstrated for only a relatively small number of sight lines (Rieke & Lebofsky 1985; Martin & Whittet 1990). In addition, measurements of extinction in the IR can be compromised because the stellar SEDs become increasingly faint at long wavelengths and other sources of light, such as circumstellar emission or scattering from dust in the near stellar environment, can contaminate the SED measurements. Furthermore, IR color excesses are usually small for stars that are detectable in the UV, so UV curves normalized by quantities derived from IR photometry may be affected by large normalization errors. Consequently, the absolute level of such curves can be poorly defined. Finally, even with the advent of the Two Micron All Sky Survey (2MASS) database, there are still many stars that do not have IR photometry available.

As a result of the complications mentioned above, and since our intent is to demonstrate how precisely curves can be measured while making a minimum number of assumptions, we have opted to use the conventional $E(B-V)$ normalization, as shown in equation (8). While the interpretation of $E(B-V)$ as a measure of the amount of interstellar dust is not straightforward, its widespread availability, observational precision, and lack of requisite assumptions make it the best choice for this study. Nevertheless, we note that it is a simple matter to transform from one normalization to another and emphasize that $E(B-V)$ is actually the basic measurable quantity.

3. EXTINCTION WITHOUT STANDARDS

3.1. Formulation of the Problem

Our earlier studies (FM99, FM05) have shown that the observed SEDs, $f_x$, of lightly or unreddened main-sequence B stars can be modeled very successfully by using a modified form of equation (1), namely,

$$ f_\lambda = F_\lambda \theta^2_\lambda 10^{-0.4E(B-V)[\lambda(B-V)+R(V)]}. $$

(10)

The use of absolutely calibrated data sets eliminates the calibration term $r_\lambda$, and the total extinction $A_\lambda$ has been broken down into a normalized shape term $[k(\lambda - V)]$, a normalized zero point $[R(V) \equiv A_V/E(B-V)]$, and a scale factor $[E(B-V)]$. Providing that the right-hand side of equation (10) can be represented in a parameterized form, the equation can be treated as a nonlinear least-squares problem and the optimal values of the parameters, which provide the best fit to the observed SED $f_\lambda$, can be derived along with error estimates. Because the stars under study were lightly reddened, we could replace the extinction curve $k(\lambda - V)$ and the offset term $R(V)$ with average Galactic values without loss of accuracy. Using the Kurucz ATLAS9 stellar atmosphere models to represent $F_\lambda$, the results of the fitting procedure were estimates of six parameters: $E(B-V)$, $\theta_\lambda$, and the four parameters that define the best-fitting model, i.e., $T_{\text{eff}}$, $\log g$, the metallicity $[\text{M/H}]$, and the microturbulence velocity $v_\text{turb}$. We performed the fits using the MPFIT procedure developed by C. Markwardt.3

*The Markwardt IDL Library is available at http://astrog.physics.wisc.edu/~craigmidl/idl.html.*

The fitting process described above begins to break down when the color excess $E(B-V)$ of the target stars exceeds $\sim 0.05$ mag. By this we mean that large systematic residuals, which greatly exceed the measurement errors, begin to appear. The reason is simple: the wavelength dependence of interstellar extinction curves varies greatly from sight line to sight line, and once $E(B-V) \gtrsim 0.05$ mag, the differences between the true shapes of the curves and the assumed mean form begin to exceed the measurement error. However, FM99 noted that the SEDs of significantly reddened stars could still be modeled using equation (10) (and the nonlinear least-squares approach) if the wavelength dependence of the extinction curve could be represented in a flexible form whose shape could be adjusted parametrically to achieve a best fit to the observations and if these parameters were determined simultaneously with the stellar parameters. This is the essence of our extinction without standards approach.

Successively modeling the shape of reddened stellar SEDs requires four principal ingredients: (1) an observed SED that spans as large a wavelength range as possible, (2) an accurate absolute flux calibration ($r_x$ or $C_0$), (3) an extinction curve whose shape can be described by a manageable set of parameters, and (4) a grid of stellar surface fluxes, $F_\lambda$, whose defining parameters can be determined from the observational data. In §4 we describe the particular data sets used in this paper to demonstrate our technique. We have already discussed how MF00 and FM05 have determined the necessary calibrations. In the remainder of this section, we describe our flexible form for the interstellar extinction curve (§3.2) and the grid of stellar surface fluxes with which we have developed our approach (§3.3).

3.2. A Flexible Representation of the Interstellar Extinction Curve

We adopt a flexible and adjustable form for the UV through IR extinction curve, whose shape can be optimized to fit the SED of a reddened star through the adjustment of a specific set of parameters in the least-squares minimization procedure. This curve is illustrated in Figure 2. It consists of two main regions: (1) the UV ($\lambda < 2700$ Å; solid curve) for which the parameterized form of FM90 is adopted and (2) the near-UV through IR ($\lambda > 2700$ Å; dashed curve) for which we use a cubic spline interpolation through a set of UV ($U_1$, $U_2$), optical ($O_1$, $O_2$, $O_3$, $O_4$), and IR ($I_1$, $I_2$, $I_3$, $I_4$) anchor points to represent the curve. The interpolation is performed using the IDL procedure SPLINE. We adopt a spline representation for the near-UV through IR curve simply because we do not have reliable, detailed information on the wavelength dependence of the extinction in the near-IR through near-UV region ($1 \mu m - 3000$ Å). It is ironic that the portion of the curve that is accessible from the ground is more poorly characterized than the portion accessible only from space. As a result, we do not know whether the optical to near-IR region of the curve can be represented by a compact analytical formula. Our hope is that, by applying our procedure to a large sample of sight lines, we will ultimately be able to characterize the shape of the extinction law in this region by simple relations and determine whether sight line to sight line variations are correlated with other aspects of the curve or with interstellar environment. The placement of the spline points resulted from considerable experimentation but certainly cannot be represented as an objectively determined optimal result. The current arrangement does, however, allow us to model the major available data sets to a level consistent with the observational errors.

