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Letter to the Editor

Dust emissivity in the far-infrared

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Abstract. We have derived the dust emissivity in the Far-Infrared (FIR) using data available in the literature. We use two wavelength dependences derived from spectra of Galactic FIR emission (Reach et al. 1995). A value for the emissivity, normalised to the extinction efficiency in the V band, has been retrieved from maps of Galactic FIR emission, dust temperature and extinction (Schlegel et al. 1998).

Our results are similar to other measurements in the Galaxy but only marginally consistent with the widely quoted values of Hildebrand (1983) derived on one reflection nebula. The discrepancy with measurements on other reflection nebulae (Casey 1991) is higher and suggests a different grain composition in these environments with respect to the diffuse interstellar medium.

We measure dust masses for a sample of six spiral galaxies with FIR observations and obtain gas-to-dust ratios close to the Galactic value.

Key words: ISM: dust, extinction – infrared: ISM: continuum – infrared: galaxies

1. Introduction

Assessing the quantity of dust in spiral galaxies is of primary importance in both understanding the intrinsic properties of galaxies themselves and interpreting observations of the distant universe: large quantities of dust can modify the optical appearance of galactic structures like spiral arms (Trewhella 1998); if the distribution of dust is extended, a large fraction of the radiation from the distant universe can be blocked (Ostriker & Heisler 1984); star formation as determined from UV fluxes could be severely underestimated thus altering our knowledge of the star formation history of the universe (Hughes et al. 1998).

Dust mass can be retrieved from extinction or from emission in the FIR. In the former case information about the star-dust relative geometry is needed and the method can only be applied to nearby edge-on galaxies, where the dust distribution can be inferred from extinction features (Xilouris et al. 1997, 1998). In the latter case there are no such limitations, and the wealth of data in the FIR and Sub-mm from instruments like the Sub-mm camera SCUBA and from the satellites ISO and COBE, can be used to measure dust mass. Unfortunately, the determination of dust mass is entangled with that of dust temperature and they both rely on knowledge of the dust emissivity (Hildebrand 1983), the form of which is currently highly uncertain.

The emissivity (or emission efficiency, i.e. the ratio between the emission cross section and the geometric cross section), $Q_{\rm em}(\lambda)$ is usually described by a function of the form

$$Q_{\rm em}(\lambda) = Q_{\rm em}(\lambda_0) \left(\frac{\lambda_0}{\lambda}\right)^{\beta} \qquad (1)$$

where $Q_{\rm em}(\lambda_0)$ is the value of the emissivity at the reference wavelength λ_0, and β is the wavelength dependence index.

While a value $\beta = 1$ seems to be plausible for $\lambda < 100\,\mu$m (Hildebrand 1983; Rowan-Robinson 1992), there is observational evidence for a steeper emissivity at longer wavelengths. The difference in emissivity is not unexpected, since emission in the Mid-Infrared (25–60 μm) is dominated by transiently heated grains, while at $\lambda > 100$ grains emit at thermal equilibrium (Whittet 1992). Sub-mm observations of spiral galaxies (Bianchi et al. 1998; Alton et al. 1998b) show that it is not possible to use an emissivity with $\beta = 1$ to fit the 450 and 850 μm emission. Reach et al. (1995) came to a similar conclusion. They used the spectrum of the Galactic plane observed by the spectrophotometer FIRAS on board the satellite COBE, to find that the data are well fitted by an emissivity:

$$Q_{\rm em}(\lambda) \propto \frac{\lambda^{-2}}{\left[1 + (\lambda_1/\lambda)^6\right]^{1/6}}, \qquad (2)$$

for the range 100 μm to 1 cm. Eq. (2) behaves like (1) with $\beta = 1$ at small λ ($\lambda \ll \lambda_1$) and $\beta = 2$ at large λ ($\lambda \gg \lambda_1$) (they set $\lambda_1 = 200$-μm).

