Studying Interstellar Dust Grain Composition
with X-ray spectroscopic imaging

Lia Corrales
MIT Kavli Institute

Collaborators
Javier Garcia (CfA), Randall Smith (SAO/CfA), Joern Wilms (Remeis), Norbert Schulz (MKI), Mike Nowak (MKI), Frederick Baganoff (MKI)
Periodic Elements of Dust

- Mg
- Si
- Fe
- C
- N
- O
- Ne
- Mg$_2$SiO$_4$
- MgSiO$_3$
- MgO
- Fe$_3$O$_4$
- SiO$_2$
- Mg$_2$SiO$_4$
- MgSiO$_3$
- SiC
- PAHs

Krasnojarsk meteorite (AMNH)

Solar Metals

Oxides:
- MgO$_3$
- SiO$_2$
- Fe$_3$O$_4$

Silicates:
- Mg$_2$SiO$_4$
- MgSiO$_3$

Graphite & PAHs

+ many other trace elements (S, P, Ca, Cl, Ti)

(99%)
Dust Life Cycle

Stellar evolution & death

Molecular clouds

growth, chemical processing

ISM processing

star formation

processing in disks

chemicals freeze out and condense, forming grains with mantles

nucleosynthesis

dust production in AGB stars, SNe?

\( \sim 2000 \text{ Myr} \)

shocks lead to shattering, sputtering

\( \sim 500 \text{ Myr} \)

Tielens

Jones & Tielens 1994, 1996
Big questions

1. What is **dust grain composition** in diffuse ISM?

2. **Where does dust grow** and **how big can it get**?

3. How does dust influence the **physics of the ISM**: star formation, feedback, and galaxy evolution?
Using bright X-ray point sources as beacons, we can **probe the dust and gas** properties of the **cool phase Universe**.

**absorption**
probes total metal column (dust + gas)

**scattering**
probes large end of the grain size distribution
Milky Way optical depth due to dust

![Graph showing Milky Way optical depth due to dust](image)

- X-ray
- Optical
- J, H, K, L (Keck)
- Herschel
- Spitzer

Opacity / $N_H$ ($10^{21}$ cm$^{-2}$)

Wavelength [µm]
Dust model used in this talk

$dn_d/da \propto a^{-3.5}$

$0.005 \mu m \leq a \leq 0.3 \mu m$

Astrosilicate and Graphite optical constants from Draine (2003)

60% silicate
40% graphite

no amorphous, iron needles, or low-filling factor (“fluffy”) dust
Using bright X-ray point sources as beacons, we can **probe the dust and gas** properties of the **cool phase Universe**.

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**scattering**
probes large end of the grain size distribution
light scattered by dust **intermediate in line of sight** produces a scattering **halo image**

\[ \theta_{\text{sca}} \lesssim 10' E_{\text{keV}}^{-1} \]

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dust scattering mainly affects **sub-arcmin resolution instruments**
X-ray scattering is a diagnostic tool for ISM grain sizes.

SGR J1550-5418
(NASA/Swift/Halpern)
X-ray scattering is a diagnostic tool for ISM grain sizes

\[
\tilde{\sigma} \approx \frac{1'}{a(\mu m) E(\text{keV})}
\]

SGR J1550-5418
(NASA/Swift/Halpern)

Strongly forward (small angle) scattering

X-ray Vision Workshop - October 8, 2015
Corrales, L. R.
X-ray scattering is a diagnostic tool for ISM grain sizes

Strongly forward (small angle) scattering

Strongly sensitive to grain size

\[ \tilde{\sigma} \approx \frac{1'}{a(\mu m) \ E(keV)} \]

\[ \sigma_{sca} \propto a^4 E^{-2} \]
Scattering halo flux yields **direct measurement of scattering cross-section**

Cyg OB2 Legacy Survey
(Wright+ 2015)

\[
\frac{F_h}{F_{ps}} = e^{\tau_{sca}} - 1
\]

Cyg X-3 (HETG)