The FM90 parameterization scheme contains six free parameters to represent three functionally separate features that are summed to produce the UV curve. An underlying linear component, indicated by the dotted line in Figure 2, is specified by an intercept $c_1$ and a slope $c_2$. The Lorentzian-like 2175 Å bump is fit by a Drude profile $D(x, x_0, \gamma)$, where $x_0$ and $\gamma$ specify the position and FWHM of the bump, respectively, whose strength is
fit to the IUE data longward of 2700 Å and the available optical and IR photometry. Although there are 10 anchor points, there are also 6 constraints, so the fit actually introduces only 4 additional degrees of freedom. We now discuss these constraints in detail.

The two UV anchor points, \( U_1 \) and \( U_2 \) at 2700 and 2600 Å, respectively, are fixed at the values of the FM90 UV fitting function at their wavelengths and are not adjustable. Together with \( O_1 \) at 3300 Å, these points guarantee that the curve passes through the IUE data between 2700 and 3000 Å will join both the UV and optical portions of the curve smoothly.

The four optical anchor points, \( O_1, O_2, O_3, \) and \( O_4 \) at 3300, 4000, 5530, and 7000 Å, respectively, are free under two constraints: that the interpolated curve produces a value of \( k(\lambda - V) = 0 \) in the \( V \) band, and that the curve be normalized to unity in \( E(B - V) \). Thus, only two free parameters emerge from this region.

The four IR anchor points, \( I_1, I_2, I_3, \) and \( I_4 \) are located at 0.25, 0.50, 0.75, and 1.0 \( \mu m^{-1} \), respectively. These four points are constrained to satisfy the formula

\[
I_n \equiv k(\lambda - V) = k_{\text{IR}} I_n^{1.84} - R(V),
\]

where the scale factor, \( k_{\text{IR}} \), and the intercept, \( R(V) \), are the only free parameters. This is the power-law form usually attributed to IR extinction, with a value for its exponent from Martin & Whittet (1990). The exponent of the power law could, potentially, be included as a free parameter in the fitting procedure, and we will investigate this in the future. However, our impression is that the IR data available to us (primarily 2MASS \( JHK \) photometry) are insufficient to determine this quantity accurately. All results presented in this paper assume an exponent of \(-1.84\) in equation (14).

3.3. The Stellar Surface Fluxes

To represent the intrinsic surface fluxes, \( F_0 \), of reddened stars we use R. L. Kurucz’s line-blanketed, hydrostatic, LTE, plane-parallel ATLAS9 models, computed in units of ergs cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\) and the synthetic photometry derived from the FM05 models. These models are functions of four parameters: \( T_{\text{eff}}, \log g, [\text{M/H}] \), and \( v_t \). All of these parameters can be determined in the fitting process, although, because of data quality, it is sometimes necessary to constrain one or more to a reasonable value and solve for the others.

The general technique of deriving extinction curves via stellar atmospheres is, of course, not dependent on the specific set of models used. In the present case, the most important consideration for our adoption of the ATLAS9 models is that they work, at least within a specific spectral domain. FM99 and FM05 have shown that these models provide excellent fits to the observed SEDs for lightly reddened or unreddened main-sequence B stars throughout the UV through near-IR spectral region. In addition, experience with eclipsing binaries (see Fitzpatrick et al. 2003 and references therein) has shown that the good SED fits also yield accurate estimates of the physical properties of the stars. Because of the physical ingredients of the models (specifically LTE and plane-parallelism), we currently restrict our attention to the main-sequence B stars. We plan to investigate how well these models reproduce the SEDs and properties of somewhat more luminous B stars and also the later O types. Also, we will take advantage of more complex models (e.g., the non-LTE TLUSTY models) as the available grids expand their parameter ranges.

3.4. Summary

To summarize, we model the observed SEDs of reddened near-main-sequence B stars by treating equation (10) as a non-linear least-squares minimization problem. As a result, we can

\[
F(x) = \begin{cases} 
0.5392(x - 5.9)^2 + 0.05644(x - 5.9)^3, & x > 5.9, \\
0, & x \leq 5.9. 
\end{cases}
\]
simultaneously obtain estimates of the physical properties of a reddened star and the shape of the interstellar extinction curve distorting the star’s SED. A total of 16 parameters specify the right-hand side of the equation, including $\theta_R$, $E(B - V)$, 4 to define $F_i$, and 10 to define the shape of the extinction curve. Depending on limitations of the available data and known properties of the stars or interstellar medium, any subset of the parameters can be constrained to predetermined values.

4. THE DATA

In § 5, we illustrate the potential of our extinction without standards technique, utilizing a set of 27 lightly to heavily reddened stars. For this demonstration, and indeed for extinction determinations in general, the ideal SED data set would consist of absolutely calibrated spectrophotometry spanning the UV through IR spectral regions. Such data would allow a straightforward comparison between observations and stellar atmosphere models (since both are presented in simple flux units) and would provide the most detailed view of the wavelength dependence of interstellar extinction. While a small amount of such data is available (see, e.g., Fitzpatrick et al. 2003), the largest existing database of absolutely calibrated spectrophotometry is the low-resolution archive of the IUE, which covers the UV region only (1150–3000 Å). In the optical and near-IR, the largest SED databases are photometric in nature, consisting of Johnson, Strömgren, and Geneva photometry in the optical and 2MASS JHK photometry in the near-IR. Using these resources, we can examine the UV region for small-scale features but can only study the broad-scale wavelength dependence of extinction in the optical and near-IR regions.

