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THE TEMPERATURE OF LARGE DUST GRAINS IN MOLECULAR CLOUDS

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ABSTRACT

The temperature of the large dust grains is calculated from three molecular clouds ranging in visual extinction from 2.5 to 8 mag, by comparing maps of either extinction derived from star counts or gas column density derived from molecular observations to I_{100}. Both techniques show the dust temperature declining into clouds. The two techniques do not agree in absolute scale.

Subject headings: interstellar: grains — interstellar: molecules

1. INTRODUCTION

Thermal emission from dust may be modeled as a Planck function modified by $Q(\lambda)$, the emissivity or absorption efficiency (e.g., Hildebrand 1983; eq. [1], this paper). It is generally assumed that $Q(\lambda)$ is a power-law function of wavelength in which the exponent depends upon the composition of the dust grains. Consequently, it is in principle possible to obtain the dust grain temperature that enters into the Planck function from the infrared signature.

One may calculate a temperature by taking a ratio of fluxes at two wavelengths, for example the *IRAS* 60 and 100 μm filters. We here define such a temperature as a "color temperature," hereafter denoted by T_c. If the observed emission is due to particles of the same composition at a single temperature, the color temperature would be the dust grain temperature, hereafter denoted by T_d.

There is growing evidence that the ratio of I_{60}/I_{100} is inadequate to derive T_d of the grains responsible for the emission at 100 μm and beyond. *IRAS* observations of the diffuse interstellar medium yield T_c of order 25 K (Laureijs, Chlewick, & Clark 1988). Such high temperatures are significantly larger than T_d predicted by comprehensive models (Draine & Lee 1984; Cox, Krugel, & Mezger 1986). Despite the fact that T_d is predicted and observed to decline with distance from the Galactic center, T_c remains constant as a function of Galactic longitude, also in disagreement with model predictions (Cox & Mezger 1989). Further, when using T_c as T_d, derived gas-to-dust ratios are systematically too high (Larger et al. 1989).

As a step toward understanding this anomalous observed 60 μm emission, we have applied other methods to estimate T_d. First, the gas column density has been derived from molecular observations and compared to 100 μm emission. Second, the dust column density has been estimated from extinction measurements and compared to 100 μm emission. T_d has been derived by imposing the column densities calculated from molecular observations or extinction to match those inferred from I_{100}.

Sources were selected which are regular and isolated, and which exhibit good morphological correlations between the extinction, molecular, and *IRAS* emission.

Two clouds of small visual optical depth, L1563 and L1780, and one visually optically thick cloud, L1535, have been investigated. L1563 and L1780 are in relatively uncomplicated areas of the sky, while L1535 lies at the eastern edge of the southernmost dust lane in Taurus. Both molecular and infrared (*IRAS*) observations confirm that these clouds do not suffer confusion with line of sight or neighboring material.

L1780 is a well-studied member of the L134/L183 high-latitude molecular cloud complex at $b = +34°$ (Clark & Johnson 1981). L1535 is a dense cloud and has been studied using molecular spectral lines by Goldsmith & Sernyak (1984). L1535 has an embedded *IRAS* point source of low luminosity (IRAS 04325+2402) which does not appear to perturb the dust in any detectable manner, despite the presence of an outflow (Heyer et al. 1987).

2. OBSERVATIONS

IRAS HCON 3 Sky Flux images were reduced using standard techniques described in Zhang *et al.* (1988) and Laureijs et al. (1989). Emission lines of both CO (^{12}CO) and ^{13}CO were observed for L1563 and L1535 with the University of Cologne[1] 3 m telescope (Winnewisser et al. 1986); the observations for L1563 are described in detail in Clark, Laureijs, & Wardell (1991). The nominal half-power beamwidth was 4′, and the data were sampled with 2′ half-beam spacing and smoothed to 6′, the nominal spatial resolution of the 100 μm *IRAS* Sky Flux images. The 6 cm ($1_{1,0} \rightarrow 1_{1,1}$) spectral line of formaldehyde was observed in L1563, oversampled to the same 2′ grid as the *IRAS* and CO data, onethird of the nominal 6′ beam size (Clark, Laureijs, & Wardell 1991).

