Properties of dust in the high-latitude translucent cloud L1780

II. 3D radiative transfer modelling

M. Ridderstad^{1,2} and M. Juvela^{1,2}

¹ Department of Physics, PO Box 64, 00014 University of Helsinki, Finland
e-mail: ridderst@kruuna.helsinki.fi

² Observatory, University of Helsinki, Finland

Received 4 October 2010 / Accepted 14 May 2010

ABSTRACT

Context. Lynds 1780 is a high-latitude cloud where, based on 2MASS, the maximum visual extinction is $A_V^{\max} = 4$ mag at a resolution of $3'$. In LDN1780, increased far-infrared (FIR) emissivity of dust grains has been observed, and the infrared emission is found to peak at different locations at different wavelengths.

Aims. By modelling the FIR observations, we try to quantify spatial variations of dust properties and to determine to what extent the observations could be affected by the asymmetry of the heating radiation field.

Methods. We have constructed a three-dimensional cloud model and, with the help of radiative transfer calculations, compare its predictions with the FIR surface brightness measurements of LDN1780 performed with the ISO satellite. The effects of anisotropic radiation, its attenuation in a diffuse extinction layer around the cloud, and variations in the dust properties are investigated.

Results. Asymmetry of the radiation field is found to have only a small effect on the morphology of mid- and far-infrared surface brightness. The general agreement between observations and the model predictions is improved by assuming the presence of a low extinction external layer with $A_V \sim 0.25$ mag. However, to explain the changes in the relative intensity of mid- and far-infrared bands, one has to assume strong variations in the relative abundance of small and large grain components and, at the very centre of the cloud, enhanced emissivity of large grains.

Conclusions. The separate emission maxima at different wavelengths in LDN1780 result from real variations in spatial distributions of dust components. Modifications to standard dust models, including a 30% increase in the FIR emissivity, are needed to explain the far-infrared observations towards the centre of LDN1780. The relative abundances of dust components are found to be very sensitive to the strength of the external radiation field.

Key words. ISM: clouds – infrared: ISM – ISM: individual objects: L1780 – dust, extinction – radiative transfer

1. Introduction

During the past three decades, the interstellar dust models have gone through an intense period of development, beginning from the large, spherical grains, and ending up with the latest observational results indicating the presence of fluffy and/or ice-coated grains with increased emissivity in the cold cores of molecular clouds (Cambrs et al. 2001; del Burgo et al. 2003; Stepnik et al. 2003; Kramer et al. 2003). The distribution, dynamics, and evolution of the interstellar dust in the clouds have become better understood. The first models of the interstellar dust were based on large grains, assumed to consist mainly of graphite and silicates (e.g. Mathis et al. 1977; Draine & Lee 1984). However, with the detection of strong emission in the IRAS $12\mu\text{m}$ and $25\mu\text{m}$ bands (Boulanger et al. 1985), it became clear that a component of very small grains needs to be included in the models of interstellar medium (ISM) (Weiland et al. 1986). The Infrared Space Observatory (ISO) and the Infrared Telescope in Space (IRTS) satellites further revealed the presence of the so-called unidentified infrared bands (UIBs) at $3\text{--}12\mu\text{m}$, which are now generally attributed to polycyclic aromatic hydrocarbons (PAHs). A number of models of interstellar dust, including not only the largest grains but also both very small grains (VSGs) and PAHs, have been presented (e.g., Dsert et al. 1990; Siebenmorgen & Krgel 1992a,b; Dwek et al. 1997;

Draine & Li 2001; and Li & Draine 2001; Zubko et al. 2004; Draine & Li 2007). For information on different dust models and their development towards the current models, see, e.g., Draine & Li (2007); Witt et al. (2000); Li & Draine (2001).

With the development of dust models and methods of continuum radiative transfer (hereinafter RT), more sophisticated models have been developed for individual clouds. These take the full grain size distribution into account and include special treatment for transiently heated grains that includes both the traditional VSGs and PAHs (see, e.g., Siebenmorgen & Krgel 1992a,b; Bernard et al. 1992, 1993; Verter et al. 2000; Stepnik et al. 2003; Rawlings et al. 2005). Bernard et al. (1993) used the dust model of Dsert et al. (1990) to compute the emission for three clouds in Chamaeleon and ρ -Ophiuchi approximated by spherically symmetric homogeneous clouds. They found that IRAS colours indicate true variations in the distributions of different dust components. Most notably, the so-called limb-brightening effect was found to be caused by increased abundance of PAHs in the outer regions of the clouds. Verter et al. (2000) modelled a sample of eight nearby translucent, high-latitude clouds using the three-component dust model of Dwek et al. (1997) that consist of grains of the Mathis-Rumpl-Nordsieck (MRN) model (Mathis et al. 1977), very small graphite grains, and PAHs. Their results show that the relative abundance of VSGs and PAHs changes from cloud to cloud. Rawlings et al. (2005) compared

ISO observations of the Chamaeleon “Blob” with theoretical predictions calculated using spherically symmetric cloud models and variations of the Li & Draine (2001) dust model. Their results indicate that, even within a single translucent cloud, there are clear variations in the relative abundances of the dust components of different sizes. Stepnik et al. (2003), also with the dust model of Désert et al. (1990), indicate that increased far-infrared emissivity is needed to produce the observed dust properties inside a cloud filament with a low temperature and extinction of the order of $A_V \sim 10^m$.

