DEEP JHK₁ AND SPITZER IMAGING OF FOUR ISOLATED MOLECULAR CLOUD CORES

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ABSTRACT

We present observations in eight wavebands from 1.25 to 24 μm of four dense cores: L204C-2, L1152, L1155C-2, and L1228. Our goals are to study the young stellar object (YSO) population of these cores and to measure the mid-infrared extinction law. With our combined near-infrared and Spitzer photometry, we classify each source in the cores as, among other things, background stars, galaxies, or embedded YSOs. L152 contains three YSOs and L1228 has seven, but neither L204C-2 nor L1155C-2 appear to contain any YSOs. We estimate an upper limit of $7 \times 10^{-5}$ to $5 \times 10^{-4} L_\odot$ for any undiscovered YSOs in our cores. We also compute the line-of-sight extinction law toward each background star. These measurements are averaged spatially, to create $\chi^2$ maps of the changes in the mid-infrared extinction law throughout our cores, and also in different ranges of extinction. From the $\chi^2$ maps, we identify two small regions in L1152 and L1228 where the outflows in those cores appear to be destroying the larger dust grains, thus altering the extinction law in those regions. On average, however, our extinction law is relatively flat from 3.6 to 24 μm for all ranges of extinction and in all four cores. From 3.6 to 8 μm, this law is consistent with a dust model that includes larger dust grains than the diffuse interstellar medium, which suggests grain growth has occurred in our cores. At 24 μm, our extinction law is two to four times higher than predicted by dust models. However, it is similar to other empirical measurements.

Key words: dust, extinction – ISM: globules – stars: formation

Online-only material: color figures

1. INTRODUCTION

In the standard model of low-mass star formation, dense cores are the precursors of star formation (Shu et al. 1987). Therefore, to understand the process of star formation, one needs to observe the physical conditions of these cores. Embedded young stellar objects (YSOs) are sometimes detected in these cores. These YSOs are partially obscured by the dust within the cores. To accurately model their physical properties requires knowledge of the quantity of dust and its composition, since both affect the degree of attenuation, or extinction, of starlight. By studying the dust, one can learn about its chemistry and evolution. Furthermore, the dust provides a direct measure of the column density and mass. Molecular tracers can suffer depletion in dense regions, making mass estimates from them unreliable.

In this paper, we use Spitzer and deep ground-based JHK₁ observations to probe the dust properties within four cores: L204C-2, L1152, L1155C-2, and L1228. Two of our cores, L1152 and L1228, have known protostars, while the other two do not. Our first goal in this paper is to examine the YSO population of these cores and to look for faintly previously unknown protostars in all four cores. Second, we will compute the extinction law in each core and compare it to the predictions of three dust models to draw conclusions about the dust properties within the cores. This paper is organized as follows: Section 2 describes our observations and data processing pipeline including source classification, the removal of misidentified background galaxies, and how we computed line-of-sight (LOS) extinctions to each star. In Section 3, we use these LOS extinctions to create extinction maps for each core. Then, Section 4 explores the YSO content in our cores. In Section 5, we compute the relative extinction as a function of wavelength, the extinction law, for each core. We also create maps of the $\chi^2$ maps of the difference between the observed and predicted extinction laws and compare to the extinction maps. Finally, we summarize our results in Section 6.

2. OBSERVATIONS

Table 1 lists the location and our assumed distance to each of our cores: L204C-2, L1152, L1155C-2, and L1228. These cores were all observed as part of the Spitzer Legacy Science program “From Molecular Cores to Planet-forming Disks” (c2d; Evans et al. 2003). Using Spitzer, we re-observed these cores with ~10 times the integration time as c2d to look for faint protostars in the cores. These observations were part of GO program 3656. We observed each core in two epochs, where the second epoch was separated from the first by as little as one day but could be up to almost a month later. L204C-2 is located at an ecliptic latitude where asteroids may be a problem; the separation of the two observing epochs ensures we can identify these sources. The Infrared Array Camera (IRAC; 3–8 μm) and the Multiband Imaging Photometer for Spitzer band 1 (MIPS1; 24 μm) were observed separately, resulting in four Spitzer Astronomical Observation Requests (AORs) per core. Our Spitzer AORs are listed in Table 2.

To complement our Spitzer data, we obtained deep JHK₁ data using the FLoridA Multi-object Imaging Near-IR Grism Observational Spectrometer (FLAMINGOS; Elston 1998) instrument installed on the 4 m telescope at Kitt Peak. These JHK₁ observations spanned four epochs from 2003 October to 2006 June. The FLAMINGOS field of view is ~11′ × 11′. Each field consisted of multiple dithers with small offsets around a central position. The total integration time per pixel was 12 minutes (J), 6 minutes (H), and 3 minutes (K). For two fields each in L1152 and L1155C-2 (centered on the core), we took even deeper observations with total integration times of ~1 hr (J), ~1 hr (H), and ~45 minutes (K). Except for a small corner in L204C-2, the
Table 1
Basic Properties of the Cores

| Core       | l   | b   | Distance (pc) |
|------------|-----|-----|---------------|
| L204C-2    | 6   | 20  | 125 ± 25a     |
| L1152      | 102 | 16  | 325 ± 25b     |
| L1155C-2   | 102 | 15  | 325 ± 25b     |
| L1228      | 111 | 20  | 200 ± 50c     |

Notes.
a de Geus et al. (1989).
b Straizys et al. (1992).
c Kun (1998).

Table 2
Summary of Spitzer Observations

| Core       | AOR Number | Date Observed   | Program ID |
|------------|------------|-----------------|------------|
| L204C-2    | 11393792   | 2005-04-07      | 3656       |
|            | 11396352   | 2005-04-08      | 3656       |
|            | 11392000   | 2005-08-22      | 3656       |
|            | 11398912   | 2005-08-23      | 3656       |
| L1152      | 11390976   | 2004-07-23      | 3656       |
|            | 11399424   | 2004-07-28      | 3656       |
|            | 11394304   | 2004-10-15      | 3656       |
|            | 11396864   | 2004-11-10      | 3656       |
| L1155C-2   | 11392768   | 2004-07-22      | 3656       |
|            | 11399936   | 2004-08-12      | 3656       |
|            | 11394816   | 2004-12-02      | 3656       |
|            | 11397376   | 2004-12-26      | 3656       |
| L1228      | 11391232   | 2004-11-28      | 3656       |
|            | 11395072   | 2004-12-07      | 3656       |
|            | 11400192   | 2004-12-16      | 3656       |
|            | 11397632   | 2004-12-26      | 3656       |

JHK data completely cover the areas mapped with Spitzer. In Figures 1–4, we show three-color images of each core and also selected subregions.

2.1. Data Reduction

We reduced our JHK data using python and PyRAF. Each FLAMINGOS field consisted of multiple dithers with small offsets around a central position. To create our science images, we first subtracted a median-filtered dark image from each dither. Second, the dithers were flat-fielded by dividing out a dome flat. Next, we subtracted off the sky. This is critical for IR observations where the sky is typically much brighter than the astronomical objects of interest. We used a two-pass sky subtraction with a running median: stars were identified from the first pass, then masked out in the second pass to produce an improved sky subtraction. Finally, we averaged together the individual dithers for each field.

We used the Two Micron All Sky Survey (2MASS) catalog to correct the coordinates in each field and also to calibrate the photometry. The stars in each field were found using the IRAF task daofind and we used daophot to compute their point-spread function (PSF) photometry. We visually inspected the results to remove false sources identified by daofind and also to add sources missed by the source extractor. Finally, we bandmerged the individual J, H, and K detections into a single JHK catalog for each core.

