On the dust abundance gradients in late-type galaxies: II. Analytical models as evidence for massive interstellar dust growth in SINGS galaxies

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ABSTRACT

We use simple analytical models of the build up of the dust component and compare these with radial dust distributions derived from observations of SINGS galaxies. The observations show that dust gradients are indeed typically steeper than the corresponding metallicity gradients and our models indicate very little dust destruction, but significant dust growth in the ISM for most of these galaxies. Hence, we conclude that there is evidence for significant non-stellar dust production, and little evidence for dust destruction due to SNe shock waves. We find that dust is reprocessed rather than destroyed by shocks from SNe. Finally, we argue that dust abundances derived using standard methods may be overestimated, since even very 'generous' estimates of the metallicity results in dust-to-metals ratios above unity in several cases, if the dust abundances given in the literature are taken at face value.

Key words: Galaxies: evolution, ISM; ISM: clouds, dust, extinction, evolution, supernova remnants;

1 INTRODUCTION

Dust grains in dense molecular can theoretically grow to micrometer sizes by accretion and coagulation (see, e.g., Ossenkopf 1993; Ormel et al. 2009; Hirashita & Kudo 2011). There is also observational evidence suggesting such large grains are abundant in many Galactic molecular clouds (see Pagani et al. 2010, and references therein), which is easily explained by efficient dust growth in these cores. Micrometer-sized dust grains can theoretically be formed in carbon rich AGB stars as well (Mattsson & H"ofner 2011), and are likely to form also in oxygen rich AGB stars (H"ofner 2008), but the probability of having any larger quantities of these grains gathering in dense molecular cores is very low. Furthermore, grains are expected to survive in the Galactic ISM for a few hundred Myr (Jones, Tielens & Hollenbach 1996; Jones 2003; Serra Diaz-Cano & Jones 2008; Jones & Nuth 2011), while the time scale for any significant stellar dust enrichment in the local ISM is about Gyr, which implies the presence of dust growth processes in the ISM. Hence, interstellar dust growth can be regarded an established phenomenon.

Shock-waves from supernovae (SNe) is thought to be able to destroy dust grains as these waves propagate through the interstellar medium (ISM). The time scale for this dust destruction is largely dependent on the supernova rate (SNR) and how much dust each SN-shock can destroy (McKee 1989; Draine 1990). This shock destruction of dust grains has been considered quite efficient (Jones, Tielens & Hollenbach 1996; Jones 2003), although more recent work show that while this is likely the case for carbon dust it may not be the case for silicates (Serra Diaz-Cano & Jones 2008; Jones & Nuth 2011) which seems consistent with the Milky Way (solar neighbourhood). Very efficient dust destruction seems on the other hand inconsistent with the high masses dust detected in high-z objects (Dwek et al. 2007; Gall, Andersen & Hjorth 2011; Mattsson 2011). It may of course be that dust destruction by SNe is less efficient in high-z galaxies, but also modelling of nearby late-type galaxies seems to work nicely without significant net destruction of dust (Inoue 2003; Hirashita 1999), and it makes it easier to explain the dust-to-gas ratios, since stellar dust production is inefficient (Hirashita 1999; Zhukovska, Gail & Trieloff 2008).

Observations imply that dust production in SNe is rather inefficient (Kotak et al. 2006, 2009), which suggest the large masses of cold dust detected in some SN remnants (see, e.g., Morgan & Edmunds 2003; Morgan et al. 2003, Dunne et al. 2009) may be the result of subsequent dust growth rather than an effect of heating or actual dust production in the actual SN. Theoretical results suggest 90% of the dust produced in SNe is destroyed by the reverse shock before it reaches the ISM (Bianchi & Schneider 2007), which leads to a relatively consistent picture where AGB stars is the most important source of stellar dust (Edmunds & Eales 1998; Ferrarotti & Gail 2006). Models of the dust evolution in the solar neighbourhood by Dwek (1998) and Zhukovska, Gail & Trieloff (2008) suggest dust production in stars and possible dust destruction by SN-shock waves need to be compensated by an efficient dust growth in the ISM. This is also supported by the fact that dust grains of considerable sizes seem to exist in the ISM (Pagani et al. 2010). However, recent results from
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Herchel observations of SN 1987A show a huge reservoir of cold dust which suggest that at least some SNe may produce significant amounts of dust (Matsuura et al. 2011). However, it is still unclear how much of this dust will survive once the reverse shock sets in.

It is obviously not clear whether dust destruction from SN-shock waves in the ISM is an efficient mechanism or not, or perhaps more accurately put: whether the net dust destruction is important or not. As mentioned above, existing models of the evolution of the dust phase in the solar neighbourhood (solar circle) rely on the assumption that both growth and destruction are important (Dwek 1998, Zhukovska, Gail & Trieloff 2008). But with only a single data point, e.g., the present-day dust abundance in the solar neighbourhood, it is hard to tell whether a model with, or without, dust destruction by SNe and/or dust growth in the ISM makes a better fit to data. Recently, however, results from the SINGS project (Kennicutt et al. 2003) have provided dust abundance profiles based on physical dust models for a good number of nearby galaxies (Munoz-Mateos et al. 2009) and the associated THINGS project has provided H i profiles for many of the SINGS galaxies (Walter et al. 2008). Hence, the dust-to-gas ratio along the disc can be derived for many of these galaxies, which opens for more precise comparisons with observations since different galactocentric distances in the discs represents different evolutionary states of the interstellar gas. Many of the late-type galaxies in this sample have also well-constrained metallicity gradients as there are sufficient numbers of detectable Hα-regions for which spectroscopy have been done (Moustakas et al. 2010).

