FAR-INFRARED EXTINCTION MAPPING OF INFRARED DARK CLOUDS

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ABSTRACT

Progress in understanding star formation requires detailed observational constraints on the initial conditions, i.e., dense clumps and cores in giant molecular clouds that are on the verge of gravitational instability. Such structures have been studied by their extinction of near-infrared and, more recently, mid-infrared (MIR) background light. It has been somewhat more of a surprise to find that there are regions that appear as dark shadows at far-infrared (FIR) wavelengths as long as \(~\sim100\,\mu m\)! Here we develop analysis methods of FIR images from Spitzer-MIPS and Herschel-PACS that allow quantitative measurements of cloud mass surface density, \(\Sigma\). The method builds on that developed for MIR extinction mapping by Butler & Tan, in particular involving a search for independently saturated, very opaque, regions that allow measurement of the foreground intensity. We focus on three massive starless core/clumps in the Infrared Dark Cloud (IRDC) G028.37+00.07, deriving mass surface density maps from 3.5 to 70 \(\mu m\). A by-product of this analysis is the measurement of the spectral energy distribution of the diffuse foreground emission. The lower opacity at 70 \(\mu m\) allows us to probe to higher \(\Sigma\) values, up to \(\sim1\,g\,cm^{-2}\) in the densest parts of the core/clumps. Comparison of the \(\Sigma\) maps at different wavelengths constrains the shape of the MIR–FIR dust opacity law in IRDCs. We find that it is most consistent with the thick ice mantle models of Ossenkopf & Henning. There is tentative evidence for grain ice mantle growth as one goes from lower to higher \(\Sigma\) regions.

Key words: dust, extinction – infrared: ISM – ISM: clouds – stars: protostars

1. INTRODUCTION

The molecular gas clumps that form star clusters are important links between the large Galactic-scale and small individual star-scale processes of star formation. Most stars are thought to form from these structures (e.g., Lada & Lada 2003; Gutermuth et al. 2009). Massive stars may form from massive starless cores buried in such clumps (e.g., McKee & Tan 2003).

Observations of clumps in their earliest stages of star formation are thus important for constraining theoretical models of massive star and star cluster formation. These early-stage clumps are expected to be cold and dense, and large populations have been revealed as “Infrared Dark Clouds” (IRDCs) via their absorption of the diffuse mid-infrared (MIR) (\(~\sim10\,\mu m\)) emission of the Galactic interstellar medium (e.g., Egan et al. 1998; Simon et al. 2006 [hereafter S06]; Peretto & Fuller 2009; Butler & Tan 2009). With the advent of longer wavelength imaging data from Spitzer-MIPS (Carey et al. 2009) and Herschel-PACS (e.g., Peretto et al. 2010; Henning et al. 2010), some IRDCs appear dark at wavelengths up to \(\sim100\,\mu m\).

Butler & Tan (2009, 2012; hereafter BTK) developed MIR extinction (MIREX) mapping with Spitzer-IRAC 8 \(\mu m\) GLIMPSE survey data (Churchwell et al. 2009). Using this method, which does not require knowledge of cloud temperature, they derived mass surface density, \(\Sigma\), maps of 10 IRDCs with angular resolutions of 2\arcsec. The maps probed \(\Sigma\) up to \(\sim0.5\,g\,cm^{-2}\) (\(A_V\sim100\,mag\)), with this limit set by the image noise level and the adopted opacity of 7.5 cm\(^2\) g\(^{-1}\) (based on thin ice mantle dust models; Ossenkopf & Henning 1994; hereafter OH94).

However, higher \(\Sigma\) clouds have been claimed based on far-infrared (FIR)/millimeter dust emission (e.g., Battersby et al. 2011; Ragan et al. 2012), although this also requires estimating the dust temperature. Some already-formed star clusters have cores with \(\Sigma > 1\,g\,cm^{-2}\) (e.g., Tan et al. 2013b). It is thus important to see if extinction mapping methods can be developed that can probe to higher \(\Sigma\) values. Butler et al. (2013; hereafter BTK) have attempted this by using more sensitive (longer exposure) 8 \(\mu m\) images. Here we develop methods that probe to higher \(\Sigma\) via FIR extinction (FIREX) mapping using Spitzer-MIPS 24 and Herschel-PACS 70 \(\mu m\) images with 6\arcsec angular resolution. At these wavelengths, IRDCs still appear dark but have smaller optical depths. Our method also requires us to examine the FIR extinction law and its possible variations within dense gas, which may be caused by grain coagulation and ice mantle formation.

