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The percentage of stellar light re-radiated by dust in late-type Virgo Cluster galaxies

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ABSTRACT

We show that the mean percentage of stellar light re-radiated by dust is ∼30 per cent for the Virgo Cluster late-spirals measured with ISOPHOT by Tuffs et al. A strong dependence of this ratio with morphological type was found, ranging from typical values of ∼15 per cent for early spirals to up to ∼50 per cent for some late spirals. The extreme BCDs can have even higher percentages of their bolometric output re-radiated in the thermal infrared. Luminosity correction factors for the cold dust component are given for general use in converting far-infrared (FIR) luminosities derived from *IRAS*.

Key words: galaxies: clusters: individual: Virgo Cluster – galaxies: fundamental parameters – galaxies: photometry – galaxies: spiral – galaxies: statistics – infrared: galaxies.

1 INTRODUCTION

Star-forming galaxies contain dust which absorbs some fraction of the emitted starlight, primarily re-radiating it in the far-infrared (FIR). This not only applies to starburst and ultraluminous systems, which radiate almost all their power in the FIR, but also to so-called 'normal' galaxies – systems which are not dominated by AGN and not undergoing a starburst. Though less spectacular than starburst galaxies, normal galaxies still account for most of the infrared emissivity of the local Universe. Their role in the distant Universe is observationally a completely open question.

Recent observations with the ISOPHOT instrument (Lemke et al. 1996) on board the *Infrared Space Observatory* (*ISO*; Kessler et al. 1996), covering the spectral peak of the dust emission between 100 and 200 μm, have shown that a significant contribution to the FIR luminosity of normal galaxies is actually radiated by grains too cold to be visible to *IRAS*. Statistical evidence for the existence of a cold dust component was established in our study (Popescu et al. 2002) of the spatially integrated FIR emissions of a complete volume and luminosity sample of 63 gas-rich Virgo Cluster galaxies measured with ISOPHOT at 60, 100 and 170 μm (Tuffs et al. 2002).[1] These observations represent the deepest survey (both in luminosity and surface brightness terms) of normal galaxies yet measured in the FIR. In particular, these data showed that the cold dust component is present in all galaxies later than S0, i.e. spiral, irregular and blue compact dwarf (BCD) galaxies.

In this letter, these new results are used to evaluate the fraction of starlight emitted in normal galaxies which is re-radiated in the FIR, the first such measurement for these systems. Previous estimates based on the *IRAS* Bright Galaxy Sample (BGS; Soifer & Neugebauer 1991) have established a canonical value of 30 per cent for the fraction of starlight to be re-radiated in the FIR in the local Universe. However, this value refers to relatively bright FIR sources in which the bulk of the dust emission is radiated in the *IRAS* 60- and 100-μm bands, and is not representative of quiescent systems like the Virgo galaxies. In addition it takes no account of measurements longwards of 120 μm, not available at that time. The percentage of stellar light re-radiated by dust was investigated by Xu & Buat (1995), using an indirect estimate for the total FIR luminosity. Here we calculate this percentage by using for the first time measurements of the bulk of the dust emission in quiescent normal galaxies.

Before evaluating the percentage of stellar light re-radiated by dust (Section 4) we describe our derivation of the total bolometric output in the ultraviolet (UV)/optical/near-infrared (NIR) in Section 3 and determine in Section 2 luminosity correction factors for the cold dust, for general use in converting *IRAS* luminosities into total FIR luminosities.

2 LUMINOSITY CORRECTION FACTORS FOR THE COLD DUST

As shown by Popescu et al. (2002) the FIR spectral energy distribution (SED) from normal galaxies in the 60–170 μm range is typically rather broad, requiring warm and cold emission components.

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[1] A subsample of these galaxies was also observed with the *ISO* LWS instrument by Leech et al. (1999).