Our Spitzer data were processed through the standard c2d pipeline. For a full description of this pipeline, please refer to the c2d data delivery documentation available on the Spitzer Science Center’s Web site. We will summarize the pipeline here. We started with the Basic Calibrated Data sets (BCDs) processed by the Spitzer Science Center using their S13 pipeline. We then corrected several image artifacts caused by bright sources and cosmic rays and also some instrumental effects. Finally, we applied location-dependent photometric corrections that account for variations in the detector response across the array.

After improving the BCDs, we combined them into mosaics for each core using the Spitzer Science Center’s software MOPEX (Makovoz & Marleau 2005). We then extracted sources using a modified version of DoPHOT (Schechter et al. 1993). DoPHOT fits PSFs and as sources are found they are subtracted from the images. Next, we bandmerged the individual detections from the 3.6 to 24 μm wavebands and attempted to determine upper limits for nondetections. Since we did not obtain any short integration “high dynamic range” (HDR) observations, we used the c2d observations that do contain HDR frames to correct for saturated fluxes. We compared our fluxes with the c2d fluxes in each IRAC band and empirically determined a flux limit at which our values systematically diverged from c2d’s. We then substituted the c2d observations that do contain HDR frames to correct for saturated fluxes. We compared our fluxes with the c2d fluxes in each IRAC band and empirically determined a flux limit at which our values systematically diverged from c2d’s. We then substituted the c2d fluxes for any sources with a c2d flux brighter than this limit. These limits were 35, 35, 300, and 150 mJy for the 3.6, 4.5, 5.8, and 8.0 μm bands, respectively.

Finally, we combined our 3.6–24 μm and deep JHK data catalogs to create bandmerged catalogs from 1.25 to 24 μm for each of the four cores.

(A color version of this figure is available in the online journal.)
Figure 2. Three-color image of L1152. The contours are from the extinction map (Section 3). The wavelengths used for the blue, green, and red emission, respectively, are listed at the top of each subfigure. (A color version of this figure is available in the online journal.)

2.2. Data Quality

The mean difference in position between sources in our $JHK_s$ catalogs and in the 2MASS catalogs is $0.15''$, and 95% of our sources have a difference in position of $\leq 0.6''$ (around 2 pixels on the FLAMINGOS CCD). We also computed the flux difference between our Kitt Peak observations and the 2MASS catalog. The resultant distributions are Gaussian with mean $\leq 0.01$ mJy and $\sigma = 4\%$-$5\%$ in all three of the $JHK_s$ bands.

Even though our Spitzer data are not part of the c2d program, we processed them through the c2d pipeline so we expect the errors in the Spitzer wavebands will be similar to c2d's. The c2d delivery documentation discusses three sources of uncertainty: statistical, systematic, and absolute. The first two of these are incorporated into the photometric uncertainties listed in the c2d catalog. These errors are derived from the repeatability of flux measurements using the c2d pipeline. The c2d documentation lists a 4.6% systematic error for IRAC and 9.2% for MIPS. Combining the systematic and statistical errors, our final photometric uncertainties are approximately 5% in IRAC and 10% in MIPS. The absolute uncertainties in the flux calibration are 1.5% and 4%, respectively, for the IRAC and MIPS1 (24 $\mu$m) bands. We obtained these values from the IRAC Data Handbook, Version 3.0, and the Multiband Imaging Photometer for Spitzer (MIPS) Data Handbook, Version 3.3.0. The absolute uncertainties are added in quadrature with the photometric errors during source classification, but are not used elsewhere since they are smaller than the photometric errors.

Table 3 lists our 10$\sigma$ and 5$\sigma$ limits for each wavelength. Our 10$\sigma$ $JHK_s$ limits are $\sim 3.5$ mag deeper than the 2MASS limits of 15.8, 15.1, and 14.3 mag, respectively. In the dense core regions of L1152 and L1155C-2, we were able to take even deeper $JHK_s$ observations. These limits are listed in parentheses in the table. As for the Spitzer wavebands, our 10$\sigma$ limits are 1.5–2 mag fainter in the IRAC bands and 2.5 mag fainter in the MIPS1 band compared to c2d.

2.3. Extinction and Star Classification

We used a modified version of the c2d data pipeline to classify sources based on their spectral energy distribution (SED) from 1.25 to 24 $\mu$m. The standard c2d pipeline uses all available wavelengths to compute the extinction toward each star:

$$\log(F_{\text{obs}}(\lambda)/F_{\text{model}}(\lambda)) = \log(k) - 0.4 \times C_{\text{ext}}(\lambda) \times A_V,$$

where $F_{\text{model}}(\lambda)$ is the stellar photosphere model, $k$ is the scaling factor of the model for a particular star, and $C_{\text{ext}}(\lambda) \equiv A_\lambda/A_V$ is the ratio of the extinction at wavelength $\lambda$ to visual extinction from the dust extinction law. $k$ and $A_V$ can be derived from the linear $\chi^2$ fit of this equation by adopting stellar photosphere and dust extinction models. The stellar models used are based on the Kurucz–Lejeune models and come from the Spitzer Science Center’s online “Star-Pet” tool. For the 2MASS bands, the observed $J - H$ and $H - K$ colors of stars (Koornneef 1983)

4 http://ssc.spitzer.caltech.edu/tools/starpet
were translated to fluxes relative to $K$ band and the difference between the $K$ and $K_s$ bands was ignored.

Sources fit by Equation (1) with a goodness-of-fit $q \geq 0.1$ were classified as reddened stars, while those that did not fit were compared with other templates to classify them. The goodness-of-fit, $q$, is the incomplete gamma function and gives the probability that the statistical $\chi^2$ distribution would exceed our observed $\chi^2$ (computed from Equation (1)) by chance. Thus, a very small $q$ means it is unlikely that the differences between our data and a given $F_{\text{model}}$ are due to chance, i.e., the model is unlikely to be an accurate fit to the data (Press et al. 1992). Our minimum $q$ value of 0.1 is the same one used by the c2d team for identifying stars.

We slightly modified this procedure for this paper. First, the extinction is computed for each source using the $JHK_s$ bands and the NICER technique (Lombardi & Alves 2001). The NICER technique relies on the assumption of intrinsic values for the $J - H$ and $H - K_s$ colors of stars. For this paper, we adopted the values $J - H = 0.50 \pm 0.12$ and $H - K_s = 0.18 \pm 0.04$. These values were derived from the average stellar model computed in the Appendix. Then, using Equation (1), we identified the stars with the extinction held fixed. We also computed extinctions in $AK_s$ rather than the more traditional $AV$ so we can directly compare our results with those of other authors.

We made this change because one of our goals in this paper is to compute the extinction law at the IRAC and MIPS wavelengths. The method we use for deriving the mid-infrared extinction law ($A_{\lambda}/AK_s$) is dependent on $AK_s$ so we cannot use these wavelengths when computing $AK_s$. However, we still need to choose an appropriate extinction law. This will be used to compute $AK_s$ from the $JHK_s$ bands and also for the source classification. We considered two dust models, the Weingartner & Draine (2001) $RV = 3.1$ and $RV = 5.5$ models. The $RV = 3.1$ model (hereafter WD3.1) is designed to reproduce the extinction law of the diffuse interstellar medium (ISM); the $RV = 5.5$ model (hereafter WD5.5) fits the observed law of denser regions. We found in Chapman et al. (2009; hereafter Paper I) that some heavily extincted stars may only fit the WD5.5 dust model rather than the more traditional WD3.1 extinction law. In lower extinction regions, both models tend to fit equally well. Therefore, for source classification we have chosen to use the WD5.5 dust model.