2. THE FAR-INFRARED EXTINCTION (FIREX) MAPPING METHOD

2.1. MIR and FIR Imaging Data for IRDC G028.37+00.07

We utilize Spitzer-MIPS 24 \(\mu m\) images from the MIPSGAL survey (Carey et al. 2009) that have 6\arcsec resolution and an estimated 1\(\sigma\) noise level of 0.25 MJy sr\(^{-1}\).

We also analyze archival 70 \(\mu m\) Herschel-PACS images. The first type (proposal ID KPGT-okrause-1) was observed with medium scanning speed and also have \(\sim6\arcsec\) resolution, but do not cover a very large area around the IRDC (\(~\sim16\) in extent). We estimate a 1\(\sigma\) noise level of \(\sim15\,MJy\,sr^{-1}\), i.e., about a factor of two better than achieved with fast scanning observations (Traficante et al. 2011). The second type (proposal ID KPOT-smolinar-1) was observed in the Galactic plane HiGAL survey (Molinari et al. 2010) in fast scanning mode with \(\sim9\arcsec\) resolution. These data are useful for assessing the intensity of the Galactic background emission, which needs to be interpolated from regions surrounding the IRDC.

Both of the Herschel data sets are obtained as already processed to level 2.5 in HIPE, so zero-level offsets need to be applied to obtain measurements of absolute values for specific intensities. We adopted a model spectral energy distribution
2.2. Radiative Transfer and Foreground Estimation

We adopt the one-dimensional radiative transfer model of BT12, which requires knowing the intensity of radiation directed toward the observer at the location just behind, $I_{\nu,0}$, and just in front, $I_{\nu,1}$, of the target IRDC. The infrared emission from the IRDC is assumed to be negligible (which imposes an upper limit on the dust temperature of $\sim 15$ K; Tan et al. 2013a), so that

$$I_{\nu,1} = e^{-\tau_\nu} I_{\nu,0},$$

where optical depth $\tau_\nu = \kappa_\nu \Sigma$ and $\kappa_\nu$ is total opacity at the frequency $\nu$ per unit total mass and $\Sigma$ is the total mass surface density. The value of $I_{\nu,0}$ is to be estimated via a suitable interpolation from the region surrounding the IRDC, while $I_{\nu,1}$ is to be derived from the observed intensity to given locations toward the cloud. However, because the observed Galactic background emission, $I_{\nu,0,\text{obs}}$, and the observed intensity just in front of the IRDC, $I_{\nu,1,\text{obs}}$, are contaminated with foreground emission, $I_{\nu,\text{fore}}$, (IRDCs are typically at several kpc distance in the Galactic plane) we actually observe

$$I_{\nu,1,\text{obs}} = I_{\nu,\text{fore}} + I_{\nu,1},$$

and

$$I_{\nu,0,\text{obs}} = I_{\nu,\text{fore}} + I_{\nu,0}.$$ 

Therefore, like MIREX mapping, FIREX mapping requires measurement of $I_{\nu,\text{fore}}$ toward each region to be mapped.

Following BT12, we estimate $I_{\nu,\text{fore}}$ empirically by looking for spatially independent dark regions that are “saturated,” i.e., they have the same observed intensity to within some intensity

(SED) of the diffuse Galactic plane emission (Li & Draine 2001; hereafter LD01) from near-infrared to FIR. We fit this model to the observed median intensities in a $2^\circ \times 2^\circ$ field centered on the cloud, considering data at 8 $\mu$m (Spitzer-IRAC), 24 $\mu$m (Spitzer-MIPS), 60 $\mu$m and 100 $\mu$m (both IRAS) and then predicted the expect intensities in the Herschel-PACS 70 $\mu$m band. A single offset value was then applied to each Herschel dataset (908 MJy sr$^{-1}$ and 241 MJy sr$^{-1}$ for medium and fast scan data, respectively). We tested this method against offset corrections reported by Bernard et al. (2010) at $l = 30^\circ$ based on Planck data, finding agreement at the $\pm$10% level.

