Infrared Extinction Toward Nearby Star-Forming Regions

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ABSTRACT

We present an independent estimate of the interstellar extinction law for the *Spitzer* IRAC bands as well as a first attempt at extending the law to the 24μm MIPS band. The source data for these measurements are observations of five nearby star-forming regions: the Orion A cloud, NGC 2068/71, NGC 2024/23, Serpens and Ophiuchus. Color excess ratios $E_{H-K_s}/E_{K_s-[\lambda]}$ were measured for stars without infrared excess dust emission from circumstellar disks/envelopes. For four of these five regions, the extinction laws are similar at all wavelengths and differ systematically from a previous determination of the extinction law, which was dominated by the diffuse ISM, derived for the IRAC bands. This difference could be due to the difference in the dust properties of the dense molecular clouds observed here and those of the diffuse ISM. The extinction law at longer wavelengths toward the Ophiuchus region lies between that to the other four regions studied here and that for the ISM. In addition, we extended our extinction law determination to 24μm for Serpens and NGC 2068/71 using *Spitzer* MIPS data. Our work confirms a relatively flatter extinction curve from 4 - 8μm than the previously assumed standard. The extinction law at 24μm is consistent with previous measurements and models, although there are relatively large uncertainties.

Subject headings: dust, extinction — infrared:general

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1. Introduction

The *Spitzer* Space Telescope, with its unpecedented sensitivty, has allowed detailed studies of young stellar clusters. An accurate extinction law in these environments is useful in classifying the young members (Gutermuth 2005; Lada et al. 2006) as well as tracing the dust using extinction maps (Lada et al. 2007; Lombardi et al. 2006). We determine the extincton law from $3-8\mu$m toward five young, nearby cluster regions and extend it to 24μm for two of these regions. This extinction law is compared to previous determinations (Lutz 1999; Rosenthal, Bertoldi & Drapatz 2000; Jiang et al. 2006; Indebetouw et al. 2005; Román-Zúñiga et al. 2007) across this wavelength range that represent a mix of diffuse ISM and dense molecular cloud dust. R. Indebetouw kindly provided the data for their regions so that we could process them using the same methods that we used to process our data.

2. Observations and Analysis

Observations of several young star-forming clusters were obtained with the IRAC camera (Fazio et al. 2004) and MIPS (Rieke et al. 2004) aboard *Spitzer*. Details on the data obtained, as well as the reduction methods, are provided in Flaherty et al. (2007). Color-excess ratios were measured from the slope of the reddening band in $H-K_s$ vs. $K_s-[\lambda]$ color-color diagrams (Figure 1). Foreground stars and stars with an infrared excess in any of the IRAC bands were removed. More details on our selection of background sources, as well as a description of the derivation of the color-excess ratios from $H-K_s$ vs. $K_s-[\lambda]$ color-color diagrams can be found in Flaherty et al. (2007).

3. Results

3.1. The Extinction Law from 3-8μm

Color-excess ratios for our five clusters are listed in Table 1. It is apparent that our derived color excess ratios are reasonably consistent from region to region. The color excess ratios for the $l = 284°, b = 0.25°$ off-cloud line-of-sight GLIMPSE data (R. Indebetouw private communication), one of the regions studied in Indebetouw et al. (2005), were derived using the same source selection criteria and methods as used for the five star-forming regions discussed here. In contrast to the general agreement among the clusters, the slopes from the GLIMPSE data listed in Table 1, and shown in Figure 2, are generally different from the cluster slopes. Román-Zúñiga et al. (2007) measure the extinction law in the IRAC bands in the dense globule Barnard 59 using color-color diagrams similar to those used here and find that it is inconsistent with Indebetouw et al. (2005), but is entirely consistent with our results. Their color-excess ratios are included in Table 1.

The values of A_λ/A_{K_s}, derived assuming $A_H/A_{K_s} = 1.55$, for each of the five regions observed here as well as the rederived extinction law for the $l = 284°$ off-cloud line of sight from Indebetouw et al. (2005) are plotted in Figure 3 and are listed in Table 2. Our extinction law deviates from a power law, as is also seen in these previous studies.