We use New Spectral Image Processing System (NEWSIPS) IUE data (Nichols & Linsky 1996) obtained from the Multi-mission Archive at STScI (MAST). These data were corrected for residual systematic errors and placed onto the HST FOS flux scale of Bohlin (1996) using the corrections and algorithms described by MF00. This step is absolutely essential for our program, since our “comparison stars” are stellar atmosphere models and systematic errors in the absolute calibration of the data do not cancel out as in the case of the pair method. (The NEWSIPS database is also contaminated by thermally and temporally dependent errors, which would not generally cancel out in the pair method; see MF00.) Multiple spectra from each of IUE’s wavelength ranges (SWP or LWR and LW) were combined using the NEWSIPS error arrays as weights. Small-aperture data were scaled to the large-aperture data, and both trailed and point-source data were included. Short- and long-wavelength data were joined at 1978 Å to form a complete spectrum covering the wavelength range 1150 ≤ λ ≤ 3000 Å. Data longward of 3000 Å were ignored, because they are typically of low quality and subject to residual systematic effects. The IUE data were resampled to match the wavelength binning of the ATLAS9 model atmosphere calculations in the wavelength regions of interest.

Mean values of the Johnson $UBV$, Strömgren $uvby\beta$, and Geneva $UBB_{GB}B_{GB}PV_1G$ photometric magnitudes, colors, and indices for the program stars were acquired from the Mermilliod et al. (1997) archive. 2MASS JHK magnitudes for all stars, along with their associated errors, were obtained from the 2MASS All-Sky Point Source Catalog at the NASA IPAC Infrared Science Archive. Johnson $V - R$, $R - I$, and JHK data are also available for some of the stars and were obtained from the Mermilliod et al. archive.

5. SOME INITIAL RESULTS

In this section, we demonstrate the potential of our extinction without standards technique, using a set of the 27 reddened stars, listed in Table 1, which fall into three groups: (1) stars in the open cluster IC 4665, (2) stars with moderate to heavy reddening, and (3) lightly reddened stars in a specific region of the sky. These representative examples illustrate the advantages of our approach and highlight several scientific applications that will be pursued in future studies, using expanded samples of stars. In addition, they provide confirmation of the error analysis incorporated in our approach.

For this demonstration sample, the SED-fitting procedure was applied as described above, with the following additional details:

1. The SED data modeled in the fitting procedure include IUE UV spectrophotometry, the Johnson $V, B - V$, and $U - B$ indices, the Strömgren $b - y$, $m_1$, $c_1$, and $\beta$ indices, the Geneva $U - B$, $V - B$, $B_1 - B$, $B_2 - B$, $V_1 - B$, and $G - B$ indices, and the 2MASS JHK magnitudes. Johnson $V - R$, $R - I$, and JHK data are also available for a few of the stars.

2. The optical extinction spline point $O_4$ at 7000 Å is only well determined when optical $R$- and $I$-band photometry are available. Therefore, in the examples below, we only solve for $O_4$ in such cases. For the other stars, the optical portion of the extinction curve is determined only by the spline points $O_1$, $O_2$, and $O_3$.

3. During the $\chi^2$ minimization, a reddened and distance-attenuated model was created from the current set of input parameters, and then synthetic photometry was performed on this model to produce the photometric indices, which were then compared with observations. The synthetic photometry was calibrated as described by FM05, with the calibration extended to redder colors by us. The UV model fluxes and recalibrated IUE fluxes, both in units of ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$, were compared directly.

4. The initial weighting factors for the various data sets in the $\chi^2$ minimization were determined from their observational uncertainties, i.e., weight $\propto \sigma^{-2}$. We then scaled the weights of the optical and near-IR photometry so that their total weight was equal to that of the IUE UV spectrophotometry, thus balancing the fit between the two data sets. This is the procedure adopted by FM05, except that we include the Strömgren $\beta$ index along with the rest of the optical and near-IR photometry, rather than assigning it its own (high) weight. FM05 weighted $\beta$ heavily in recognition of its value as a surface-gravity indicator. However, we have found that the temperature sensitivity of $\beta$ (particularly in the later B stars), combined with observational errors, can lead to very unsatisfactory fits when $\beta$ is overemphasized. Treating $\beta$ in the same manner as the rest of the photometric indices seems to be the simplest and most reasonable approach.

5. Because interstellar H I Ly$\alpha$ absorption in reddened stars can have a significant impact on the star’s apparent continuum level far from line center at 1215 Å, we convolve the profile of this heavily damped line with the model atmosphere SEDs before comparing with observations. Along heavily reddened sight lines, for which the H I column density $N(H \ i)$ is high and the signature of the atomic absorption strong, the value of $N(H \ i)$ can actually be incorporated into the fitting procedure as a free parameter to be optimized. We will use this capability in future studies. For the present, mostly lightly reddened sample, however, the $N(H \ i)$ values used to construct the line profiles were taken from the survey of Dipas & Savage (1994) or else computed from the general relation $N(H \ i) = 4.8 \times 10^{13} (E(B - V))$ cm$^{-2}$ from Bohlin et al. (1978). The inclusion of the Ly$\alpha$ line ensures that we distinguish the effects of dust extinction from atomic absorption in the far-UV region.

6. The uncertainties in the best-fit parameters were determined by running 50 Monte Carlo simulations for each star, during which the input data were randomly varied assuming a Gaussian
distribution of observational uncertainties and a new fit performed. The zero points and random photometric uncertainties of the short-wavelength and long-wavelength IUE fluxes were varied as described in FM04, the assumed observational errors in the Johnson, Strömgren, and Geneva indices were as given in Table 7 of FM04, and the uncertainties in the 2MASS data were as obtained from the 2MASS archive. In addition, the $V$ magnitude was assumed to have a 1 $\sigma$ uncertainty of 0.015 mag. The adopted 1 $\sigma$ uncertainties for each parameter were taken as the standard deviation of the values produced by the 50 simulations.