Previous work on dust evolution modelling has shown that the dust-to-metals ratio may change as the evolution proceeds. The analytical relations derived by, e.g., Edmunds (2001) and Mattsson (2011), show that the dust abundance may not necessarily follow the metal abundances in the ISM. More detailed results, obtained through numerical modelling, suggest the same (Dwek 1998; Inoue 2003; Zhukovska, Gail & Trieloff 2008). The reasons for the changing dust-to-metals ratio are mainly the destruction (including astration) and growth of dust grains that may occur in the ISM, which suggest that dust and metallicity gradients may not have the same slope, i.e., there is a dust-to-metals gradient. As suggested in Mattsson, Andersen & Munkhammar (2011), henceforth ‘Paper II’) the dust-to-metals gradient along a galactic disc can essentially be regarded as a diagnostic for net dust growth or net destruction depending on whether the slope is negative or positive, respectively.

We demonstrate here a way to estimate the efficiency of the net dust destruction by SNe in nearby late-type galaxies using dust-and metallicity gradients. Comparing the dust abundance gradients along the disc with the metallicity gradients may give an indication of whether net destruction or net growth of dust is important or not, as we will show in this paper.

2 MODEL

2.1 Basic equations

Following Paper I we use the instantaneous recycling approximation (IRA, which essentially means all stars are assumed to have negligible lifetimes compared to the time scale for the build-up of metals and dust, see Pagel (1997) throughout this paper. Then, assuming a ‘closed box’, gas and dust destruction in the ISM from SN-shocks, the equations for the metallicity $Z$ and the dust-to-gas ratio $Z_d$ becomes

\[ \frac{dZ}{dt} = \gamma_Z \frac{d\Sigma_g}{dt} = -y_{\delta} \frac{d\Sigma_g}{dt} \]  \[ \frac{dZ_d}{dt} = \gamma_{Z_d} \frac{d\Sigma_g}{dt} + Z_d(r,t) \left( \frac{1}{\tau_{gr}} - \frac{1}{\tau_d} \right) \]

where $\tau_d$ is the dust destruction time scale, $\gamma_{Z_d}$ is the dust-growth time scale and $y_{\delta}$, $y_{Z_d}$ denote the yields (dust and metals, respectively) as defined in Paper I, and $\Sigma$, $\Sigma_g$ denotes surface density by mass of stars and gas, respectively. Combining equations (1) and (2), we have

\[ \frac{dZ_d}{dZ} = \frac{y_d + Z_d(\tau_{gr}^{-1} - \tau_d^{-1})}{y_{\delta}} \]

which thus has no explicit dependence on the gas mass density $\Sigma$ or the stellar mass density $\Sigma_\ast$, although $Z$, $Z_d$ as well as the time scales $\tau_{gr}$, $\tau_d$ may implicitly depend on $\Sigma$ and $\Sigma_\ast$.

2.2 Destruction and growth of dust in the ISM

Following McKee (1989) the dust destruction time-scale is

\[ \tau_d = \frac{\Sigma}{\langle m_{\text{ISM}} \rangle R_{\text{SN}}} \]

where $\langle m_{\text{ISM}} \rangle$ is the effective gas mass cleared of dust by each SN event (which is not necessarily the same as the gas mass affected by each SN), and $R_{\text{SN}}$ is the SN rate. As shown in Paper I, the time scale $\tau_d$ may be expressed as

\[ \tau_d^{-1} \approx \delta \frac{d\Sigma_g}{\Sigma_g} dt \]

where $\delta$ will be referred to as the dust destruction parameter, which is a kind of measure of the efficiency of dust destruction. For a Larson (1998) IMF and $m_{\text{ISM}} \approx 1000 M_\odot$, Jones, Tielens & Hollenbach (1994) (Jones, 2004), then $\delta \approx 10$ (see Mattsson 2011).

We define the rate per unit volume at which the number of atoms in dust grains may grow by accretion of metals onto these dust grains as (see, e.g. Dwek 1998) at a rate which naturally depends on metallicity $Z$, the typical grain radius $a$ and the sticking coefficient $f_s$ (i.e., the probability that an atom will stick to the grain). Additionally, the mean thermal speed of the gas particles (including metals) (\langle v_g \rangle) will affect this rate, which suggest a temperature dependence. The timescale of grain growth can thus be expressed as (again, see Paper I for brief derivation)

\[ \tau_g = \tau_0 \left( \frac{Z}{Z_0} \right)^{-1}, \quad \tau_0 = \frac{\langle m_g \rangle d_c}{f_s \pi a^2 Z \Sigma_{\text{mol}} \langle v_g \rangle} \]

where $\langle m_g \rangle$ is the average mass of individual dust grains in the gas, $d_c$ is the characteristic size of the molecular clouds where dust grows and $\Sigma_{\text{mol}}$ is the surface density of molecular gas. As in Paper I, we will assume $\Sigma_{\text{mol}} \approx \Sigma_{\text{HI}}$, since most of the gas in molecular gas clouds is in the form of molecular hydrogen. We also assume $\Sigma_{\text{HI}}$ traces the star-formation rate (Rownd & Young 1999; Wong & Blitz 2002; Bistel et al. 2008; Leroy et al. 2008; Bistel et al. 2011; Feldmann, Gnedin & Kravtsov 2011; Schruba et al. 2011). This is also supported by theory and recent numerical experiments (see, e.g. Krumholz, McKee & Tumlinson 2009; Krumholz, Leroy & McKee 2011). Moreover, the mean thermal speed ($\langle v_g \rangle$) is roughly constant in the considered ISM environment and the typical grain radius does not vary much. Hence, as shown in Paper I, $\tau_0$ is essentially just a simple function of the metallicity and the growth rate of the stellar component, the latter of which increases with metallicity.
\[ \tau_0^{-1} = \frac{\varepsilon Z}{\sum g} \frac{dZ}{dt}, \]