### 2.4 High-reliability Star Catalogs

The c2d data pipeline classifies sources according to their SED and infrared colors. Among other classifications, sources are identified as stars, “Galaxy candidates” (Galc), or “Young Stellar Object candidates” (YSOc’s). With YSOc, Galc, and other infrared excess sources we cannot separate out the expected flux of the SED from changes in those fluxes due to variations in the extinction law. Therefore, we want to concentrate on those sources classified as stars for studying the variations in the extinction law.
To create our high-reliability star catalogs, we first selected all sources classified as stars, excluding those classified as stars when one waveband was dropped because we did not want a prominent absorption or emission line to bias our results. Furthermore, because accurate extinctions are essential to our analysis, we required sources to have detections $\geq 7\sigma$ in each of the $JHK_s$ bands. Finally, we removed suspected faint background galaxies from our star catalogs using the criteria listed in Section 2.5.

The number of stars in our high-reliability catalogs is 3244 (L204C-2), 4038 (L1152), 3926 (L1155C-2), and 1850 (L1228). We then removed a few sources, as described below, to obtain
our final catalogs. The percentage of sources removed is <1% for L204C-2, L1152, and L1155C-2, and 2.2% in L1228.

2.5. Misidentified Background Galaxies

Although we carefully selected only the most reliable stars to construct our catalogs, it appears that some faint background galaxies are misidentified as stars. This can be readily seen in Figure 5, where we plot $J - H$ versus $H - K_s$ for the stars in our cores. The stars brighter than 15th magnitudes at $K_s$ (black points) follow the reddening vector, while many of the fainter sources (gray crosses) do not. The “known” stars and background galaxies are shown as white and dark gray circles, respectively. Our method for creating these two populations of sources is described below. Most of the “known” background galaxies are grouped to the right of the bright sources, in the same area as those gray crosses which do not follow the reddening vector. This suggests that these gray crosses are actually background galaxies. Foster et al. (2008), using near-infrared data from Perseus, also concluded that sources in this approximate region of a $J - H$ versus $H - K_s$ color–color diagram are likely to be background galaxies. Background galaxies are not the only explanation for these sources. It is possible that a few of them may be YSOs. In Section 4.3, we will discuss the prospects for faint YSOs in the cores.

To create samples of “known” stars and background galaxies, we could not start from the high-reliability catalogs since those explicitly exclude nonstar objects. Instead, we began with the full catalogs and imposed the same 7σ cutoff in the $JHK_s$ bands as we did for the high-reliability star catalogs. Second, we selected only those sources with 24 μm detections $\geq 3\sigma$. The resultant sources are plotted in Figure 6. We used different symbols depending on how sources were classified in Section 2.3: stars are shown as circles, GaLCs sources are squares, YSOc’s are shown as triangles, and plus signs for everything else. Furthermore, the shaded contours are the c2d processed SWIRE data of region ELAIS N1 (Surace et al. 2004). Since the ELAIS N1 region is near the north Galactic pole, it should contain nothing but stars and background galaxies making it useful for comparison. From this figure, we selected “known” populations of stars and background galaxies. The stars are those sources with $K_s - [24] \leq 1$ and the background galaxies have $K_s \geq 15$ and $K_s - [24] \geq 4$.

We will follow a procedure similar to that in Paper I to eliminate the misidentified background galaxies from our high-reliability star catalogs. First, we select suspected background galaxies with the following colors: $J - H \geq 0.6$, $H - K_s \geq 0.6$, and $J - H \leq 1.9 \times (H - K_s) - 0.16$. These selections are shown as dashed lines in Figure 5. Then, just using the sources selected by these colors, we plotted them on two color–color diagrams in Figure 7 along with our “known” star and background galaxy samples. There is a clear separation between the “known” stars and background galaxies. The dashed line in the figure is: $H - K_s = 1.32 x$, where $x$ is either $K_s - [3.6]$ or $K_s - [4.5]$. We combine these two selections to remove our misidentified background galaxies. These selection criteria are the same empirically derived ones used in Paper I, but with one important difference: because there is such a large degree of non-overlap spatially between the four IRAC bands, we relaxed the second criterion from Paper I so that sources only need to satisfy either the first half or the second half of it. Our criteria are the following.

1. $J - H \geq 0.6$, $H - K_s \geq 0.6$, and $J - H \leq 1.9 \times (H - K_s) - 0.16$;
2. $H - K_s \leq 1.32 \times (K_s - [3.6])$ or $H - K_s \leq 1.32 \times (K_s - [4.5])$.

Sources satisfying both criteria were removed from our catalogs. After removal of these sources, the number of stars in our final high-reliability catalogs is 3219 (L204C-2), 4010 (L1152), 3891 (L1155C-2), and 1810 (L1228).

3. EXTINCTION MAPS

Our star catalogs contain an LOS extinction measurement to each star calculated using the NICER technique (Lombardi & Alves 2001) and the WD5.5 dust model. We converted these randomly distributed samplings of the true extinction within each core into uniformly sampled maps by overlaying a grid on each core with an 18′′ spacing between grid elements. At each grid position, an extinction value was computed as the average of the individual measurements within a 90′′ radius. This average

| Band | Central λ (µm) | 10σ (mag) | 5σ (mag) |
|------|----------------|-----------|----------|
| J    | 1.235          | 19.5 (19.9) | 20.3 (20.7) |
| H    | 1.662          | 18.8 (19.7) | 19.5 (20.4) |
| $K_s$| 2.159          | 17.7 (18.6) | 18.4 (19.3) |
| IRAC1| 3.550          | 18.6       | 19.7      |
| IRAC2| 4.493          | 17.8       | 18.8      |
| IRAC3| 5.731          | 15.5       | 16.4      |
| IRAC4| 7.872          | 14.7       | 15.6      |
| MIPS1| 23.7           | 10.4       | 11.7      |

Note. The parenthetical values are the limits obtained for our deeper observations toward the dense core regions L1152 and L1155C-2.

Figure 5. $J - H$ vs. $H - K_s$ color–color diagram of the high-reliability stars for each core. The gray crosses are all the stars, while the black points are those stars brighter than 15th magnitude at $K_s$. Overlaid on the stars are white and dark gray circles, which are the “known” stars and background galaxies, respectively. These sources were selected from Figure 6. The reddening vector for our extinction law, WD5.5, is also shown. See Section 2.5 for a description of the dashed lines and further details.
Figure 6. $K_s$ vs. $K_s - [24]$ plot of all sources with $JHK_s$ detections $\geq 7\sigma$ and 24 $\mu$m $\geq 3\sigma$. We used four different symbols to correspond to different source classifications: stars are circles, Galc sources are squares, YSOc objects are triangles, and plus signs denote all other classifications. The shaded contours are from the c2d processed catalog of part of ELAIS N1 (Surace et al. 2004). The dashed lines denote the cutoffs we used for selecting “known” stars and background galaxies, while the dotted lines are the cutoffs for different YSO evolutionary classes as defined by Greene et al. (1994). The YSOs discussed in this paper are numbered for easy reference.

is weighted both by the uncertainty of each LOS extinction value and also by a Gaussian function with full width at half-maximum (FWHM) equal to $90''$. Thus, our final maps have 90'' resolution with 5 pixels across the FWHM. By setting our integration radius to equal the FWHM (2.3548$\sigma$), we capture 98.14% of the total area of the Gaussian weighting function, and avoid the unrealistic scenario of utilizing extinction values from arbitrarily large distances away from each grid position.