Especially for later spirals and irregulars, most of the FIR luminosity is carried by the cold dust component primarily emitting longwards of the *IRAS* limit of 120 μm. Studies based on *IRAS* data have used various corrections to account for the emission beyond 120 μm, under the assumption of a single dust temperature component (e.g. Helou et al. 1988). In the light of our new results, these will underestimate the true FIR luminosity, especially for normal galaxies. Since most galaxies do not yet have measurements at these longer wavelengths, it is useful to derive correction factors based on our ISOPHOT Virgo cluster sample. Such corrections should be generally applicable to convert *IRAS* luminosities into total FIR luminosities.

First we define a correction factor *corr*1 by which the total FIR luminosity L_{FIR} differs from the FIR luminosity L_{40-120}:

$$corr1 = \frac{L_{\mathrm{FIR}} - L_{40-120}}{L_{40-120}}. \quad (1)$$

Here $L_{40-120}[\mathrm{W\,m^{-2}}] = 1.26 \times 10^{-14}(2.58 f_{60\,\mu\mathrm{m}} + f_{100\,\mu\mathrm{m}})$, where $f_{60\,\mu\mathrm{m}}$, $f_{100\,\mu\mathrm{m}}$ are in Jy (Helou et al. 1988). The total FIR luminosities L_{FIR} were taken from tables 2 and 3 of Popescu et al. (2002). L_{FIR} were derived by fitting the FIR SEDs with two modified blackbody (Planck) functions of fixed emissivity index $\beta = 2$ (for details see Popescu et al. (2002)) and integrating between 40 and 1000 μm. Only galaxies with detections at all three wavelengths (60, 100 and 170 μm) were considered, which make a total of 38 objects.

We also define a correction factor *corr*2 by which L_{FIR} differs from a single dust component extrapolated total FIR luminosity $L^{\mathrm{extrapolated}}_{60;100}$:

$$corr2 = \frac{L_{\mathrm{FIR}} - L^{\mathrm{extrapolated}}_{60;100}}{L^{\mathrm{extrapolated}}_{60;100}}. \quad (2)$$

$L^{\mathrm{extrapolated}}_{60;100}$ were calculated based solely on our ISOPHOT 60 and 100 μm flux densities, by fitting the FIR SED with a single modified blackbody (Planck) function, otherwise following the same procedure used to derive the total L_{FIR}.

The results for the cold dust luminosity correction factors (only for *corr*2) are illustrated in Fig. 1, as a function of Hubble type. A large scatter can be seen, showing that it is not possible to apply a meaningful correction for the cold dust to individual galaxies.

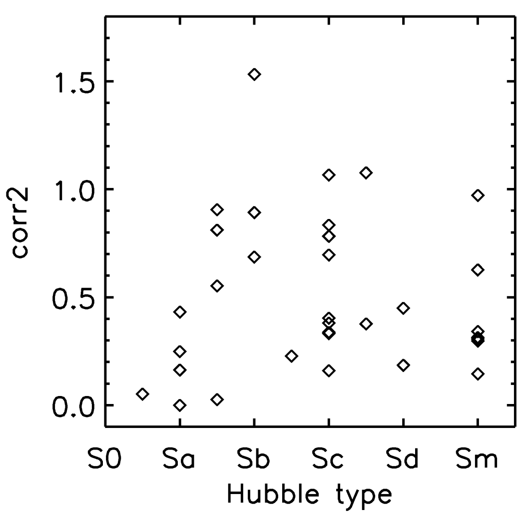

Figure 1. The luminosity correction factor *corr*2 for the cold dust versus Hubble type.

Table 1. The cold dust luminosity correction factors (median, mean and standard deviation of the mean)

Type	*corr*1			*corr*2		
	Median	Mean	ϵ	Median	Mean	ϵ
S0a/Sa	0.85	0.73	0.17	0.11	0.12	0.09
Sab–Sm	1.04	1.11	0.09	0.43	0.56	0.07
Im–BCD	1.06	1.81	0.89	0.85	1.19	0.64

Nevertheless, these numbers give some idea of the corrections to be expected for statistical samples.