where \( \varepsilon \) will, in the following, be treated as a free (but not unconstrained - see Paper I) parameter of the model. The rate of change of the dust-to-gas ratio \( Z_t \) due to accretion of metals onto pre-existing dust grains in the ISM is then

\[ \frac{dZ_t}{dt} = \left( 1 - \frac{Z_t}{Z} \right) \frac{Z_t}{\tau g} \]  \( \text{(8)} \)

The \( \varepsilon \) used above should also not be confused with the dust-destruction efficiency parameter used by McKee (1989), and it also differs slightly from the dust-growth parameter used in Mattsson (2011) as we in this work consider the free atomic metals rather than the total metallicity.

### 2.3 Models of radial dust-to-gas distributions

For simplicity we stick to a closed-box model as in Paper I, i.e., no in- or outflows to/from the disc will be considered. This is not in agreement with the widely accepted ideas about galaxy-disc formation, where the baryons (in the form of essentially pristine gas) are assumed to be accreted over an extended period of time. But as shown by Edmunds (1999), the most prominent effect of unenriched infall is to make the effective yield smaller, i.e., to dilute the gas so that the metallicity builds up more slowly. As we use the present-day metallicity as input (see section 3.2), the overall effects of assuming a closed box are rather small. Note also, that Garnett (1997) have showed that the simple closed-box model of chemical evolution seem to work quite well for modelling oxygen (O/H) gradients. In particular, adopting the Clayton (1987) infall model neither means a significant improvement of the fit, nor a very large change of the required yield.

Adopting a closed-box scenario, the dust destruction and dust growth models as described above, we arrive at the equation

\[ \frac{dZ}{dZ} = \frac{1}{y_Z} \left[ y_d + Z \left( \varepsilon \left( 1 - \frac{Z_t}{Z} \right) Z - \delta \right) \right], \]  \( \text{(9)} \)

where \( y_Z \) is the metal yield. With \( 0 \leq y_d \leq y_Z \) as a basic requirement, the general closed-box solution (of equation 9) for the dust-to-gas ratio \( Z_t \) in terms of the metallicity \( Z \) can then be expressed in terms of the confluent hypergeometric Kummer-Tricomi functions of the first and second kind (usually denoted \( U \) and \( M \)), respectively (Kummer 1837; Tricomi 1947). We refer to Paper I for further details.

In case there is no dust destruction by SNe (\( \delta = 0 \)) the solution reduces to

\[ Z_d = \frac{y_d}{y_Z} \frac{M \left( 1 + \frac{1}{y_Z} \right)}{M \left( \frac{1}{y_d} \right)} Z, \]  \( \text{(10)} \)

where \( M(a, b; z) = {}_1F_1(a, b; z) \) is the Kummer-Tricomi function of the first kind, which is identical to the confluent hypergeometric function \( {}_1F_1(a, b; z) \) that is often implemented in computer algebra software. If there is neither growth, nor destruction of dust in the ISM (\( \varepsilon = \delta = 0 \)), we have the trivial case

\[ Z_d = \frac{y_d}{y_Z} Z, \]  \( \text{(11)} \)

corresponding to pure stellar dust production. These are the two cases we consider in detail in this paper.

### 3 RESULTS AND DISCUSSION

We have compared the theory of interstellar dust evolution presented in Paper I with data on dust gradients in late-type galaxies taken from the analysis of SINGS sample by Munoz-Mateos et al. (2009). They present radial distributions of dust (surface densities) in galactic discs derived from UV-, IR- and gas mass profiles, which have relatively small errors. These data are likely the best constraints on radial dust gradients in galactic discs available at present. Here we summarise and discuss the results.

#### 3.1 General results and limitations

In a previous paper (Paper I) we have shown that dust destruction by shocks from exploding SNe will flatten a negative (declining with galactocentric distance) dust-to-gas gradient over a galactic disc, while dust growth in general acts as to make it steeper (see the Theorem proved in Paper I). From this result, we expect dust-to-metals gradients to have positive gradients (rising with galactocentric distance) if dust destruction is more important than dust growth, and if dust growth is the more important process we expect them to be negative.

In our limited sample of late-type galaxies taken from Munoz-Mateos et al. (2009), we found that the dust-to-metals gradients are typically negative or in some cases flat. There is only one counter-example (NGC 5194) where the metallicity gradient may be somewhat steeper than the dust-to-gas gradient (see figure 1), resulting in a positive dust-to-metals gradient (see figure 3). However, it should be stressed that the metallicity gradients (as traced by the O/H gradients in the discs) we adopt in this study may not be correct in all cases. We have taken the metallicity gradients from Moustakas et al. (2010), which are derived using the strong-line calibration by Kobulnicky & Kewley (2004), except for the dwarf irregular galaxy Holmberg II. For the latter we assume an essentially flat metallicity gradient with a slope of only 1%, since dwarf galaxies typically have no metallicity gradients, but the slope cannot be exactly zero if a dust-to-gas/metals gradient is to be obtained from the model. Moustakas et al. (2010) also provide gradients based on abundances derived using the P-method (Pilyugin & Thuan 2005), which suggest significantly lower metallicities and somewhat flatter gradients. Using the latter, the amount of metals are clearly inconsistent with the dust abundances derived by Munoz-Mateos et al. (2009), i.e., dust-to-metals ratios are above unity for a majority of data points. Therefore, we present only models (see section 3.2) based on metallicity gradients derived using the Kobulnicky & Kewley (2004) calibration, which are also closer to the dust-to-gas gradients in terms of steepness (cf. the models with pure stellar dust production in Figure 1) which in several cases are relatively close to the dust-to-gas gradients.