We subtracted foreground stars in a simple way: for each cell with more than two stars, we computed the mean and median $AK_s$ values. If these two statistics differed by $>25\%$, then we dropped the source with the lowest $AK_s$ and recomputed the mean. If the difference between the old and new mean is less than 25%, we re-added the dropped source to our catalog. After identifying all sources to drop, we recomputed the extinctions in every cell. Despite its simpleness, we found this procedure to be very effective in removing foreground stars. The 25% cutoff was empirically chosen after we ran some tests with different cutoff parameters.

We chose the 90'' resolution because this gave us a reasonable number of stars per cell for good statistics. The median number of stars per cell is $\sim35–40$ for L204C-2, L1152, and L1155C-2, and 18 in L1228. The percentage of cells with $\leq 5$ stars is 6% in L1152 and L1155C-2, 11% in L204C-2, and 14% in L1228. Figures 8–11 are extinction maps of our four cores. The contours in each map start at $AK_s = 0.5$ mag in steps of 0.15 ($3\sigma$). We also plotted the YSOc and Galc sources from our catalogs on the extinction maps and numbered the YSOs from Section 4. Finally, because YSOc and Galc sources can be classified only in regions with IRAC1 through IRAC4 and MIPS1, we outlined the area in each core where all these bands overlap.

The core of L204C-2 has a peak extinction of $AK_s = 2.1$. Extending northward from the central core is a dust filament with two other lower density extinction peaks. West of the core is a low-density clump with a peak extinction of $AK_s = 0.8$. We detect no YSOs in L204C-2. One Galc object is located near the center of the core, however, as we will discuss in Section 4 this source has an SED consistent with a heavily extincted background star.

L1152 is a small core with peak $AK_s = 1.8$. To the east are two additional separate extinction peaks. Both of these have a lower column density than the main core. A bright YSOc is embedded in the primary core, slightly northeast of the extinction peak. One lobe of an outflow can be seen in $J$ through IRAC4 extending southwest from this YSO. The other two YSOs are northeast of the core, and slightly offset from the northernmost extinction peak.

L1155C-2 is an extended core with two extinction peaks, the northernmost has a higher peak extinction of 1.7 mag. A dust filament that is part of L1155E appears in the southern third of the map. Like L204C-2, this core also appears starless.

The central core of L1228 contains two extinction peaks and appears pinched in the middle. The peak extinction in this core is 2.2 mag. This pinching may simply be an artifact caused by the lower median number of stars per cell compared with...
Figure 8. Extinction map of L204C-2. The map has a resolution of 90″ with a maximum $A_K$ value of 2.1 mag. The contours start at $A_K = 0.5$ mag in steps of 0.15 (3σ). Sources classified as Galc are shown as squares, while YSOs are shown with one of the three symbols, depending on their evolutionary classification (Greene et al. 1994). There are no YSOs plotted in this figure. The dashed region denotes the approximate area covered with both IRAC and MIPS. The gray circle denotes the resolution of the map.

Figure 9. Extinction map of L1152. The maximum $A_K$ value in the map is 1.8 mag. See Figure 8 for a description of the contours, symbols, and dashed lines. The numbered sources are the YSOs discussed in Section 4.

Figure 10. Extinction map of L1155C-2. The maximum $A_K$ value in the map is 1.7 mag. See Figure 8 for a description of the contours, symbols, and dashed lines. There are no YSOs plotted in this figure.

Figure 11. Extinction map of L1228. The maximum $A_K$ value in the map is 2.2 mag. See Figure 8 for a description of the contours, symbols, and dashed lines. The numbered sources are the YSOs discussed in Section 4.

Figure 4. Several other extinction peaks are nearby, mostly north of the core. L1228 has previously been classified as a starred core, and several YSOs are identified in the core; most have not been previously identified. Despite having similar Galactic coordinates as L1152 and L1155C-2, only two Galc objects appear in this core. This is because L1152 and L1155C-2 have deeper $JHK_s$ data than L1228, therefore many more Galc objects fall into our high-reliability catalogs for those cores than in L1228.
Ten sources are classified as YSOc in our cores. However, a source can be classified as a YSOc only if it is detected in all Spitzer wavebands from 3.6 to 24 \(\mu m\). This is because various empirically derived Spitzer colors and magnitudes are used in classifying YSOc sources (Harvey et al. 2007). Therefore, to our initial list of 10 sources we added six potential YSOs that were not classified as YSOc. First, we included sources from Figure 6 with \(K_s - [24] \geq 3\) and \(K_s \leq 14.5\). Most of the sources in this region are classified as YSOs already. This selection added two sources in L1228, neither of which is classified as YSOc because they are outside of the area observed in IRAC2 and IRAC4 (4.5 and 8 \(\mu m\)). It is also possible that faint YSOs may be misidentified as Galc. Therefore, we also selected four Galc objects from Figures 8–11 that were located near the dense cores; one source each in L204C-2 and L1152 and two in L1228. This brought our total number of possible YSOs to 16.

After we visually inspected all 16 sources, we excluded the Galc objects in L1152 and L1228 since all were visually extended in mosaics, meaning they are likely to be true background galaxies. We also excluded the one Galc object from L204C-2 because this source has the SED of a heavily extincted star. In Figure 6, this source is the Galc at \(K_s - [24] = 1.5\). Furthermore, we excluded one of the YSOc objects in L1228 that is clearly a knot of emission from the outflow and not a real source. Finally, we also excluded one of the non-YSOc sources in L1228 that only has an infrared excess at 24 \(\mu m\). The 24 \(\mu m\) flux for this source appears confused with two other nearby sources detected at shorter wavelengths. We are left with 10 YSOs, three in L1152 and seven in L1228. Note that now we are identifying these sources as Young Stellar Objects and not Young Stellar Object candidates. In Table 4, we list the fluxes and positions of these 10 YSOs present in our cores. For each YSO, we added the 70 \(\mu m\) flux from c2d, if detected. Neither L204C-2 nor L1155C-2 appear to contain any YSOs. In Section 4.3, we will place some upper limits on unidentified YSOs in our cores.

We modeled the SED for our 10 YSOs using an online tool (Robitaille et al. 2007). This tool fits an input SED to a precomputed grid of YSO models. In Figure 12, we show all models with \(\chi^2 \leq 2 \times \chi^2_{\text{best}}\), where \(\chi^2_{\text{best}}\) is the \(\chi^2\) for the best-fitting model. The best-fit model for each YSO is shown in black with other models shown in gray. Each model has numerous parameters, a few of which we have listed in Table 5. We show the range of values for envelope accretion rate, disk mass, interstellar extinction \((A_V)\), and bolometric luminosity plus the average value for each quantity. Note that the Robitaille models do include stellar masses, however these are not constrained for embedded objects, so we will not use them here (T. Robitaille 2007, private communication).