The star counts by Mattila (1979) of L1780 were reanalyzed, using the conversion to extinction described in Laureijs et al. (1989). The distance to L1563 was established by means of optical photometric data as 180 pc (Clark, Laureijs, & Wardell (1991). The distance to L1780 was established by Mattila

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(1979) and Franco (1989) as 100 pc, and L1535 is part of the well-studied Taurus complex at 140 pc.

3. CALCULATION OF THE DUST TEMPERATURE

For a resolved cloud, the infrared surface brightness at 100 μm, I_{100} in Jy sr^{-1}, due to thermal emission from the dust is given by

$$I_{100} = N_d Q_{100} \sigma B_\nu(T_d) , \tag{1}$$

where N_d is column density of dust grains, Q_{100} the infrared emissivity, B_ν the Planck function, σ the geometrical cross section of one grain, and T_d the dust grain temperature.

3.1. *The Diffuse Interstellar Medium*

The temperature of 18 K derived by Terebey & Fich (1986) from comparison of H I column density and 100 μm emission along random lines of sight is adopted as T_d in the diffuse interstellar medium.

3.2. *Molecular Column Density*

A related technique has been applied to estimate T_d in molecular clouds by comparing gas column densities and I_{100}. As applied here, the molecular method yields a robust column density determination, verified by assuming that a cloud has a depth comparable to its width, which permits a volume-density estimate. This estimate is subsequently probed with a volume-density-sensitive molecular spectral line.

The CO molecular observations of L1563 were converted to column density by means of a large velocity gradient (LVG) model (Snell 1981). The resulting gas column density map is sensitive to changes in fractional abundance of the molecular probe and variations in molecular excitation due to changes in gas volume density and gas kinetic temperature. Identical results were obtained for this low-opacity cloud using the simplifying relationship suggested by Liszt (1982), indicating that opacity effects in CO are not important at this spatial resolution, and that the results are not model dependent.

The CO data were supported by observations made with different molecules, ^{13}CO and H$_2$CO. The latter transition has exacting excitation requirements. The CO column densities were used to estimate the volume density of the cloud, and an excitation model (Fulkerson & Clark 1984) was then used to predict the strength of the 6 cm spectral line of H$_2$CO, which is sensitive to volume density; this line was subsequently detected as predicted, supporting the original column density determination.

The consistency between the CO, ^{13}CO, and H$_2$CO measurements in L1563 and L1535, which depend on the column density as well as the volume density of the gas, lends confidence to the estimates of total mass and average volume density in these clouds.

Column density maps obtained from molecular observations (Goldsmith & Sernyak 1984; plus our own observations) were used in the analysis of L1535, again confirmed by observations of excitation-specific spectral lines. L1535 is a dense cloud, with an estimated peak visual opacity of 8 mag estimated from star counts.

Molecular data may be modeled and interpreted in terms of column density of gas, number of hydrogen atoms or molecules cm^{-2}, $N_{\rm gas}$, but a gas-to-dust ratio must be assumed to utilize these data with equation (1).

T_d can be solved for in equation (1)

$$T_d = h\nu\left(k\left\llbracket \ln\left\{1 + \frac{2h\nu^3 N_{\rm gas}[(N_d/N_{\rm gas})a\sigma]Q_{100}/a}{c^2 I_{100}}\right\}\right\rrbracket\right)^{-1} , \tag{2}$$

where h is Planck's constant, ν is frequency, k is Boltzmann's constant, a is grain radius, and c is the speed of light. Hildebrand shows that Q/a is expected to be independent of a. Equation (2) shows explicitly the functional dependence of T_d on changes in both the gas-to-dust ratio (note here expressed as *number* per unit column, not mass), and in dust volume ($a\sigma$).

Average values of the gas-to-dust ratio (100/1 by mass), grain size (0.1 μm), and absorption efficiency in the infrared (0.0094) suggested by Hildebrand (1983) were adopted. For L1563 the column density as estimated from molecular data was compared to an *IRAS* 100 μm map on a pixel-pixel basis to derive estimates of T_d. The peak extinction of this column was estimated from I_{100}, CO, and formaldehyde data, with all yielding a consistent value of $A_B = 2.5$ mag with 6′ effective resolution.