This inconsistency (that the dust-to-metals ratio exceeds unity), is indeed a problem, and the reader should bear in mind that we have not used these metallicity data because they are the most reliable, but rather because they are not obviously inconsistent with the dust-to-gas ratios we compare with. As will be shown below, there are still a few data points at small galactocentric distances which would correspond to dust-to-metals ratios above unity also when using the metallicity gradients derived using the Kobulnicky & Kewley (2004) calibration. Either the dust abundances should be about a factor of 2-3 lower, or the metal abundance should be increased by a similar factor. The latter is less likely, however, since we already use oxygen abundances which are at the high end of the possible range (set by the various meth-
ods and calibrations for abundance determination) to estimate the metallicity along the disc and assume a relatively low oxygen fraction. Hence, it is more likely the dust abundance is overestimated in general, which is an interpretation that is supported by recent results on the dust content of dwarf galaxies (Madden et al. 2011) and which we will discuss in more detail in section 3.5. But for now, in order to avoid constructing strange inconsistent models, we have just scaled down the dust abundances for some galaxies such that the dust-to-metals ratio never exceeds 0.9 anywhere along the discs.

3.2 Models and fitting

We have fitted simple analytical models (see section 3.2) to the dust-to-gas profiles derived from observations by Munoz-Mateos et al. (2009). In doing so we have used the Levenberg-Marquardt scheme for \( \chi^2 \)-minimisation. More precisely, we have used the IDL-routine package MPFIT (Markwardt 2009) in combination with a numerical implementation (for IDL) of the Kummer-Tricomi functions (see Paper I). This setup has proven very stable for the cases we consider here (equations 10 and 11).

3.2.1 Input data

For the model fits we have fixed the metal yield \( y_d \) to the value obtained from a simple closed-box scenario

\[
y_d = \frac{Z}{\mu} \left( R = 0.4 R_{25} \right) \ln(1/\mu),
\]

where \( \mu \) is the overall gas mass fraction of the galaxy (see Table 1). The metallicity at a galactocentric distance \( R = 0.4 R_{25} \) is known to be a good proxy for the typical metallicity of a galaxy disc (Garnett et al. 2002), which is why we define the effective metal yield as above. We have used the same gas mass fractions as in Pilyugin, Vilchez & Contini (2004). Note that the stellar dust yield \( y_d \), on the other hand, is treated as a free parameter.

Furthermore, we use oxygen (O/H) gradients derived using the strong-line calibration by Kobulnicky & Kewley (2004) as input to our model (see Moustakas et al. 2010, for further details). We use the log-linear-fits and do not consider possible bends and features of the metallicity profiles as metallicities derived from H II regions can be quite uncertain. To obtain the total metal fraction (metallicity) we first convert the number abundances of oxygen into oxygen mass fractions using the relation (Garnett et al. 2002)

\[
X_O = \frac{12}{\mu} Z
\]

in which we then have implicitly assumed \( M_{\text{gas}} = 1.33 M_H \). Then, we assume that oxygen typically makes up about a third of all metals (this is certainly at the low end of the possible range, see e.g., Garnett et al. 2002, where 45-60% is the suggested value), hence,

\[
Z = \frac{36}{\mu}
\]

The fraction of oxygen in the metals is of course not a universal constant and may vary from one environment to another. In particular, the oxygen fraction is likely higher in low-metallicity environments than it is in high-metallicity environments where low- and intermediate stars as well as SNe type Ia have contributed significantly to the metal enrichment of the ISM.

3.2.2 Modelling results

Allowing dust destruction (\( \delta > 0 \)) does not seem to improve the agreement between model and the dust-to-gas profile inferred from observations. For example, we considered the case where \( \delta \) is fixed to a specific value (we assumed \( \delta = 10 \), see section 3.2.3 for a motivation of this value), but with \( \epsilon \) being an essentially free parameter constrained only by \( \epsilon > \delta/Z_{\text{max}} \) (where \( Z_{\text{max}} \) is the maximum/central metallicity of the galaxy) in order to avoid the singularity that occurs at \( Z = \delta/\epsilon \) (see Paper I). In such case the dust-to-gas/metal profiles cannot be reproduced for any of the galaxies in our sample. With \( \delta \) as a third free parameter (but still \( \epsilon > \delta/Z_{\text{max}} \)), the best fit is typically obtained for \( \delta < 1 \). The only exceptions are NGC 2403 and 3031 for which moderate dust destruction (\( \delta \sim 4 \)) leads to a slight improvement, albeit with a too high degree of freedom for the model fit to be better from a statistical point of view. This more or less rules out any significant net destruction of dust. Hence, we present here (in detail) only models without dust destruction due to SN shocks for the selected galaxies, since dust destruction hardly improves the models but rather just adds another free parameter (constraining more the two free parameters is also clearly not justified from a statistical point of view, given the small number of data points we have at our disposal for several galaxies).

