OBSERVATIONAL 5–20 μm INTERSTELLAR EXTINCTION CURVES TOWARD STAR-FORMING REGIONS DERIVED FROM SPIZTER IRS SPECTRA

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ABSTRACT

Using Spitzer Infrared Spectrograph observations of G0–M4 III stars behind dark clouds, I construct 5–20 μm empirical extinction curves for 0.3 ≤ AK < 7, which is equivalent to AV between ∼3 and 50. For AK < 1, the curve appears similar to the Mathis diffuse interstellar medium extinction curve, but with a greater degree of extinction. For AK > 1, the curve exhibits lower contrast between the silicate and absorption continuum, develops ice absorption, and lies closer to the Weingartner and Draine 5.5 Case B curve, a result which is consistent with that of Flaherty et al. and Chiar et al. Recently, using Spitzer Infrared Array Camera data by Chapman et al. independently reaches a similar conclusion that the shape of the extinction curve changes as a function of increasing AK. By calculating the optical depths of the 9.7 μm silicate and 6.0, 6.8, and 15.2 μm ice features, I determine that a process involving ice is responsible for the changing shape of the extinction curve and speculate that this process is a coagulation of ice-mantled grains rather than ice-mantled grains alone.

Keywords: infrared: stars – ISM: clouds – stars: formation

Online-only material: machine-readable table

1. INTRODUCTION

Extinction along the line of sight to a young stellar object must be accounted for when considering the nature of that object. Discrepancies between the diffuse interstellar medium (DISM) extinction curve and observations of dark clouds, where young stellar objects form, have been noted at UV and visible wavelengths (Savage & Mathis 1979, and references therein). These variations were successfully modeled by parameterizing the extinction curve with RV, the total-to-selective extinction (Cardelli et al. 1989; Weingartner & Draine 2001; hereafter CCM89 and WD01), which varies from an average value of 3.1 in the DISM to about 5 in dense clouds (Whittet et al. 2001). Most of the resulting curves are remarkably consistent at wavelengths longer than 0.9 μm regardless of the assumed RV (see CCM89 and WD01 Case A), the exception being a WD01 RV = 5.5 curve in which the maximum grain size is 10 μm. This “Case B” extinction curve is considerably higher than either the other WD01 or CCM89 extinction curves at wavelengths longer than 3.0 μm. More recent work has demonstrated that extinction toward dense molecular clouds is different from DISM extinction over the 3–24 μm range, particularly over the 3–8 μm region (Indebetouw et al. 2005; Flaherty et al. 2007; Chapman et al. 2009) and the shape of the 9.7 μm silicate feature (Chiar et al. 2007, hereafter C+07). Many of the nearby star-forming regions (e.g., Ophiuchus, Orion) have a large fraction of highly extinguished members. For AV < 12 (equivalent to AK = 1.5) past the breaking point of the local ISM correlation in dark clouds (C+07), the sample size for these regions is drastically reduced.

To analyze a full sample from these regions, a new extinction curve is required. Using Spitzer Infrared Spectrograph (IRS; Houck et al. 2004) observations of stars with known intrinsic spectra behind various dense molecular clouds, I determine the spectrum of extinction from 5–20 μm for 31 lines of sight. While any curves derived for a particular line of sight are unlikely to be universal, the median curves for specific ranges of extinction should characterize the shape of the extinction curve for dark clouds.

2. SAMPLE AND ANALYSIS

I began my analysis with 28 of the G0–M4 III stars discussed in C+07 that lie behind the Taurus, Chameleon I, Serpens, Barnard 59, Barnard 68, and IC 5146 molecular clouds. Most of these have been observed with some combination of the Spitzer IRS low-resolution (λ/Δλ = 60–120) short-wavelength (SL; 5.2–14 μm) and long-wavelength second-order (LL2; 14.0–21.3 μm), and the high-resolution (λ/Δλ = 600) short-wavelength (SH; 10–19 μm) modules. With the exception of HD 29647, a B8III star which has yet to be observed with the IRS, these background stars have spectral types in the range G0–M4 and should have little intrinsic emission in the mid-infrared, as long as they are not supergiants, which are quite rare. One of these background stars, CK 2, was serendipitously observed with the first order of the long-wavelength low-resolution module (LL1; 20–35 μm) as part of a GTO program in Serpens. I supplemented this list of objects with three other background K and M III stars from Shenoy et al. (2008) that have been observed with the IRS. The final list follows, with the AOR numbers, in Table 1. With the exception of background emission subtraction in SL and LL, which was done from the opposite nod position in most cases, I extracted these spectra using the method described in Furlan et al. (2006). Two of the objects, Elias 3 and Elias 13, were observed with SL and SH, but SH was clearly contaminated by sky, as indicated by the excess flux above the level of SL and a different slope over the 10–14 μm range, so I only used SL for these observations. I also declined to use Elias 9, as it was only observed with SH.