Ridderstad et al. (2006, hereinafter Paper I) presented ISO far-infrared (FIR) observations of the cloud Lynds 1780. LDN1780 is a cometary-shaped, translucent ($A_V^{\max} = 4$ mag), high-latitude cloud. It is one of the few clouds where infrared emission clearly shows different distributions at different wavelengths, suggesting the presence of spatially distinct dust populations (Chlewicki & Laureijs 1987; Laureijs et al. 1995; Paper I and references therein). The FIR emission at $100\mu\text{m}$ and $200\mu\text{m}$, mainly caused by big grains (BGs), peaks in the westernmost part of the cloud, whereas the $60\mu\text{m}$ emission, showing the presence of very small grains (VSGs), has its maximum in the middle of the cloud, eastwards of the $200\mu\text{m}$ maximum. The PAH emission is traced by IRAS $12\mu\text{m}$ emission, which is strongest towards the east, in the less dense “tail” of the cloud. In Paper I, increased emissivity of large grains and reduced emission of small grains, both of which could be indicators of grain coagulation, were reported in the centre of LDN1780. Similar results were, simultaneously and independently, announced by del Burgo & Cambrsy (2006).

In this paper, we report results from 3D radiative transfer modelling of LDN1780. We use, in particular, the $100\mu\text{m}$ and $200\mu\text{m}$ observations made with the ISOPHOT instrument (Lemke et al. 1996) onboard ESA’s ISO satellite. At shorter wavelengths, these are complemented by surface brightness data from the IRAS satellite. As a starting point, we use the dust model of Li & Draine (2001). With the help of the models, we investigate what dust abundance variations and qualitative changes of dust properties are needed so that the observations can be explained. The effect of anisotropic radiation field and the role of the possible existence of a low-extinction layer surrounding LDN1780 are also estimated. Beyond the study of LDN1780, we wish to demonstrate the usefulness of such modelling in separating the effects resulting from radiation field, density field, and dust properties. Routine 3D modelling can be used for quantitative analysis of all these factors.

2. Observations

In Paper I, the maps of $100\mu\text{m}$ and $200\mu\text{m}$ emission, observed with the ISOPHOT instrument onboard the Infrared Space Observatory (ISO) (Kessler et al. 1996), were presented (see also del Burgo & Cambrsy 2006). Maps of FIR colour temperature and $200\mu\text{m}$ optical depth were also shown and compared with maps of visual extinction A_V . In this paper, those observations are complemented with IRAS $12\mu\text{m}$, $25\mu\text{m}$, and $60\mu\text{m}$ data. These and the ISOPHOT maps were modified to be consistent with the DIRBE surface brightness, as explained in Paper I. The uncertainty in the relative calibration of the bands is 20–30% (see, e.g., del Burgo et al. 2003). The sky background subtraction of the ISOPHOT maps was performed as explained in Paper I, using the reference area shown in Fig. 1a of that paper. The same area was used for the background subtraction of the IRAS maps.

Fig. 1. Upper frame: the contours show the maxima of the IRAS $12\mu\text{m}$ (at 2.0, 2.2, and 2.4 MJy sr), $25\mu\text{m}$ (at 3.0 MJy sr), $60\mu\text{m}$ (at 4.5 and 5.5 MJy sr), and $100\mu\text{m}$ (at 18 and 28 MJy sr) emission. The circles show the positions corresponding to the pointings of the intensity profile plots both in Paper I and the present paper. Lower frame: the $200\mu\text{m}$ ISOPHOT map. The contours are drawn at 10, 30, 40, and 50 MJy sr $^{-1}$.

In Appendix A, new ISOPHOT photometric observations at the wavelengths $7.3\mu\text{m}$, $7.7\mu\text{m}$, $10\mu\text{m}$, $11.3\mu\text{m}$, $12\mu\text{m}$, and $20\mu\text{m}$ are presented. The sky positions of these observations are shown in Fig. 1. The same positions are used in surface profile plots later in this paper.

3. Radiative transfer modelling

In the following, the radiative transfer method used in the modelling, the dust model, and the radiation field used here are described. We present eight cases, denoted by letters A–H and introduced in Table 1.

3.1. Radiative transfer methods

The dust emission was computed using a Monte Carlo radiative transfer program (Juvela & Padoan 2003; Juvela 2005). The program allows us to add a certain number of dust components with distinct spatial distributions. The temperature distributions of transiently heated small grains are solved using the thermal discrete approach of Li & Draine (2001).

The cloud models were discretized into 50^3 cells. Because direct calculation of the emission of transiently heated particles

Table 1. Model parameters.

Model	$\lambda_{\text{fitted}} [\mu\text{m}]$	Dust model	Heating	Free parameters ^a	$A_V^{\text{bg}} [\text{mag}]^b$	$A_V^{\text{mod}} [\text{mag}]^c$
A	200	LD	ISRF	N	0.0	4.8
B	100, 200	LD	ISRF	N, χ	0.0	7.1
C	200	LD	ISRF	N	0.5	9.1
D	200	LD	ISRF	N	0.25	6.8
E	100, 200	LD	ISRF	N, χ	0.25	6.7
F	200	LD	ISRF+OB	N	0.25	2.8
G	12, 100, 200	LD+mod.1	ISRF	N, X	0.25	9.1
H	12, 60, 100, 200	LD+mod.2	ISRF	N, X	0.25	8.6

Notes. ^(a) The possible free parameters are the column density N , the scaling of the radiation field, χ , and the dust abundances, X . ^(b) A_V^{bg} refers to additional extinction around the model cloud. ^(c) A_V^{mod} is the visual extinction of the model cloud averaged over a 3' beam.

is time-consuming, the so-called library method was used (see Juvela & Padoan 2003). For an individual cell, the emission is obtained by interpolation from a grid of pre-calculated solutions. In our case, the local radiation field was characterized using intensity at three wavelengths, 0.36 μm , 0.55 μm , and 2.0 μm , each discretized into 20 intensity intervals. The accuracy of this approach was tested with 30^3 cell models by comparing the results with direct, more time-consuming calculations. The rms error in the observed intensity was found to be only of the order of 1%. The library, i.e., the mapping between the incoming radiation and the resulting dust emission, is valid only as long as intensities remain in the range used in the construction of that library. Therefore, when the column density (or radiation field) in the model was optimized, the library was re-created from time to time during the iterations. This ensures that the final result is correct, even when the optimization results in a model that is far from the initial state.

