Dust emissivity in the submm/mm

SCUBA and SIMBA observations of Barnard 68

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Abstract. We have observed the dark cloud Barnard 68 with SCUBA at 850 μm and with SIMBA at 1.2 mm. The submillimetre and millimetre dust emission correlate well with the extinction map of Alves et al. (2001). The $A_V/850 \mu m$ correlation is clearly not linear and suggests lower temperatures for the dust in the inner core of the cloud. Assuming a model for the temperature gradient, we derive the cloud-averaged dust emissivities (normalised to the $V$-band extinction efficiency) at 850 μm and 1.2 mm. We find $\kappa_{850 \mu m}/\kappa_V = 4.0 \pm 1.0 \times 10^{-3}$ and $\kappa_{1.2 \ mm}/\kappa_V = 9.0 \pm 3.0 \times 10^{-2}$. These values are compared with other determinations in this wavelength regime and with expectations for models of diffuse dust and grain growth in dense clouds.

Key words. radiation mechanisms: thermal – dust, extinction – ISM: clouds, individual objects: Barnard 68 – submillimeter – radio continuum: ISM

1. Introduction

Despite being a fundamental parameter in Far Infrared, Submillimetre and Millimetre astronomy, few measurements of the dust emissivity$^1$ are available (for a review, see Alton et al. 2000; James et al. 2002). The submm/mm dust emissivity is particularly important for star formation studies. Since molecules are known to deplete inside prestellar cores (Bergin et al. 2002), dust emission may represent the best tracer of the gas density distribution just prior to the onset of gravitational collapse. Thus measurements in the submm/mm define the initial conditions from which a core collapses to form a star. Alternatively, the density distribution can be mapped through extinction, by measuring the near-infrared colour excess towards giant stars in the background of a cloud (Lada et al. 1994). High resolution and $S/N$ maps can be obtained for object in the foreground of dense stellar fields (Alves et al. 2001).

This is the case for the dark cloud Barnard 68, a starless globule seen in the foreground of the Galactic Bulge. Alves et al. (2001) have produced a high resolution extinction map of the cloud, measuring the $H - K$ colour excess of nearly 4000 stars in its background. In this paper, we compare the extinction map with observations of submm/mm dust emission of similar resolution. Observations are described in Sect. 2. In Sect. 3 we derive the dust emissivity from the correlation between emission and extinction (in a way similar to Kramer et al. 1998, 2003). We will also adopt a temperature gradient within the cloud, which was derived from a model of dust heating. Finally, the derived emissivities are compared with other estimates from literature in Sect. 4.

2. Submm/mm observations

Barnard 68 was observed with the Submillimetre Common User BolometerArray (SCUBA) at the JCMT (Holland et al. 1999) and with the SEST Imaging Bolometer Array (SIMBA; Nyman et al. 2001). Both instruments have hexagonal arrays of 37 bolometers: SCUBA can observe in the submm at 850 μm with $FWHM = 14.5''$ while SIMBA operates at 1.2 mm and has a beamsize of 24''.

SCUBA observed an area of $5' \times 5'$ around Barnard 68 in scan-map mode, chopping within the field of view. The resultant image is convolved with the chop function, which is removed by means of Fourier Transform analysis. The Emerson II technique is used to minimise the noise (Jenness et al. 1998): six scans of the field are made with different chop throws (20'', 30'' and 65'' in RA and Dec). In total, we coadded eight sets of scans, six observed in March/June 2002 and two in July 1998 (the latter retrieved from the SCUBA Archive). Standard data reduction was performed with the dedicated package SURF. After flat-fielding and masking of

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$^1$ The emissivity proper is the emission [absorption] cross section normalized to the geometrical cross section of a dust grain. Other authors prefer the cross section normalized to the mass of the grain. Both quantities are the same when normalised to the analogous quantity for $V$-band extinction.
and it is not possible to conduct the surface brightness analysis of Barnard 68 were rebinned in a single image, with pixel sampling of small spatial frequencies and to uncertainties in the background fluctuations and of the larger sky opacity \( \tau_{500} \approx 0.1 \pm 0.086 \). The final SIMBA image of Barnard 68 has a residual noise of 5.5 mJy beam\(^{-1} \) (1\( \sigma \)), equivalent to 0.36 MJy sr\(^{-1} \) for the SIMBA resolution. The integrated flux is \( F_{1.2\text{ mm}} = 0.7 \pm 0.2 \text{ Jy} \).

The emission is compared to the extinction map of Alves et al. (2001) (the measured NIR colour excess has been converted to \( A_V \) using a standard reddening law; Rieke & Lebofsky 1985). All images have been smoothed to the SIMBA resolution, registered together (pointing accuracy is better than a few arcsec for the submm/mm observations) and resampled to a common pixel size of 12\( \arcsec \). Figure 1 shows the final SCUBA (left) and SIMBA (right) images, with superimposed \( A_V \) contours.