Despite the scatter in Fig. 1, there is a visible trend for the early spirals (S0a, Sa) to have smaller corrections than the later spirals. It is therefore meaningful to derive statistical corrections for the early spirals and the later spirals separately. The median (and mean) values given in Table 1 indeed show a segregation between the early and the later types. Not shown in Fig. 1 are the corrections for the Im-BCDs. Since most of the BCDs were not detected at 60 and 100 μm (Tuffs et al. 2002), suggesting the coldest dust temperatures from all Hubble types, only three galaxies could be used for this statistic. Their median (and mean) correction factor has the highest value. Possible explanations for the unusual behaviour of the Virgo BCDs were given in Popescu et al. (2002).

The correction factors for the cold dust luminosity were derived under the assumption of an emissivity index $\beta = 2$, which is consistent with the graphite/silicate dust model of Draine & Lee (1984). If we were to adopt an emissivity index $\beta = 1$, the correction factors for the cold dust luminosity would decrease by $\sim$0.11.

No evidence was found for a dependence of the luminosity correction factor on galaxy mass, as traced by the dependence of the K' magnitudes from Boselli et al. (1997).

3 THE UV/OPTICAL/NIR OBSERVED OUTPUT

In order to derive the total observed output in the optical bands, we considered a subsample (28 galaxies) of our Virgo sample which had multi-aperture photometry in the Cousins U, B, V, R, I bands from SV96 Schröder & Visvanathan (1996, SV96). We applied the $U-B$, $B-V$, $V-R$ and $R-I$ colours taken from the largest aperture to the total B_{T} magnitude from Binggeli, Sandage & Tammann (1985, BST85). This converts the aperture photometry to the total magnitudes, but is still affected by differences between the photographic system and the photometric Cousins system. To correct for the latter effect we compared the B magnitudes taken from SV96 with those from BST85, for the galaxies having Binggeli's 25.5 B-mag arcsec^{-2} isophotal diameters smaller or equal to the largest 142.7 arcsec aperture of SV96. We found an average value $B_{\mathrm{T}} - B = -0.088$ which we applied to our derived magnitudes. For the extinction in our Galaxy we used the A_B values from Burstein & Heiles (1982) and the R_λ/R_{V} factors from Cardelli, Clayton & Mathis (1989). The conversion factors from magnitudes to flux densities were calculated from the Vega spectrum taken from table 4 of Dreiling & Bell (1980), and using the filter profiles from table 2 of Bessell (1990). A white spectrum source was assumed.

For the NIR output we used the H and K' magnitudes from Boselli et al. (1997). The K' magnitudes were available for all galaxies in the sample, while the H ones only for a few cases. Corrections for Galactic extinction were applied using the same procedure as in the optical bands. For the conversion factor between magnitudes and flux densities we used the values from Longair (1992). For the K' magnitudes we had to interpolate to the appropriate 2.1-μm wavelength.

In the UV we used the derived total magnitudes at 2500 Å taken from Rifatto, Longo & Capaccioli (1995) and the 1650-Å flux densities from Deharveng et al. (1994). The observed UV luminosity was derived by integrating the estimated UV SED until 912 Å. For seven galaxies with no UV data we extrapolated the UV SED, by using the $U - UV$ median colours derived (as a function of Hubble type) from the 21 galaxies in our sample which have UV data. Since the average contribution of the observed UV to the total bolometric luminosity was ~1 per cent for the Virgo early spirals and ~8 per cent for the Virgo later spirals, the inaccuracies incurred by this procedure are not severe.

The UV/optical/NIR SED obtained in this way for each galaxy was integrated to derive the observed stellar luminosity.

4 THE RATIO OF THE DUST LUMINOSITY TO THE BOLOMETRIC LUMINOSITY

For the 28 ISOPHOT Virgo galaxies that have the SV96 photometry we can derive the percentage of the dust radiative output to the total bolometric output. The dust luminosities were derived by augmenting the total FIR luminosity ($L_{\rm FIR}$) with the mid-infrared (MIR) output. Since most of the galaxies from our sample were not detected by *IRAS* at 12 and 25 μm we made an average correction of 30 per cent for the MIR luminosity (this was derived from the galaxies with MIR data). The results are plotted in Fig. 2 against Hubble type. This time a good correlation can be seen, with the early-spirals having less stellar light re-radiated by the dust and with the later types having a larger contribution from the FIR. This can be also seen from Table 2, where the mean value for the early spirals is 15 per cent as compared with the 30 per cent for the later spirals. The validity of the correlation with Hubble type was checked for any possible alteration due to environmental effects. In Fig. 2 this is done by plotting the cluster core and periphery galaxies with different symbols.[2] Within the available statistics no environmental dependence is found.