The line-of-sight extinction in a particular band can be determined from a color excess. Taking H and KS (henceforth K) photometry from the Two Micron All Sky Survey (2MASS; Cutri et al. 2003) and using the most recent online update of the
Carpenter (2001) color transformations to convert the intrinsic luminosity class III colors from Bessell & Brett (1988) into the 2MASS system, I calculated the color excess \( E(H - K) \), assuming a spectral type of K2 for objects with spectral types listed as G0–M4. Uncertainties in the \( E(H - K) \) include the independent contributions of uncertainties in 2MASS colors and transformed intrinsic colors. For objects with spectral types in the range G0–M4, the uncertainty in \( E(H - K) \) is taken to be the difference between \( E(H - K) \) for an M4 giant and a K2 giant, since this was greater than the difference between a K2 and G0 giant, resulting in uncertainties in \( E(H - K) \) of \( \pm 0.13 \). The choice of K2 to represent the spectral types of objects with a range of G0–M4 may affect the precise value of extinction, but it will have less effect on the shape of the extinction curve over the IRS spectrum, since most photophores follow a Rayleigh–Jeans tail at \( \lambda > 5 \mu m \). For objects with a known spectral type, the uncertainty was calculated by assuming a range of \( \pm \) one subgroup. The color excess is defined as \( E(H - K) = A_H - A_K \), from which the extinction, \( A_K \), for these stars was calculated using the following expression:

\[
A_K = \frac{[E(H - K)]}{(A_H / A_K) - 1}
\]  

and uncertainties in \( A_K \) determined via error propagation. I took \( A_H / A_K = 1.56 \) from the Mathis (1990) extinction law, interpolated to the 2MASS \( H \) and \( K \) wavelengths. The slopes of extinction laws in the literature are relatively uniform over \( JHK \) (CCM89; WD01).
Two of the stars required special consideration. SSTc2dJ182852.7+02824 was undetected in the K band of the 2MASS, but a magnitude at K was given by The Denis Consortium (2005). I calculated $A_K$ as above but without converting the DENIS K into the 2MASS system and note that there is a small additional uncertainty associated with this extinction (which is much smaller than the uncertainty of the spectral type). B59-bg1 was undetected at $H$, so this extinction is a lower limit to the true value.

Next I interpolated a model photosphere (Castelli et al. 1997) of appropriate spectral type to the resolution of the 2MASS data and the IRS spectrum for each object, then extinction corrected the 2MASS K flux using $A_K$. $A_\lambda$ can then be found using the following expression, where $F_{K_{\text{corrected}}}$ is used to scale the photosphere appropriately:

$$A_\lambda = 2.5 \log \left( \frac{F_{K_{\text{corrected}}}}{F_{\text{photosphere}} / F_{K_{\text{spatial}}}} \right). \tag{2}$$

I also calculated the peak optical depth of the 9.7 (silicates), 6.0 (H$_2$O ice), 6.8 (\textquoteleft{methanol\textquoteleft} ice), and 15.2 $\mu$m (CO$_2$ ice) absorption features for each source with, e.g., $\tau_{9.7} = -\ln \left( \frac{F_{\text{photosphere}}}{F_{\text{continuum}}} \right)$, where the continuum was the photosphere scaled to $F_{K_{\text{corrected}}}$.*

3. RESULTS AND DISCUSSION

3.1. New Extinction Curves

To analyze these extinction curves, I first normalized $A_\lambda$ to $A_K$ for each object, then separated the objects into groups according to their level of extinction. 11 objects were in the 0.3 $\leq A_K < 1$ category, 10 in 1.0 $\leq A_K < 2.0$, 6 in 2.0 $\leq A_K < 3.0$, and 4 in 3.0 $\leq A_K < 7$. Of these objects, all had 5−14 $\mu$m spectra and the majority had coverage from 14 to 20 $\mu$m, either in SL or SH, with one of these having additional coverage in LL1. The medians of all four groups are shown in Figure 1 (top); the means were very similar to the medians, but with poorer signal-to-noise ratio (S/N). The medians of all four groups are shown in Figure 1 (top); the means were very similar to the medians, but with poorer signal-to-noise ratio (S/N). The medians of all four groups are shown in Figure 1 (top); the means were very similar to the medians, but with poorer signal-to-noise ratio (S/N).