Masi et al. (1995) measure a value $\beta = 1.54$ by fitting a single temperature grey-body spectrum to Galactic plane data in four bands between 0.5 and 2-mm taken by the balloon born telescope ARGO. Reach et al. (1995) suggest that a single temperature fit may bias towards lower values of β (see also Wright et al. 1991); over the whole FIRAS spectral range, a two temperature grey-body with $\beta = 2$ at large λ provides a significantly better fit than a single temperature spectrum with $\beta \approx 1.5$. At long

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wavelengths theoretical calculations for crystalline substances constrain β to be an even integer number (Wright 1993). For amorphous materials β depends on the temperature: Agladze et al. (1996) find $1.2 < \beta < 2$ for amorphous silicate grains at a temperature of 20 K.

A value for the emissivity at a specific wavelength $Q_{\rm em}(\lambda_0)$ normalised to the extinction efficiency in the optical can be determined by carrying out an energy balance in a reflection nebula, comparing the energy absorbed from the central star with the FIR output from the surrounding dust. Alternatively, the extinction measured toward the star can be directly compared to the optical depth in the FIR (Whitcomb et al. 1981; Hildebrand 1983; Casey 1991). These methods are complicated by the unknown nebular geometry and by temperature gradients in the dust; as an example, Casey (1991) found that the extinction method usually retrieves higher values than the energy balance.

In this paper we use the extinction method comparing the Galactic extinction to FIR emission: in this case the same column density of dust is responsible both for emission and extinction and a reliable result can be obtained.

2. The method

Schlegel et al. (1998; hereafter SFD) have presented a new map of Galactic extinction. After removing emission from zodiacal light and a cosmic infrared background, they have combined the 100 μm map of Galactic emission taken by the DIRBE experiment on board the COBE satellite with the 100 μm large-area ISSA map from satellite IRAS, to produce a map of Galactic emission with the quality calibration of DIRBE and the high resolution of IRAS. The dust temperature has been retrieved using the DIRBE maps at 100 μm and 240 μm assuming β=2. Knowing the temperature, the 100 μm map has been converted into a dust column density map and subsequently calibrated to E(B-V) using colours and Mg_2-index of elliptical galaxies. We would like to stress that the colour excess has been derived from the 100 μm emission without any assumption about the value of the emissivity at any wavelength. Moreover, the choice of β does not affect significantly their results: when β=1.5 is used, the dust column density map varies only of 1%, aside from an overall multiplicative factor that is taken account of when calibrating with the colour excess. We have accessed the electronic distribution of this remarkable dataset to retrieve the 9.5′/pixel maps of the intensity at 100 μm, I(100 μm), the temperature and the colour excess E(B-V) for the north and south Galactic hemispheres.

When the same dust grains are responsible for emission and extinction, the ratio between the extinction coefficient in the V-band and the emissivity at 100 μm is equivalent to the ratio of the optical depths

$$\frac{Q_{\rm ext}(V)}{Q_{\rm em}(100\,\mu{\rm m})} = \frac{\tau(V)}{\tau(100\,\mu{\rm m})}. \tag{3}$$

The above formula is correct if all of the dust grains are identical. In a mixture of grains of different sizes and materials, the ratio of emissivities in Eq. (3) can still be regarded as a mean value characteristic of diffuse galactic dust, if the dust composition is assumed to be the same on any line of sight.

The optical depth at 100 μm, in the optically thin case, is measured using

$$\tau(100\,\mu{\rm m}) = \frac{I(100\,\mu{\rm m})}{B(100\,\mu{\rm m}, T_{\rm d})}, \tag{4}$$

where $B(100\,\mu{\rm m}, T_{\rm d})$ is the value of the Planck function at 100 μm for a dust temperature $T_{\rm d}$, both the intensity $I(100\,\mu{\rm m})$ and $T_{\rm d}$ coming from the maps of SFD. The optical depth in the V-band can be found from the colour excess E(B-V) maps,

