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Spatially resolved dust-to-gas mass ratios in nearby galaxies

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Abstract. We analyse the dust-to-gas mass ratio (DGR) in nearby galaxies on kiloparsec scales. We focus on their dependence on metallicity and the CO-to-H_2 conversion factor, α_{CO}. We use a sample of 25 nearby galaxies from SINGS and combine our data with CO (2-1) and H I observations from the HERACLES and THINGS surveys. We implement a Hierarchical Bayesian method to derive the dust mass via fitting the infrared data from 100 to 500 μm with a single modified blackbody. We find that the DGR-metallicity relation follows a power law and we study its strong dependency on the conversion factor α_{CO}. Our results indicate a strong connection between interstellar dust and gas. The resolved DGR-metallicity relation cannot be represented with a single power law. The scatter in this relation shows the strong impact of several processes that take place in every galaxy.

Keywords. evolution - dust, extinction - galaxies: ISM - infrared: ISM

1. Introduction

Interstellar dust plays a central role in the astrophysics of the interstellar medium (ISM), although it represents only ∼1% of the total mass. Dust particles constitute an important agent in the fluid dynamics, chemistry, heating, cooling and ionisation balance of the ISM. Despite its importance, a comprehensive understanding of dust is still challenging, given the inherent complexity of its evolution in the ISM.

In the far-IR regime ($\lambda \gtrsim 60$ μm), the shape of the Spectral Energy Distribution (SED) coming from dust emission can be modelled as a modified blackbody with a frequency-dependent opacity. This model depends on three main components: dust mass, dust temperature, T, and emissivity index, β. Most observational analyses employ least-squares (χ^2) SED fits to estimate T and β. However, due to its degeneracy, these methods can lead to erroneous estimates and uncertainties in the flux measurements. Kelly *et al.* (2012) found that a Hierarchical Bayesian (hereafter, HB) fitting-technique can accurately estimate the dependence between SED parameters and therefore may be used to further understand grain evolution in the ISM. Additionally, Shetty *et al.* (2016) concluded that the HB methods explicitly treat the correlation between T and β among all pixels and accurately accounts for noise, while the normal χ^2-fit biased the distribution between these parameters towards an artificial anti correlation.

The evolution of the ISM is closely linked with metal enrichment. Elements present in the ISM are processed by gas and dust, providing the conditions to form more complex molecules. The relation between DGR and metallicity provides an important tool to study the evolutionary stage of a galaxy as it links the amount of metals bound in dust and in the gas phase. Therefore, it allows to put constrains on dust evolution models which predict the balance between dust formation, growth and destruction, and the total amount of metals. Rémy-Ruyer *et al.* (2014) analysed the relation between the DGR and metallicity for 126 galaxies and found that the DGR-metallicity relation cannot be represented by a single power law as in our galaxy, but rather a broken power law with a steeper trend for low metallicities. The DGR shows a large scatter for given metallicity throughout the metallicity range, indicating that metallicity is not the only driver for the DGR, and that environmental effects, variations in the star formation histories, dust properties and dust destruction efficiencies may play a role.

In the present work, we study the DGR-metallicity relations in nearby galaxies on kiloparsec scales.

2. Data and method

We use a sample of galaxies that are part of SINGS (Kennicutt *et al.* 2003) and combine it with H I data from THINGS (Walter *et al.* 2008) and VIVA (Chung *et al.* 2009), ^{12}CO $J=(2-1)$ from HERACLES; (Leroy *et al.* 2009), and far-infrared emission from KINGFISH (Kennicutt *et al.* 2011). The resulting sample consists of 25 galaxies. We perform a multi-wavelength analysis and convolve the data to the same resolution, using the lower SPIRE 500 μm resolution. All maps are trimmed to a common size and projected to a common grid with a pixel size of 36". Further details of the convolution and background subtraction can be found in Albrecht *et al.* (in preparation).

Data selection. We select all the pixels with a signal-to-noise (S/N) greater than 2 in the five bands that were used to fit the SED (100 to 500 μm) and in the CO maps. Additionally we exclude pixels with galactocentric radius, $r_{25} > 1.0$, with the exception of galaxy NGC 5055 where we use $r_{25} > 0.7$. The resulting pixels of our 19 galaxies correspond to physical regions that range from 0.28 to 2.6 kpc. We also use the gas-phase oxygen abundances and gradients given by Moustakas *et al.* (2010) for the SINGS sample and combine them with Schruba *et al.* (2018) work. Using the results of both works, we are able to derive a metallicity on every pixel of our galaxy sample.