The mean value of $L_{\rm dust}/(L_{\rm dust} + L_{\rm stars})$ for the later spirals is the same as the canonical value of 30 per cent obtained for the *IRAS* BGS by Soifer & Neugebauer (1991). This is probably due to the fact that there are two factors influencing this percentage, and working in opposite directions. The addition of the *ISO* cold dust luminosity increases the FIR contribution to the total bolometrics. However, our sample consists of more quiescent galaxies than those from BGS and we expect them to have smaller FIR contributions. To check this assumption we derive the same percentage based on our calculated $L^{\rm extrapolated}_{60;100}$, which is the *ISO* equivalent of what *IRAS* would have seen for our sample. The resulting median percentage is now 18 per cent for the later spirals. So indeed *IRAS* would have derived a smaller percentage for our Virgo sample than for the BGS. By the same token, it is probable that the contribution of dust emission to the total luminosity of the BGS galaxies will be greater than the 30 per cent derived from *IRAS*.

The percentage of stellar luminosity transformed into FIR luminosity takes large values for some Scd/Sm galaxies, up to 50 per cent. Furthermore, some of our Virgo BCDs exhibit even higher percentages (Popescu et al. 2002), increasing the strength of the correlation with morphological type. The energy balance between observed UV/optical/NIR and FIR is thus a strong function of the morphological type and this can be also seen from Fig. 3, where the averaged SEDs (as observed, not corrected for internal extinction) are plotted for our main bins in Hubble type. A general flattening can be seen when progressing from the early to the later types; both between the FIR and UV–optical emissions, and within the UV–optical regime.

[2] The selection procedure for cluster core and periphery galaxies is described by Tuffs et al. (2002) and is based on the cluster membership classification of Binggeli, Popescu & Tammann (1993).

Table 2. The percentage of the total FIR luminosity to the total bolometric luminosity (median, mean and standard deviation of the mean).

Type	Median	*corr* Mean	ϵ
S0a–Sa	0.11	0.15	0.05
Sab–Sc	0.23	0.23	0.03
Scd–Sm	0.27	0.30	0.04

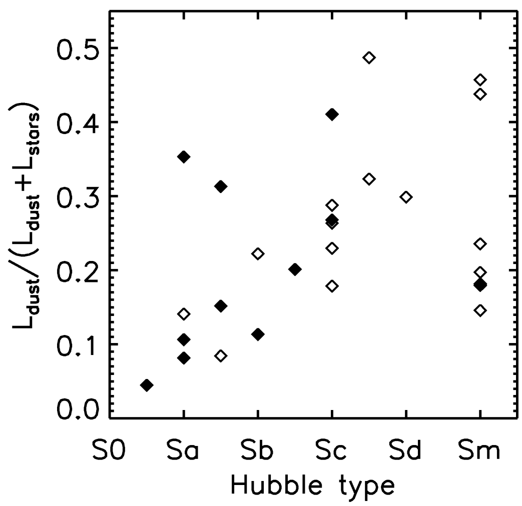

Figure 2. The ratio of dust luminosity ($L_{\rm dust}$) to total bolometric luminosity ($L_{\rm dust} + L_{\rm stars}$) versus Hubble type. The filled symbols denote cluster core galaxies and the open symbols galaxies from the cluster periphery.

No dependence of $L_{\rm dust}/(L_{\rm dust} + L_{\rm stars})$ on K' magnitudes was found, indicating that the conversion of starlight into IR thermal light in the local Universe is statistically independent of galaxy mass.