3. Analysis

The morphology of the extinction and emission maps in Fig. 1 is quite similar. Dust emission with \( S/N > 3 \) traces regions with extinction \( A_V > 6 \) and \( A_V > 10 \), in the SCUBA and SIMBA images, respectively. In analogy with extinction, emission comes from a round region with a south-east tail. At 1.2 mm, there are hints for a secondary emission peak. In Fig. 2 we show the pixel-to-pixel correlation of the emission maps with \( A_V \). As already seen in Fig. 1, there is a clear correlation between emission and extinction. For regions with \( A_V > 10 \) the scatter in the correlation with the submm data is of the order of the sky noise (1.7 MJy sr\(^{-1} \) for the smoothed image). For \( A_V < 10 \) the scatter increases because of the (possibly hotter) south-east tail. The pixels clearly belonging to the tail can be seen in Fig. 2 around \( A_V = 8 \) and \( I_e = 10 \text{ MJy sr}^{-1} \). The scatter at 1.2 mm is more uniform and slightly larger than the sky noise, because of the complex central morphology. A forthcoming paper will be devoted to the analysis of the central peaks and of the south-east tail.

For optically thin radiation (as for the submm/mm emission of Barnard 68) we can write

\[
I_e = \frac{k_{\nu}}{k_{T}} \times \frac{A_V}{1.086} \times \frac{\int \rho \cdot B_{\nu}(T) \, dI}{\int \rho \cdot dI},
\]

where \( T \) and \( \rho \) are the temperature and density of dust grains, functions of the position within the cloud, \( B_{\nu} \) is the Planck function and the integral extends along the line of sight through the dust. In the isothermal case, the last term on the right is
reduces to \( B_\nu(T) \). Otherwise, a knowledge of the dust temperature and density distribution is needed.

In Fig. 3 we show the Spectral Energy Distribution (SED) of Barnard 68. Our integrated fluxes at 850 \( \mu m \) and 1.2 mm are similar to those presented by Ward-Thompson et al. (2002), from which we took the ISOPHOT fluxes at 170 \( \mu m \) and 200 \( \mu m \). We fitted a isothermal modified blackbody to the datapoints assuming a value for \( \beta \), the emissivity spectral index (\( \kappa_\nu \propto \nu^\beta \)). For \( \beta = 1.5 - 2 \) (Dunne & Eales 2001), we find acceptable fits for temperatures \( T_{\text{iso}} = 11 - 13 \) K. We adopt \( T_{\text{iso}} = 12 \pm 2 \) K (1-\(\sigma\)) for the isothermal case, incorporating in the broad error the large uncertainties on \( \beta \). The solid line in Fig. 3 is an indicative SED for \( \beta = 1.7 \) and \( T_{\text{iso}} = 12 \) K. Similar temperature have been previously obtained for Barnard 68 (Ward-Thompson et al. 2002; Hotzel et al. 2002). Using \( T_{\text{iso}} \), we fitted Eq. (1) to the correlations of Fig. 2 and derived a single cloud-averaged value for the submm and mm emissivities. We obtained \( \kappa_{850 \mu m}/\kappa_\nu = 3.5 \pm 1.0 \times 10^{-5} \) and \( \kappa_{1.2 \text{ mm}}/\kappa_\nu = 9.0 \pm 3.0 \times 10^{-6} \). Errors were estimated with a bootstrap technique and are dominated by the uncertainty on calibration and on temperature.

The fitted correlations are shown as solid lines in Fig. 2. While the fit is acceptable at 1.2 mm, a simple linear relation is unable to reproduce well the correlation observed at 850 \( \mu m \) for \( A_V > 20 \) since the \( I_e/A_V \) ratio decreases for increasing \( A_V \). This is expected if the temperature in the cloud core is lower than in the external part, as a result of the dust shielding of the external radiation field (Zucconi et al. 2001). Such a trend has been observed in other clouds (see, e.g. Kramer et al. 1998). A similar behaviour could also be explained with an isothermal dust distribution, if the dust emissivity is lower in denser regions. However, models and observations suggest that emissivities increase in dense cores (Ossenkopf & Henning 1994; Kramer et al. 2003).