Atomic and molecular gas. The atomic gas mass was derived using the H I observations from THINGS (Walter *et al.* 2008). We use the CO (2-1) integrated intensity to derive the molecular gas mass through the CO-to-H_2 conversion factor, α_{CO}. We convolve each moment 0 map with a PSF kernel following the procedure explained in Leroy *et al.* (2009). We study three possible scenarios for α_{CO}: a "standard value" of $\alpha_{CO} = 4.4\ M_\odot\ \mathrm{pc}^{-2}$ $(\mathrm{K\ km\ s}^{-1})^{-1}$ given by Bolatto *et al.* (2013), and a metallicity dependent α_{CO} according to Galametz *et al.* (2011) and Schruba *et al.* (2012).

Dust modelling. To provide a consistent determination of the dust masses throughout our sample, we use the model described in Albrecht *et al.* (in preparation). They use the specific intensity I_ν of the dust emission between 100 and 500 μm in galaxies to fit the SED with a single-component modified blackbody. For the SED fitting, we use a hierarchical bayesian approach, which define the joint posterior probability density function for every pixel of the galaxy and a hyperparameter vector for each galaxy through Monte Carlo sampling. From these hyperparameters we can derive mean values for the dust parameters: dust mass surface density, Σ_{dust}, dust temperature, T_{dust}, and emissivity index, β_{dust}, for each pixel of the source.

3. Analysis and results

In Fig. 1 we show the DGR-metallicity relation for our 19 galaxy sample for three scenarios: on the left side, constant α_{CO}, and metallicity dependent according to Galametz *et al.* (2011) and Schruba *et al.* (2012), at the centre and right side respectively. The colours on the data points denote the dust temperature in K. We also show with a red line the power law that Sandstrom *et al.* (2013) found. Our best fit is shown as a blue dashed line. Spearman-rank order is shown as ρ_s. We can see that for a constant α_{CO}

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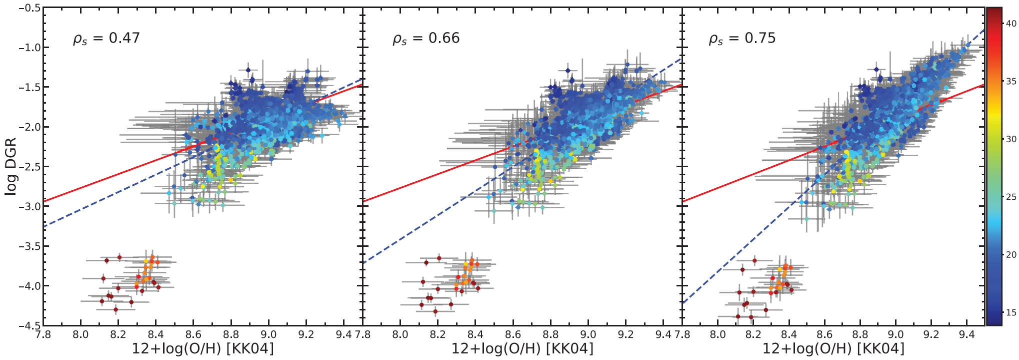

Figure 1. Dust-to-gas mass ratio (DGR) as a function of the metallicity according to the KK04 calibration for three scenarios: constant α_{CO} (left panel), metallicity dependent α_{CO} (centre and right panel). The color coding denotes the dust temperatures T_{dust} in K. The red line is the linear fit found by Sandstrom *et al.* (2013). The blue dashed line show our best linear fit.