5.1. The Open Cluster IC 4665

We begin our examples by examining the extinction toward an open cluster. While multiple scientific rewards can result from the study of extinction toward cluster stars (see the discussion in §6), our primary interest in IC 4665 is to demonstrate the technical advantages of our approach, namely, the use of cluster extinction curves to help evaluate the magnitude of the uncertainties in the measurement of extinction curves, as discussed in detail by Massa & Fitzpatrick (1986). In particular, and because of its low $E(B - V)$ and late B stellar population, IC 4665 extinction curves provide an especially sensitive test of the precision and range of our extinction without standards approach. The wavelength dependence of extinction toward IC 4665 was first examined by Hackwell et al. (1991; hereafter HHT91) for the purpose of studying the relationship between extinction and IR emission, as measured by the Infrared Astronomical Satellite (IRAS). This remains one of the most challenging extinction studies yet performed for two reasons: (1) the mean reddening in the cluster is very low, $E(B-V) < 0.2$ mag, and (2) the spectral types of the available targets run from mid to late B. Both facts exacerbate errors in the standard pair-method approach, as has been shown in Figure 1. HHT91 recognized these uncertainties and ultimately concluded that the wavelength dependence of extinction among the cluster stars is uniform to within their ability to measure it.

Figure 3 shows the results of the SED fits for the nine IC 4665 stars considered here. The SEDs of the best-fitting, reddened models are shown by the histogram-style curves. In the UV, the binned IUE fluxes are shown by the small circles. In the optical
been converted to flux units for display purposes only. As discussed in
x performed in the native format of the photometry.

The comparison between models and photometric magnitudes, colors, and indices is
UB1B2VV1G Johnson JHK

ward of 6000

only the average Galactic curve is shown for wavelengths long-

below, we assumed a value of $R_{\text{JHK}}$ did not include the IR
data have been converted to flux units for display purposes only.

The comparison between models and observations was per-
data, respectively. In the IR, the large open and filled circles are
Johnson JHK and 2MASS JHK data, respectively. The photometric data have
have been converted to flux units for display purposes only. As discussed in § 5, the

The various parameters determined by the fits are listed in
Tables 1 and 2. The flexible extinction curves themselves, in the
form $E(\lambda - V)/E(B - V)$ can be reconstructed from the par-
parameters given in Table 2. The 1 $\sigma$ uncertainties of the extinc-
tion curves are indicated in Figure 4 by the gray, shaded regions.
The regions are centered on the means of the 50 Monte Carlo
simulations with which we performed our error analysis, and
their thickness shows the standard deviation of the individual curves. Note that this
scatter is comparable to the 1 $\sigma$ errors of the individual curves, indicating that the
shape of the extinction curve in IC 4665 is uniform to within our (small) mea-
surement errors.

Figure 4 shows our extinction without standards curves for the
IC 4665 stars. The symbols show the actual normalized ratios
between the models and the stellar SEDs, while the solid curves
show the flexible UV through IR extinction curves whose shapes
were determined by the fitting procedure. The curves have been
arbitrarily shifted vertically for clarity, but all are shown com-
pared with a similarly shifted estimate of the average Galactic
extinction curve for reference [dash-dotted curves corresponding to $R(V) = 3.1$; from Fitzpatrick 1999]. As is discussed further
below, we assumed a value of $R(V) = 3.1$ toward the cluster and
did not include the IR JHK data in the fitting procedure. Thus,

only the average Galactic curve is shown for wavelengths long-
ward of 6000 Å.

Figure 5 compares our new curves in the UV with those
derived by HHT91 using the standard pair method. HHT91’s
curves were reconstructed from the data in their Table 5. Note
that the HHT91 study originally included 17 stars. We have elim-
inated four A-type stars, three chemically peculiar B-type stars,
and one B-type shell system from consideration here, since their
extinction curves are particularly uncertain. Thus, Figures 4 and
5 show only the best determined curves in the cluster, from the

region, Johnson UBVRI magnitudes (converted to flux) are
indicated by circles, Strömgren $uvby$ magnitudes by triangles, and
Geneva $UB1B2VV1G$ magnitudes by diamonds. In the near-IR,
2MASS and Johnson JHK magnitudes are shown by the large
filled and open circles, respectively. Note that the photometric
data have been converted to flux units for display purposes only.
The comparison between models and observations was per-
formed in the native format of the photometry (i.e., in magnitudes or
colors as noted above).

The regions are centered on the means of the 50 Monte Carlo
simulations. For comparison, the dash-dotted curves show the average
Galactic extinction curve [corresponding to $R(V) = 3.1$]. Because of an apparent
conflict in the 2MASS and Johnson JHK data, we assumed that the shape of the
IC 4665 curves in the near-IR follows the average Galactic curve. The top solid
curve and the square symbols show the simple mean of the nine IC 4665 ex-
tinction curves, along with the average Galactic curve for comparison. The error
bars indicate the sample standard deviation of the individual curves. Note that this
scatter is comparable to the 1 $\sigma$ errors of the individual curves, indicating that the
shape of the extinction curve in IC 4665 is uniform to within our (small) mea-
surement errors.