To create composite extinction curves with my data and those from the literature, I renormalized the Mathis (1990) and WD01 $R_V = 5.5$ Case B extinction curves to $A_K$. I noticed that the WD01 curve parallels the 0.3 $\leq A_K < 1.0$ curve from 16 $\mu$m and longward, and it roughly matches the slope of the 1.0 $\leq A_K$ extinction curve beyond 30 $\mu$m. Consequently, I scaled the Weingartner & Draine (2001) curve up and appended it to the polynomial fit curves past approximately 16 $\mu$m and 30 $\mu$m. Since my extinction curves were already normalized to the $K$ band of the Mathis (1990) curve, I prefixed my new curves with the 3.6 and 4.5 $\mu$m extinctions from Flaherty et al. (2007) and with the Mathis curve up to 2.3 $\mu$m, assuming $R_V$ of 5.0 for $\lambda < 0.9$ $\mu$m. The portions of the curves derived solely in this work are compared with other curves from the literature in Figure 1 (bottom) and the final, composite curves are tabulated in Table 2.

Comparing the curves in the bottom panel of Figure 1, it appears that there is a real variation in the shape of the extinction curve as a function of $A_K$ in the mid-infrared. The 0.3 $\leq A_K < 1.0$ extinction has a similar overall slope to the Mathis (1990) curve but has higher extinction all around. Originally, I had subdivided the objects with 0.3 $\leq A_K < 1.0$ into two groups, and the lower group appeared even closer to the Mathis (1990) curve, but the uncertainties on both $A_K$ and the poor S/N in some of the spectra in that subset necessitated using a larger range of objects (and hence $A_K$) to construct a good polynomial fit to the curve. The 1.0 $\leq A_K$ curve is much higher than the Mathis (1990), WD01, or the 0.3 $\leq A_K < 1.0$ curve but is consistent with the results of Indebetouw et al. (2005) and Flaherty et al. (2007), which were based on Spitzer Infrared Array Camera (IRAC) and Multiband Imaging Spectrometer data.
Photometer (MIPS) photometry. Significantly, the extinction over the 9.7–20 μm region is also higher than both the Mathis (1990) curve and the 0.3 ≤ A_K < 1.0 curve; in fact, it is almost flat. This result, that the extinction curve transitions from a shape similar to the DISM Mathis (1990) curve to a higher, flatter extinction, was independently derived from IRAC photometry for several molecular clouds by Chapman et al. (2009), whose extinction curves roughly match mine over the 5–8 μm region for A_K > 0.5. The range of 24 μm extinctions given by both Flaherty et al. (2007) and Chapman et al. (2009) are consistent with the flat slope of the 1 ≤ A_K extinction curve derived here from 8 to 24 μm. Unfortunately, none of the data with A_K < 1 extended beyond 20 μm for comparison.

3.2. Shape of the 9.7 μm Silicate Feature

In addition to changes in the slope of the extinction curve, the silicate features change shape with increasing A_K as well. The amplitude relative to the 7 and 14 μm regions of the 9.7 μm silicate feature in the 0.3 ≤ A_K < 1.0 curve is somewhat smaller than in the Mathis (1990) curve or the WD01 Case B curve. As A_K passes 1 mag, the amplitude decreases even further and the longer wavelength wing begins to broaden. Noticeably, the 18 μm silicate feature is considerably wider and flatter in the 1.0 ≤ A_K curve than in the literature curves. That the amplitude of the 9.7 μm silicate feature relative to the rest of the curve changes as a function of A_K is similar to the findings of C+07. Plotting A_K against τ_9.7, the optical depth increases linearly as a function of the extinction (Figure 2). Taking a least-squares fit to the data, I find that the linear relationship is A_K/τ_9.7 = 1.48 ± 0.02 with R = 0.989, which is equivalent to A_V/τ_9.7 = 11.46 if R_V = 5.0 (see footnote to Table 1 for conversion factor). I do not find the same break in the relationship between τ_9.7 and A_K at A_K = 1.5, equivalent to A_V = 10–12, that C+07 do. Additionally, their data (open diamonds, Figure 2) are much lower than mine. This discrepancy is caused by the difference in how we calculate our continua. I take the continua to be the photospheres scaled to the extinction corrected K-band fluxes, while C+07 take theirs from second or third degree polynomial fits to regions of silicate-free continuum emission at 5.2–7 μm and 13.5–15 μm. As a result, I am measuring the total optical depth at 9.7 μm, while the C+07 data denote the 9.7 μm optical depth in excess of the adjacent continuum optical depth.

At higher A_K, if the effects of grain growth contribute to the extinction, one expects the silicate profile to broaden to longer wavelengths and extinction from scattering to be important, which could affect the 13.5–15 μm region used to anchor the polynomial fit of C+07. In fact, broadening of the longer wavelength wing of the silicate profile is one of the changes between the 0.3 ≤ A_K < 1.0 and 1.0 ≤ A_K extinction curves. However, H_2O absorption around 13 μm could also contribute to broadening of that wing. The difference between the total optical depth (my data) and the relative silicate optical depth (C+07 data) represents the continuum extinction underlying the silicate feature, which is presumably part of the shallow shape of the extinction curve beyond 3 μm. To test whether water ice is associated with this underlying extinction, I plotted the difference between the total and excess optical depths (mine – C+07) against the optical depths of all three ices seen in the extinction curves (Figure 3). Surprisingly, the correlation between the excess continuum extinction and all the ices is very strong, not just H_2O ice. In addition, H_2O and CO_2 ice have formation threshold extinctions around A_K = 0.5 (≈3–4 in A_V).

