Galactocentric variation of the gas-to-dust ratio and its relation with metallicity

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In collaboration with S. Leurini, J. Urquhart, F. Wyrowski, C. König, K. M. Menten
Main source of extinction for non-ionising photons
Interstellar dust

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Re-emits in the IR
Interstellar dust

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Fundamental for chemistry of the ISM
Interstellar dust

Main source of extinction for non-ionising photons

Re-emits in the IR

Fundamental for chemistry of the ISM

Two main components: silicates and carbonaceous grains
Public surveys of galactic disk are now available providing a complete view of the dust throughout the MW disk.

Dust continuum emission commonly used methods to derive masses and distribution of molecular material.
INTRODUCTION

MASSES FROM DUST CONTINUUM
Dust represent a minor fraction of the total mass in MCs
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Conversion to gas mass via gas-to-dust mass ratio $\gamma$. 
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Common to use this values across the entire disk.
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But...
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Models of dust evolution indicate that $\gamma$ decreases with metallicity $Z$...
At low metallicity, less heavy elements are available to form dust.

Models of dust evolution indicate that $\gamma$ decreases with metallicity $Z$... and thus increases with galactocentric radius.

Taken from Hirashita & Harada 2017

Taken from Dwek 1998
Models of dust evolution indicate that $\gamma$ decreases with metallicity $Z$... and thus increases with galactocentric radius.

Is there evidence for this?

At low metallicity, less heavy elements are available to form dust.
Indications come from observations of external galaxies
Extragalactic observations

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VARIATION OF $\gamma$ IN OUR GALAXY

Motivation
Spatial resolution and sensitivity hard to match in external galaxies
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Direct determination of metal abundance gradients through Cepheids
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Low-metallicity in outer disk can be taken as model for low-metallicity environments.
Spatial resolution and sensitivity hard to match in external galaxies

Direct determination of metal abundance gradients through Cepheids

Low-metallicity in outer disk can be taken as model for low-metallicity environments

More accurate estimates of molecular gas quantity and distribution
WHY \( \gamma \) AND WHY THE MILKY WAY

Spatial resolution and sensitivity hard to match in external galaxies

Direct determination of metal abundance gradients through Cepheids

Low-metallicity in outer disk can be taken as model for low-metallicity environments

More accurate estimates of molecular gas quantity and distribution

Implications for early Universe and low-resolution extragalactic observations
VARIATION OF $\gamma$ IN OUR GALAXY

THE EXPERIMENT
Sources in the far outer Galaxy ($R > 14$ kpc)

Associated with MIR emission (WISE or MSX @ $\approx 22$ micron)

Surface density of molecular gas $> 20 \, M_\odot \, pc^{-2}$, using local $\gamma$
($70 - 230 \, M_\odot \, pc^{-2}$ using values for the Magellanic clouds)
THE SAMPLE

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Surface density of molecular gas $> 20 \, M_\odot \, pc^{-2}$, using local $\gamma$

(70 -- 230 $M_\odot \, pc^{-2}$ using values for the Magellanic clouds)

TOP100: 110 sources with the potential of forming massive stars

Extremely well characterised

Cover the entire evolutionary sequence: only MIR-bright selected

57 sources between $2 \, kpc \lesssim R \lesssim 7 \, kpc$
Far-outer Galaxy:

Single-pointing APEX-1 in setup around $\approx 218$ GHz

Includes $^{18}\text{C} \text{O}$ (2-1)
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Single-pointing APEX-1 in setup around $\approx 218$ GHz

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Inner Galaxy:

TOP100 observed as part of several spectral surveys

$^{17}\text{O}$ (3-2) observed with FLASH$^+$ for entire sample
Variation of $\gamma$ in our Galaxy

Methods
SEDs & DUST SURFACE DENSITIES
From the SEDs we compute the mass of the dust within the aperture and the peak surface density.
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Ossenkopf & Henning model used for the dust composition and properties.
We assume LTE and use $T_{dust}$ to estimate $T_{ex}$. 