We also classified our YSOs based on their value of \(\alpha \equiv d \log \lambda F_\lambda / d \log \lambda\), the best-fit slope of a straight line to the SED from \(K_s\) to 24 \(\mu m\). We then separated the YSOs into one of the four classes using the method of Greene et al. (1994). Following an evolutionary sequence from youngest to oldest YSO, they

| Index | Core  | R.A. (J2000) | Decl. (J2000) | \(J\) (mJy) | \(H\) (mJy) | \(K_s\) (mJy) | 3.6 \(\mu m\) (mJy) | 4.5 \(\mu m\) (mJy) | 5.8 \(\mu m\) (mJy) | 8.0 \(\mu m\) (mJy) | 24 \(\mu m\) (mJy) | 70 \(\mu m\) (mJy) |
|-------|-------|-------------|--------------|-------------|-------------|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1     | L1152 | 20 35 46.3  | 67 53 02.2   | 0.130       | 0.696       | 1.57        | 3.59           | 6.44            | 5.50            | 3.36            | 280             | 3670            |
| 2     | L1152 | 20 36 11.6  | 67 57 09.3   | 9.19        | 25.5        | 36.1        | 41.3           | 47.9            | 60.8            | 77.8            | 183             | 347             |
| 3     | L1152 | 20 36 19.9  | 67 56 31.6   | 52.8        | 130.0       | 205.0       | 228.0          | 243.0           | 259.0           | 262.0           | 597.0           | 1080            |
| 4     | L1228 | 20 55 37.1  | 77 38 19.6   | 5.76        | 7.18        | 7.21        | 5.69           | 4.68            | 3.78            | 3.89            | 4.58             | ...             |
| 5     | L1228 | 20 57 06.8  | 77 36 56.1   | 0.541       | 1.78        | 3.13        | 7.81           | 11.1            | 13.9            | 18.5            | 271.0           | 2240            |
| 6     | L1228 | 20 57 08.0  | 77 36 59.7   | 0.624       | 1.91        | 2.82        | 3.16           | 3.46            | 3.28            | 7.32            | 154.0           | ...             |
| 7     | L1228 | 20 57 13.0  | 77 35 43.3   | 8.74        | 58.5        | 143.0       | 262.0          | 374.0           | 499.0           | 762.0           | 2680.0          | 7850            |
| 8     | L1228 | 20 57 15.5  | 77 34 23.6   | 0.141       | 0.715       | 1.79        | 2.00           | 2.41            | 2.46            | 2.94            | 5.04             | ...             |
| 9     | L1228 | 20 57 17.0  | 77 36 58.6   | 5.14        | 15.1        | 26.1        | 31.3           | 38.0            | 37.2            | 42.1            | 83.8             | 334.0           |
| 10    | L1228 | 20 58 40.0  | 77 27 45.5   | 1.17        | 3.08        | 6.53        | 22.9           | 24.7             | ...             | 43.6             | ...             | ...             |

4. YOUNG STELLAR OBJECTS

Figure 12. SEDs for our 10 YSOs. The black curve is the best-fit YSO model from Robitaille et al. (2007), while the gray curves show other model fits with \(\chi^2 \leq 2 \times \chi^2_{\text{best}}\) (Section 4). The error bars are smaller than the data points. Each YSO is numbered for reference.
are: Class I ($\alpha \geq 0.3$); Flat spectrum ($0.3 > \alpha \geq -0.3$); Class II ($-0.3 > \alpha \geq -1.6$); and Class III ($\alpha < -1.6$). We have included sources with $\alpha = 0.3$ in Class I since these were undefined by Greene et al. (1994). Our YSOs are a mixture of Class I, Flat spectrum, and Class II sources, but no Class III objects. This suggests that the YSO population in these cores is relatively young.

4.1. L1152 YSOs

Two of the three YSOs in L1152, IRAS 20353+6742 and IRAS 20359+6745, are previously known and both have outflows associated with them. IRAS 20353+6742 is the source embedded in the L1152 core and is source 1 in Tables 4 and 5. Only one lobe of the outflow is visible, but it can be seen from $J$ through IRAC4 (Figure 2). The second known source, IRAS 20359+6745, is source 3 in Tables 4 and 5. This YSO has an outflow associated with it that is visible in $JHK_s$ but not at longer wavelengths. The Herbig-Haro object HH376A is located 2.6′′ to the southwest. The bowshock shape of HH376A and its location along the apparent axis of the $JHK_s$ outflow from source 3 suggests it may be part of the same system. We show both of these features in Figure 2. The remaining YSO is approximately 1′ to the west of IRAS 20359+6745. We found no references to this source in SIMBAD.5

4.2. L1228 YSOs

We identified seven YSOs in L1228. Six of these are classified as YSOc based on their colors, while the remaining one cannot be classified as such because it appears outside of the area covered by IRAC2 and IRAC4. Five of the YSOc sources appear to be spatially coincident with the core of L1228. The brightest source is 7 and is identified as IRAS 20582+7724. This is the only previously known YSO in the core of L1228. It appears to be the driving source for a CO outflow, HH 199 (Haikala & Laureijs 1989; Bally et al. 1995). The axis of the CO outflow is about 40° different from the east–west axis formed by the infrared knots. Bally et al. (1995) conclude this is likely due to precession of the jet that drives the outflow. In Figure 4, the green dashed line shows the axis of the infrared knots while the red dashed line shows the axis of the CO outflow.

Sources 5 and 6 are located about 1′/2 northwest of IRAS 20582+7724 and separated from each other by 5′/3. Because of this separation, they are not resolved at 70 µm (FWHM = 17″) and not fully resolved at 24 µm (FWHM = 5′/7). Even though we were able to extract a flux at 24 µm for both sources, we suspect that the 24 µm flux for source 6 is artificially high.

When fitting YSO models, we found that excluding this data point decreased $\chi^2_{\text{best}}$ from 174 to 48, the latter is more in line with the $\chi^2_{\text{best}}$ for the other sources. Therefore, we excluded this data point for the models listed in Table 5 and shown in Figure 12. It is also possible that the 70 µm flux for source 5 includes some contribution from source 6 as well. Bally et al. (1995) detected a series of infrared emission knots that form the HH 200 outflow which has its origin at the position of sources 5 and 6. It is unknown which of these is the driving source of the outflow. We show the approximate axis of this outflow as a yellow dashed line in Figure 4. There is some outflow emission immediately to the northeast of sources 5 and 6 which lies along the outflow axis.

Finally, the two YSOs not spatially coincident with the L1228 core are sources 4 and 10. Source 10 does not meet the criteria for YSOc because it is lacking IRAC2 and IRAC4 fluxes.

4.3. Constraints on New Faint YSOs

We did not detect any YSOc sources that were not already detected by c2d. The converse is also true, in the c2d catalogs of all four cores, there is only one YSOc object not in our catalogs. However, after inspection we determined this object to be another emission knot from the east–west outflow. This lack of additional YSOc sources is not too surprising since the YSOc selection criteria were tuned to the sensitivity of the c2d-processed SWIRE data. Therefore, any sources fainter than these limits is likely to be automatically classified as Galc. It was for this reason that we also considered some Galc sources when compiling our YSO catalog. However, from Figures 1–4 it is clear that there are many bright 24 µm sources in our cores, far more than the number of YSOc and Galc objects.

We would like to use these objects to place limits on possible faint YSOs in these cores. If we select sources from the overlap region of all five bands with 24 µm detections $\geq 3\sigma$, then exclude any star or YSOc sources and also any Galc sources in Figure 6, we are left with 634 sources in all four cores. These 634 sources have a median 24 µm flux of 0.21 mJy (11.3 mag). Just 47 of them are detected at $K_s$, but these have a median flux of 0.04 mJy (18.1 mag). Our 5σ detection limit for $K_s$ is 18.4 mag, or 19.3 mag for the deep observations. If we assume that the remaining sources must be fainter than these limits in order to be undetected at $K_s$, that means they must

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5 http://simbad.u-strasbg.fr/simbad/
have $K_s - [24] \gtrsim 7-8$. From Figure 6, the boundary between Flat/Class I is at $K_s - [24] = 8.31$. Therefore, we expect any new YSOs existing among these 634 sources to be fainter than 18–19 mag at $K_s$ and to be very young Flat/Class I objects.