3.1.1. Molecular Cloud vs. Diffuse Interstellar Extinction

A plausible explanation for the agreement between our extinction law and the extinction law of Román-Zúñiga et al. (2007) as well as the separation from the extinction law of Indebetouw et al. (2005) is a variation in the extinction law between that through the diffuse ISM and through molecular clouds. Changes in the extinction law originating in these regions are likely due to grain growth, either by coagulation of small grains or the growth of icy mantles, both of which will affect the continuum level of extinction. Pendleton et al. (2006); Chiar et al. (2007) find evidence for grain growth based on a change in the silicate feature, which overlaps the [8.0] band of IRAC, in dense molecular clouds. Dust in molecular cloud cores is protected both from the UV interstellar radiation field and from cosmic ray processing; those dust grains may therefore have larger mantles consisting of water and organic ices (Gibb et al. 2004). Absorption features between 3 and 8μm due to ices are often seen along lines of sight intersecting dense molecular clouds (Knez et al. 2005; Gibb et al. 2004) while they are not seen in the diffuse ISM (Whittet et al. 1997). Changes in the emissivity due to grain growth in dense molecular clouds is also observed (Stepnik et al. 2003; del Burgo et al. 2003; Cambresy et al. 2005).

The measurements of Lutz (1999) and Jiang et al. (2006) represent a mix of diffuse ISM and dense molecular cloud and the extinction law measured by these two groups also varies between our results and the Indebetouw et al. (2005) results. Given the uncertainties in the derived laws of Jiang et al. (2006) and Lutz (1999), we cannot distinguish whether any agreement, or lack of agreement with either our law or that of Indebetouw et al. (2005) depends on whether the material causing extinction is part of the diffuse ISM or a dense cloud.

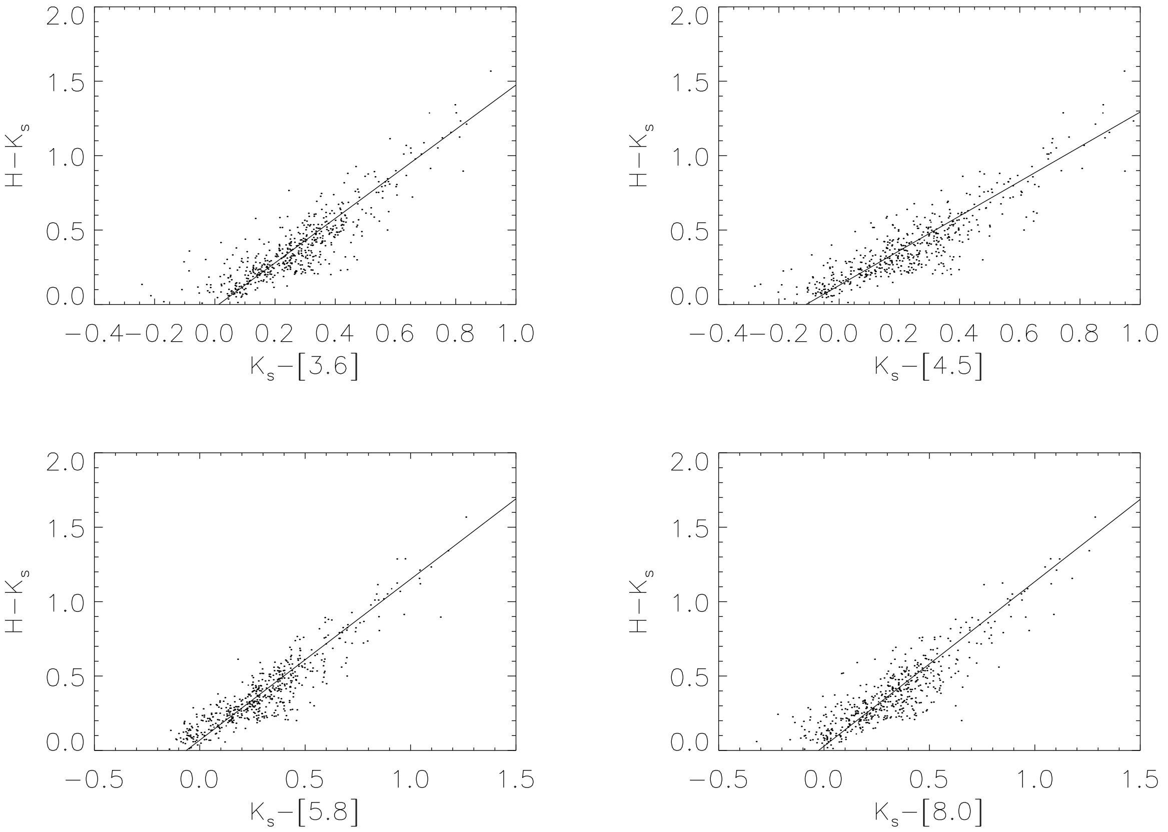

Fig. 1.— 2MASS and IRAC color-color diagrams for NGC 2024/2023 nonexcess sources, including best fit lines. Color-color diagrams for the other four clouds can be found in Flaherty et al. (2007).

