Constraining the properties of interstellar silicate dust using X-ray and infrared spectroscopy

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The life cycle of dust in the universe

Dust has an important role in the processes that drive the evolution of the Interstellar Medium (ISM)
Interstellar dust

Two main groups:
• Carbonaceous dust
• Silicate dust

Depending on the environment there is ice: (CO, H₂O, NH₃, CH₄, CO₂ etc.)

And perhaps: Sulfide minerals: FeS, FeS₂, MnS (?)
What we think we know about silicates in the ISM ...

Main composition: Si, O, Mg and Fe
olivine and/or pyroxene silicates with smaller quantities of silicon oxides and SiC
Exact composition is still uncertain!

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass Number</th>
<th>Atomic Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>16.00</td>
<td>8</td>
</tr>
<tr>
<td>Silicon</td>
<td>28.09</td>
<td>14</td>
</tr>
<tr>
<td>Magnesium</td>
<td>24.31</td>
<td>12</td>
</tr>
<tr>
<td>Iron</td>
<td>55.84</td>
<td>26</td>
</tr>
</tbody>
</table>
What we think we know about silicates in the ISM …

• Silicate dust in the Galaxy is mainly amorphous
  Formation process uncertain, contradiction with X-rays

Kemper et al. 2004

Westphal et al. 2014

NDT Resource Center, Center for NDE, Ioawa State University
What we think we know about silicates in the ISM …

The sizes of the dust particles range from small molecular size to micron size dust

Many different size distribution models

Zubko et al. 2004, Mathis 1977 et al.  
Draine & Fraisse 2009  
Weingartner & Draine 2001
Observational constraints on Silicate Dust properties

- What is the composition of the dust?
- What is the ratio of crystalline/amorphous dust?
- What is the size distribution of dust in the ISM?
- Do the properties of dust vary in different environments?

X-rays can provide an answer!
Why study dust in the X-rays?

• X-ray band offers complementary information with respect to longer wavelengths

• X-rays are sensitive to a wide range of column densities; makes it possible to analyze dust content in various regions

• Scattering and absorption of X-rays by dust simultaneously studied

• Absorption of both gas and dust can be measured simultaneously (element depletion easy to determine)
What can we study in the X-rays?

Observe absorption features in the soft X-rays of O, Mg, Si and Fe

Perfect for Silicates!
What can we study in the X-rays

Costantini, Zeegers 2019
Observing dust in the X-rays

e.g. Lee 05,09 Costantini 12, Pinto 10,13, Corrales 16, Zeegers 17
Sightlines towards the Galactic Plane

We can probe different lines of sight along the Galactic Plane
Diffuse and Dense sightlines

Depending on the environment we can observe different edges

\[ N_H = 7 \times 10^{20} \text{ cm}^{-2} \]
Observing dust in the X-rays

XAFS provide a unique fingerprint of Interstellar Dust
XAFS: X-ray absorption fine structure

\[ E_{\text{kin}} = E_{\text{photon}} - E_0 \]

\[ \frac{\text{Absorption probability}}{E_0 \text{ Energy}} \]
What can we learn from X-ray edges?

XAFS: Unique features for different dust compositions

Crystalline versus Amorphous

Olivine Mg$_{1.56}$Fe$_{0.4}$SiO$_4$
Pyroxene Mg$_{0.75}$Fe$_{0.25}$SiO$_3$
Laboratory dust campaign

Dust samples ➔ Synchrotron measurements ➔ Data analysis ➔ Fitting Spectra

Natural or synthetized:
Olivines
Pyroxenes
Quartz types
(courtesy of H. Mutschke)

Obtain optical constants

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X-ray dust campaign

LUCIA
Mg K at 1.3 keV
Si K at 1.84 keV

DUBBLE
Fe K at 7.11 keV

Cadiz (TITAN)
O K at 0.543 keV
Fe L at 0.7 keV
Laboratory dust campaign

Dust samples → Synchrotron measurements → Data analysis → Fitting Spectra

Conversion from lab absorption spectra to extinction models
From measurements to ID Models

\[ m = n + ik \]

Refractive index

Energy

Size distribution

Dust

Mie scattering code

Extinction profiles

From absorption to Extinction
Laboratory dust campaign

Dust samples → Synchrotron measurements → Data analysis → Fitting Spectra

Conversion from lab absorption spectra to extinction models

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Extinction curve

Figure: D. Rogantini
Analyzing the Si K-edge with:
9 Sources (Chandra)
14 dust samples
Best fit: Mix of amorphous Olivine
( \( [\text{Mg}_{0.5}\text{Fe}_{0.5}]_2\text{SiO}_4 \) ) and
Crystalline Olivine
( \( \text{Mg}_{1.56}\text{Fe}_{0.4}\text{Si}_{0.91}\text{O}_4 \) )
(Zeegers et al.2017, Zeegers et al. 2019)
Results Si K-edge using X-ray spectroscopy

• Olivine dust preferred over pyroxene

• Best fitting dust mixtures: 60-90% amorphous olivine and 4-12% crystalline dust

• Best fitting dust mixes contain within 3 sigma <30%:
  - Quartz
  - Iron poor pyroxenes

Zeegers et al. 2019, Rogantini 2019 accepted
Si Abundances toward the GC

Zeegers et al. 2019
What can we learn from X-ray edges?

Scattering feature: Information about particle sizes
Grain size distribution

New method to investigate grain sizes of interstellar dust

Figure by: Irene Abril Cabezas
Grain size distribution

ATHENA Simulation of amorphous olivine

Expected launch: early 2030s

Figure by: Irene Abril Cabezas
Combining edges for global modelling

Importance of broad band extinction models for interstellar dust, for example:
- Constraints on iron
- Constraining silicates in various environments
- Sulfur in dust (?)

Goal:

Combine models of all the measured edges

Corrales et al. 2016
Hoffman & Draine 2016
Draine 2003
Bright future for X-rays and dust!

Costantini, Zeegers 2019
Bright future for X-rays and dust!

Carbon K-edge

Sulfur K-edge

Costantini, Zeegers 2019
The properties of small silicate grains

[Diagram showing the relationship between particle size (µm) and the number of particles, with a transition to the nano-particle regime and bulk properties.]
Small particles in the infrared

Olivine \((\text{Mg}_2\text{SiO}_4)_{10}\)

Small Silicates database:
10 olivines
10 pyroxenes

Calculations by:
A. Macià Escatllar et al. ACS Earth and Space Chemistry 2019
Small silicates in the infrared

The presence of small silicates can tell us about the formation history of grains

Infrared spectrum of Cyg OB2 no. 12

Stay tuned!

Fogerty et al. 2016
Summary & conclusion

• Multi wavelength approach necessary to constrain the dust properties:
  ➢ Small silicate particles can give new insights in the formation and destruction processes of interstellar grains, as well as crystallinity
  ➢ X-ray provide complimentary information on the properties of silicates:
    - crystallinity
    - composition
    - grain size
• Bright future with upcoming observatories and new dust models in both X-rays and infrared!