We found an astrometric difference of a few arcseconds between the Herschel and Spitzer maps. We corrected this by the average value of the mean positional offset of four point sources seen at 8, 24, and 70 $\mu$m, amounting to a $3^\prime\!3^\prime$ translation at P.A. 62:7. The resulting three-color image of the IRDC is shown in Figure 1.

While our focus is on FIR data, we also make a comparison with Spitzer-IRAC 3.5, 4.5, 5.9, 8 $\mu$m (GLIMPSE) images, which have 2$''$ resolution at 8 $\mu$m. For these, we adopted 1$\sigma$ noise levels of 0.3 MJy sr$^{-1}$, 0.3 MJy sr$^{-1}$, 0.7 MJy sr$^{-1}$, 0.6 MJy sr$^{-1}$, respectively (Reach et al. 2006).

To compare multiwavelength extinction mapping pixel by pixel, we regrid the IRAC images to the 24 $\mu$m MIPS frame with its $1\prime\!25 \times 1\prime\!25$ pixels, similar to the $1\prime\!2$ IRAC pixels. However, for the Herschel-PACS data, with their $3\prime\!2$ pixels, we first carry out extinction mapping on the original pixel grid (especially searching for saturated pixels, see below), before finally regridding to the MIPS frame for multiwavelength comparison.

Figure 1. (a) Left: three-color image of IRDC G028.37+00.07 (red: 70 $\mu$m, green: 24 $\mu$m, and blue: 8 $\mu$m). Small circles indicate massive cores studied by BT12 and BTK. Squares are regions inspected for local saturation around cores C1, C4, and C11. The dashed ellipse shows the IRDC boundary from S06. (b) Right top: total IR to submillimeter SED (solid line) of the Galactic plane in the “MIRS” region at $l \approx 44^\circ$ (LD01). The dotted line shows the contribution to this from dust; stars dominate at short wavelengths. Large diamonds indicate convolution of these SEDs with the filter response function of corresponding instruments (panel (b)). The red/blue/green symbols show foreground intensities, relative to the LD01 IRAC 8 $\mu$m value, measured to the three saturated cores C1/C4/C11, respectively. (c) Right middle: filter response of IRAC bands 1–4 (solid lines), MIPS 24 $\mu$m (dotted line), and PACS 70, 100, and 160 $\mu$m (dashed lines). (d) Right bottom: dust opacities relative to effective opacity measured in the IRAC 8 $\mu$m band. Black/blue lines show thin/thick ice mantle models of OH94. Solid lines show the initial, uncoagulated MRN grain population. Dotted and dashed lines indicate these models after 10$^5$ and 10$^7$ yr of coagulation at $n_H = 10^4$ cm$^{-3}$, respectively. The red/blue/green symbols (for C1/C4/C11 regions, slight wavelength offsets applied for clarity) show $\kappa_\nu/\kappa_8$ for the indicated $\Sigma$ ranges.
range set by the noise level of the image. Using 8 μm GLIMPSE images with 2′ resolution and 1σ noise level of 0.6 MJy sr−1, BT12 defined saturated pixels as being within a 2σ range above the observed global minimum value in a given IRDC. However, for the IRDC to be said to exhibit saturation, these pixels needed to be distributed over a region at least 8′ in extent.