The various parameters determined by the fits are listed in
Tables 1 and 2. The flexible extinction curves themselves, in the
form $E(\lambda - V)/E(B - V)$ can be reconstructed from the pa-
parameters given in Table 2. The 1 $\sigma$ uncertainties of the extinc-
tion curves are indicated in Figure 4 by the gray, shaded regions.
The regions are centered on the means of the 50 Monte Carlo
simulations with which we performed our error analysis, and
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inated four A-type stars, three chemically peculiar B-type stars,
and one B-type shell system from consideration here, since their
extinction curves are particularly uncertain. Thus, Figures 4 and
5 show only the best determined curves in the cluster, from the
| Star            | IR Coefficients \( k_R \) | Optical Spline Points \( O_1 \) | UV Coefficients |
|-----------------|--------------------------|-------------------------------|----------------|
| HD 161165       | ...                       | 1.90 ± 0.11                   |                |
| HD 161184       | ...                       | 1.87 ± 0.18                   |                |
| HD 161572       | ...                       | 1.53 ± 0.35                   |                |
| HD 161573       | ...                       | 1.65 ± 0.21                   |                |
| HD 161603       | ...                       | 1.67 ± 0.27                   |                |
| HD 161660       | ...                       | 1.30 ± 0.31                   |                |
| HD 161677       | ...                       | 1.78 ± 0.23                   |                |
| HD 161734       | ...                       | 2.03 ± 0.18                   |                |
| HD 162028       | ...                       | 1.81 ± 0.27                   |                |
| HD 21483        | 2.90 ± 0.06               | 2.25 ± 0.08                   |                |
| HD 27778        | 2.63 ± 0.09               | 2.22 ± 0.10                   |                |
| HD 37061        | 4.51 ± 0.06               | 1.93 ± 0.03                   |                |
| HD 37367        | 2.98 ± 0.10               | 2.08 ± 0.06                   |                |
| HD 37903        | 3.85 ± 0.10               | 2.01 ± 0.09                   |                |
| HD 147933       | 4.30 ± 0.08               | 1.97 ± 0.07                   |                |
| HD 204827       | 2.45 ± 0.05               | 2.17 ± 0.03                   |                |
| HD 210121       | 2.19 ± 0.11               | 2.76 ± 0.11                   |                |
| HD 294264       | 5.55 ± 0.08               | 1.85 ± 0.08                   |                |
| HD 142096       | 3.82 ± 0.24               | 2.02 ± 0.17                   |                |
| HD 142165       | 3.08 ± 0.26               | 1.87 ± 0.30                   |                |
| HD 142315       | 3.37 ± 0.34               | 1.96 ± 0.18                   |                |
| HD 142378       | 3.64 ± 0.18               | 2.28 ± 0.25                   |                |
| HD 143567       | 2.76 ± 0.18               | 1.88 ± 0.08                   |                |
| HD 145554       | 3.65 ± 0.19               | 1.79 ± 0.10                   |                |
| HD 146001       | 3.53 ± 0.22               | 1.69 ± 0.22                   |                |
| HD 146029       | 3.56 ± 0.27               | 2.11 ± 0.17                   |                |
| HD 146416       | 2.81 ± 0.36               | 2.05 ± 0.22                   |                |

\( k_R \) were not determined for IC 4665 stars, i.e., the first group of entries (HD 161165 through HD 162028). See the discussion in § 5.1. For the lightly reddened stars in the third group of entries (HD 142096 through HD 146416), the values of \( k_R \) and \( k_R \) were constrained to follow the relation \( k_R = 0.63 k_V \). See the discussion in § 5.3.

The stars HD 37061, HD 37903, HD 147933, and HD 294264 have Johnson \( R \) and \( I \) photometry available and thus allowed us to solve for the fourth optical spline point \( O_4 \) at 7000 Å. The values are \(-0.92 \pm 0.04 \), \(-0.92 \pm 0.04 \), and \(-1.16 \pm 0.03 \), respectively. For the rest of the sample, the optical spline is determined only by the points \( O_1 \), \( O_2 \), and \( O_3 \) at 3300, 4000, and 5530 Å, respectively.
indicates that the (small) curve-to-curve variations seen are at a level consistent with our expected uncertainties and that the intrinsic level of variation among the cluster stars must be very low.

Another way to approach the issue of variability is to look at the scatter among the various parameters that define the extinction curves. These are shown in Table 3, in which columns (2) and (3) list the weighted mean values of the parameters and their observed standard deviations, respectively. The predicted uncertainties, i.e., the rms of the Monte Carlo–based errors for the individual stars, are listed in column (4). If our error analysis is reasonable, then the observed scatter should be the quadratic sum of the expected errors plus any intrinsic variability. The value of examining cluster extinction curves is that one might reasonably suppose (at least as a starting point) that the individual curves, derived for nearly coincident lines of sight, are actually independent measurements of a single “cluster curve,” i.e., no intrinsic scatter. In such a case, the measured scatter actually reflects the real measurement errors and provides an important test of the error analysis. Examination of Table 3 shows that the predicted and observed scatters are indeed generally very similar, supporting the position that any intrinsic variations among the IC 4665 curves are close to the level of our ability to measure them and that we have accurately assessed the uncertainties in our results.

The final column of Table 3 shows the implied values of the possible small intrinsic variations.

Several of the individual parameters merit some additional comment. Both the 2175 Å bump FWHM (γ) and its strength (c3 or A_bump) show evidence for some small level of variability within the sample, above our expected measurement errors. However, this is not clear-cut, because these measurements involve the region of the IUE spectra that typically has the lowest quality data, and it is possible that weak systematic effects in the data themselves, which are not accounted for in the error analysis, could produce the small level of variability seen. One such systematic effect is a reciprocity effect in long-wavelength data that is not corrected by the MF00 algorithms (see Figs. 12 and 13 of MF00).