To estimate the surface density of molecular gas, we need the $^{18}$O abundance. We assume that CO abundance follows the C/H gradient and we use the local CO/$^{18}$O ratio.
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C is less abundant than oxygen and remain so throughout the disk
VARIATION OF $\gamma$ IN OUR GALAXY

THE GAS-TO-DUST GRADIENT
We obtain a gradient for $\gamma$ of 0.087 dex kpc$^{-1}$
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O/H can be used as a proxy of metallicity

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VARIATION OF $\gamma$ IN OUR GALAXY

FACTORS THAT CAN CHANGE THE GRADIENT SLOPE
Several factors may influence the slope of the gradient:

- Dust composition (e.g. Pei 1992; Weingartner & Draine 2001)
- Degree of coagulation
- CO abundance can be shallower than C/H or steeper: CO/C\textsubscript{18}O gradient
- Increased fraction of CO-dark gas
- Decreased molecular fraction
ADDRESSING UNCERTAINTIES

Several factors may influence the slope of the gradient and make it flatter:

- Dust composition (e.g. Pei 1992; Weingartner & Draine 2001)
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Addressing uncertainties

Several factors may influence the slope of the gradient and make it **flatter**:

- Dust composition (e.g. Pei 1992; Weingartner & Draine 2001)
- Degree of coagulation
- CO abundance can be shallower than C/H

or **steeper**:

- CO/C\textsuperscript{18}O gradient
- Increased fraction of CO-dark gas
- Decreased molecular fraction
We consider as limiting cases:

- Flat - CO abundance following O/H gradient
- Steep - CO abundance computed with CO/C18 O gradient

Thus \( \gamma \propto Z^{-1} - Z^{-2}.4 \)

\[ \log(\gamma) = 0.132 R_{GC} + 0.99 \]

\[ \intrinsic\ \text{scatter} = 0.2 \]

\[ \log(O/H) + 12 \]

\[ \gamma \]

\[ R_{GC} \ [\text{kpc}] \]

9.0 8.8 8.6 8.4 8.2 8.0

\[ 10^1 \]

\[ 10^2 \]

\[ 10^3 \]

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Flat - CO abundance following O/H gradient

Steep - CO abundance computed with CO/C$^{18}$O gradient

Thus $\gamma \propto Z^{-1.1} - Z^{-2.4}$
Magellanic Clouds have $Z = 0.5, 0.2Z_{\odot}$.
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For this $Z$ we obtain $\gamma = 420, 1750$ accounting for He; excellent agreement with Roman-Duval et al. 2014
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Our results show that the dust-to-metal ratio decreases with $R$

Most common situation in external late-type galaxies, and suggests that dust growth dominates over destruction

Taken from Mattsson et al. 2012
VARIATION OF $\gamma$ IN OUR GALAXY

SUMMARY
Summary

The gas-to-dust ratio in the Milky Way shows a radial gradient. It increases by 0.087 dex kpc\(^{-1}\), or, equivalently it varies as \(Z^{-1.4}\).

Predicted \(\gamma\) for \(Z\) of Magellanic Clouds is in excellent agreement with observational estimates.

Metal-to-dust ratio decreases radially, as commonly observed in external late-type galaxies. This indicates that dust growth dominates over destruction.
JAGS is used to model the $\Sigma_{\text{gas}}/\Sigma_{\text{dust}}$ ratio, considering uncertainties.
CO ABUNDANCE

C/H is significantly steeper than O/H
CO ABUNDANCE

C/H is significantly steeper than O/H

\[ C/H \approx 0.080 \, \text{dex kpc}^{-1} \]
C/H is significantly steeper than O/H

\[ \text{C/H} \approx 0.080 \text{ dex kpc}^{-1} \]

\[ \text{O/H} \approx 0.056 \text{ dex kpc}^{-1} \]
Dust coagulation

Table 1. Dust opacities at the beginning and after 10^5 years of coagulation at 10^6 and 10^8 cm^{-3} for the three different initial distributions.