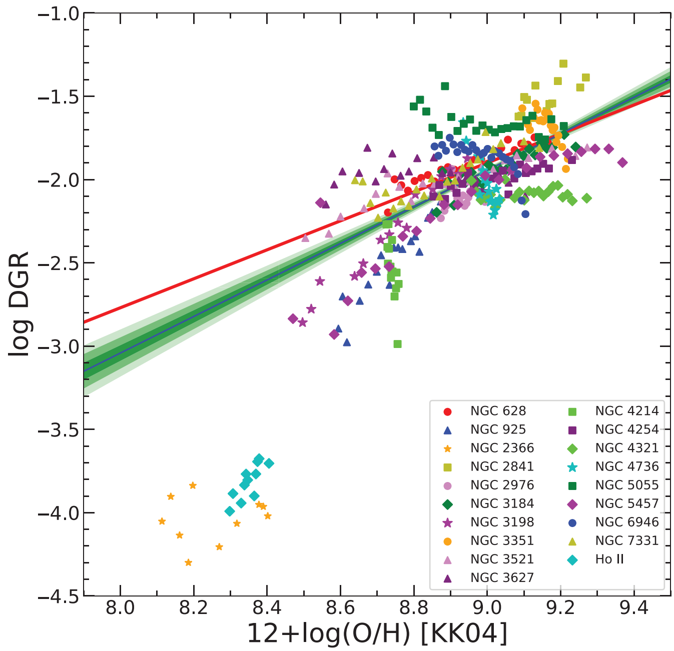

Figure 2. Dust-to-gas mass ratio (DGR) as a function of the metallicity according to the KK04 calibration for the galaxy sample. The red line is the fit found by Sandstrom *et al.* (2013). The blue line show our best linear fit and green shaded regions represent 1-, 2- and 3-σ deviation.

our results are similar with literature, although there are big differences for metallicity dependent α_{CO}. The low metallicity galaxies, represented by NGC 2366 and Holmberg II, do not follow the single power law, but a broken power law as Rémy-Ruyer *et al.* (2014) suggested, with a steeper slope for the low metallicity end. Additionally, we see that dust temperature is also correlated with metallicity, where higher dust temperatures are associated with low metallicity regions and low DGR. On the other hand, the DGR-metallicity relation using a stronger dependency of α_{CO} (right panel) could be explained with a single power law covering the entire metallicity range. More low metallicity galaxies are needed for further analysis.

Figure 2 shows the DGR-metallicity relation for the galaxy sample, considering a constant α_{CO}. The binned values for every galaxy are shown with different symbols and

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colours. We do not find a correlation between the slope on the DGR-metallicity relation with metallicity and morphology of the galaxy. We see that the low metallicity regions located in the outskirts from galaxies NGC 925, NGC 3198 and NGC 5457 follow a different trend than more metal-rich galaxies, more similar to the low metallicity galaxies on the left end of the plot, which is consistent with the broken power law with a steeper slope. However, galaxies like NGC 3351, NGC 4321 and NGC 5055 tend to show a constant or a decreasing DGR with increasing metallicity, showing that DGR-metallicity relation is also dependent on the star formation rate, nucleus type and other internal processes that take place within the galaxies.

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Discussion

Tomotsugu Goto: Can you explain what are the differences amongst the curves plotted in the DGR-metallicity relation?

Basilio Solís-Castillo: The curves in the DGR-metallicity relation represent different models for global values and resolved studies of nearby galaxies, and our best fit. Major differences can be found from galaxy to galaxy due to different morphologies, grain composition and dust temperature.

Adam Carnall: Are you using a Bayesian hierarchical model to fit your galaxies or to combine the data from different galaxies in order to fit your linear relationship? It would be interesting to try SED fitting in a hierarchical Bayesian framework.

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Basilio Solís-Castillo: I am using a hierarchical Bayesian model to fit the SED using FIR data. I also implemented a Bayesian method to make linear fitting in the relations I am studying.

Tsutomi T. Takeuchi: One of the galaxy in you sample shows an increasing tendency of the DGR towards lower metallicity. Could you explain what happens to this galaxy?

Basilio Solís-Castillo: The galaxy that shows an increasing tendency in the DGR-metallicity relation is NGC 5055, and it is not the only one. This galaxy has a central AGN that is affecting the dust distribution and, therefore the DGR. Another important thing we can have to take into account is about the scatter in the metallicity gradient, which could also affect the relation.

Lapo Fanciullo: Does your dust model (which you fit with a modified black body) assume the same dust optical constants (k_0, β) everywhere in the galaxy? If so (especially for the constant k_0), couldn't part of the DGR variation you see be actually an effect of spatial variation in dust optical constants inducing a bias on the fit?

Basilio Solís-Castillo: The dust modelling assumes a frequency dependent opacity (with a given k_0), giving as an output three different free parameters: dust mass surface density, emissivity index and dust temperature. So, on every kpc region there is a β and T, which is different to other regions of the same galaxy. This kind of resolved study allows us to fit pixel-by-pixel the dust model and help us to understand the internal processes of nearby galaxies.