We follow a similar method here for the images in the IRAC bands at 24 and 70 μm, but with the following differences. (1) We search for “local saturation” in smaller 1′ fields of view that contain dense cores previously identified by BT12. This helps to minimize the effects of foreground spatial variation. (2) In addition to a standard 2σ intensity range we also consider 4σ and 8σ ranges. This is because we regard the estimate of the noise level in the images as somewhat uncertain. We will also gauge the likelihood of saturation by considering the morphology (e.g., connectedness) of the saturated pixels, together with their overlap with saturated pixels at other wavelengths. In general we expect the saturated region to be larger at wavelengths with larger dust opacities (i.e., generally increasing at shorter wavelengths), but the size is also affected by the relative noise levels in the different wavebands. The ability to detect saturation can also be compromised by the presence of a nearby source that enhances the local level of foreground emission. (3) Given the larger beam sizes at 24 and 70 μm, we adopt a less stringent spatial extent criterion, requiring separation of saturated pixels by about two times the beam FWHM, i.e., 12′.

Our method for estimating the background intensity is the same as that adopted by BT09 and BT12, i.e., the small median filter method applied outside the defined IRDC ellipse from S06 (filter size set to 1/3 of the major axis, i.e., 4′), followed by interpolation inside this ellipse. We inspected the background fluctuations in three control fields equal to this filter size just outside the ellipse: after foreground subtraction the average 1σ fluctuations (from a fitted Gaussian) were 17.3%, 25.3%, and 42.3% at 8, 24, and 70 μm, respectively. In the optically thin limit, these values provide an estimate of the uncertainty in the derived τ and thus Σ in any given pixel due to background fluctuations.

2.3. MIR to FIR Opacities

Following BT09, we adopt a spectrum of the diffuse Galactic background from the model of LD01. We will see below that a by-product of our extinction mapping is the measurement of this spectrum of the foreground emission.

We then consider several different dust models (Table 1), especially the thin and thick ice mantle models for moderately coagulated (i.e., coagulation for 105 yr at nH = 106 cm−3) grains (OH94). For all models we adopt a total (gas plus dust) mass to refractory dust mass ratio of 142 (Draine 2011; see the value of 156 used in BT09 and BT12). This choice will not affect the measurement of relative opacities. Finally, we obtain the effective opacities in different wavebands, i.e., convolution of the background spectrum, filter response function, and opacity function (see Figures 1(b)–(d) and Table 1).

3. RESULTS

3.1. Saturated Regions and Measurement of the Spectrum of the Galactic Foreground

After a global investigation of the IRDC, we focus on three 1′×1′ regions around BT12 and BTK core/clumps, C1 (Figure 2), C4 (Figure 3), and C11 (Figure 4) to search for local saturation at 8, 24, and 70 μm. As seen in the top panels of these figures, the 8 μm saturation is more widespread than seen by BT12, i.e., in C1 and C4, which is a consequence of searching in local regions and thus reducing the masking effect of foreground variations. There is generally good correspondence of saturated regions across the different wavebands, although this can be disrupted by the presence of discrete sources. There is a tendency for saturation to be more extended at 8 and 24 μm, than at 70 μm (however, not in C11). The size of the 2σ saturated region in C1 at 70 μm is not greater than 12′ but it is larger if the condition is relaxed to 4σ, so we consider this likely to be a saturated core. In general, comparing the 2σ limits at 8, 24, and 70 μm to the 105 yr at nH = 106 cm−3) grains (OH94). For all models we adopt a total (gas plus dust) mass to refractory dust mass ratio of 142 (Draine 2011; see the value of 156 used in BT09 and BT12). This choice will not affect the measurement of relative opacities. Finally, we obtain the effective opacities in different wavebands, i.e., convolution of the background spectrum, filter response function, and opacity function (see Figures 1(b)–(d) and Table 1).