| Initial distribution: | MRN 10^6 | MRN 10^8 | MRN with thin ice mantles 10^6 | MRN with thick ice mantles 10^6 | MRN 10^8 | MRN with thin ice mantles 10^8 | MRN with thick ice mantles 10^8 |
|-----------------------|----------|----------|-------------------------------|---------------------------------|----------|-------------------------------|---------------------------------|
| Gas density [cm^{-3}] |          |          |                               |                                 |          |                               |                                 |
|                      | Fig. 1a  | Fig. 2a  | Fig. 2b                       | Fig. 1b                         | Fig. 3a  | Fig. 3b                       | Fig. 1c                         | Fig. 4a  | Fig. 4b                       |
|                      |          |          |                               |                                 |          |                               |                                 |          |                               |
| λ [µm]               |          |          |                               |                                 |          |                               |                                 |          |                               |
| 5.41e+1              | 9.05e+1  | 1.45e+2  | 2.19e+2                      | 1.92e+2                        | 2.80e+2  | 3.48e+2                      | 9.79e+2                        | 1.19e+3  | 1.34e+3                      |
| 6.31e+1              | 7.16e+1  | 1.16e+2  | 1.76e+2                      | 1.43e+2                        | 2.11e+2  | 2.63e+2                      | 6.59e+2                        | 8.21e+2  | 9.37e+2                      |
| 7.36e+1              | 5.60e+1  | 9.19e+1  | 1.41e+2                      | 1.05e+2                        | 1.58e+2  | 1.97e+2                      | 4.25e+2                        | 5.41e+2  | 6.22e+2                      |
| 8.58e+1              | 4.37e+1  | 7.32e+1  | 1.14e+2                      | 7.76e+1                        | 1.18e+2  | 1.47e+2                      | 2.62e+2                        | 3.40e+2  | 3.90e+2                      |
| 1.00e+2              | 3.44e+1  | 5.92e+1  | 9.38e+1                      | 5.56e+1                        | 8.65e+1  | 1.07e+2                      | 1.72e+2                        | 1.95e+2  | 1.95e+2                      |
| 1.17e+2              | 2.70e+1  | 4.82e+1  | 7.86e+1                      | 4.30e+1                        | 6.75e+1  | 8.30e+1                      | 8.30e+1                        | 1.13e+2  | 1.28e+2                      |
| 1.36e+2              | 2.07e+1  | 3.88e+1  | 6.57e+1                      | 3.30e+1                        | 5.25e+1  | 6.45e+1                      | 5.73e+1                        | 7.91e+1  | 8.85e+1                      |
| 1.58e+2              | 1.59e+1  | 3.16e+1  | 5.61e+1                      | 2.53e+1                        | 4.09e+1  | 5.03e+1                      | 3.98e+1                        | 5.57e+1  | 6.19e+1                      |
| 1.85e+2              | 1.17e+1  | 2.53e+1  | 4.74e+1                      | 1.87e+1                        | 3.07e+1  | 3.77e+1                      | 2.71e+1                        | 3.84e+1  | 4.23e+1                      |
| 2.26e+2              | 8.16e+0  | 1.95e+1  | 3.89e+1                      | 1.30e+1                        | 2.17e+1  | 2.67e+1                      | 1.75e+1                        | 2.51e+1  | 2.74e+1                      |
| 3.50e+2              | 3.64e+0  | 1.13e+1  | 2.58e+1                      | 5.91e+0                        | 1.01e+1  | 1.24e+1                      | 7.79e+0                        | 1.12e+1  | 1.20e+1                      |
| 5.00e+2              | 1.77e+0  | 7.61e+0  | 1.98e+1                      | 2.90e+0                        | 5.04e+0  | 6.21e+0                      | 3.79e+0                        | 5.50e+0  | 5.72e+0                      |
| 7.00e+2              | 9.09e−1  | 4.56e+0  | 1.25e+1                      | 1.48e+0                        | 2.57e+0  | 3.18e+0                      | 1.93e+0                        | 2.81e+0  | 2.93e+0                      |
| 1.00e+3              | 4.77e−1  | 2.74e+0  | 7.85e+0                      | 7.81e−1                        | 1.37e+0  | 1.69e+0                      | 1.01e+0                        | 1.48e+0  | 1.54e+0                      |
| 1.30e+3              | 3.09e−1  | 1.99e+0  | 5.86e+0                      | 5.11e−1                        | 8.99e−1  | 1.11e+0                      | 6.48e−1                        | 9.62e−1  | 1.00e+0                      |