$$\tau(V) = \frac{A(V)}{1.086} = 2.85E(B-V), \tag{5}$$

where we have used a mean galactic value $A(V)/E(B-V)$=3.1 (Whittet 1992). Reach et al. (1995) suggest that dust emitting in the wavelength range 100–300 μm traces interstellar extinction. Since the FIR optical depth in Eq. (4) has been measured using data at 100 and 240 μm, it is then justified to compare it with extinction as in Eq. (5) to find the ratio of the extinction coefficient and emissivity. Knowing the optical depths from (4) and (5), we can compute a map of the ratio as in Eq. (3); we obtain a mean value of

$$\frac{Q_{\rm ext}(V)}{Q_{\rm em}(100\,\mu{\rm m})} = 760 \pm 60$$

for both hemispheres. This value is included, together with other multiplicative factors, in the calibration coefficient p as in Eq. (22) in SFD. As pointed out by the referee, an estimate for $Q_{\rm ext}(V)/Q_{\rm em}$ can be easily derived from that equation, if the DIRBE colour corrections factors, slowly depending on T, are omitted. Following this way we obtained a value of 765.5. SFD give an error of 8% for p and this is the value quoted here. Since most ($\approx$ 90%) of the elliptical galaxies used to calibrate colour excess maps have galactic latitude $b > 20^\circ$, one may argue that the measured value is characteristic only of high latitude dust.

Reach et al. (1995) find that the emissivity (Eq. 2) is best determined by fitting the FIRAS spectrum on the Galactic plane. They say that high latitude data have a smaller signal-to-noise ratio and can be fitted satisfactory with $\beta = 2$ (Eq. 1) although the same emissivity as on the plane cannot be excluded. Under the hypothesis that the same kind of dust is responsible for the diffuse emission in the whole Galaxy, we have corrected SFD temperatures using Reach et al. emissivity (Eq. 2). The new temperatures are a few degrees higher than those measured with $\beta = 2$ (as an example we pass from a mean value of 18 K in a 20° diameter regions around the north pole to a new estimate of 21 K). It is interesting to note that the difference between the two estimates of temperature is of the same order as the difference between the temperatures of warm dust at high and low Galactic latitude in Reach et al. (1995) and this may only be a result of the different emissivity used to retrieve the temperature.

When the correction is applied

$$\frac{Q_{\rm ext}(V)}{Q_{\rm em}(100\,\mu{\rm m})} = 2390 \pm 190.$$

The new ratio is about three times higher, and this is a reflection of the change of temperature in the black body emission in (4): for a higher temperature, a lower emissivity in the FIR is required to produce the same emission. Uncertainties in $Q_{\rm ext}(V)/Q_{\rm em}(\lambda_0)$ are thus greatly affected by assumptions about the emissivity spectral behaviour.

3. Comparison with other measurements

We now compare our emissivity for $\beta=2$ with literature results derived under the same hypothesis. Since no emissivity has been derived to our knowledge assuming Eq. (2), we do not attempt any comparison with that result. All the data are scaled to $\lambda_0 = 100\,\mu$m.

Studying the correlation between gas and dust emission from FIRAS and DIRBE, Boulanger et al. (1996) derived an emissivity $\tau/N_H = 1.0\cdot10^{-25}$ cm^2 at 250 μm for dust at high galactic latitude; assuming the canonical $N_H = 5.8{\cdot}10^{21} E(B-V)$ cm^{-2} mag^{-1} and $A(V)/E(B-V)$=3.1 (Whittet 1992), this is equivalent to $Q_{\rm ext}(V)/Q_{\rm em}(100\,\mu$m)=790. Quite similar values are found in the Draine & Lee (1984) dust model, which has a $\beta=2$ spectral dependence in this wavelength range. At 125 μm the optical depth is $\tau/N_H = 4.6{\cdot}10^{-25}$ cm^2 which corresponds to $Q_{\rm ext}(V)/Q_{\rm em}(100\,\mu$m)=680. Sodroski et al. (1997) finds a value for the ratio at 240 μm, using literature data identifying a correlation between B-band extinction and 100 μm IRAS surface brightness in high latitude clouds, assuming a dust temperature of 18 K. Converted to our notation, using a standard extinction law, the ratio is $Q_{\rm ext}(V)/Q_{\rm em}(100\,\mu$m)=990.