3. RESULTS

Table 1

| Dust Model   | IRAC3.5 | IRAC4.5 | IRAC5  | IRAC6  | IRAC8  | MIPS24 | PACS70 | PACS100 | PACS160 |
|--------------|---------|---------|--------|--------|--------|--------|--------|---------|---------|
| WD01 Rv = 3.1 | 8.73    | 5.45    | 3.63   | 5.45   | 3.92   | 0.392  | 0.185  | 0.0756  |         |
| WD01 Rv = 5.5 | 11.5    | 7.59    | 4.86   | 6.13   | 4.10   | 0.420  | 0.213  | 0.1076  |         |
| OH94 thin mantle, 0 yr | 19.3 (14.0) | 11.8 (9.57) | 8.56 (7.77) | 6.89 (6.77) | 4.88 | 0.762 | 0.389 | 0.180 |         |
| OH94 thin mantle, 10³ yr, 10⁶ cm⁻³ | 24.7 (17.9) | 16.4 (11.9) | 10.9 (9.43) | 8.24 (8.09) | 6.86 | 1.14 | 0.603 | 0.290 |         |
| OH94 thick mantle, 0 yr | 26.5 (19.2) | 16.2 (13.2) | 11.7 (10.6) | 9.18 (9.01) | 8.33 | 1.42 | 0.746 | 0.356 |         |
| OH94 thick mantle, 10³ yr, 10⁶ cm⁻³ | 36.0 (26.1) | 15.1 (12.3) | 16.7 (15.1) | 9.34 (9.17) | 10.6 | 3.13 | 0.950 | 0.290 |         |
| OH94 thick mantle, 10⁷ yr, 10⁶ cm⁻³ | 43.5 (31.5) | 17.8 (14.5) | 18.7 (17.0) | 10.7 (10.5) | 13.2 | 3.96 | 1.27 | 0.404 |         |
| OH94 thick mantle, 10⁷ yr, 10⁶ cm⁻³ | 45.7 (33.1) | 18.2 (14.8) | 19.4 (17.6) | 10.9 (10.7) | 14.8 | 4.55 | 1.44 | 0.450 |         |

Notes: A common total to dust mass ratio of 142 is adopted (Draine 2011).

References. WD01, Weingartner & Draine (2001); OH94, Ossenkopf & Henning (1994); opacities have been scaled from the values in parentheses to include the contribution from scattering.

a Mean wavelengths weighted by filter response and background spectrum.
IRDC is at 5 kpc distance and this appears to be close enough that foreground stars are not making significant contributions to the foreground emission as measured on ~ arcsecond scales in these saturated cores.

### 3.2. FIR Extinction Maps

Following the method described in Section 2, given estimates of the foreground and background intensities toward each region, we derive the extinction maps at 8, 24, and 70 μm, displaying Σ in g cm$^{-2}$ under the assumption of the opacities of the thick ice mantle model of OH94 (middle rows of Figures 2–4). The choice of this thick, rather than thin, ice mantle dust model is motivated by the observed opacity law (below), and is different from BT12’s use of the thin ice mantle model. For 8 μm-derived maps the resulting variation of opacity per unit mass and thus Σ is quite small, ~30%, but it can make more than a factor of three difference at 70 μm.
The value of $\Sigma$ at which our saturation-based extinction mapping begins underestimating the true mass surface density is (BT12)

$$\Sigma_{\text{sat}} = \frac{\tau_\nu}{k_\nu} = \frac{\ln(I_{\nu,0}/I_{\nu,1})}{k_\nu},$$

where $I_{\nu,1}$ is set equal to the 2$\sigma$ noise level, i.e., 1.2, 0.5, and 30 MJy sr$^{-1}$ for the 8, 24, and 70 $\mu$m images. At these wavelengths, the saturated cores have average values of $I_{\nu,0} = 92.7, 53.7,$ and 1302.3 MJy sr$^{-1}$, respectively. Thus for thick ice mantle opacities, $\Sigma_{\text{sat}} = 0.44, 0.39, 1.05$ g cm$^{-2}$, respectively, while for thin ice mantle opacities it is 0.58, 0.75, 3.66 g cm$^{-2}$. Note, as discussed by BT12, higher values of $\Sigma$ than $\Sigma_{\text{sat}}$ will be present in the map, but these will tend to be increasingly affected by saturation, leading to underestimation of the true $\Sigma$ values.