We derived the temperature gradient inside the cloud from an improved version of the Zucconi et al. model (Gonçalves et al., in preparation). As in Alves et al. (2001), the adopted density distribution is that for a Bonnor-Ebert sphere, a pressure confined isothermal sphere in hydrostatic equilibrium. Dust is heated by a local Interstellar Radiation Field (Galli et al. 2002). The internal dust absorption is fixed by the measured extinction and the assumed absorption law \( \kappa_\nu/\kappa_\nu \), for which we used the tabulated values given by Ossenkopf & Henning (1994) for different models of dust coating/coagulation in dense clouds. While the absolute value of the temperature depends on the adopted dust model (for \( \lambda > 30 \mu m, \kappa_\nu/\kappa_\nu \) increases going from bare grains to grains with ice coating up to grains that undergo coagulation), the temperature gradient is found to be relatively independent of grain characteristics, with the temperature at the truncation radius \( T_{\text{ext}} \) (0.06 pc; Alves et al. 2001) about 1.5 times higher then the core temperature. This is because the absorption law does not change significantly with the dust model at shorter wavelengths, where most of the absorption occurs. In the following, we adopt the model radial gradient and derive \( T_{\text{ext}} \) from the data.

For the assumed density and temperature distributions, we simulated emission maps with 24” resolution and 12” pixels, in analogy with the data. The integrated SED is shown with a dashed line in Fig. 3. Again, a broad range of best fit temperatures is obtained, \( T_{\text{ext}} = 12 - 15 \) K. We use \( T_{\text{ext}} = 14 \pm 2 \) K (1-\(\sigma\)). Finally, the simulated \( A_V \) vs. \( I_e \) correlation of Eq. (1) is fitted to the observed data to derive \( \kappa_e/\kappa_\nu \). We obtained\(^2\)

\[
\begin{align*}
\kappa_{850 \mu m}/\kappa_\nu &= 4.0 \pm 1.0 \times 10^{-5} \\
\kappa_{1.2 \text{ mm}}/\kappa_\nu &= 9.0 \pm 3.0 \times 10^{-6}.
\end{align*}
\]

\(^2\) Equivalent to \( \kappa_{850 \mu m} = 1.5 \pm 0.4 \text{ cm}^2 \text{ g}^{-1} \) and \( \kappa_{1.2 \text{ mm}} = 0.35 \pm 0.1 \text{ cm}^2 \text{ g}^{-1} \) (assuming grain radius 0.1 \( \mu m \), grain density 3 \text{ g cm}^{-3} \) and V-band extinction efficiency 1.5; Hildebrand 1983).
4. Discussion

The derived submm/mm emissivities are shown in Fig. 4 together with estimates from literature. Emissivities derived from IRAS/Cobe observations of diffuse galactic dust (Boulanger et al. 1996; Bianchi et al. 1999) are within 10% of the values predicted by the popular Draine & Lee (1984) model, which is shown in Fig. 4 as a solid line. Dotted lines refer to the Ossenkopf & Henning (1994) models for bare grains, grains with a thin ice coating and grains with thin ice after coagulation has proceeded for 10^5 years in a gas with density 10^6 g cm^{-3} (from bottom to top, respectively).

Bianchi et al. (2002) derived the emissivity from a sample of local galaxies observed with SCUBA, estimating the dust mass from metals. Their value is compatible to that of Birkinshaw & Lebofsky (1985) and is within 10% of the values predicted by the popular Draine & Lee (1984) model, which is shown in Fig. 4 as a solid line. Dotted lines refer to the Ossenkopf & Henning (1994) models for bare grains, grains with a thin ice coating and grains with thin ice after coagulation has proceeded for 10^5 years in a gas with density 10^6 g cm^{-3} (from bottom to top, respectively).

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Fig. 4. Submm/mm emissivities compared with other literature estimates (details in the text). A standard ratio $\kappa_\nu/\kappa_V$ (Rieke & Lebofsky 1985) has been used to derive $\kappa_\nu/\kappa_V$ from Ossenkopf & Henning (1994). Data from Draine & Lee (1984) and James et al. (2002) are converted to $\kappa_\nu/\kappa_V$ as in Bianchi et al. (1999) and Alton et al. (2000). Points at 850 $\mu$m have been slightly shifted in $\lambda$ for ease of presentation.

These correlations are also shown in Fig. 2 with dashed lines. Although the fit to the submm data has improved, the emissivities are nearly the same as for the isothermal case.

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James et al. (2002) derived the emissivity from a sample of local galaxies observed with SCUBA, estimating the dust mass from metals. Their value is compatible to that of Draine & Lee (1984), indicating similar properties for diffuse dust and on laboratory cosmic dust analogues (Mennella et al. 1998). However, the error on the ratio is large and $\beta = 2$ is still compatible (within 1-$\sigma$) with our result. Contamination of the submm and mm fluxes by the ^12CO(3-2) and ^12CO(2-1) lines (Avery et al. 1987) was found to be negligible.

Clearly, more observations are needed to narrow down the errors in the determination of the emissivity. The analysis presented here has to be repeated on a large sample of objects of relatively simple morphology like Barnard 68. Only with a statistical sample will it be possible to study the variation of dust properties with the environment.