To put an upper limit on the luminosity of any embedded YSOs, we integrated our median SED assuming a blackbody temperature of the blackbody was derived from the flux ratio $F_{\lambda_{24}}/F_{\lambda_{36}}$. Starting from Equation (1), but using $A_{K_s}$ instead of $A_V$, we rearrange it to solve for $C_{\text{ext}}$, defined as $A_{\lambda}/A_{K_s}$:

$$C_{\text{ext}}(\lambda) = \frac{2.5}{A_{K_s}}[\log(k) - \log(F_{\lambda_{\text{obs}}}/F_{\lambda_{\text{model}}})].$$ (2)

Since we are only interested in differences in the extinction law, we can subtract $C_{\text{ext}}(K_s)$ to eliminate the need for $k$, the scaling factor. Furthermore, because $C_{\text{ext}}(K_s) \equiv 1$ and $F_{\lambda_{\text{model}}}(K_s) \equiv 1$ (all stellar models are scaled relative to $K_s$), the equation simplifies to

$$C_{\text{ext}}(\lambda) = \frac{2.5}{A_{K_s}}[\log(F_{\lambda_{\text{obs}}}/F_{\lambda_{\text{model}}}) + \log F_{\lambda_{\text{model}}}(\lambda)] + 1.$$ (3)

For $F_{\lambda_{\text{model}}}$, we use the average stellar model derived in the Appendix.

5.1. Spatial Dependence of the Extinction Law

In this section, we will create a two-dimensional map of how the extinction law changes in each core. We start by defining a reduced $\chi^2$ for each star:

$$\chi^2 = \frac{1}{n - 1} \sum_{\lambda} \left(\frac{C_{\lambda_{\text{obs}}}(\lambda) - C_{\lambda_{\text{model}}}(\lambda)}{\sigma_{\lambda}}\right)^2,$$ (4)

where $C_{\lambda_{\text{obs}}}(\lambda)$ is computed from Equation (3), $C_{\lambda_{\text{model}}}$ is the extinction law for a given dust model, and $\sigma_{\lambda}$ is the uncertainty in $C_{\lambda_{\text{obs}}}$. We sum only over the IRAC bands because, as we will see, the extinction law at 24 $\mu$m does not fit any current dust models and therefore we excluded this wavelength to avoid biasing our $\chi^2$. Furthermore, we excluded any negative values for $A_{\lambda}/A_{K_s}$, as unphysical. We will discuss the biases introduced by this assumption in Section 5.3. We will refer to this reduced $\chi^2$ as “$\chi^2$” in this paper.

Using Equation (4), we computed the LOS $\chi^2$ value for each star. Then, to convert our LOS measurements into a map, we followed the same procedure as we did when creating our $A_{K_s}$ maps. In Figures 13–16, we show maps of the extinction and $\chi^2$ calculated using both the WD3.1 and WD5.5 dust models. The $\chi^2$ maps have the same resolution as the extinction maps, 90". Our contours start at $\chi^2 = 4$ because we observe a definite transition between the WD3.1 and WD5.5 dust models at this approximate $\chi^2$ value (see Figure 17). Statistically, a $\chi^2 = 4$ would arise by chance about 5% of the time.

The correspondence between the extinction, $A_{K_s}$, and the $R_V = 3.1 \chi^2$ maps is quite remarkable. In all of our cores, the overall shape and the extinction peaks are mirrored in the WD3.1 $\chi^2$ map. Many of the extinction features not associated with the cores also appear in the $\chi^2$ map such as the dusty filament to the north of L204C-2, the two separate extinction peaks in L1152, and much of the structure in L1228.

To make a quantitative comparison between $\chi^2$ and $A_{K_s}$, we binned our data in $A_{K_s}$ and for each bin determined the average $\chi^2$ with both the WD3.1 and WD5.5 models. Our results are shown in Figure 17. $R_V = 3.1 \chi^2$ is shown in black, while $R_V = 5.5$ is shown in gray. At low extinction, $A_{K_s} \lesssim 0.6$, the $R_V = 3.1$ and $R_V = 5.5 \chi^2$ are very similar to each other, suggesting that at low extinctions it is difficult to distinguish between these two models with our technique. Above $A_{K_s} \sim 0.6$, the $R_V = 3.1 \chi^2$ rises sharply, while the $R_V = 5.5 \chi^2$ stays roughly constant or increases only slightly.

The observed behavior in our $\chi^2$ maps is consistent with the idea of grain growth in dense cores. Most regions of moderate to
high extinction show up in the $R_V = 5.5$ $\chi^2$ map but not in the $R_V = 3.1$ $\chi^2$ map. This suggests the WD3.1 extinction law is not valid in extincted regions because $\chi^2 = 4$ (the first contour level) corresponds to at least a 95% chance that the data do not fit the model. The differences in these two extinction laws is reflected by the differences in the properties of the dust models. The WD3.1 dust model was constructed to match observations of the diffuse ISM. In contrast, the WD5.5 model has significantly fewer small silicate grains ($r < 0.1 \mu m$) and significantly more large carbonaceous ones (maximum radius $\sim 10$ times larger).

Although most of our observations can be explained by the idea of grain growth within dense regions, both L1152 and L1228 contain regions that appear strong in the WD5.5 $\chi^2$ map. Both of these cores have outflows associated with them which may be changing the dust sizes and compositions. In the following section, we explore changes in the observed extinction law as a function of wavelength and $A_K$. This will help us to understand exactly how the dust is changing within our cores.

5.2. Wavelength Dependence of the Extinction Law

As we saw in the last section, the $\chi^2$ is strongly dependent on $A_K$. To explore this further, we started by binning the observed extinction law for each star into three $A_K$ ranges: $0 < A_K \leq 0.5$, $0.5 < A_K \leq 1$, and $A_K > 1$. In each extinction bin, we combined the individual $C_{\text{obs}}(\lambda)$ measurements to obtain a weighted average value of $A_{\lambda}/A_K$. As we did when computing $\chi^2$, we again excluded any negative values of $C_{\text{obs}}(\lambda)$.

Figure 18 shows the observed average extinction law as a function of wavelength for our cores. Each row is a different core and each column is a different range of $A_K$. The error bars for each data point are the minimum uncertainty due to systematic errors in measuring flux. In addition to the WD3.1 and WD5.5
dust models, we also plot a third one, labeled KP v5.0 (K. Pontoppidan et al., 2009, in preparation). This model is one from a grid of models constructed starting from the Weingartner & Draine (2001) parameterization of the grain size distribution. icy mantles of water and other volatiles were then added. The specific model we use from this grid is the one with the “best fit” to the c2d mid-infrared extinction law and ice features. Several ice absorption features in this model can be seen in the figures, these are due to H₂O, CO₂, or CO.

5.2.1. The Extinction Law From 3.6 to 8 μm

From 3.6 to 8 μm, our extinction law is relatively flat for all ranges of AK, with the trend that it becomes slightly flatter as AK increases. In Table 6, we list the average extinction law combined over all four cores (β = 1.6). Again, the uncertainties represent the minimum error due to uncertainty in the flux. For comparison, we also list the extinction law from Indebetouw et al. (2005), Flaherty et al. (2007), Lutz (1999), and our three dust models. Our data are in good agreement with other authors’ results and also with the WD5.5 dust model.