Dust growth in the ISM, on the other hand acts as to improve the overall agreement between models and dust-to-gas/metal profiles derived from observations. In fact, allowing dust growth (\( \epsilon \geq 0 \), \( \delta = 0 \)) improves the fits rather dramatically compared to the case of pure stellar dust production (\( \epsilon = \delta = 0 \)). We find only one case (NGC 3031) where a really good fit cannot be obtained. This galaxy show a peculiar central depression in the dust-to-gas profile (see figure 1 middle panel on the second row from the top), which may not have anything to do with the physics of dust formation. A possible scenario is that a merger-induced starburst may have cleansed the central regions from dust, since NGC 3031 appear in a relatively dense environment (it is for example interacting with NGC 3034 and 3077). For all other galaxies (including the outer part of NGC 3031) we obtain more or less good fits (see figure 1 and figure 2).

In most cases there certainly seem to be need for dust growth, or another kind of 'secondary' dust production, that depends on dust abundance and/or metallicity and thus steepens the dust-to-gas gradient and creates a dust-to-metals gradient. The very steep dust-to-metals gradients in the outer parts of NGC 2403 and 3031, as well as that of NGC 3351, are particularly good examples. In most cases the required stellar dust yield \( y_d \) is well below 50% of the total metal yield \( y_d \) according to the model fits with \( \delta = 0 \) and \( \epsilon \) being free a parameter (see Table 1). This is a very reasonable result, suggesting our model is sound. Models with \( \delta = 0 \), but with a significant \( \epsilon \) and relatively modest (or even insignificant) stellar dust production provide very good fits in general to the dust-to-gas profiles derived by Munoz-Mateos et al. (2009). The cases requiring a high stellar dust yield have high dust-to-metals ratios over the whole disc (after down-scaling of the dust abundance), suggesting that not only may the dust abundances derived from observations for these galaxies be too high, but also the metallicities could be too low.

In figure 3 we show \( \epsilon \) as function of the B-band luminosity (data taken from Pilyugin & Ferrini 2000; Pilyugin, Vilchez & Contini 2004) and the mean gas mass density, here estimated as

\[
\langle \Sigma_g \rangle \sim \frac{M_g}{2\pi R_{25}^2}
\]

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The model with pure stellar dust production fits quite nicely to the dust-to-gas/metals profile, albeit with a rather large uncertainty. The dust-to-metals ratio in the ISM is much more efficient in smaller and less luminous late-type galaxies. It is unclear why this correlation exists, but we believe there could be a connection to star formation and the formation of cold molecular clouds. Low-luminosity disc galaxies tend to have less star formation which may create a suitable environment for dust growth in molecular clouds. If star formation is too intense, dust growth may simply be inhibited by the radiation field. Indirect support for this hypothesis is that primarily young stars (due to their emission at UV/blue wavelengths) may be responsible for heating cold dust. The $\epsilon$-values does not at all seem to correlate with $(\Sigma_d)$, which suggest the parameterisation we introduced in Paper I is very much reasonable.

### 3.3 Comments on models of individual galaxies

Here we summarise and comment on the modelling results of individual galaxies.

#### 3.3.1 NGC 628

The dust-to-metals gradient is clearly negative. Assuming pure stellar dust production implies that the stellar dust yield $\gamma_d$ must be equal to the total metal yield $\gamma_Z$ in order to match the dust abundance in general, which is obviously unrealistic (especially since the dust abundance has been scaled down by 62%). Adding significant dust growth in the ISM provides a good model with $\gamma_d$ being only about 10% of $\gamma_Z$. A fairly strong indication of nonstellar dust production.

#### 3.3.2 NGC 925

This galaxy also show a negative dust-to-metals gradient, but the slope is shallower. The dust-to-gas/metals gradient can be nicely modelled with dust growth. May be (or have been) interacting with a low-mass galaxy, which could explain dynamical and morphological asymmetries. (Pisano, Willcots & Elmegreen 1998).

#### 3.3.3 NGC 2403

This is a somewhat peculiar case. The inner part of the dust-to-gas gradient has a slope which is very much consistent with the slope of the metallicity gradient, while the outer part is significantly steeper. Beyond $R/R_{25} \sim 0.3$ the observationally inferred dust-to-metals profile show a steep drop which is clearly inconsistent with the model with only stellar dust production. In that case, the model prediction falls outside the error bars for $R/R_{25} \geq 0.7$.

Adding dust growth improves the agreement between model and observation tremendously. This is one of the strongest cases in support of grain growth being the dominant mechanism for dust production in the ISM. However, the very inefficient stellar dust production ($\gamma_d$ only $\sim$ 1% of $\gamma_Z$) suggested by the model fit to the data is indicative of a possibly too low dust-to-metals ratio in the outer disc. The ratio is less than 1% in the outskirts of the disc and $\sim$ 50% in the inner disc (see figure 2).

#### 3.3.4 NGC 2841

The dust-to-metals gradient is quite steep, but flattens out towards the centre of the galaxy. Both features can be perfectly reproduced by a model including dust growth and the required/implied stellar dust yield is just 7% of the metal yield, which makes this galaxy another strong case for dust growth - in particular since the error bars are quite small in this case. A model fit with only stellar dust production is clearly inconsistent with the dust-to-gas/metals gradient. The dust abundance was only scaled down by 5% in this case.