The measurement by Whitcomb et al. (1981) on the reflection nebula NGC 7023 is the most commonly quoted value for the emissivity (Hildebrand 1983). Their value derived at 125 μm for $\beta = 2$ is only marginally consistent with our result. Following our notation, their result is equivalent to $Q_{\rm ext}(V)/Q_{\rm em}(100\,\mu{\rm m}) = 220$ and 800[1], using the energy balance and the extinction method, respectively. The values obtained by Casey (1991) on a sample of five nebulae using the energy balance method are a factor of 3 smaller than ours (corresponding to $Q_{\rm ext}(V)/Q_{\rm em}(100\,\mu{\rm m}) = 80$–400).

In Fig. 1 we show the literature data (plotted at the wavelength they have been derived in the original papers) together with our derived emissivity laws. We have added the value for Draine & Lee (1984) model at 250 μm.

4. Gas-to-dust ratio of external spiral galaxies

We now exploit the FIR emissivity derived in this work by determining dust masses for nearby spiral galaxies. Following Hildebrand (1983) dust masses can be measured from FIR emission using

$$M_{\rm dust} = \frac{F(\lambda)D^2}{B(\lambda,T_{\rm d})}\cdot\frac{4a\rho}{3Q_{\rm em}(\lambda)}, \qquad (6)$$

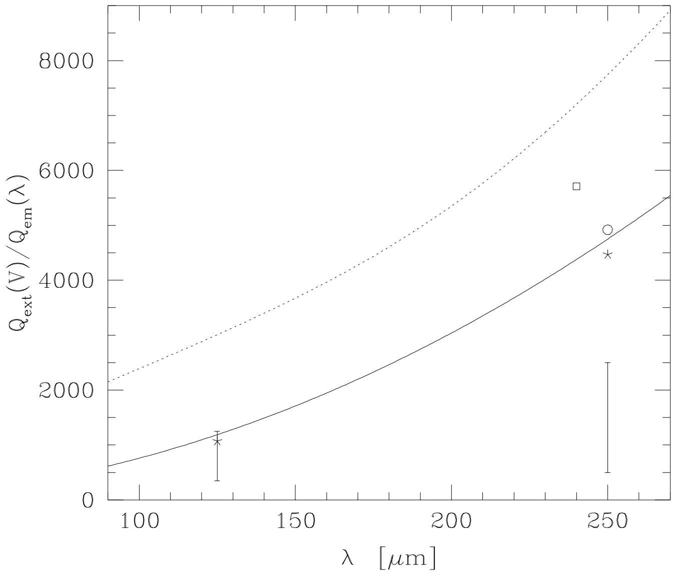

Fig. 1. FIR emissivity derived in this work: assuming β=2 (solid line) and the Reach et al. (1995) spectral dependence (dotted line). Error bars at 125 μm give the range of values of Whitcomb et al. (1981). The error bar at 250 μm gives the range of values of Casey (1991). Data points are from Draine & Lee (1984) model (stars), Sodroski et al. (1997) (square) and Boulanger et al. (1996) (circle).

Table 1. Sample of galaxies from Alton et al. (1998a). Gas masses have been derived from Devereux & Young (1990) (Van Driel et al. (1995) for NGC 660) and corrected to the distances quoted by Alton et al. (1998a). Dust temperature and gas-to-dust ratio are derived using Eq. (1) with β=2 ($Q_{\rm ext}(V)/Q_{\rm em}(100\,\mu$m)=760), and Eq. (2) ($Q_{\rm ext}(V)/Q_{\rm em}(100\,\mu$m)=2390). Values within brackets are derived under the hypothesis that ISO fluxes are overestimated by 30%.