We conclude conservatively that there is marginal evidence for bump variations within the IC 4665 sample, but we will ultimately rely on studies of several open clusters to determine whether our error analysis faithfully predicts the real measurement errors in the bump region.

| Parameter        | Weighted Mean | Sample Standard Deviation | rms of Monte Carlo Errors | Implied Intrinsic Scatter |
|------------------|---------------|---------------------------|---------------------------|---------------------------|
|                  | (1)           | (2)                       | (3)                       | (4)                       | (5)                       |
| O1               | 1.819         | 0.219                     | 0.244                     | ...                      |
| O2               | 1.306         | 0.024                     | 0.021                     | 0.012                     |
| O3               | -0.004        | 0.003                     | 0.001                     | 0.003                     |
| O4               | 4.569         | 0.015                     | 0.011                     | 0.010                     |
| c1               | 0.922         | 0.096                     | 0.050                     | 0.081                     |
| c2               | 0.380         | 0.475                     | 0.428                     | 0.206                     |
| c3               | 0.478         | 0.108                     | 0.085                     | 0.067                     |
| c4               | 3.273         | 0.736                     | 0.359                     | 0.643                     |
| A_bump           | 5.633         | 0.709                     | 0.319                     | 0.184                     |

a Mean values computed using $1/\sigma^2$ weighting, with $\sigma$ values as given in Table 2.
b Standard deviation of the nine measurements shown in Table 2 for each parameter.
c rms value of the nine Monte Carlo–based uncertainties listed in Table 2 for each parameter.
d Computed based on the assumption that the observed scatter (in the third column) is the quadratic sum of the measurement errors (in the fourth column) and the intrinsic scatter.
e $A_{\text{bump}}(\equiv c_3/2\gamma)$ is the area of the Lorentzian-like 2175 Å bump for an extinction curve normalized by $E(B - V)$.
The case of the far-UV curvature (parameter $c_4$), for which the implied intrinsic scatter is 3 times greater than our measurement errors, is more interesting. It is clear from Figures 4 and 5 and Table 3 that most of this apparent variability arises from two sight lines, namely, those toward HD 161165 and HD 161184. In fact, the observed scatter in $c_4$ toward the other seven sight lines is essentially identical to the expected measurement error. Because HD 161165 and HD 161184 are the two coolest stars in the sample and the only stars with effective temperatures less than 12,000 K, we suspected that the high $c_4$ values in their extinction curves might be artifacts of the analysis, resulting from a failure of the models to accurately portray the far-UV SEDs of these stars. The investigation presented below suggests that this could well be the case, with the extinction curve anomalies possibly arising from a difference between the chemical composition profiles of the stars and the atmosphere models.

The data in Table 1 show a very uniform metallicity [M/H] for the cluster, with a weighted mean of $-0.50$ and a standard deviation of 0.04. This is close to, and actually slightly smaller than, our estimate of the measurement errors, simultaneously confirming the accuracy of our error analysis and imposing a small upper limit on the intrinsic compositional variability within the cluster. Although our [M/H] values are simple scale factors that apply to a template set of ATLAS9 solar abundances, FM99 showed that the [M/H] derived in our analysis is most sensitive to the abundance of Fe (because of a very strong opacity signature in the mid-UV) and is most analogous to [Fe/H]. Since the Fe abundance in the ATLAS9 models is $-0.2$ dex larger than the currently accepted solar value of 7.45 (where $H = 12.00$; Asplund et al. 2005), our results suggest that the IC 4665 stars are deficient by about a factor of 2 in Fe as compared to the Sun. The small scatter observed in [M/H] is both satisfying and expected, since the surface composition of Fe is not subject to evolutionary modification in these young stars, which presumably all formed from the same parent material.

We experimented with forcing [M/H] to a more solar-like level for the IC 4665 stars and immediately found two effects: (1) the $c_4$ values all increased significantly because the Fe features in the mid-UV could not be fit as well, and (2) most of the extinction curves remained unchanged, but the anomaly in the far-UV region for HD 161165 and HD 161184 decreased dramatically. The first result was expected. The second was a surprise but is understandable. If the cluster stars (or at a minimum, the two coolest stars HD 161165 and HD 161184) have a nonsolar ratio of Fe to the light metals, e.g., $[C/Fe] > 0$, then our best-fit models, which are biased toward the Fe abundance, would underestimate the opacity due to the light metals. For the cooler stars, such elements provide significant opacity in the far-UV region and the ATLAS9 models would not be able to account for such a specific opacity difference. The fitting procedure would respond by finding a higher far-UV extinction curve. The curves for the hotter stars are less affected by changing [M/H], since the light-metal opacity is less significant. We tentatively conclude that the chemical composition of the B stars in IC 4665 may deviate strongly...
from that of the Sun, with subsolar Fe but with a more “normal” level of the light metals such as C. This suggestion is easily tested with a fine analysis of high-resolution stellar spectra, and we will pursue this in the future. On the positive side, this result suggests that the UV continua of late B and early A stars might be used to determine both a scaled $[\text{M}/\text{H}]$ and a mean $[\text{CNO}/\text{Fe}]$ index, assuming a grid of models parameterized by both these composition indices is available. On the more sober side, it is a reminder that our technique is susceptible to stellar abnormalities. As with the pair method, all available data should be consulted to determine whether a particular star is suitable for deriving an extinction curve.

Our final comment on the IC 4665 results concerns the behavior of the IR data. In Figure 4 we show two sets of $JHK$ photometry for each star and for the average cluster curve. The filled symbols indicate 2MASS measurements, and the open symbols show HHT91’s data. The two sets of data systematically differ, with the 2MASS results suggesting a value of $R(V)$ somewhat smaller than the average Galactic value of 3.1 and with the HHT91 data suggesting a slightly larger value [HHT91 derive a mean of $R(V) = 3.25$]. This latter result is more consistent with expectations, given that the mean far-UV curve is lower than the Galactic average (see, e.g., Cardelli et al. 1989), but this is insufficient evidence for rejecting the 2MASS data. For now, our solution for this quandary has been to ignore both sets of data in fitting the IC 4665 SEDs and adopt a default value of $R(V) = 3.1$. However, the discrepancy for measurements in this very complex region bears further investigation, as does that fact that, in both data sets, the mean curves actually show more extinction in the 2.2 $\mu$m $K$ band than in the 1.65 $\mu$m $H$ band.