3.3. *Extinction Column Density*

Blue extinction, A_B expressed in magnitudes, is related to the dust column density by

$$A_B = 1.086 N_d Q_{\rm blue} \sigma , \tag{3}$$

(Spitzer 1978 eq. [7-1]). Equation (3) can be substituted into (2)

$$T_d = h\nu\left\llbracket k\left\{\ln\left[1 + \frac{2h\nu^3 A_B Q_{100}}{1.086 c^2 I_{100} Q_{\rm blue}}\right]\right\}\right\rrbracket^{-1} . \tag{4}$$

The extinction map for the cloud L1780 was compared to *IRAS* 100 μm emission. Hildebrand's value of $Q_{\rm blue}/Q_{100}$ was used. The total mass of this cloud was estimated from the data of Mattila (1979), Mattila & Sandell (1979), and Clark & Johnson (1981), and provides a sensitive constraint on $Q_{\rm blue}/Q_{100}$. Equation (4) shows that the major source of uncertainty in T_d is the ratio $Q_{\rm blue}/Q_{100}$ μm.

Difficulties with the extinction method involve: (1) the assumption that the grains which cause the blue extinction are identical to those responsible for the far-infrared emission, (2) the small numbers of star counts from which to calculate extinction, especially toward a cloud center, (3) the calibration of the star counts into extinction (Laureijs et al. 1989), and (4) the low *IRAS* flux levels at the cloud edge.

4. DUST TEMPERATURE

4.1. *Results*

Figure 1 shows the results determined using the molecular method. The dust temperature clearly exhibits an initial rapid decline at the edge of a cloud followed by a much lesser decline after $A_B > 0.3$ mag. The temperature at low extinction is of order 18–19 K, consistent with the value derived by Terebey and Fich (1986) for the diffuse interstellar medium using H I column densities, rather than molecular.

Figure 2 shows the results determined using the extinction method. The dust temperature again exhibits an initial rapid decline at the edge of a cloud followed by a much lesser decline after $A_B > 0.3$ mag. These temperatures are higher than those of the molecular method at all extinctions.

The L1780 data were least-squares fitted to the L1563 data, with the ratio $Q_{\rm blue}/Q_{100}$ as the permitted variable, and accept-

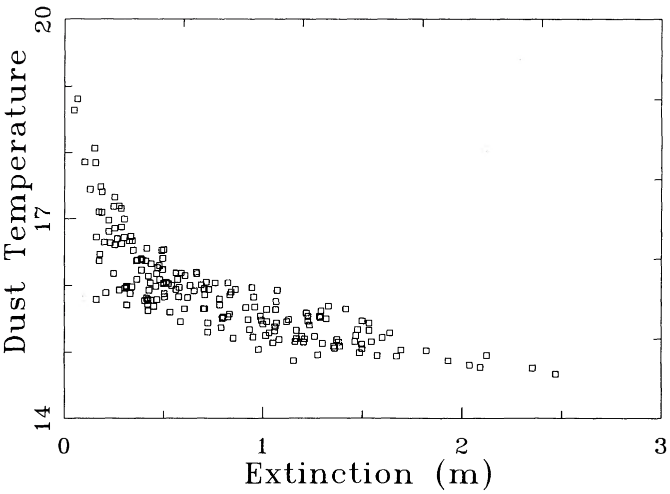

FIG. 1.—Calculated dust grain temperature, T_d, as a function of extinction calculated from CO, A_B, for L1563. Each square represents a 2′ pixel. Errors are represented by the scatter in the data.

able agreement was obtained with a ratio $Q_{\mathrm{blue}}/Q_{100}$ of 0.37 times the generally accepted value (discussed below). The results are shown in Figure 3, along with the data for the denser cloud L1535. The data for L1563 and L1780 have been binned, and the model results of Chlewicki & Laureijs (1988) are also shown for a spherical homogeneous cloud of $A_B = 4$ mag in the center.

4.2. *Discussion*

In view of the uncertainties, there is surprisingly small scatter, of order 0.5 K rms, in each data set for these two very similar clouds. The difference in spatial resolution sampled by the two methods can be examined in some detail.