The initial column densities of the cloud model are based on the map of the 200 μm optical depth, derived from the 100 μm and 200 μm ISO observations (see Paper I). The density distribution along the line-of-sight is taken to be Gaussian, corresponding to the cloud size in the plane of the sky. The size of the map area is 1.2 pc, and the *FWHM* of the cloud model along the line of sight is 0.26 pc. This provides the initial cloud model. The dependence of final results on the original column densities is weak, because they only provide a starting point for the fitting procedure.

The column densities and, in the modified dust models, the abundances of the different dust components are updated pixel by pixel using the ratios of the observed and the modelled surface brightness values. The column density N is updated according to 200 μm ISO data. Therefore, the resolution of the modelled density field is effectively 1.5'. This is twice the cell size in the model. When computed on the basis of 100 μm and 200 μm observations, abundance data share the same resolution. However, when abundance calculation involves IRAS observations, the resolution of the corresponding abundance field has a resolution of $\sim 4.5'$. The comparison of model surface brightness maps with IRAS is done at the resolution of 4.5'.

3.2. The dust model

To model interstellar dust emission, we use the dust model of Li & Draine (2001, hereinafter the LD model) as a starting point. This model assumes two main classes of spherical dust grains: amorphous silicate grains and carbonaceous grains, with sizes ranging from 0.35 nm to 350 nm for both types of grains. At

very small sizes ($a < 5$ nm), the carbonaceous grains have properties like PAHs and above 5 nm, they have graphitic properties. Therefore, also in our modelling, the carbonaceous grains are divided into these two components, i.e., the carbonaceous grains distribution was divided in two at the grain size 5 nm. Later, in models G and H, we considered modifications to this basic dust model, i.e., changes in the relative abundance of small and large grains and increased emissivity at long wavelengths. Qualitatively, these could correspond to the expected effect of grain coagulation and/or the formation of ice mantles. To create two grain components of different sizes for both types of grains, carbonaceous and silicate, we divided their distributions at 7.5 nm and 5.35 nm, respectively. We then have five different dust grain components: large silicate and large carbonaceous (the big grains component), small silicate and small carbonaceous (the small grain component), and PAHs. In model H, two more large-grain components, carbonaceous and silicate, with increased emissivity (see Sect. 4.3) are added.

3.3. The radiation field

For modelling the local interstellar radiation field (ISRF), we use the model by Mathis et al. (1983). However, the ISRF around LDN1780 may not be symmetric, not only because LDN1780 is situated at a high galactic latitude, but also because the young OB stars of the Scorpius-Centaurus association, especially the Upper Scorpius subgroup (USco), are located nearby (de Geus et al. 1989; Tóth et al. 1995). Because of the stronger radiation coming from the direction of the galactic plane, we take the radiation intensity incident to LDN1780 from the upper half-space to be one third of the intensity coming from the side of the Galactic plane. The scale height of stars responsible for the ISRF is ~ 100 pc (see, e.g., Mathis et al. 1983). For a cloud located 100 pc above the Galactic plane, the geometry implies a $\sim 3:1$ ratio for radiation coming from lower and higher Galactic latitudes, respectively. If interstellar extinction is taken into account, the ratio gets smaller. However, the scale height of OB stars is much below 100 pc and the assumed ratio of 3:1 seems a wise approximation, at least for the UV part of the ISRF.

Tóth et al. (1995) calculated that the radiation energy density reaching LDN1780 from USco is $U_{\text{USco}} \approx 2.2 \times 10^{-15} \text{ erg cm}^{-3}$ integrated in the UV (912–1300 Å). This additional component is of the same order of magnitude as the ISRF calculated using the model by Mathis et al. (1983), defined above. Therefore, when the effect of the OB association is included, the total radiation incident on LDN1780 is about twice the normal value of the ISRF. The OB association is in the direction of the Galactic

Fig. 2. Differences between the observed surface brightnesses and model predictions at $25\,\mu\text{m}$, $60\,\mu\text{m}$, $100\,\mu\text{m}$, and $200\,\mu\text{m}$. In the $200\,\mu\text{m}$ maps, the contours of the $200\,\mu\text{m}$ emission are also shown. The results are shown for models A, E, G, and H. The plots corresponds to the size of the model, which is equal to the area, $38' \times 38'$, that is covered by the ISOPHOT observations (Fig. 1b, excluding the black borders).

plane, at an angle of about 15 degrees relative to the Galactic meridian (Tóth et al. 1995). The radiation, coming from a narrow solid angle, could affect the location of the IR emission maxima at different wavelengths. Section 4.2 contains the tests where the effect of the OB association of USco is estimated.

4. Results

We studied eight models listed in Table 1. In Sect. 4.1 we calculate a baseline model by assuming the Mathis et al. (1983) ISRF model and the LD dust model. In the following section (Sect. 4.2), we investigate the effects of the external radiation field by scaling its intensity, by introducing an extinction layer around the cloud, and by estimating the potential effect of the USco group. Finally, in Sect. 4.3 we consider what changes in dust properties are needed to fit all observations from $12\,\mu\text{m}$ to $200\,\mu\text{m}$.