Taken from Ossenkopf & Henning 1994
## Dust coagulation

Table 1. Dust opacities at the beginning and after $10^5$ years of coagulation at $10^6$ and $10^8$ cm$^{-3}$ for the three different initial distributions.

| Initial distribution: Gas density [cm$^{-3}$] | MRN $10^6$ | MRN with thin ice mantles $10^6$ | MRN with thick ice mantles $10^6$ | $10^8$ | $10^8$ | $10^8$ | $10^8$ |
|---------------------------------------------|-------------|---------------------------------|---------------------------------|-------|-------|-------|-------|
| Fig. 1a                                     | Fig. 2a     | Fig. 2b                         | Fig. 1b                         | Fig. 3a| Fig. 3b| Fig. 1c| Fig. 4a|
| $\lambda [\mu m]$                           | $\kappa$ [cm$^2$/g]| $\kappa$ [cm$^2$/g]| $\kappa$ [cm$^2$/g]| $\kappa$ [cm$^2$/g]| $\kappa$ [cm$^2$/g]| $\kappa$ [cm$^2$/g]| $\kappa$ [cm$^2$/g]| $\kappa$ [cm$^2$/g]|
| 5.41e+1                                     | 9.05e+1     | 1.45e+2                         | 2.19e+2                         | 1.92e+2| 2.80e+2| 3.48e+2| 9.79e+2| 1.19e+3| 1.34e+3|
| 6.31e+1                                     | 7.16e+1     | 1.16e+2                         | 1.76e+2                         | 1.43e+2| 2.11e+2| 2.63e+2| 6.59e+2| 8.21e+2| 9.37e+2|
| 7.36e+1                                     | 5.60e+1     | 9.19e+1                         | 1.41e+2                         | 1.05e+2| 1.58e+2| 1.97e+2| 4.25e+2| 5.41e+2| 6.22e+2|
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| 1.36e+2                                     | 2.07e+1     | 3.88e+1                         | 6.57e+1                         | 3.30e+1| 5.25e+1| 6.45e+1| 5.73e+1| 7.91e+1| 8.85e+1|
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| 5.00e+2                                     | 1.77e+0     | 7.61e+0                         | 1.98e+1                         | 2.90e+0| 5.04e+0| 6.21e+0| 3.79e+0| 5.50e+0| 5.72e+0|
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| 1.00e+3                                     | 4.77e−1     | 2.74e+0                         | 7.85e+0                         | 7.81e−1| 1.37e+0| 1.69e+0| 1.01e+0| 1.48e+0| 1.54e+0|
| 1.30e+3                                     | 3.09e−1     | 1.99e+0                         | 5.86e+0                         | 5.11e−1| 8.99e−1| 1.11e+0| 6.48e−1| 9.62e−1| 1.00e+0|

Taken from Ossenkopf & Henning 1994
Wilson & Rood (1994) find
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Steeper when considering sources in the outer Galaxy
Wilson & Rood (1994) find
$^{16}\text{O} / ^{18}\text{O} = 58.8 R_{GC} + 37.1$

Steeper when considering sources in the outer Galaxy

However unclear from OH measurements

Taken from Nittler et al. 2012
WLM galaxy in the local group: $D \sim 1$ Mpc, $Z \sim 0.13Z_{\odot}$

Red: H$\alpha$

Green: H$\text{I}$

Blue: [C$\text{II}$] 158 micron
WLM galaxy in the local group: $D \sim 1\,\text{Mpc}, Z \sim 0.13Z_\odot$

Red: H$_\alpha$

Green: H$\text{I}$

Blue: [C$\text{II}$] 158 micron

CO is detected in clumps only!
Uncertainties on $\gamma$

Dust: composition, two temperatures, opacity

Is a model with a constant value of $\gamma$ to be favoured?

From Bayesian model comparison odds ratio of $\gtrsim 8$ in favour of the gradient models.
Uncertainties on $\gamma$

Dust: composition, two temperatures, opacity

Gas: CO canonical abundance, LTE assumption, CO-C$^{18}$O conversion

Overall uncertainty: factor of $\approx 6$

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