The available observational data suggest that L1780 and L1563 are very similar on the scale size studied. These two clouds are quiescent, nearby, and exhibit similar peak A_B, peak I_{100}, molecular line strength, and I_{100}/A_B, and both clouds are bright on red photographs. For example, I_{100}/A_B is 7.1 ± 0.3 MJy sr^{-1} mag^{-1} for L1780 and 7.2 ± 3 MJy sr^{-1} mag^{-1} for L1563. These values are indistinguishable from those of L1642, 6.3 ± 0.7 (Laureijs, Mattila, & Schnur 1987), and G300−17, 8.1 ± 0.3 MJy sr^{-1} mag^{-1} (Laureijs et al. 1989). The similarity of these clouds argues that the difference in temperature scale is due to a lack of knowledge of the dust properties, and is not attributable to a physical difference between the two clouds.

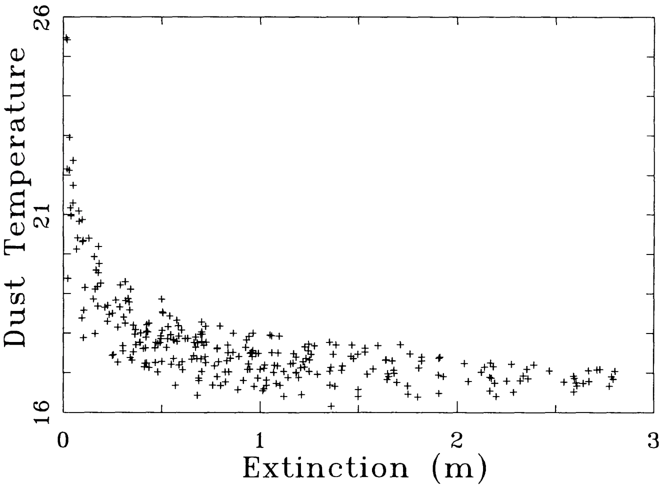

FIG. 2.—Calculated dust grain temperature, T_d, as a function of extinction calculated from star counts, A_B, for L1780. Each + represents a 2′ pixel. Errors are represented by the scatter in the data.

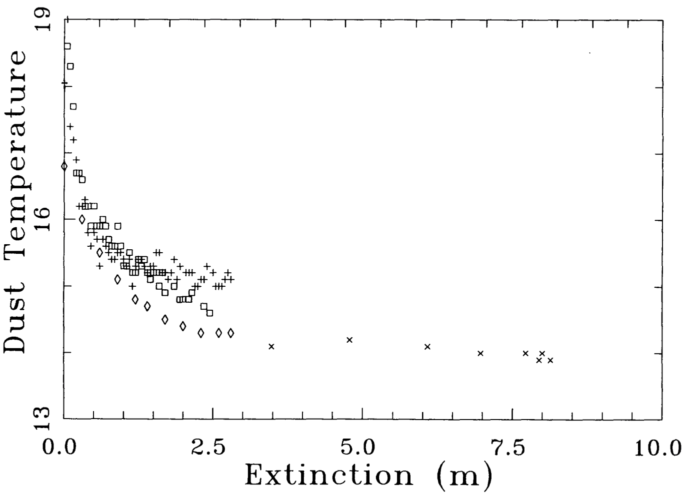

FIG. 3.—Calculated and model T_d as a function of extinction, A_B, for all three clouds. L1780 data have been least-squares fitted to that of L1563. The data of L1563 and L1780 have been binned for clarity. + is L1780, □ is L1563, × is L1535, and ◇ is the model. Errors are represented by the range of scatter in each technique and the disagreement between techniques.

Given the expectation that the two methods should yield the same actual values for dust temperature, it is assumed that the vertical offset between the results from the extinction and molecular methods is due to inadequately known variables in either equation (2) or (4) or both.

There are other possibilities. For example, the difference could be due to some inadequacy of the extinction derived from star counts. Should these clouds be clumped on extremely small scale sizes, it is conceivable that star counts, which probe on the micro-arcsecond scale, sample the clouds in a different manner from dust and molecular emission, both of which are observed with large effective sampling sizes.