![Figure 17. χ² vs. AK for our cores. The WD3.1 χ² values are black; the WD5.5 χ² values are light gray. The error bars shown are the standard deviations of the mean in each bin.](image)

Our flat extinction law for 0 < AK ≤ 0.5 seems surprising since this result contradicts our expectation that low extinction regions should follow WD3.1, a diffuse ISM dust model. In Paper I, we calculated the extinction law in three molecular clouds and found that for 0 < AK ≤ 0.5 the extinction law was consistent with WD3.1. These conflicting results may be because extinction measures the column density, not the number density, along the LOS. If we assume each core has an approximate angular size of ~15' (the lengthwise distance of any IRAC observation), and given the distances listed in Table 1, then our cores have linear sizes of (1–3) × 10⁶ AU. Compare these sizes to those of the clouds in Paper I. The cloud distances in Table 1 of that paper are 125 ± 25 pc (Ophiuchus), 250 ± 50 pc (Perseus), and 260 ± 10 pc (Serpens). Assuming cloud angular sizes of ~2°, then the clouds have linear sizes of (1–2) × 10⁶ AU. Finally, if we assume spherical clouds and cores, then these linear sizes also represent the depth of each cloud and core. Therefore, the number densities in our cores may be up to 10 times larger than in our clouds for a given column density (extinction). Grain growth is a collisional process and proceeds more rapidly at higher number densities. Hence, the grains in our isolated cores quickly achieve at least modest grain growth (represented by WD5.5 and KP v5.0) compared with the WD3.1 dust grains.

L1152 and L1155C-2 both show a strong deviation at 5.8 μm from WD5.5 for AK > 1. Water ice has an absorption peak at 6.02 μm due to H–O–H bending (Gibb et al. 2004). It is possible that the high value of AS/AK is due to the presence of water ice in these two cores, even more than predicted by the KP5.0 dust model. Mid-infrared spectra will be necessary to address this possibility.

5.2.2. The Extinction Law at 24 μm

We have only 13 stars with positive A24/AK values. These have an average value of A24/AK = 0.59 ± 0.12. This value compares favorably with other empirical results. Flaherty et al. (2007) were able to measure the 24 μm extinction law for two of their five regions and found A24/AK = 0.44 ± 0.02 and 0.52 ± 0.03 for Serpens and NGC 2068/71, respectively. Even though Lutz (1999) did not measure the extinction law in Serpens, our A24/AK value is similar. If we assume spherical clouds and cores, then these linear sizes also represent the depth of each cloud and core. Therefore, the number densities in our cores may be up to 10 times larger than in our clouds for a given column density. Grain growth is a collisional process and proceeds more rapidly at higher number densities. Hence, the grains in our isolated cores quickly achieve at least modest grain growth (represented by WD5.5 and KP v5.0) compared with the WD3.1 dust grains.

Table 6

| Source     | 3.6 μm    | 4.5 μm    | 5.8 μm    | 8 μm    | 24 μm   |
|------------|-----------|-----------|-----------|---------|---------|
| All cores, β = 1.6 | 0.64 ± 0.07 | 0.49 ± 0.06 | 0.48 ± 0.06 | 0.47 ± 0.05 | 0.59 ± 0.12 |
| All cores, β = 1.8 | 0.57 ± 0.08 | 0.40 ± 0.07 | 0.40 ± 0.06 | 0.37 ± 0.05 | 0.47 ± 0.06 |
| Flaherty et al. (2007) | 0.632 ± 0.004 | 0.54 ± 0.01 | 0.50 ± 0.02 | 0.50 ± 0.01 | 0.46 ± 0.04 |
| Indebetouw et al. (2005) | 0.56 ± 0.06 | 0.43 ± 0.08 | 0.43 ± 0.10 | 0.43 ± 0.10 | 0.43 ± 0.10 |
| Lutz (1999) | 0.53 ± 0.03 | 0.50 ± 0.08 | 0.49 ± 0.06 | 0.42 ± 0.06 | 0.42 ± 0.06 |
| WD3.1       | 0.40      | 0.25      | 0.17      | 0.22     | 0.17    |
| WP5.0       | 0.60      | 0.49      | 0.40      | 0.41     | 0.24    |
| KP, v5.0    | 0.48      | 0.38      | 0.34      | 0.38     | 0.38    |

Notes.

1 The extinction for the closest ISO wavelength to each Spitzer band is listed: 3.6, 4.4, 5.9, and 7.5 μm.

2 Extinctions for dust models are computed at the central wavelength in each band.
times larger than either the WD3.1 or WD5.5 models. The KP v5.0 dust model has a much broader 18 \( \mu \)m silicate peak which significantly raises the predicted 24 \( \mu \)m extinction. Even so, it is still too low by about 50% compared to our empirical measurement. New dust models will need to incorporate additional extinction at 24 \( \mu \)m.

5.2.3. Outflows in L1152 and L1228

We circled in red two regions in L1152 and L1228 (Figures 14 and 16) with high \( R_V = 5.5 \chi^2 \). These regions stand out because their high \( \chi^2 \) values are not caused by a single star, nor are they associated with regions of high \( A_K \). We selected all the sources within the red circles and within the \( \chi^2 = 4 \) contour and plotted the average extinction law for each region in Figure 19. Compared to elsewhere in the cores, the extinction law is much steeper in these two regions and more similar to the WD3.1 dust model rather than WD5.5. Because these regions are near known outflows, one possible explanation is that the outflows in each core have destroyed the bigger dust grains via shocks to produce a dust grain distribution that more closely resembles the WD3.1 diffuse ISM dust. Since neither region lines up with the outflow axis, this may be evidence for precession of the outflows, which is already observed in L1228 (Bally et al. 1995). These extinction laws could not be caused by a foreground star skewing the average because we have a total of 35 stars in the two selected regions, none with \( A_K < 0.20 \). A foreground star would appear to have almost zero or negative extinction, and would not greatly impact the average extinction law.

5.3. Sources of Error

5.3.1. Negative \( C_{\text{ext}}(\lambda) \)

In this paper, we have excluded negative values for \( C_{\text{ext}}(\lambda) \) as unphysical because it would imply that dust amplification, rather than extinction, is occurring. A more likely explanation is that the derived extinction or the measured flux for that wavelength is incorrect. By excluding these negative values, we introduce some potential bias into our results, which will be discussed here.

The magnitude of the bias varies with wavelength and extinction, but is much larger at low \( A_K \). The percentage of negative \( C_{\text{ext}}(\lambda) \) values for a given wavelength ranges from 32%–61% for \( 0 < A_K \leq 0.5 \), 3%–17% for \( 0.5 < A_K \leq 1 \), and 0%–1.8% for \( A_K > 1 \). If we utilized these negative \( C_{\text{ext}}(\lambda) \) values when computing the average extinction law, then the averages shown in Figure 18 would be 0.42\( \sigma \)–1.08\( \sigma \) lower for \( 0 < A_K \leq 0.5 \), where \( \sigma \) is the displayed error bar due to the minimum uncertainty in the flux. For higher extinctions, the bias is much lower because there are far fewer negative \( C_{\text{ext}}(\lambda) \) values. The average extinction law decreases 0.50\( \sigma \)–0.52\( \sigma \) for \( 0.5 < A_K \leq 1 \) and for \( A_K > 1 \), the decrease is 0–0.06\( \sigma \).

The large bias we find for \( 0 < A_K \leq 0.5 \) suggests that our technique for computing the extinction law breaks down at low extinctions. We discussed this before in relation to Figure 17. We have not attempted to incorporate any bias from excluding the negative \( C_{\text{ext}}(\lambda) \) into our error bars since the bias is partially due to the fluxes, and we already set a lower limit on the errors due to our minimum uncertainty in
measuring the fluxes at different wavelengths. However, our results presented in this paper may slightly overestimate the mid-infrared extinction law, primarily for $A_K \leq 0.5$.