The discussion above leads us to three primary conclusions: (1) the extinction toward IC 4665 shows at most only a small degree of spatial variability (comparable with our measurement errors) and that the cluster extinction curve would be best represented by averaging the results for the seven hottest cluster stars studied here; (2) we are able to determine accurate $[\text{M}/\text{H}]$ values from the observations; and (3) our analysis yields reliable estimates of the (small) uncertainties in the extinction without standards curves and parameters, barring the presence of unusual systematic anomalies in the data sample. The first and second conclusions are scientific issues that we will pursue further in the future. The third provides a formidable demonstration of the superiority of the extinction without standards technique over the classical pair method for deriving extinction curves in both the precision of the results and the quantification of the uncertainties.

5.2. Moderately Reddened Stars

With our error estimates verified, we now examine how curves derived by the current approach compare to pair-method curves. Figure 6 shows the UV through IR fits to the SEDs of a set of nine moderately reddened early B stars, most of which are well known for their extinction properties, and Figure 7 shows the corresponding extinction curves. These stars were selected because they illustrate the wide range that exists in the wavelength dependence of both UV and IR extinction. For these stars the IR data allow us to determine the values of $R(V)$, and so the flexible extinction curve fits are shown throughout the IR-to-UV domain.
As for the IC 4665 stars, all the parameters describing the fits are given in Tables 1 and 2.

Also shown in Figure 7 are UV curves based on the pair-method technique. The curve for HD 294264 is from Valencic et al. (2004), the curves for HD 210121 and HD 277778 are from unpublished measurements by us, and the others are from the catalog of FM90. The agreement between the model-based and pair-method curves is reasonable and much better than seen for IC 4665. This is consistent with spectral mismatch as the prime cause of the existing discrepancies, since the nine stars have both higher \( E(B - V) \) values and earlier spectral types than the IC 4665 stars, both of which tend to reduce the influence of mismatch errors. Note also that the best agreement between the pair method and the model-based curves occurs for the star HD 204827, for which identical results are found. Again, this is as it should be, since its \( E(B - V) \) is the largest of any star in the sample, minimizing the impact mismatch effects. The 1 \( \sigma \) uncertainties for our flexible extinction curve fits are indicated by shaded regions around the curves, as in Figure 4.

The curves shown in Figure 7 demonstrate the ability of the parameterized, flexible extinction curve (see § 3.2) to conform itself to the wide range of extinction curve shapes encountered in interstellar space.

### 5.3. Lightly reddened stars

Figure 8 shows a set of nine SED fits for low color excess stars \([0.10 \text{ mag} \leq E(B - V) \leq 0.21 \text{ mag}]\) located along sight lines bounded by the Galactic coordinates \(347^\circ < l < 355^\circ \) and \(18^\circ < b < 26^\circ\). Figure 9 shows the corresponding extinction curves. These stars are all mid to late B members of the Upper Scorpius complex (Garrison 1967), and we encountered them while testing a procedure for scanning the IUE archives and automatically generating model-based extinction curves for stars in the appropriate spectral range. When examining the results for this pilot program, which sampled high-latitude stars, it became obvious that curves derived from stars in this specific region demonstrated similar curve morphology that is distinctly different from the Galactic average. Given the low reddening and preponderance of late B stars, this strong systematic behavior would be missed by a pair-method survey, with its large inherent mismatch errors.

Strong regional signatures are important in extinction studies, because they may highlight the effects of specific physical processes on dust grain populations. Although we will examine this specific region in the future, two points are worth mentioning. First, it is important that similar curves result from stars with spectral types ranging from B2.5 to B9, verifying that the curves are not the result of some temperature-dependent systematic effect in fitting process. It is also worth noting that the region is near the \( \rho \) Oph dark cloud. The star \( \rho \) Oph A (HD 147933, whose extinction curve is shown in Fig. 7) is located at a comparable distance and just south of the region, at Galactic coordinates of \((l, b) = (353.7, 17.7)\). The mean curve for the nine lightly reddened stars is shown at the top of Figure 9, along with the average Galactic curve (dash-dotted curve) and the HD 1479433 curve (dotted curve) for comparison. In the UV, the regional curve is seen to be almost identical to that for the more heavily reddened HD 147933 \([E(B - V) \approx 0.5 \text{ mag}]\), suggesting that the sight lines sample similar dust populations. Interestingly, however, the curves are not identical in the IR. The mean 2MASS \( JHK \) data for the nine star sample implies a value of \( R(V) \approx 3.4 \), slightly larger than the Galactic mean of 3.1, while HD 147933 has a value of \( R(V) \approx 4.3 \). This contrast between UV and IR behavior may indicate different physical processes at work along the higher density sight line toward HD 147933, or perhaps different timescales in the response of UV and IR extinction to modifications of dust grain properties.

In producing the extinction curves for these lightly reddened stars, we found that, in some cases, the value of \( k_{IR} \) was very poorly determined and produced (presumably) spurious “bumps and wiggles” in the IR portion of the curves. To eliminate this effect, we imposed a constraint on \( k_{IR} \) for the whole sample, namely, \( k_{IR} = 0.63R(V) - 0.84 \). This is taken from F04, who found a very strong relationship between \( R(V) \) and \( k_{IR} \) from a larger sample of more heavily reddened stars (see Fig. 6 of F04). The ability to impose scientifically reasonable constraints on the fitting procedure is a major advantage of the extinction without standards approach and can potentially allow high-quality extinction results to be derived from stars with even lower reddenings than those shown in Figure 9.