4.1. The basic model

We start by studying a model where dust properties follow the LD dust model, and the intensity of the radiation field is set according to Mathis et al. (1983). This is our model A (see

Table 1). Although the total ISRF strength is assumed to be normal, its distribution is anisotropic as described in Sect. 3.3. We fit the model to the ISO $200\,\mu\text{m}$ data, updating the column density N according to the ratio of modelled and observed surface brightness. After each change in the column density, the radiative transfer calculations are repeated. The iterative fitting procedure is continued until the remaining errors at $200\,\mu\text{m}$ become less than $0.2\,\text{MJy sr}^{-1}$.

Figure 2 (first row) shows the differences, at different wavelengths, $I_{\text{OBS}} - I_{\text{MOD}}$, between the observed surface brightness and the predictions of model A. Because column density is adjusted according to $200\,\mu\text{m}$ data and for each map pixel separately, one may expect that the $200\,\mu\text{m}$ fit residuals can be reduced to zero. This is still not necessarily the case. For example, if the intensity of the radiation field is severely underestimated, the model might not be able to produce sufficient surface brightness. However, a good fit is obtained for model A. At $200\,\mu\text{m}$, the errors are below $0.1\,\text{MJy/sr}$, which is better than the observational accuracy and small compared to the absolute surface brightness that, after background subtraction, goes up to $\sim 50\,\text{MJy/sr}$.

At other wavelengths, the deviations from the observed surface brightness are significant. In the densest part of the cloud

(i.e., at the location of the maximum optical extinction and maximum $200\mu\text{m}$ emission, see Paper I), the predicted $100\mu\text{m}$ intensities are up to $\sim 3\text{ MJy/sr}$ too high. This corresponds to $\sim 20\%$ of the observed signal. On the other hand, in the outer parts of the cloud, the predicted intensities are generally too low by $\sim 1\text{ MJy/sr}$ and the relative error rises to $\sim 30\%$. This error could be caused, at least partially, by an inaccuracy in the background subtraction, and a gradient in the $100\mu\text{m}$ map relative to the $200\mu\text{m}$ map. In the north, model A shows too much emission both at $25\mu\text{m}$ and $60\mu\text{m}$. On the other hand, towards east and southeast, in the tail of LDN1780, the observed surface brightness is higher than predicted by the model. At $25\mu\text{m}$, the surface brightness is only $\sim 40\%$ of the observed. At $60\mu\text{m}$, the discrepancy is smaller, some 15% at the centre of the map. The mass of the model cloud A is $15.3 M_{\odot}$, close to the estimate of $18 M_{\odot}$ given in Paper I.

4.2. Models with modified radiation field

Model A could not explain the different locations of the infrared emission peaks. Therefore, we investigate whether model predictions are affected by changes in the heating radiation field. In model B, the column densities are again adjusted according to the $200\mu\text{m}$ observations, but the scaling of the ISRF is added as another free parameter. The radiation field is adjusted so that the average ratio of the $100\mu\text{m}$ and $200\mu\text{m}$ intensities agrees with the observations. The comparison is limited to areas where the $200\mu\text{m}$ surface brightness is above 10 MJy sr^{-1} (~ 960 square arcmin; see Fig. 1b). This eliminates areas of low signal-to-noise (S/N) and decreases the sensitivity to possible errors in the sky background subtraction. Within this area, the average ratio between $100\mu\text{m}$ and $200\mu\text{m}$ intensities becomes equal to the observed value when the intensity of the ISRF is reduced to $\sim 77\%$ of its original value. The cloud mass is correspondingly increased to $20.6 M_{\odot}$.

While the previous models are illuminated directly by the full ISRF, the radiation reaching LDN1780 may be attenuated by diffuse dust layers around the cloud. The effect could differ from simple scaling of ISRF intensity because not only the level but also the radiation spectrum is affected. In models C and D, the ISRF is attenuated by an external dust layer of $A_V = 0.5^{\text{m}}$ or $A_V = 0.25^{\text{m}}$.

With $A_V = 0.5$ (model C), the $100\mu\text{m}$ emission is generally too low and, at the location of the emission peak, the error is $\sim 15\%$ (see Fig. B.1). Since the $100\mu\text{m}$ peak intensity in model A is too high by a similar amount, model D with $A_V = 0.25$ is also tested. In this case, the average level of the $100\mu\text{m}$ emission fits observations better and, at the location of the emission maximum, the $100\mu\text{m}$ error is only $\sim 5\%$. The cloud mass of model D is $21.3 M_{\odot}$.

In model E, the ISRF scaling is optimized like in the case of model B but using the extinction layer of $A_V = 0.25$ around the cloud. The best fit is obtained when the ISRF level is scaled by 1.01. Therefore, with the assumed amount of external extinction, the FIR data agree with the Mathis et al. (1983) ISRF estimates. The cloud mass, $21 M_{\odot}$, and the surface brightness maps are almost identical to those of model B (see Fig. B.1).

In models B and E, the ratio of $100\mu\text{m}$ and $200\mu\text{m}$ surface brightness is adjusted by scaling the radiation field. This clearly does not change the short wavelength emission in the LDN1780 tail. The asymmetric illumination provided by the USco OB association may be responsible for that. The exact strength of the radiation from USco is not accurately known (see Sect. 3.3). In model F, we set the total energy input from the OB association

Fig. 3. Comparison of intensity profiles of models F and A. Model F includes additional radiation coming from the direction of the Upper Scorpius OB association. The intensities correspond to the positions shown in Fig. 1. For plotting, the $100\mu\text{m}$ data have been multiplied by 2, $60\mu\text{m}$ data by 10, and $25\mu\text{m}$ data by 20. Reading from the top, the curves of model F are in the order $100\mu\text{m}$, $200\mu\text{m}$, $60\mu\text{m}$, and $25\mu\text{m}$. For the observations, we plot 10% error bars to illustrate the order of magnitude of the calibration uncertainty.

equal to that of the normal ISRF. The association is modelled as a distant point source and with the same spectrum as the ISRF. As shown in Fig. 3, the added radiation increases the $60\mu\text{m}$ and the $100\mu\text{m}$ emission far above the observed values. Nevertheless, the effect on the IR morphology is negligible and, for example, the location of the $25\mu\text{m}$ maximum is practically unchanged.