#### 3.3.5 NGC 3031

NGC 3031 (M 81) is another peculiar case, where there is a clear dust depletion in the central parts. This is certainly not predicted by the model. The mid part of the disc has a dust-to-metals gradient which is nearly flat, but beyond $R/R_{25} \sim 0.6$ it steepens in a way similar to NGC 2403. It is worth noting that this galaxy is known to be in a relatively dense environment and interact with at least two other galaxies (Davis 2008), which suggest that the central parts likely have formed by one or more mergers. A merger is a violent event, quite capable of destroying large amounts of dust, which is a possible explanation of the central depression in the dust-to-gas profile. SN-shock waves may not be efficient dust destroyers, although the environment in merger-driven nuclear starburst may be hostile enough to actually destroy dust grains and not just crush them into smaller grains. A model with significant dust growth in the ISM, but almost no stellar dust production, reproduces the slope of the outer dust-to-gas/metals profile nicely. Again, we argue this is strong evidence for grain growth in the ISM being the most important dust formation mechanism. The dust abundance was scaled down by 25%.

#### 3.3.6 NGC 3198

Once again the dust-to-metals gradient is clearly negative. Assuming pure stellar dust production is quite reasonable in this case ($\gamma_d$ being about 36% of $\gamma_Z$), although including dust growth enhances the agreement between model and observation significantly. Stellar dust production is still relatively important in this case, where $\gamma_d$ is about 19% of $\gamma_Z$.

#### 3.3.7 NGC 3351

This case is interesting, since it shows the largest discrepancy between the distributions of metals and dust. The metallicity gradient is almost flat all over the disc. A model without dust growth is ruled out for two reasons: pure stellar dust production implies $\gamma_d = \gamma_Z$, and the corresponding dust-to-gas/metals profile does not fit the data at all. Adding dust growth, however, we obtain a clearly better fit to the observations (see figure 1 and figure 2). Yet another case in favour of somewhat lower dust abundances. To ensure the dust-to-metals ratio never exceeds 0.9, the dust abundance had to be scaled down by a massive 85%, which indicate there is a strong case for dust growth - in particular since the error bars are quite small in this case. A model fit with only stellar dust production is clearly inconsistent with the dust-to-gas/metals gradient. The dust abundance was only scaled down by 5% in this case.

#### 3.3.8 NGC 3521

The model with pure stellar dust production fits quite nicely to the observational dust-to-gas/metals profile, albeit with a rather large uncertainty.

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stellar dust yield ($y_d$ being about 75% of $y_Z$) and with an exception for the inner most data point. With dust growth, the inner most point is still not reproduced, so the agreement with the observations is not clearly better (see figure 1 and figure 2). The dust abundance was scaled down by 71%, which again provide evidence that there is a problem with how dust abundances are derived.

### 3.3.9 NGC 3621

The dust-to-metals gradient have clearly a negative slope, but the disagreement with a pure stellar dust production is moderate. Dust growth improves the overall agreement between model and observation, and an essentially perfect fit is obtained for very reasonable parameter values. The model clearly reproduces the dust-to-gas as well as the dust-to-metals profile within the error bars. The dust abundance was scaled down by 35%.

NGC 3621 is considered to be a pure disc (bulgeless) galaxy, which imply a quiescent formation history without major mergers and that central regions are fairly unevolved compared to other late-type galaxies (Gliozzi et al. 2009). Hence, this galaxy may be a good test case for an idealised model such as the one we have applied here.

### 3.3.10 NGC 4736

This galaxy has a clear dust-to-metals gradient, which is nicely reproduced by a model with significant dust growth. Stellar dust production is essentially rejected by the fitting algorithm ($y_d \sim 10^{-5}$), which is unphysical, although it implies dust growth is needed and clearly dominating. A model fit with only stellar dust production is inconsistent with the dust-to-gas gradient, but almost within the error bars, which makes it marginally consistent with the dust-to-metals gradient since the error bars are larger for dust-to-metals ratios. However, a model with dust growth is clearly preferred. The dust abundance was scaled down by 54%, which yet again seems problematic.

### 3.3.11 NGC 5055

Here, the dust-to-metals gradient is almost exactly flat (see figure 2). As a consequence the fitting routine reject the dust growth contribution ($\epsilon \rightarrow 0$). The required stellar dust yield $y_d$ is 62% of the metal yield $y_Z$, which is not a totally unreasonable figure. The inner most data point suggest a mild central depletion in the dust-to-gas profile. NGC 5055 is possibly interacting with UGC 8365. The dust abundance was scaled down by 14%.

### 3.3.12 NGC 5194

NGC 5194 is the only galaxy in the present study which deviates from the general trend that dust-to-metals gradients have negative slopes. In this galaxy the dust-to-gas profile is in principle flat over the whole disc, while the dust-to-metals gradient shows a mildly positive slope. Hence, NGC 5194 could seem better modelled with some moderate dust destruction, but dust destruction would require a higher stellar dust yield, and since the model with only stellar dust production suggest that 88% of the metals ejected from stars is in the form of dust, there is not much room for dust destruction. Dust growth means no improvement of the fit in this case. This galaxy show unrealistic dust-to-metals ratios at several locations along the disc, without down-scaling of the dust abundance. The dust abundance was scaled down by 60%, which was not enough to bring down the stellar dust yield to a reasonable number, however. This galaxy is somewhat unusual in that it appears to have an essentially flat metallicity gradient, something which is not expected for this morphological type (SABbc). The need for a 60% down-scaling of the dust abundance would not be if the metallicity of the central parts were as much higher as needed to create a more typical metallicity gradient.