### 6. DISCUSSION

In this paper we first provided an overview of the process used to determine an extinction curve, clarifying the measurement process. We then presented a new method for deriving UV through IR extinction curves, based on the use of stellar atmosphere models to provide estimates of the intrinsic (unreddened) stellar SEDs rather than reddened (or lightly reddened) standard stars. We have shown that this “extinction without standards” technique greatly increases the accuracy of the derived extinction curves, particularly in the cases of low reddening and cool spectral types (i.e., late B), and allows a realistic estimation of the uncertainties. A side benefit of the technique is the simultaneous determination of fundamental properties of the reddened stars themselves \( (T\text{eff}, \log g, [M/H], \text{ and } v\text{turb}) \), making the procedure valuable for both stellar and interstellar studies. Given the physical limitations of the ATLAS9 models we currently employ, the technique is limited to near-main-sequence B stars. However, in principle, the procedure can be adapted to any class of star for which accurate model SEDs are available and for which the signature of interstellar reddening can be distinguished from those of the stellar parameters. Although we developed the procedure based on IUE spectrophotometry in the UV and photometry in the optical and near-IR (requiring a calibration of synthetic optical and near-IR photometry), the ideal application of the technique would be with spectrophotometric data throughout the UV through IR domain, allowing the most detailed examination of the UV through IR domain, allowing the most detailed examination of the UV through IR domain. The specific scientific advantages afforded by the extinction without standards technique can be summarized as follows:

**Increased precision.**—The increased precision in the derived extinction curves allows us to improve our understanding of extinction in a number of ways. First and most simply, we will determine the basic UV to IR wavelength dependence of extinction along a wide variety of sight lines more precisely than has been possible in the past. Second, and given that we know that extinction curve morphology varies widely from sight line to sight line (see Fig. 7), we will be able to study the form of the variability and search for relationships between various features and wavelength domains using a data set with small and well-defined uncertainties. Such relationships, e.g., the correlation between \( R(V) \) and the steepness of UV extinction discovered by Cardelli et al. (1989), provide important constraints on the dust grain population causing the extinction. Noncorrelations can be equally important. For example, the lack of a correlation between
the position and width of the 2175 Å bump demonstrated by Fitzpatrick & Massa (1986) remains a strong constraint on models for the bump carrier (Draine 2003). In either case, a precise knowledge of the measurement errors is required for transforming an observation into a scientific constraint. Finally, we will be able to place much stronger and more well-defined limits on the relationship between extinction curve morphology and interstellar environment. Curves derived from lines of sight to specific, localized regions, such as toward open clusters, can be particularly useful for relating curve properties to physical processes occurring in the interstellar medium (see, e.g., the study of Cepheus OB3 by Massa & Savage [1984] and Trumpler 37 by Clayton & Fitzpatrick [1987]).

Access to lightly reddened sight lines.—The ability to accurately probe low-\(E(B-V)\) sight lines (as exemplified in Figs. 4 and 9) opens the door to studies of dust in regions that have not been thoroughly explored. These include halo dust, dust in very low density regions, and local dust. Halo dust is especially important, since we must contend with its effects every time we look out of the Galaxy. There are indications (Kiszkurwno-Kozieć & Lequeux 1987) that its properties differ systematically from dust at lower Galactic altitudes, and this result needs to be verified on a star-by-star basis. The nature of low-density dust provides insights into the processing that occurs in hostile environments. Clayton et al. (2000) presented observations of dust from low-density sight lines, and their results were intriguing. However, they were forced to select sight lines that accumulate fairly substantial color excesses, introducing the possibility of mixed grain populations. Furthermore, the results for their least reddened sight lines were, as they acknowledge, poorly determined, forcing them to base their conclusions on a global average of properties of their sample. Finally, measuring the properties of local dust is important, because it allows us to search for isolated, relatively homogeneous environments with uniform extinction curve shapes. These may signal physically and kinematically isolated regions that would be ideal for follow-up interstellar line studies. In addition, Hipparcos parallax data exist for nearby stars and provide an opportunity to study the three-dimensional structure of local extinction.

Access to the mid to late B stars.—These stars are especially important, because their space density is higher than that of the early B stars usually used in extinction studies, and thus their inclusion increases the number of stars available to create curves for nearby sight lines. Studies of the mid to late B stars will enable the examination of the spatial structure of local dust absorption more thoroughly than previously possible and will greatly enhance our understanding of the local interstellar medium. The ability to construct accurate curves for mid to late B stars will also allow us to study extinction in open clusters and associations that are dominated by these stars, such as the Pleiades, \(\alpha\) Per cluster, and IC 4665 (see Fig. 4).

Automation.—Because our model atmosphere approach does not require human intervention, once the basic data have been assembled, it is possible to process large data sets at one time. Naturally, the automated results must be inspected for outliers and data anomalies. Nevertheless, this approach reduces the workload considerably, and a first attempt yielded the regional anomaly shown in Figure 9. Furthermore, since the results are produced in a uniform manner, it is a relatively simple matter to inspect them for correlations between various curve properties, for anomalous curve shapes, and for spatial trends on the sky.

Stellar properties.—In addition to dust parameters, our technique provides meaningful, quantitative physical properties for the reddened stars. The temperature and surface gravity information will be useful for population studies of B stars in the field and in clusters. However, perhaps the most useful property will be the metallicity. We have demonstrated that several stars in the same cluster, which have a range of temperatures and gravities, all yield the same \([M/H]\). This verifies the sensitivity of our fitting procedure to this important quantity. As a result, we are confident that application of our procedure to large-scale surveys of reddened, near-main-sequence B stars can provide a census of the distribution of metallicity throughout the Galaxy and the local universe.

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