The above analysis predicts that we should be able to probe to higher values of $\Sigma$ in the 70 $\mu$m maps than in the 8 and 24 $\mu$m maps, and that such high $\Sigma$ structures will be in regions that have been identified as being saturated at the two shorter wavelengths. In core/clump C1, we indeed see this morphology: the 70 $\mu$m map peaks at around 1 g cm$^{-2}$ at a position close to the C1 core center identified by BT12 and BTK. This highest column density region is coincident with the C1-N $N_2D^*$ (3–2) core identified by Tan et al. (2013a). We also infer that the 70 $\mu$m map is revealing real structures in the range $\Sigma \sim 0.5–1$ g cm$^{-2}$, which are not so reliably probed by the shorter wavelength maps.
In the C4 region, we see two main high $\Sigma$ peaks that exhibit local saturation, with the western structure identified as C4 by BT12 and the eastern as C13 by BTK. In between are two sources seen most clearly at 24 $\mu$m. These sources undoubtedly affect the MIREX and FIREX methods in this region, so it is possible that there is a high $\Sigma$ bridge between the two cores.

In C11, there is a relatively widespread high $\Sigma$ region, which is part of a highly filamentary structure extending toward C12 to the north-east (BTK). The 70 $\mu$m map also reveals a relatively high $\Sigma$ region extending to the north-west. This extension is seen in the 8 and 24 $\mu$m maps, but at lower $\Sigma$. It is possible that localized foreground variations at the shorter wavelengths are affecting the 8 and 24 $\mu$m maps (see also BTK, where this extension is more prominent in an 8 $\mu$m map derived with a finer decomposition of foreground variations).

### 3.3. The MIR to FIR Extinction Law and Evidence for Grain Growth

The relative values of $\Sigma$ derived in non-saturated regions at different wavelengths yield information about the shape of the dust extinction law. This law is expected to vary as grains undergo growth via coagulation and increasing deposition of volatiles, such as water, methanol, and CO, to form ice mantles (see Figure 1(d)). The $\Sigma$ maps of Figures 2–4 are derived assuming the moderately coagulated thick ice mantle model of OH94, so deviations in the $\Sigma$ ratios, e.g., $\Sigma_{70 \mu m}/\Sigma_{8 \mu m}$, from...
unity tell us about deviations of the actual dust extinction law from the OH94 model.

In the bottom rows of Figures 2–4 we present maps of $\Sigma_{70\mu m}/\Sigma_{8\mu m}$, $\Sigma_{70\mu m}/\Sigma_{8\mu m}$ and $\Sigma_{70\mu m}/\Sigma_{24\mu m}$. Some of the variation in these ratio maps is due to the different saturation levels, i.e., the $70\mu m$ map is able to probe to $\Sigma \simeq 1$ g cm$^{-2}$, while the other maps saturate at $\sim 0.4$ g cm$^{-2}$ (and tend to have ratio maps closer to unity). Thus we focus on variations present in non-saturated regions, especially considering intervals of $\pm 0.05$ g cm$^{-2}$ centered on $\Sigma_{8\mu m} = 0.1, 0.2, 0.3$ g cm$^{-2}$. For pixels in these ranges, we evaluate the mean values of $\Sigma_{24\mu m}/\Sigma_{8\mu m}$ and $\Sigma_{70\mu m}/\Sigma_{8\mu m}$. These mean ratios can be reconciled to unity by assuming different values of $\kappa_{24\mu m}$ and $\kappa_{70\mu m}$ relative to $\kappa_{8\mu m}$, and these are shown in Figure 1(d) for each of the three cores.

We also derived $\Sigma$ maps in IRAC bands 1, 2, and 3 for each of the three regions, following the same methods described above and in BT12, and used their ratio maps compared to the three regions, following the same methods described above.

The opacity features in the thick ice mantle models around 3, 6, 20, and 50 $\mu m$ are mostly caused by H$_2$O ice, but CH$_3$OH ice makes an $\sim 1/3$ contribution to the 6 $\mu m$ feature (Hudgins et al. 1993). It is possible that astrochemical variations in the abundance of CH$_3$OH could be contributing to the observed dispersion of the 6 $\mu m$ opacity, and potentially also affecting the 8 $\mu m$ opacity, which sets the normalization of the curves and data shown in Figure 1(d). Again a larger sample of regions and a search for potential correlations with other astrochemical indicators is needed to assess these possibilities.

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