4.3. Models with modified dust properties

In the following, we do not include the OB association as an additional radiation source. It would not affect the location of mid-infrared maxima and, as shown by model F, its intensity must be small compared to the normal ISRF. On the other hand, we keep a thin external extinction layer corresponding to $A_V = 0.25^{\text{m}}$ even though this will reduce surface brightness especially at shorter wavelengths. It is clear that the small volume included in our models ($38'$ on the sky plane) must be surrounded by some diffuse material.

In model G, the silicate and the carbonaceous grains are divided into two components, small grains ($a \lesssim 5\text{ nm}$) and large grains ($a \gtrsim 5\text{ nm}$). The PAH dust component is left unmodified, leading to a total of five dust components. However, the abundances of large grains (silicate and carbonaceous) are not modified, and the same relative abundance is used for both small silicates and small carbon grains. This results in three free parameters. The column densities are adjusted according to the $200\mu\text{m}$ data, while the abundances of small grains are adjusted according to $60\mu\text{m}$ data and the abundances of PAHs according to $12\mu\text{m}$ data. Each dust component contributes to emission over a wide range of wavelengths. Nevertheless, each of these wavelengths is primarily affected by a single dust component and, with this simple update scheme, the iterative fitting procedure quickly converges to one solution.

The results of model G are shown in Figs. 2 and 4. The overall errors are smaller than in previous cases (models A–E). The

Fig. 4. Intensity profiles of the cloud in the modified-dust model G, compared to the results of model A, and the observations. The intensities correspond to the positions shown in Fig. 1. For plotting, the $100\,\mu\text{m}$ data have been multiplied by 2, $60\,\mu\text{m}$ data by 10, and $25\,\mu\text{m}$ data by 20.

Fig. 6. Intensity profiles of the cloud in the modified-dust model H, compared to observations and the results of model A. The values at 25, 60, and $100\,\mu\text{m}$ have been multiplied with 20, 10, and 2, respectively.

Fig. 5. Spatial distributions of the abundances of the dust components of model G: PAHs, small grains, and large grains. The abundances are given relative to the abundance of large grains, which is normalized to one. Regions of low column density have been masked. The field of view of the maps is the same as in Fig. 2. The contours correspond to the $200\,\mu\text{m}$ surface brightness (see Fig. 1b).

$100\,\mu\text{m}$ emission is overestimated at the location of the column density maximum and further in the LDN1780 tail. The $100\,\mu\text{m}$ surface brightness is underestimated over most of the remaining area. At the centre of the map, the difference is below $2\,\text{MJy sr}^{-1}$, i.e., less than $\sim 10\%$ of the $100\,\mu\text{m}$ maximum value. The relative error has its maximum in the west, along the edge of the cloud. As shown in Fig. 4, the fit to $25\,\mu\text{m}$ and $60\,\mu\text{m}$ observations has improved with respect to the previous models. At $25\,\mu\text{m}$, the predicted intensities are too high but the error is only $\sim 10\%$ over most of the area. At $60\,\mu\text{m}$, the errors are mostly below 10% . Because the abundances of PAHs are also free parameters, the errors are negligible at $12\,\mu\text{m}$. The spatial distributions of the three dust components are shown in Fig. 5. Because the column density was a separate free parameter, it is possible to show only relative abundances. In Fig. 5, these are shown relative to the large grain component, which, of course, itself might also have significant abundance variations. Small grains are abundant everywhere in the LDN1780 tail, east of the column density maximum, i.e., east of the area of the $200\,\mu\text{m}$ maximum emission. To produce the observed $60\,\mu\text{m}$ surface brightness, the abundance is increased by one order of magnitude. The PAH abundance peaks further in the tail and more towards the south. The displacement

towards the south might also indicate of a stronger radiation field in that direction, which, in the model, is compensated by a larger PAH abundance.

By merely separating the small and the large grain components, the $100\,\mu\text{m}$ emission in the cold core of LDN1780 can still not be reproduced. In model H, we introduce an additional large-grain component (consisting of both silicates and graphite grains) that has an increased FIR emissivity. In this component, the original emission cross sections of the LD model have been multiplied by $(\lambda/100\,\mu\text{m})^{1.0}$ for wavelengths longer than $100\,\mu\text{m}$. The modification corresponds to the models of Ossenkopf & Henning (1994), where the FIR/sub-millimetre dust opacity has increased 4–5 times relative to dust in the diffuse ISM because of coagulation and the presence of dirty ice on the grains. Model H includes a total of seven grain components: PAHs, very small silicate grains, very small carbonaceous grains, large silicate grains, large carbonaceous grains, and large silicate and carbonaceous grains with increased emissivity. In the fit, there are only four free parameters: PAH abundance, small grain abundance, the abundance of large grains with increased emissivity, and the cloud column density. Although the abundance of large grains is not directly changed, the column density is again fitted according to the $200\,\mu\text{m}$ surface brightness. Therefore, the errors at $200\,\mu\text{m}$ should be zero, while some residuals can be expected at the other wavelengths. The PAH abundance is again updated according to the $12\,\mu\text{m}$ values and the abundance of small grains according to $60\,\mu\text{m}$ values. The abundance of large grains with increased emissivity is updated by comparing the modelled ratio of $200\,\mu\text{m}$ and $100\,\mu\text{m}$ surface brightness with the observed ratio.