5.3.2. Changes in the Near-Infrared Extinction Law

Many authors have fit the near-infrared extinction to a power law, $A_{\lambda} \propto \lambda^{-\beta}$, with $\beta = 1.6$–1.8 (Draine 2003, and references therein). The WD3.1 and WD5.5 models are very similar in the near-infrared $JHK_s$ bands, reflecting this apparent universality of the near-infrared extinction law. These two models both have $\beta \approx 1.6$. This law does agree with the apparent reddening vector in our data (see Figure 5) and makes our results directly comparable with other authors’ results who have made the same assumption. However, it is possible that the extinction law could be steeper in some regions. This would introduce another source of error into our calculated extinction law. To calculate the magnitude of this effect, we modified the WD5.5 dust model to have $\beta = 1.8$ in the $JHK_s$ bands and used this law instead of the WD5.5 model for classifying sources and computing the extinctions and the extinction law. Our results can be seen in Table 6 and Figure 20. As stated before, the uncertainties in our average extinction law are the minimum errors due to uncertainty in the flux.

Using a $\beta = 1.8$ law slightly decreases our mid-infrared extinction law, however the qualitative results of this paper are unchanged. Even with $\beta = 1.8$, our extinction law is more consistent with WD5.5 for all ranges of extinction. The biggest difference is for $A_K > 1$ in L1152 and L1155C-2. With $\beta = 1.8$, the excess $A_{5.8}/A_K$ extinction disappears. We argued in Section 5.2.1 that this excess could possibly be explained by the existence of water ice in these two cores. The circled regions in our $\chi^2$ figures that may be caused by outflows destroying the big dust grains appear even stronger with our $\beta = 1.8$ law. This is because the difference from WD5.5 is enhanced.

6. CONCLUSIONS

In this paper, we presented deep $JHK_s$ and Spitzer photometry of four isolated cores: L204C-2, L1152, L1155C-2, and L1228. Based on previous observations, two of these cores were classified as starred and two were classified as starless. Our data support these original classifications. We detect 10 YSOs, three within L1152, seven within L1228, and none within L204C-2 or L1155C-2. Seven of these YSOs have not been previously discovered. Among these, we are able to resolve the driving source of the HH200 outflow in L1228 into two sources separated by $5\arcsec 3$, but we were unable to identify which of the two sources is responsible for the outflow.

To put constraints on possible faint YSOs in all four cores, we selected 634 sources with 24 $\mu$m detections $\geq 3\sigma$ which are either undetected or too faint at other wavelengths to be considered in our high-reliability catalogs. We computed the median SED for these sources and integrated the SED to obtain a luminosity of $7 \times 10^{-5}$ to $5 \times 10^{-4} L_\odot$ with colors of a very young Flat spectrum or Class I YSO (Greene et al. 1994).

In addition to studying the YSO content of these cores, we used the LOS measurements of the extinction and the extinction law to create maps of the extinction and $\chi^2$ deviation from specific dust grain models. Our extinction law is nearly flat for all ranges of extinction in all four cores. In the IRAC bands (3.6–8 $\mu$m), this extinction law matches the predictions of the WD5.5 dust model, a model designed to simulate the grain growth that occurs in dense regions, and also agrees with the other authors’ results (Indebetouw et al. 2005; Flaherty et al. 2007; Lutz 1999). In the densest regions of L1152 and L1155C-2, the 5.8 $\mu$m extinction law is higher than the WD5.5 model. This could be evidence for water ice in these cores or a steeper near-infrared extinction law than the average value. At 24 $\mu$m, our data are consistent with the extinction law remaining constant as the total extinction increases. The observed extinction law is much higher than that predicted by dust grain models, but does confirm the similarly large value found by other authors (Chapman et al. 2009; Flaherty et al. 2007; Lutz 1999).

From the $\chi^2$ maps, we identified cavities in L1152 and L1228 where the extinction law is more consistent with the WD3.1 dust model. The molecular outflows in these cores produce shocks, which may be destroying the large dust grains, thus producing a dust distribution similar to WD3.1. These cavities are visible in our $\chi^2$ maps, but would be missed in averages over an entire core.

It is critical to create new dust grain models which reproduce the observed flat extinction law, especially at 24 $\mu$m. In this paper, we used the Robitaille et al. (2007) models to estimate the luminosities of our YSOs. However, Robitaille et al. (2007) assumed an extinction law that is between WD3.1 and WD5.5 in the IRAC bands and predicts a 24 $\mu$m extinction that is about 25% of our observed value. The best-fit YSO parameters would undoubtedly change with a flatter extinction law. Furthermore, it is important to understand the mid-infrared extinction law because future telescopes, such as the James Webb Space Telescope, will operate at these wavelengths.

Figure 19. Averaged extinction laws for the sources near the outflows in L1152 (left) and L1228 (right). Three different dust models are plotted for comparison. The error bars are the minimum uncertainty due to the systematic errors in the flux.
Figure 20. Same as Figure 18 except using an extinction law with $\beta = 1.8$ in the $JHK_s$ bands for computing extinctions and source classification.

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APPENDIX

AVERAGE STELLAR MODELS

To compute the expected stellar distribution for each core, we used the galaxy model from Jarrett (1992) and Jarrett et al. (1994). Given the Galactic coordinates, distance, and average extinction for a core, this model produces source counts broken down by spectral type. These source counts provide a rudimentary weighting function that can be used in computing the average stellar model. However, a weighting function from the raw source counts ignores the reality that not all spectral types are equally observable at each wavelength. Our next step was to correct for the detection limits of our actual observations.

The galaxy model lists the extincted $K_s$ magnitude for each star and its extinction, $A_V$. We used this information, the Weingartner & Draine (2001) $R_V = 3.1$ extinction law, and the stellar templates from the Spitzer Science Center’s “star-pet” tool to compute the magnitude of each star at every observed wavelength from $J$ to $24$ μm. We then arbitrarily discarded any detection falling below the 5σ cutoff for the given waveband (Table 3). Finally, we used the normalized, final, corrected source counts at each waveband as a weighting function, and computed the overall average stellar model. We repeated this procedure using both the Weingartner & Draine (2001) $R_V = 5.5$ extinction law and also using the magnitude limits from our deeper $JHK_s$ observations. Both variables have a negligible effect on the final fluxes.

After these calculations, we made one final adjustment to our average stellar model. In Paper I, we determined that the above method produces a $24$ μm flux that is very likely too high. However, we can independently put an upper limit on the $24$ μm flux value. If we select all stars with LOS $0 < A_{K_s} \leq 0.5$, and compute the average $24$ μm to $K_s$ flux ratio, this will give us an estimate of the true average $24$ μm stellar flux.

Since these stars have small amounts of extinction, this ratio will overestimate the true value because the $K_s$ band is more extincted than $24$ μm. There are 28 stars in our cores with $24$ μm fluxes $\geq 3\sigma$ and within the extinction range $0 < A_{K_s} \leq 0.5$. These have an average $24$ μm to $K_s$ flux of $0.013 \pm 0.001$

6 http://ssc.spitzer.caltech.edu/tools/starpet
with an average extinction of 0.19 $A_K$. This is the same as the value derived using the Galaxy count models. Given the non-zero average extinction, the true flux ratio will be lower. Therefore, in this paper we will assume it is actually 0.012. Our final average stellar flux for the $JHK_s$, IRAC1–4, and MIPS1 bands, respectively, is $1.282 \pm 0.144$, $1.302 \pm 0.050$, $0.453 \pm 0.010$, $0.268 \pm 0.005$, $0.179 \pm 0.005$, $0.102 \pm 0.003$, and $0.012 \pm 0.001$. Note that all fluxes are scaled relative to the $K_s$ band.

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