According to equation (2), the molecular method is sensitive to uncertainty in the gas column density, the gas-to-dust ratio, and the grain volume. According to Hildebrand, to first order Q_{100}/a will be constant, assuming both clouds have similar dust grains. The gas column density estimate is sensitive to gas column density, gas kinetic temperature, and fractional abundance of CO, since CO is used as an indirect probe. However, there are two indications that the molecular data is faithfully returning column densities. First, the atomic hydrogen result of Terebey & Fich (1986) is in agreement with the low extinction limit of L1563. Second, the temperature difference between the two methods is constant over the range of column densities measured, indicating a systematic discrepancy that is independent of column density. Therefore it is unlikely that the offset in the results of the two methods is caused by an error in the gas column density estimate, due, for example, to subthermal excitation of CO at low extinction, or rising gas kinetic temperature at low extinction, or changes in CO fractional abundance, as such changes are expected to have a strong functional dependence on extinction. Therefore, we argue that the only sensible variable that could explain the offset in the two data sets is the gas to dust ratio.

However, theoretical studies of classical dust grains predict temperatures below 20 K in the diffuse interstellar medium (Spencer & Leung 1978; Draine & Lee 1984; Lee & Rogers 1989; Draine 1990). For example, Draine & Lee predict 15 K for silicate particles in the diffuse interstellar medium. It is difficult to construct a model of dust that can fit all imposed constraints and produce a temperature above 20 K.

With these theoretical and observational constraints in mind, the extinction method can also be examined for a potential resolution to this problem. The temperature scale returned by the extinction method depends logarithmically on the ratio of $Q_{\rm blue}/Q_{100}$ (eq. [4]). The scales can be brought into acceptable agreement if the assumed ratio of $Q_{\rm blue}/Q_{100}$ is decreased by an amount of order 3. A_B is not a permitted variable to this order of magnitude. We estimate that the star counts and molecular data set the extinction scale to at least within 40%, while changes well over 5 times this are required.

The preferred value of $Q_{\rm blue}$ in the literature is 1.2 (range 1.07–3; e.g., references listed above and does not permit a correction of the order required to reconcile the two data sets. Hence, Q_{100} appears to be the only variable which can reconcile the data. A value of Q_{100} of 0.0025 can reconcile the methods. The value of Q_{100} advocated by Hildebrand for λ^{-1} emissivity is 0.00094, and the range in the literature is 3×10^{-5} to 0.01. Note that advocacy of a different exponent in the emissivity law does not change the discrepancy, since both methods have the same dependency on Q_{100}.

However, the common dependency of both methods on Q_{100} means that an increase in Q_{100} of 2.7 must be accompanied by a corresponding compensating change of comparable quantities in equation (2). Such a necessity of simultaneously altering two imperfectly known variables is displeasing.

If the potential variables in equation (2) are reduced to their measured forms, one has

$$\frac{N_{\rm gas}}{M_{\rm gas}/M_{\rm dust}\,\rho_{\rm dust}}\,\frac{Q_{100}}{a} = \text{constant}\ . \qquad (5)$$

From previous arguments, if Q_{100} is changed, the compensating variable must change across the range of extinction from 0–2.5 mag, and not just at low or at high extinction. The indicated change in Q_{100} implies either a reduction in $N_{\rm gas}$ by 0.37, or an increase of $M_{\rm gas}/M_{\rm dust}$ by 2.7, or an increase in $\rho_{\rm dust}$ by 2.7. The variable that is likely in error by this much is the ratio $M_{\rm gas}/M_{\rm dust}$. The acceptable agreement with atomic data indicates that the calibration of the column density returned by molecular indicators is perfectly satisfactory.

The rapid decline in T_d within the first 0.5 mag of extinction is consistent with a simple geometrical explanation, shadowing by the cloud. Near the edge of a cloud, a dust grain responds to the reduced radiation field from practically half of the solid angle of the sky. The less rapid decline up to higher extinctions results because the opaque core itself subtends only a small solid angle, as seen by a dust grain. This effect is even more pronounced in centrally condensed clouds, of which all three of these are examples.