### 3.3.13 NGC 7331

The dust-to-metals gradient is again nearly flat. Adding dust growth means only a minor improvement and the stellar dust yield required in the pure stellar dust model is very much reasonable ($y_d$ being about 36% of $y_Z$). NGC 7331 is therefore an example of that there is not always an obvious need for dust growth. A remarkable property of this galaxy is its retrograde bulge (counter-rotating relative to the
Figure 1. Dust-to-gas ratio as function of galactocentric distance (circles) together with the best-fit models with stellar dust production only (dashed blue lines) and simple models including dust growth (solid red lines). The grey symbols in the background shows the original dust-to-gas ratio before lowering the dust abundance.
Figure 2. Dust-to-metal ratio as function of galactrocentric distance (circles) together with the best-fit models with stellar dust production only (dashed blue lines) and simple models including dust growth (solid red lines). The dotted (black) line shows the case of 50% metals locked-up in dust, which roughly corresponds to the dust-to-metals ratio in the Solar neighbourhood. The grey symbols in the background shows the original dust-to-metals ratio before lowering the dust abundance. The light-red/pink shaded regions correspond to dust-to-metals ratios above unity.
3.3.4 Holmberg II

This galaxy is the only one in our sample which is not really a disc galaxy. It is a dwarf irregular galaxy, which seems to have an essentially flat metallicity gradient and generally a low dust abundance, as is usually the case with galaxies of this morphological type. There is a dust-to-metals gradient, however, which must be the dominating process for dust production. However, it should be noted that a model with only stellar dust production is in principle consistent (within the errors) of the dust-to-gas/metallicity gradients derived from observations. The stellar dust yield would in such case need to be only 5% of the metal yield.

3.4 If dust is not destroyed - then what is the effect of shocks from SNe?

Clearly, our results presented above suggest dust is not destroyed in any significant quantities due to SN shocks, as have been suggested by several studies and authors (see, e.g. Draine & Salpeter 1979; McKee 1989; Tielens et al. 1994; Nozawa & Kozasa 2006; Jones, Tielens & Hollenbach 1996; Jones 2004; Jones & Nuth 2011). We propose dust reprocessing rather than destruction, which we motivate as follows.

The first thing to consider is what we mean by 'dust destruction'. Here, we prefer to look at dust destruction as a process that will atomise a dust grain/molecule. A SN-shock wave contains a vast amount of energy, which can certainly be harmful for dust grains, but it is quite possible that dust grains are shattered to small splinters, rather than completely evaporated. Small grains tend to survive better when exposed to energetic shock waves (see, e.g. Jones, Tielens & Hollenbach 1996), which implies there might be a lower size limit at which the shattering stops being effective. Such a scenario has the advantage of being favourable to dust growth in the ISM. Assuming spherical grains the total surface area \( A_{\text{tot}} \) of all dust grains is related to the total volume \( V_{\text{tot}} \) of dust as

\[
A_{\text{tot}} = \frac{3}{\langle a \rangle} V_{\text{tot}},
\]

where \( \langle a \rangle \) is the average grain radius. Thus, if the average grain size is decreases by a certain factor, the total surface area \( A_{\text{tot}} \) increases by the same factor. The dust-growth timescale then decreases with a similar factor (see equation 6). Recent, more detailed, analysis of this fact is presented by Jones & Nuth (2011) and Hirashita & Kuo (2011). In the latter study, Hirashita & Kuo (2011) show that the time-scale of the grain growth is very sensitive to the grain-size distribution, because the grain growth is mainly regulated by the surface-to-volume ratio of grains, as mentioned above.

This 'grain-shattering scenario' also helps to avoid a too large population of extremely large grains in the ISM, as recent developments in modelling of dust growth and wind formation in...
AGB-star atmospheres suggest dust grains may be relatively large (micron-sized) already when they leave these stars (Höfner 2008; Mattsson & Höfner 2011). Attempts to solve the inverse-problem of finding the grain-size distribution from interstellar extinction measurements suggest dust grains are typically not larger than ~ 1 \( \mu \)m (see, e.g., Clayton et al. 2003), which would pretty much rule out the existence of extremely large grains in the ISM. AGB stars contribute a significant fraction of stellar dust, so the apparent absence of grains larger than ~ 1 \( \mu \)m must either suggest that grains are both grown and shattered to smaller fragments in the ISM, or the micron-sized grains predicted by dynamic AGB-star atmosphere modelling is a false prediction.

Dust grains may also have their chemical-bond structure altered due to external forces rather than being shattered or destroyed (see, e.g., Telles et al. 1987; Jones, Duley & Williams 1990; Vollmer et al. 2003). For example, production of graphite-like carbon dust and even nano-diamonds, is a likely outcome of shock-processing of interstellar dust. This type of dust re-processing is desirable since it is unlikely stars can produce the amount of graphite (or graphite-like) material needed to explain the 2175Å-bump in, e.g., the Milky Way extinction curve (Mathis, Rumpl & Nordsieck 1977; Pel 1992; Kim, Martin & Hendry 1994; Clayton et al. 2003). Carbonaceous dust may also produce hydrocarbons when exposed to shock waves (Taylor & Williams 1993), which would be desirable for similar reasons, as hydrocarbons may contribute to the 2175Å-feature (Blanco et al. 1993) as well as explain infrared features (Kwok & Zhang 2011).