Table 1. Selective Color Excess Ratios

Region	$E_{H-K_s}/E_{K_s-[3.6]}$	$E_{H-K_s}/E_{K_s-[4.5]}$	$E_{H-K_s}/E_{K_s-[5.8]}$	$E_{H-K_s}/E_{K_s-[8.0]}$
NGC 2024/23	$1.49 \pm 0.02(0.08)$	$1.17 \pm 0.02(0.06)$	$1.08 \pm 0.01(0.06)$	$1.11 \pm 0.02(0.07)$
NGC 2068/71	$1.49 \pm 0.02(0.07)$	$1.13 \pm 0.01(0.05)$	$1.03 \pm 0.01(0.05)$	$1.07 \pm 0.01(0.05)$
Serpens	$1.49 \pm 0.02(0.08)$	$1.17 \pm 0.02(0.06)$	$1.08 \pm 0.01(0.05)$	$1.07 \pm 0.01(0.06)$
Orion A	$1.51 \pm 0.01(0.04)$	$1.197 \pm 0.008(0.03)$	$1.109 \pm 0.007(0.03)$	$1.116 \pm 0.008(0.03)$
Ophiuchus	$1.46 \pm 0.02(0.07)$	$1.17 \pm 0.01(0.05)$	$1.01 \pm 0.01(0.05)$	$1.01 \pm 0.01(0.05)$
Ind05data	$1.27 \pm 0.02(0.09)$	$1.11 \pm 0.02(0.08)$	$0.92 \pm 0.02(0.06)$	$0.90 \pm 0.01(0.06)$
Ind05 paper	1.17 ± 0.07	1.0 ± 0.03	0.92 ± 0.03	0.92 ± 0.04
B59	1.52 ± 0.05	1.20 ± 0.04	1.03 ± 0.02	1.04 ± 0.02

Note. — See Flaherty et al. (2007) for more details. The extinction law from Román-Zúñiga et al. (2007) (B59) has been added from their "C-C" method which more closely resembles our method for calculating the extinction law.

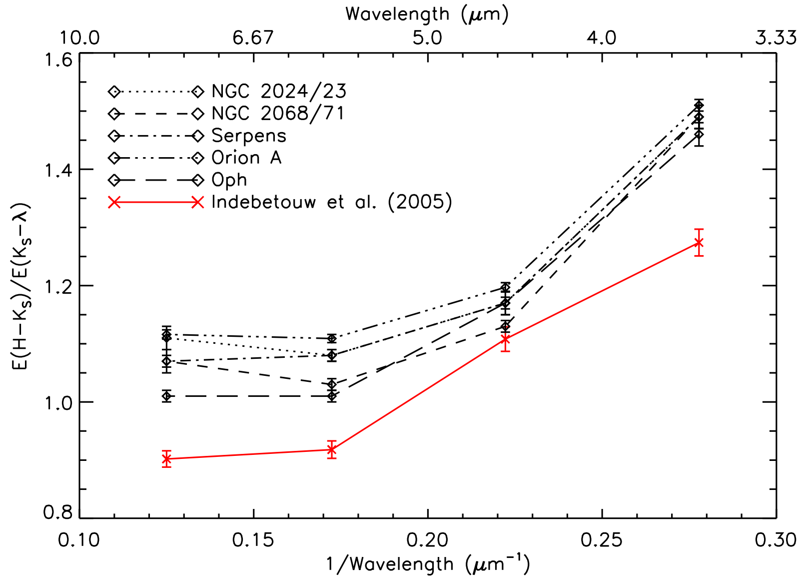

Fig. 2.— Selective color-excess ratio vs. inverse wavelength for our five clouds and the rederived Indebetouw et al. (2005) law.