These data indicate that 100 μm emission probes cloud interiors at least up to extinctions of order 8 mag. Deriving column density from I_{100} becomes feasible if the dust temperatures shown in Figure 3 can be confirmed by independent methods. The utility of I_{100} as a probe of column density in these regimes is evidenced by the excellent pixel-pixel correlation between I_{100} and extinction in clouds with A_B up to 3 and between I_{100} and column density derived from molecular data.

Implicit in our results is the fact that I_{100} cannot be perfectly linearly proportional to extinction at extinctions smaller than about 0.5 mag. This result is apparent in published data as a change in slope at about 0.5 mag visual extinction (e.g., Laureijs et al. 1989; Fig. 3), although the eye is captured by the nearly linear relationship from 0.5 to 3 mag.

The fact that I_{100} correlates well with extinction while T_c is higher than the actual T_d has previously been noted by others, including Langer et al. They apply the same basic technique and also conclude that the actual T_d is considerably lower than T_c. As extinction increases toward a cloud centroid, the I_{60}/I_{100} ratio declines while I_{100} increases, resulting in a stronger correlation between "dust opacity" derived using T_c and extinction than that correlation found between I_{100} alone and extinction (Jarrett et al. 1989; Snell et al. 1989). However, the conclusion reached in the above references and here is that this effect involves two different dust emission processes.

4.3. 60 μm *Emission*

The strength of the emission in the *IRAS* 60 μm band is uncomfortably high for emission which originates in the same grains as those detected at 100 μm. Even in the outermost diffuse regions of the clouds, T_d calculated here is lower than the T_c calculated from the ratio I_{60}/I_{100} (= 0.20), 25 K.

This apparent difference in temperature can be resolved by assuming that a large fraction of the 60 μm emission is due to another emission mechanism, for example, a separate dust population emitting at a characteristic temperature of 50–60 K. A number of explanations have been suggested (Draine & Anderson 1985; Chlewicki & Laureijs 1988; Laureijs et al. 1989; etc.), but an unambiguous identification of the emission mechanism for the carriers is still lacking. In any case, the hypothesis of a different carrier in the 60 μm band implies that the straightforward conversion of the ratio I_{60}/I_{100} to a T_c lacks physical meaning.

We find that the grains at 100 μm exhibit an initial rapid decline in T_d within 0.5 mag of extinction followed by a much smaller decline in T_d up to extinctions of at least 8 mag. The I_{60}/I_{100} ratio decreases continuously with increasing extinction over this entire range, with indications that I_{60} completely disappears at moderate extinctions. Thus both T_d and T_c drop toward higher column densities in clouds. Although I_{60}/I_{100} cannot be converted to a meaningful temperature, it declines as would be expected if due to a single grain component.

The qualitative correspondence between variations in T_c and T_d in the denser parts of clouds affords an explanation for the results of Langer et al. (1989), who find a better correlation between dust optical depth τ_{100} calculated using T_c and the integrated line profile of CO, $W_{\rm co}$, than between I_{100} and $W_{\rm co}$. Their τ_{100}, derived using T_c, and the variations in I_{60}/I_{100} tend to stretch the optical depth scale, enhancing the magnitude of the variations seen at 100 μm and therefore improving the correlation.

The correlation between τ_{100} and $W_{\rm co}$ would be even tighter if T_d was used, since the declining dust temperature introduces an even larger stretch to the optical depth scale.

5. CONCLUSIONS

1. T_d calculated by extinction and molecular methods has a similar decline into a cloud, but there is an offset between the two methods that cannot be reconciled by changes in a single variable.

2. T_d calculated by both methods quickly declines up to extinctions of order 0.5, and then declines more slowly.

3. I_{100} can be used as a probe of dense cloud interiors up to extinctions of 8 mag.

4. Reconciliation of the dust temperature derived from the molecular and extinction methods requires a cloud-independent and extinction-independent (up to $A_B \approx 3$) change of order 3 in two variables, which we suggest are Q_{100}, and an inverse change of the same magnitude in some other quantity to which the molecular method is sensitive. We suggest that the best candidate for the latter is the gas-to-dust ratio.

5. $Q_{100\,\mu m}$ is estimated as 0.0025 if $Q_{\rm blue}$ is taken as 1.2.

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