Figure 2 shows that the quality of the fit is for model H mostly similar to that of model G. The only noticeable difference is that, while model G overestimates the $100\,\mu\text{m}$ intensity by up to $\sim 1\,\text{MJy sr}^{-1}$ west of the density maximum, the error is now close to zero. The overall quality of the fit is satisfactory and much of remaining deviations can be attributed to systematic errors and uncertainty in the background subtraction. Figure 7 shows the relative abundances of the dust components. The grains with increased emissivity are concentrated

Fig. 7. Spatial distributions of the abundances of the different dust components of model H: PAHs, small grains, large grains, and large grains with increased emissivity. The large grains are used as a reference for the plotted relative abundances. Regions of low column density have been masked. The field of view of the maps is the same as in Fig. 2. The contours correspond to the $200\,\mu\text{m}$ surface brightness (see Fig. 1b).

in the region of high density on the western edge of the cloud. There is also an excess of these grains in the tail, but that is less significant because of the lower surface brightness of that region. The PAHs and the VSGs are, respectively, concentrated to the regions of the IRAS $12\,\mu\text{m}$ and $60\,\mu\text{m}$ emission maxima. High PAH abundance is also seen at the southern edge of the cloud.

Table 1 shows that the A_V values given by the models are higher than those calculated using the 2MASS data for LDN1780 (see Paper I). The difference between the 2MASS and the model A_V values are greatest in the densest part of the cloud. When A_V drops to $\sim 3^{\text{m}}$, the difference is reduced to $\sim 50\%$. The 2MASS values might be biased towards lower values, if the column density increases rapidly in a region that is small compared to the resolution of the extinction map. The difference between the A_V values could mean that the true large grain emissivity is higher than employed in the model; however, the difference could also be reduced by increasing the radiation field.

5. Discussion

Our first model A assumed normal ISRF and dust properties. The column densities were adjusted according to the observed surface brightness at a single wavelength. This way, one observed map can be fit perfectly while significant residuals remain at other wavelengths. The main advantage of such simple models is that they highlight the differences between observations and the naïve model. This helps to visualize the second-order effects that can be associated with subtle variations in the properties of dust and radiation field. In general, such simple models may already be sufficient to reveal and to quantify such effects or, at least, they will serve as a starting point for more complete modelling.

The results for model B (Sect. 4.1) show that the high $200/100\,\mu\text{m}$ surface brightness ratio in the centre of LDN1780 cannot be produced simply by treating the intensity of the local ISRF and column density as free parameters. Model E (Sect. 4.2) shows that, although the results are improved compared to

previous models, the assumption of additional extinction around LDN1780 does not help in explaining the strong long wavelength emission in the core of the cloud. Furthermore, models A–F show that the observed differences in the locations of emission maxima cannot be explained by a homogeneous distribution of dust. Neither an extra layer of dust around the cloud, variations in the intensity of the local ISRF, nor increased radiation from the direction of the OB association changes this conclusion.

The differences in the emission maxima at $12\,\mu\text{m}$, $60\,\mu\text{m}$, and $100\text{--}200\,\mu\text{m}$ can only be explained by resorting to a dust model, where the small and large grain populations are concentrated in different parts of the cloud (model G in Sect. 4.4). The abundance of PAHs must peak on the eastern side, in the less dense part of the cloud, and the large grains are concentrated in the dense core of LDN1780. The $60\,\mu\text{m}$ emission and, consequently, the abundance of VSGs peaks in between in the central part of the mapped area.

Although the ISOPHOT photometric observations at $7.3\,\mu\text{m}$, $7.7\,\mu\text{m}$, $10\,\mu\text{m}$, $11.3\,\mu\text{m}$, and $12\,\mu\text{m}$, presented in Appendix A, do not have high enough quality to allow a detailed feature-to-feature comparison with the models, they all show their maxima at the locations of the IRAS $12\,\mu\text{m}$ maximum emission and the maximum abundance of the PAHs in models G and H. The results of model G confirm that the observed separate emission maxima result from true variations in the abundances of populations of dust grains of different sizes in LDN1780.

However, even with the ratio of small and large grains as a free parameter, as we had in model G, the $100\,\mu\text{m}$ and $200\,\mu\text{m}$ emission in the densest part of LDN1780 was not perfectly reproduced. The data could be better fit only with model H, where about 30% of the large dust grains have the high emissivity that corresponds to calculations of Ossenkopf & Henning (1994, Fig. 13).

The improved $100\,\mu\text{m}$ fit of model H, seen in Fig. 2, is directly related to the addition of large grains with high emissivity. At $200\,\mu\text{m}$, the emissivity of the new dust component is twice as high as in the LD model. In Fig. 7, the abundance of the new component rises up to 30%. Therefore, in the centre of LDN1780, the $200\,\mu\text{m}$ emissivity is effectively higher by $\sim 30\%$.

In model H, as in model G, the abundance of the large grains is highest in the centre of the cloud, and the distributions of the PAHs and the VSGs peak at the observed IRAS $12\text{--}25\,\mu\text{m}$ and $60\,\mu\text{m}$ emission maxima, respectively. The model predicts hardly any PAHs and VSGs in the dense core of the cometary-shaped cloud. This is in accordance with the ISOPHOT photometric data presented on Appendix A, which shows that at the wavelengths between $7.3\,\mu\text{m}$ and $20\,\mu\text{m}$, there is little emission in the area of the ISO $100\,\mu\text{m}$ emission maximum (see Fig. A.1). This effect can be explained by the depletion of the smaller grains in the coagulation process.