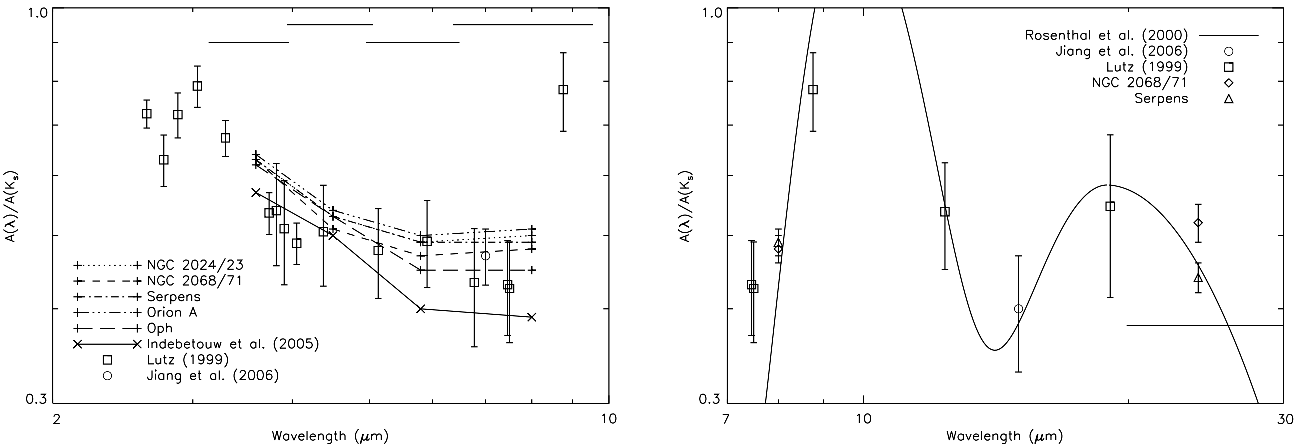

Fig. 3.— Extinction law vs. wavelength. Horizontal lines are the IRAC and MIPS 24μm passbands. In the plot on the right the solid curve is the model of Rosenthal, Bertoldi & Drapatz (2000).

Table 2. Relative Extinction

Region	$A_{[3.6]}/A_{K_s}$	$A_{[4.5]}/A_{K_s}$	$A_{[5.8]}/A_{K_s}$	$A_{[8.0]}/A_{K_s}$
NGC 2024/23	0.632 ± 0.005	0.53 ± 0.01	0.49 ± 0.01	0.50 ± 0.01
NGC 2068/71	0.632 ± 0.005	0.51 ± 0.01	0.47 ± 0.01	0.48 ± 0.01
Serpens	0.630 ± 0.005	0.53 ± 0.01	0.49 ± 0.01	0.49 ± 0.01
Orion A	0.636 ± 0.003	0.540 ± 0.003	0.504 ± 0.003	0.506 ± 0.003
Ophiuchus	0.623 ± 0.005	0.53 ± 0.01	0.45 ± 0.01	0.45 ± 0.01
Ind05 data	0.57 ± 0.01	0.50 ± 0.01	0.40 ± 0.01	0.39 ± 0.01
Ind05 paper	0.57 ± 0.05	0.43 ± 0.07	0.41 ± 0.07	0.37 ± 0.07
B59	0.62 ± 0.08	0.53 ± 0.06	0.46 ± 0.06	0.46 ± 0.06

Note. — See Flaherty et al. (2007) for more details. The extinction law from Román-Zúñiga et al. (2007) (B59) has been added from their "C-C" method which more closely resembles our method for calculating the extinction law.

3.2. The Extinction Law beyond 8μm

Extending our analysis out to 24μm we measure $E_{H-K}/E_{K-[24]} = 0.98 \pm 0.04$ and 1.14 ± 0.06, $A_{24}/A_{K_s} = 0.44 \pm 0.02$ and 0.52 ± 0.03, assuming $A_H/A_{K_s} = 1.55$, for Serpens and NGC 2068/71 respectively. Figure 3 illustrates that our 24μm determinations are in reasonable accord with those of Lutz (1999), given the large uncertainties, as well as with the measurement at 15μm by Jiang et al. (2006). T. Huard et al. (2008 in preperation) also measured the extinction law at 24μm and found it to be consistent with our results. While the assumption of a power law from $3 - 8\mu$m is clearly not valid, the extinction law from $10 - 30\mu$m is very well fit by a law dominated by silicate emission with the adopted strengths of the two silicate features given by Rosenthal, Bertoldi & Drapatz (2000), as can be seen in Figure 3.

4. Conclusion

We measured the extinction law from $3 - 8\mu$m toward five nearby star-forming regions and found it to be relatively internally consistent among different cluster-forming molecular clouds although there is evidence that the Ophiuchus extinction law deviates from the other four regions at 5.8 and 8μm. The extinction laws we present here differ systematically from the extinction at IRAC wavelengths derived by Indebetouw et al. (2005) but are consistent with Román-Zúñiga et al. (2007), as seen in both the color excess ratios and the relative extinction ratios. The result could reflect a physical difference in the extinction law between the diffuse ISM and molecular clouds.

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