5 DISCUSSION

We have shown that the luminosity correction for cold dust does not correlate with morphological type and exhibits a huge scatter, with values ranging from 0 to 150 per cent. Only the S0a/Sa galaxies have relatively small corrections, as many of them are lacking the two dust temperature components. The big scatter in the correction factors for cold dust suggests that the FIR SEDs are strongly influenced by opacity effects, and not only by variations in the intensity and colour of the radiated starlight. Opacity depends on the geometrical distributions of the stellar populations and of the dust, both on large and small scales, as well as on metallicity, and the sheer sizes of the discs. All these quantities vary not only along the Hubble sequence, but also within a given morphological class, so that the scatter in Fig. 1 is not surprising, and no simple recipe can be considered to predict the luminosity of the cold dust emission component.

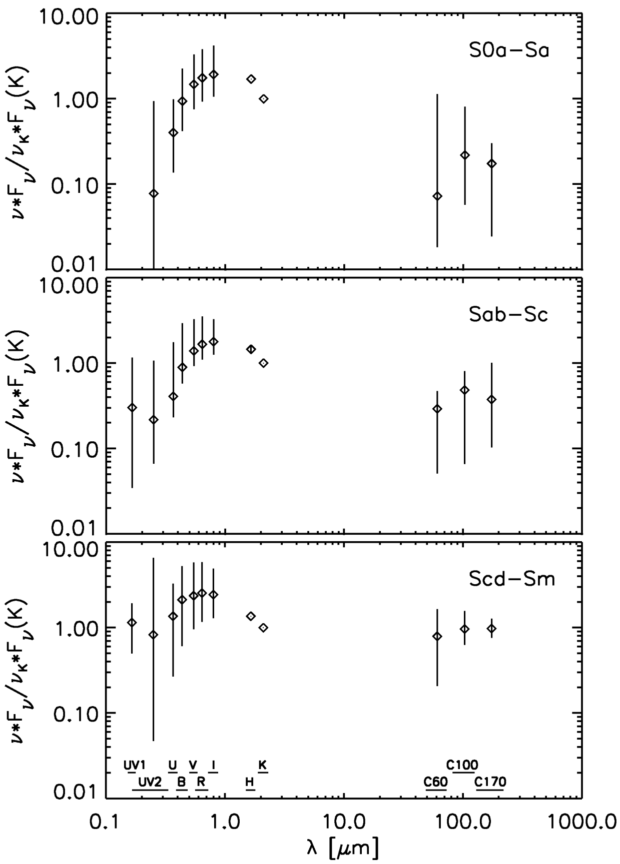

Figure 3. Averaged SEDs (as observed), normalized to the flux in K'-band, for subsamples of 6, 10, and 12 Virgo Cluster galaxies of type S0a–Sa, Sab–Sc and Scd–Sm, respectively. The vertical bars denote the range of normalized fluxes in each band. The spectral widths of the pass bands are delineated by the horizontal bars in the lower panel. UV1 and UV2 denote bands centred on 1650 and 2500 Å, respectively.

Ultimately, radiative transfer calculations have to be performed for the derivation of the energy densities that heat the grains and thus produce FIR emission (e.g. Silva et al. 1998; Popescu et al. 2000a; Misiriotis et al. 2001; Popescu & Tuffs 2002). Our results also imply that there is not a one to one conversion of the FIR luminosity into star-formation rates.

A second result of this paper is the correlation of the ratio of the dust to the stellar output with morphological type. This correlation can be also interpreted as a sequence from normal to dwarf gas-rich galaxies, with the dwarfs having an increased contribution of the FIR output to the total bolometric output. These findings could be important for our perception of the distant Universe, where, according to the hierarchical galaxy formation scenarios, gas rich dwarf galaxies should prevail at those epochs. We would then expect these galaxies to make a higher contribution to the total FIR output in the early Universe than previously expected. This, together with the cosmic-ray driven winds, in which grains can survive and be inserted in the surrounding intergalactic medium (Popescu et al. 2000b), could potentially change our view of the high-redshifted Universe.

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