The results of model H agree with our findings in Paper I, which concluded that the FIR emissivity of large grains has increased in the cold core of LDN1780, i.e., in the region of $200\,\mu\text{m}$ maximum emission and maximum visual extinction. A similar conclusion was reached by del Burgo & Cambrs (2006) who, after separating the cloud emission into a warm and a cold component, could observe a small enhancement in the emissivity of the cold component. This effect is expected in the presence of grain coagulation or ice-coated grains (see Cambrs et al. 2001, and references therein). Such effects have been observed by Stepnik et al. (2003) in a Taurus filament, which, like LDN1780, also has the maximum visual extinction of about 4 mag. Del Burgo & Laureijs (2005) found emissivities of large grains increased a few times in another Taurus cloud,

Table 2. The parameters of the individual ISOPHOT PHT-P observations.

Detector	Filter	λ_{ref} (μm)	λ_{c} (μm)	$\Delta\lambda$ (μm)	TDT number	Number of pointings	Absolute accuracy (%)	Filter-to-filter accuracy (%)	Mean error (in PIA) (M Jy sr^{-1})
P1	P7.3	7.3	7.41	3.38	43100201	2×13	40	<20	6.18
P1	P7.7	7.7	7.66	0.82	43100211	2×13	40	<20	3.59
P1	P10	10.0	10.00	1.80	43100202	2×13	40	<20	4.73
P1	P11.3	11.3	11.36	0.81	43100203	2×13	40	<20	9.00
P1	P11.5	12.0	11.88	6.53	43100204	2×13	40	<20	0.46
P2	P20	20.0	21.03	9.03	43100205	2×13	<15	5	0.54

Notes. λ_{ref} , λ_{c} , and $\Delta\lambda$ are the reference wavelength, the central wavelength, the width of the PHT filter, respectively.

Fig. 8. Surface brightness profiles from model H after the external illumination was increased by 50%. The observed profiles are also shown. The values at 25, 60, and 100 μm have been multiplied with 20, 10, and 2, respectively.

TMC-2. However, Nutter et al. (2008), who modelled a filament in TMC-1, argue that no increased emissivity is needed to explain the observations in that cloud but, instead, a model with a layer of extinction corresponding to $A_V = 0.39$ was able to explain the observations.

Our modelling did not provide any strong constraints on the strength of the external radiation field. If the field is assumed to be too weak, the observed surface brightness cannot be reproduced even with very high column densities. The high abundances obtained for the PAH and VSG components indicate that, in the case of LDN1780, the ISRF by Mathis et al. (1983) is close to the lower limit of possible values. A strict upper limit is more difficult to derive. We recalculated model H after increasing the external heating by either 50% or 100%. With a 50% increase, the quality of the fit was marginally improved (Fig. 8). At the same time, the peak abundances of PAHs and VSGs were reduced by one third, while the abundance of large grains with higher emissivity was increased by a factor of four. With a 100% increase in the radiation field, the relative abundances of PAHs and VSGs, relative to the *sum* of the large grain components, is still lower. In the tail of the cloud, the abundance ratio is ~ 4 times the corresponding value in the Li & Draine (2001) model. However, there is a clear gradient so that, on the NW side of the tail, the ratio is below 2 but increases to ~ 5 in the SE. In contrast,

the relative VSG abundance peaks in the middle of the tail where it reaches a value of ~ 6 . In the core of LDN1780, the PAH abundance (still relative to the sum of the large grain components) is close to the Li & Draine value, while the VSG abundance is reduced almost to zero. Clearly, the estimates of relative grain abundances are sensitive to the intensity of the radiation field, which could not be constrained further within the limitations of this model.

6. Conclusions

Results of 3D radiative transfer modelling of LDN1780 have been presented. Eight cases were studied to find a model that correctly produces the ISOPHOT observations presented in Paper I. We tested the effects of variations in the local interstellar radiation field, the presence of a thin extinction layer around the cloud, and modifications in the dust model of Li & Draine (2001). The results of the modelling lead to the following conclusions.

- Neither the variations of the local radiation field nor a thin layer of diffuse dust around the cloud are sufficient to explain the observed FIR emission of LDN1780.
- Modifications in the properties of the big grains in the standard diffuse dust model are needed to explain the far-infrared emission from the cloud core and the ratio of MIR and FIR intensities elsewhere in the cloud.
- The relative abundances of the dust components were found to be very sensitive to the strength of the external radiation field, which still remains poorly constrained.
- The best fit was obtained by using seven different dust components: PAHs; silicate and carbonaceous very small grains; silicate and carbonaceous large grains; and large grains with increased long wavelength emissivity. In this model, 30% of the large grains in the centre of LDN1780 have their far-infrared emissivities increased corresponding to the values given by Ossenkopf & Henning (1994).
- In our model, the PAHs and the VSGs are concentrated in the regions of maximum 12 μm and 60 μm emission of LDN1780, respectively. The ISOPHOT observations at 7.3–20 μm show maxima at the location of the maximum concentration of PAHs.
- We conclude that the separate emission maxima at different wavelengths in LDN1780 results from true and significant variation in the distribution of dust grains of different sizes and compositions.

Acknowledgements. We wish to thank the anonymous referee for his/her comments. The work of M.R. has been supported by the Finnish Academy of Science and Letters (Foundation of Vilho, Yrjö and Kalle Väisälä), the Magnus Ehrnrooth Foundation, and the Finnish Graduate School in Astronomy and Space Physics, which are gratefully acknowledged. We acknowledge the support from the Academy of Finland through grants Nos. 124620, 115056, and 105623.