Galaxy	Gas Mass	emissivity (1)		emissivity (2)	
	10^{10} M$_\odot$	T(K)	G/D ratio	T(K)	G/D ratio
NGC 628	1.1	16 (17)	90 (190)	18 (20)	100 (200)
NGC 660	0.91	19 (21)	110 (230)	23 (26)	120 (250)
NGC 5194	0.75	18 (20)	90 (180)	21 (24)	90 (190)
NGC 5236	3.5	19 (21)	240 (500)	22 (25)	255 (540)
NGC 6946	3.0	17 (19)	75 (150)	20 (22)	80 (160)
NGC 7331	1.0	17 (19)	70 (145)	20 (22)	70 (155)

where $F(\lambda)$ is the total flux at the wavelength λ, D the distance of the object, $B(\lambda,T_{\rm d})$ the Planck function, a the grain radius (0.1 μm) and ρ the grain mass density (3 g cm^{-3}). The emissivity $Q_{\rm em}(\lambda)$ is derived from the ratio $Q_{\rm ext}(V)/Q_{\rm em}(\lambda)$ assuming $Q_{\rm ext}(V)$=1.5 (Casey 1991; Whittet 1992).

Alton et al. (1998a) provide total fluxes at 100 μm and 200 μm from IRAS and ISO for a sample of spiral galaxies. We have derived dust temperatures and masses using $Q_{\rm ext}(V)/Q_{\rm em}(100\,\mu$m)=760 and 2390, for β=2 and Reach et al. (1995) emissivities, respectively. Using literature values for gas masses, we have computed the gas-to-dust ratios. Values of gas masses, temperatures and gas-to-dust ratios are presented in Table 1.

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[1] Whitcomb et al. (1981) and Casey (1991) originally presented values for $Q_{\rm ext}(UV)/Q_{\rm em}(FIR)$: we have corrected to $Q_{\rm ext}(V)/Q_{\rm em}(FIR)$ using the provided $\tau(UV) = 2\tau(V)$.

The mean value of the gas-to dust ratio for the sample is 100 using Eq. (1), 110 using Eq. (2). Mean temperatures go from 18 K with the $\beta = 2$ emissivity to 21 K when the Reach et al. (1995) behaviour is assumed (as for the north galactic pole in Sect. 2). Alton et al. (1998a) pointed out that ISO 200 μm fluxes could be overestimated by about 30%; correcting for this we obtain a mean gas-to-dust ratio of 220–240 (for β=2 and Reach et al. (1995) emissivity, respectively). As shown above, dust masses obtained with the two methods are quite similar. This can be explained substituting Eqs. (3) and (4) into (6). For $\lambda = 100\,\mu$m we can derive

$$M_{\rm dust} \sim \frac{B(100\,\mu{\rm m}, T_{\rm d}^{\rm G})}{B(100\,\mu{\rm m}, T_{\rm d})},$$

where $T_{\rm d}^{\rm G}$ is the mean temperature of dust in the Galaxy. From the equation it is clear that the dust mass determination is insensitive to the emissivity law used, as long as the dust temperature in external galaxies and in our own are similar.

Our range of values for the gas-to-dust ratio (100–230) encompasses the Galactic value of 160 (Sodroski et al. 1994). As a comparison, the mid-value of Whitcomb et al. (1981) would have given dust-to-gas ratios larger by a factor 1.5.