Table 2

| Wavelength (μm) | A_K/A_V | A_K/A_K |
|----------------|---------|---------|
| 0.3 ≤ A_K < 1  | 1 ≤ A_K < 7 |
| 5.19           | 4.13E-1  | 4.89E-1 |
| 5.22           | 4.10E-1  | 4.87E-1 |
| 5.25           | 4.08E-1  | 4.85E-1 |
| 5.28           | 4.06E-1  | 4.83E-1 |
| 5.31           | 4.04E-1  | 4.81E-1 |
| 5.34           | 4.02E-1  | 4.79E-1 |
| 5.37           | 4.00E-1  | 4.77E-1 |
| 5.40           | 3.98E-1  | 4.75E-1 |
| 5.43           | 3.96E-1  | 4.73E-1 |
| 5.46           | 3.94E-1  | 4.71E-1 |
| 5.49           | 3.92E-1  | 4.70E-1 |
| 5.52           | 3.90E-1  | 4.68E-1 |

Notes. The wavelengths over the mid-infrared are sampled to the SL and LL Spitzer IRS modules. (This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Figure 2. A_K vs. τ. Top: τ_9.7 from this work (the filled squares with error bars). Stars with τ_9.7 from C+07 (open diamonds) are plotted using the A_K I derive here. The dotted and dashed lines represent the linear relationships between A_K and τ_9.7 for the diffuse ISM (DISM; A_V = 18.5, i.e., A_K = 2.39) and galactic center (GC; A_V = 9, i.e., A_K = 1.16), respectively (WD01, and references therein). Bottom: τ_6.0, for H_2O, “methanol,” and CO_2.
which is consistent with the lowest extinctions in our sample. This 0.5 mag of extinction is also the threshold at which \( R > 3 \) changes from the DISM value of 3.1 to a value of \( \approx 5 \) over 0.35–2.2 \( \mu m \) along lines of sight in Taurus (Whittet et al. 2001) and other nearby star-forming regions (Chapman et al. 2009).

Taken together, these results indicate that ices are associated with the transition from a DISM extinction curve to the molecular cloud profile. However, the result that all of the ices correlate with the underlying continuum extinction indicates that all the ice species contribute to the process that creates this continuum extinction. Since only the water ice libration band at 13 \( \mu m \) could widen the silicate profile, but not the other ice species, another process, such as grain growth, could be the main contributor to the widened silicate profile. Scattering from larger grains could also explain both the shallower 5–8 \( \mu m \) and 12–14 \( \mu m \) regions. In fact, Figures 16–18 of Chapman et al. (2009) show how their IRAC extinction curves compare with the best-fitting model curve from a paper in preparation by Pontoppidan et al., a model which was constructed for solid grains with ice mantles (Chapman et al. 2009), and this model does not provide enough extinction over the 5–8 \( \mu m \) and 12–14 \( \mu m \) regions to match the Chapman et al. (2009) data. Given that ices contribute to the shape of the extinction curve, but ice mantles do not match the data well, and we see signs of grain growth, it is likely that we need to consider a different structure in the grains. A possibility is that after water ice mantles the grains, they become “sticky” in collisions, forming porous coagulations of smaller grains held together by icy coatings on their surfaces.

4. CONCLUSIONS

These new curves demonstrate that the shape of the extinction curve changes from a shape close to the DISM extinction curve at \( A_K \approx 0.5 \) to a new shape at higher \( A_K > 1 \), a result which is addressed for the first time here and, independently, in Chapman et al. (2009). That our results, derived with different methods from different data, agree so well is a strong statement in favor of their validity. Additionally, comparison of the optical depths of the silicate and ice features in these extinction curves indicates that while ices play a significant role in the transition from DISM to molecular cloud extinction, grain growth via coagulation with the ice as a “glue” between the particles is likely to contribute more to the extinction than simple ice mantles alone. Theoretical models are needed to confirm the role played by ices and grain growth in changing the shape of the extinction curve, but the empirical extinction curves presented here seem appropriate for extinction-correcting the flux of objects with \( A_K > 0.5 \) in molecular clouds. Future Spitzer observations of objects behind dark clouds will hopefully refine our understanding of the change in the shape of the silicate profiles from 0.5 < \( A_K < 1 \) and to what component or environmental condition this change can be attributed.

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