From a more general point of view, there is evidence for dust reprocessing in SN remnants from differences in dust species ratios. In a recent study, Andersen et al. (2011) found the ratio of very small grains to big grains to be higher than that found in the plane of the Milky Way in a study of molecular interacting SN remnants. The discrepancy is typically a factor of 23. They suggest that dust shattering is responsible for the relative over-abundance of small grains, which is consistent with the grain-shattering scenario we suggest and in agreement with prediction from dust destruction models (Jones & Nuth 2011). In some cases small carbon grains are severely underabundant, which is likely evidence for sputtering, according to Andersen et al. (2011).

### 3.5 Are dust abundances generally overestimated?

As it was pointed out above, we believe the dust abundance may be overestimated in a several (if not all) cases. (Munoz-Mateos et al. 2009) uses the model by Draine & Li (2007), which assumes a specific composition of different dust species based on the inferred dust properties of the solar neighbourhood (except the variations of the PAH abundance) and a fixed grain-size distribution. We believe this to be a too simple model of the dust component in a galaxy, mainly because the dust properties in the local Galaxy most certainly do not reflect the dust properties everywhere else and that the grain-size distribution most likely changes with environment (Hirashita & Kuo 2011).

We would also like to point out that the dust-to-hydrogen ratio suggested for the local Galaxy by Draine et al. (2007), i.e., \( M_d/H_0 \sim 0.010 \), is similar to the metals-to-hydrogen ratio for the solar neighbourhood (essentially the same as in the Sun), which implies a dust-to-metals ratio of ~ 0.6. Observationally, this ratio is ~ 0.3 – 0.5 (Whittet 1991), which is also roughly the ratio found in most local galaxies of similar type (see, e.g., Issa et al. 1990). Hence, there is a possibility that the dust abundance could be overestimated due to the model itself. Evidence in support of this idea has recently been presented by Madden et al. (2011), suggesting that the dust-to-gas ratios of dwarf galaxies are not in accord with the low metallicity of these systems.

Furthermore, the estimates by Draine & Li (2007) uses a total carbon abundance of 245 ± 30 ppm relative to H from Asplund et al. (2005). However, Landi, Feldman & Doschek (2007) and Centeno & Socas-Navarro (2008) obtain values of (O/H)\(0\) which are ~ 1.9 times larger than the solar oxygen value of (O/H)\(0\) = 457 ± 56 ppm from Asplund et al. (2005). The solar carbon abundance might therefore be significantly larger than the 245ppm used by Draine & Li (2007). If the total carbon abundance is rather 350 ppm, the mass of carbon in dust would increase by 75% according to Shen, Draine & Johnson (2008). Note, however, that Compiègne et al. (2011) also obtain \( M_d/M_H = 0.010 \) using a different model than that of Draine & Li (2007), which suggest a total carbon abundance of 269 ± 33 ppm relative to H (from Asplund et al. 2004) where 26% is gas phase carbon (to be compared to the 4% in the model by Draine & Li (2007).

Even if the dust abundances may need to be scaled down, we believe the errors are systematic in a way which will not affect the actual slope of the dust-to-gas profile very much. Hence, we consider the results we have obtained here being most likely qualitatively correct, i.e., the dust-to-gas gradients are indeed steeper than the metallicity gradients, suggesting significant dust growth in the ISM.

### 4 CONCLUSIONS

Dust destruction by shocks from exploding SNe is believed to be a rather efficient process, evaporating dust grains such that large volumes of surrounding interstellar space is essentially cleared from dust. We challenge this viewpoint, and suggest that SN shocks induce reprocessing of interstellar dust rather than destroying it. We base our conclusion on the fact that the effect of dust destruction by SN-shock waves on the dust-to-metals gradients in late-type galaxies is not compatible with these gradients being negative in general, which is what observations tell us at this point. SN-shocks may indeed still crush dust grains into small splinters, thus changing the grain-size distribution, but perhaps not disintegrate dust grains completely. Moreover, dust grains may change properties in other ways as well, e.g., through annealing or restructuring of the chemical bonds. The latter may be a way to produce graphite-like dust in the ISM - a type of carbon dust which is unlikely to be formed in any larger quantities in stellar atmospheres.

Two other results also stand out: (1) dust growth in the ISM seem to be the most important dust formation mechanism, and (2) conventional methods for estimating dust abundances may include systematic errors which are not fully under control. Assuming stellar dust production only, we found that dust-to-gas gradients are generally too steep to be reproduced by such a model. Dust growth is an efficient way to steepen the dust-to-gas gradient relative to the metallicity gradient, which makes it an inevitable ingredient in any attempt to model the distribution of dust along galactic discs. In many cases we found the dust growth to be the totally dominant dust production mechanism. However, the need for dust growth may be slightly exaggerated in our models, since there are cases suggesting the dust abundances derived from observations are too high, even after the dust abundances have been scaled down. In these cases the dust-to-metals ratio (as obtained from observations) exceeds unity without rescaling, which is clearly unphysical. If the
amount of dust is systematically overestimated, this may of course affect the need for dust growth.

Regardless of whether the dust abundances should be lower or not, the metal content of the inner part of the galaxies seem dominated by dust in most cases. Even if the dust-to-metals ratios suggest the dust abundances may be overestimated in the central regions in particular, there is a general trend towards higher dust-to-metals at low galactocentric radii (a natural consequence of the dust-to-gas gradient being steeper than the metallicity gradient). This suggest the extinction properties may vary significantly over the disc of a late-type galaxy and the amount of extinction may not simply scale with metallicity. If so, corrections for extinction should not be made using a generic correction method applied to the whole disc.

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