References

- Bernard, J. P., Boulanger, F., Désert, F. X., & Puget, J. L. 1992, *A&A*, 263, 258
 Bernard, J. P., Boulanger, F., & Puget, J. L. 1993, *A&A*, 277, 609
 Boulanger, F., Baud, B., & van Albada, G. D. 1985, *A&A*, 144, L9
 del Burgo, C., & Laureijs, R. J. 2005, *MNRAS*, 366, 901
 del Burgo, C., & Cambrésy, L. 2006, *MNRAS*, 368, 1463
 del Burgo, C., Laureijs, R. J., Ábrahám, P., & Kiss, Cs. 2003, *MNRAS*, 346, 403
 Cambrésy, L., Boulanger, F., Lagache, G., & Stepnik, B. 2001, *A&A*, 375, 999
 Chlewicki, G., & Laureijs, R. J. 1987, in *Proc. of the NATO Advanced Research and CNRS Workshop, NATO ASI Series 191*, ed. A. Leger, L. D. Hendecourt, & N. Boccara (Dordrecht: D. Reidel Publ. Co.), 335
 Désert, F.-X., Boulanger, F., & Puget, J. L. 1990, *A&A*, 237, 215
 Dwek, E., Arendt, R. G., Fixsen, D. J., et al. 1997, *ApJ*, 475, 565
 Gabriel, C., Acosta-Pulido, J., Heinrichsen, I., et al. 1997, in *Proc. of the ADASS VI Conf.*, ed. G. Hunt, & H. E. Payne, *ASP Conf. Ser.*, 125, 108
 de Geus, E. J., de Zeeuw, P. T., & Lub, J. 1989, *A&A*, 216, 44
 Draine, B. T., & Lee, H. M. 1984, *ApJ*, 285, 89
 Draine, B. T., & Li, A. 2001, *ApJ*, 551, 807
 Draine, B. T., & Li, A. 2007, *ApJ*, 657, 810
 Juvela, M., & Padoan, P. 2003, *A&A*, 397, 201
 Juvela, M. 2005 *A&A*, 440, 531
 Kessler, M. F., Steinz, J. A., & Anderegg, M. E. 1996, *A&A*, 315, L27
 Kramer, C., Richer, J., Mookerjee, B., et al. 2003, *A&A*, 399, 1073
 Lemke, D., Klaas, U., Abolins, J., et al. 1996, *A&A*, 315, L64
 Li, A., & Draine, B. T. 2001, *ApJ*, 554, 778
 Lopez, B., Mékarnia, D., & Léfevre, J. 1995, *A&A*, 296, 752
 Mathis, J. S., Rimpl, W., & Nordsieck, K. H. 1977, *ApJ*, 217, 425
 Mathis, J. S., Metzger, P. G., & Panagia, N. 1983, *A&A*, 128, 212
 Nutter, D., Kirk, J. M., Stamatellos, D., & Ward-Thompson, D. 2008, *MNRAS*, 384, 755
 Ossenkopf, V., & Henning, T. 1994, *A&A*, 291, 943
 Rawlings, M. G., Juvela, M., Mattila, K., Lehtinen, K., & Lemke, D. 2005, *MNRAS*, 356, 810
 Ridderstad, M., Juvela, M., Lehtinen, K., Lemke, D., & Liljeström, T. 2006, *A&A*, 451, 961
 Siebenmorgen, R., & Krügel, E. 1992a, *A&A*, 259, 614
 Siebenmorgen, R., & Krügel, E. 1992b, *A&A*, 266, 501
 Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, *AJ*, 131, 1163
 Stepnik, B., Abergel, A., Bernard, J.-P., et al. 2003, *A&A*, 398, 551
 Tóth, L. V., Haikala, L. K., Liljeström, T., & Mattila, K. 1995, *A&A*, 295, 755
 Verter, F., Magnani, L., Dwek, E., & Rickard, L. J. 2000, *ApJ*, 536, 831
 Weiland, J. L., Blitz, L., Dwek, E., et al. 1986, *ApJ*, 306, L101
 Witt, A. N. 2000, in *Astrochemistry: From Molecular Clouds to Planetary Systems*, ed. Y. C. Minh, & E. F. van Dishoeck, *Proc. IAU Symp.*, 197, 317
 Zubko, V., Dwek, E., & Arendt, R. G. 2004, *ApJS*, 152, 211

Appendix A: New ISOPHOT observations at 7.3–20 μm

We present additional photometric observations at the wavelengths 7.3 μm , 7.7 μm , 10 μm , 11.3 μm , 12 μm , and 20 μm . The observations were made with the ISOPHOT instrument aboard ISO, using the PHT03 detector (Lemke et al. 1996). The sky positions of the photometric measurements are the same as for the raster scan measurements shown in Fig. 1. The data reduction was performed using PIA (ISOPHOT Interactive Analysis) V10.0 (Gabriel et al. 1997). The data reduction steps have been explained in Paper I. The details for the observations are listed in Table 2.

Most of the PHT03 measurements showed detector response drifts, especially in the beginning of an observing sequence. We modelled and subtracted the drift assuming it follows an

Fig. A.1. The ISOPHOT photometric observations of LDN1780 at 7.3 μm , 7.7 μm , 10 μm , 11.3 μm , 12 μm , and 20 μm . A linear baseline was fitted to the measurements indicated with squares. The observation points are those marked with crosses in Fig. 1, running from west to east and back.

exponential drift curve. Finally, we fitted a linear baseline to the measurements indicated with squares in Fig. A.1. The figure shows the PHT observations after these corrections. The intensities from the narrow bandpass P11.3 filter are higher than those from the much wider P11.5 filter. This suggests that the main contribution in the P11.5 filter, which corresponds to the IRAS 12 μm filter, comes from the most prominent feature in this wavelength region, the 11.3 μm emission peak, which is generally attributed to PAHs.

Appendix B: Surface brightness maps of the models

In Sect. 4 maps of surface brightness error were shown for models A, E, G, and H. For completeness, the error maps for the remaining models B, C, D, and F are shown here.

Fig. B.1. Surface brightness error, $I_{\text{OBS}} - I_{\text{MOD}}$, for models B, C, D, and F. The plots correspond to the mapped area shown in Fig. 1b (excluding the black borders).