5. Conclusion

We have derived the dust emissivity $Q_{\rm em}$ in the FIR using the wavelength dependence derived from the FIR Galactic spectrum (Reach et al. 1995). The emissivity has been normalised to the extinction efficiency in the V band using dust column density maps calibrated to Galactic extinction (SFD). $Q_{\rm em}$ depends strongly on the assumed wavelength dependence. For a $\beta = 2$ emissivity index we obtained

$$Q_{\rm em}(\lambda) = \frac{Q_{\rm ext}(V)}{760}\left(\frac{100\,\mu{\rm m}}{\lambda}\right)^2.$$

This result is consistent with other values derived from FIR Galactic emission (Boulanger et al. 1996; Sodroski et al. 1997) and with the Draine & Lee (1984) dust model. The widely quoted emissivities of Whitcomb et al. (1981; Hildebrand 1983) derived from the reflection nebula NGC 7023 are only marginally consistent with our values, while the emissivity measured by Casey (1991) on a sample of five nebulae are smaller by a factor of 3. This may suggest a different grain composition for dust in the diffuse inter-stellar medium compared to reflection nebulae.

When the wavelength dependence derived by Reach et al. (1995) on the Galactic plane is used, we obtain

$$Q_{\rm em}(\lambda) = \frac{Q_{\rm ext}(V)}{2390}\left(\frac{100\,\mu{\rm m}}{\lambda}\right)^2 \frac{2.005}{\left[1+(200\,\mu{\rm m}/\lambda)^6\right]^{1/6}}.$$

We have used the derived emissivities to measure dust masses from 100 μm and 200 μm fluxes of a sample of six spiral galaxies (Alton et al. 1998a). We have retrieved similar dust masses with both the spectral dependences. The gas-to dust ratios of our sample (100–230) are close to the Galactic value of 160 (Sodroski et al. 1994).

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References

Agladze N. I., Sievers A. J., Jones S. A., Burlitch J. M., Beckwith S. V. W., 1996, ApJ 462, 1026

Alton P. B. et al., 1998a, A&A 335, 807

Alton P. B., Bianchi S., Rand R. J., Xilouris E. M., Davies J. I., Trewhella M., 1998b, ApJ 507, L125

Bianchi S., Alton P. B., Davies J. I., Trewhella M., 1998, MNRAS 298, L49

Boulanger F., Abergel A., Bernard J.-P., Burton W., Desert F.-X., Hartmann D., Lagache G., Puget J.-L., 1996, A&A 312, 256

Casey S. C., 1991, ApJ 371, 183

Devereux N. A., Young J. S., 1990, ApJ 359, 42

Draine B. T., Lee H. M., 1984, ApJ 285, 89

Hildebrand R. H., 1983, QJRAS 24, 267

Hughes D. H. et al., 1998. In: The Birth of Galaxies (in press) astro-ph/9810273

Masi S. et al., 1995, ApJ 452, 253

Ostriker J. P., Heisler J., 1984, ApJ 278, 1

Reach W. T. et al., 1995, ApJ 451, 188

Rowan-Robinson M., 1992, MNRAS 258, 787

Schlegel D. J., Finkbeiner D. P., Davis M., 1998, ApJ 500, 525 (SFD)

Sodroski T. J. et al., 1994, ApJ 428, 638

Sodroski T. J., Odegard N., Arendt R. G., Dwek E., Weiland J. L., Hauser M. G., Kelsall T., 1997, ApJ 480, 173

Trewhella M., 1998, MNRAS 297, 807

Van Driel W. et al., 1995, AJ 109, 942

Whitcomb S. E., Gatley I., Hildebrand R. H., Keene J., Sellgren K., Werner M. W., 1981, ApJ 246, 416

Whittet D. C. B., 1992, Dust in the Galactic Environment, Institute of Physics Publishing, Bristol

Wright E. L., 1993. In: Holt S. S., Verter F. (eds.) Back to the Galaxy. AIP, New York, p. 193

Wright E. L. et al., 1991, ApJ 381, 200

Xilouris E. M., Kylafis N. D., Papamastorakis J., Paleologou E. V., Haerendel G., 1997, A&A 325, 135

Xilouris E. M., Alton P. B., Davies J. I., Kylafis N. D., Papamastorakis J., Trewhella M., 1998, A&A 331, 894