*image credit: Jeremy Drake*
Scattering halo flux yields **direct measurement of scattering cross-section**

Cyg OB2 Legacy Survey  
(Wright+ 2015)

$$\frac{F_h}{F_{ps}} = e^{\tau_{sca}} - 1$$

Cyg X-3  
(HETG)

image credit: Jeremy Drake
Scattering halo flux yields **direct measurement of scattering cross-section**

Cyg OB2 Legacy Survey
(Wright+ 2015)

\[ \frac{F_h}{F_{ps}} = e^{\tau_{sca}} - 1 \]

\[ \frac{F_{h}^{obs}}{F_{ps}} = f_{cap} \left( e^{\tau_{sca}} - 1 \right) \]

image credit: Jeremy Drake

Cyg X-3 (HETG)
The scattering halo of Cyg X-3 supports several solutions, degeneracy might be broken with energy resolved scattering halos

Corrales & Paerels (2015)
The scattering halo of Cyg X-3 supports several solutions, degeneracy might be broken with energy resolved scattering halos
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$\text{Corrales & Paerels (2015)}$

$A_{\text{max}} = 1.5 \ \mu\text{m}$

$p = 3.6$
Spectrum of dust scattered light should have features coincident with absorption edge structure from constituent elements.
Simulated spectrum (micro-calorimeter)

Source spectrum (black), Scattering halo spectrum (red)

\[ F_a [1 - \exp(-\tau_{\text{sca}})] \]
Ratio of halo to source reveals dust spectral features

\[
\frac{F_h}{F_a} = 1 - \exp(-\tau_{\text{sca}})
\]
Approach 1: X-ray Scattering

1. **Wide field of view is important**

2. Need to image SB over several orders of magnitude

3. **High resolution imaging**
   — avoid confusion (point source vs halo)
   — probe deeper into sight line (dust closer to source)
   — image fainter scattering echoes

4. **Can we push to C-K edge?**
   — PAHs (2175 Angs) are lever-arm for many dust models
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X-ray Absorption Fine Structure (XAFS)
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scattering contribution: see also Costantini, Zeeger, Hoffman & Draine (2015)

X-ray Vision Workshop - October 8, 2015
Fraction of dust scattering halo captured within source extraction region (PSF)

- Uniform
- Screen

* new xspec model coming soon
Absorption edge fine structure is also dependent on imaging resolution and grain size.

MRN dust

0.3 micron grains

X-ray Vision Workshop - October 8, 2015
Corrales, L. R.
$N_H = (3.15 \pm 0.21) \times 10^{21} \text{ cm}^{-2}$

LMXB GX 9+9 (96 ks)

Fe-L edge

$N_H = (3.15 \pm 0.21) \times 10^{21} \text{ cm}^{-2}$

Gatuzz et al. (2015)
GX 9+9 with X-ray Surveyor Gratings, exp=50.0 ks

Counts/bin

Wavelength (Å)

abs + sca

abs only

MEG 1 (96 ks)
We need lab astrophysics and scattering models

Use absorption cross-section to measure optical constants -> compute extinction

LAB
Kortright & Kim (2000)
van Aken & Liebscher (2002)
Lee et al. (2009)
Lee (2010)
Costantini (e.g. 2013)

MODELS
Draine (2003)
Hoffman & Draine (2015)
Smith, Valencic, Corrales (in prep)

Figure 5.

Figure 6.
Approach 2: X-ray Absorption Fine Structure

1. We need to be able to observe bright objects!!

2. **Gratings**
   - mitigate pileup
   - high-resolution spectroscopy in the soft X-ray

3. Need high S/N, high resolution spectroscopy
The distance to Circinus X-1 is highly uncertain. As a result of the source's high variability, it has undergone a secular decline in flux to its brightest flares. While the source was consistently bright during the 1990s, it underwent a secular decline in flux during the five years it has been monitored by MAXI. Flare properties depend on the distance to the source, with near-Eddington flares sometimes in excess of one Crab equivalent. The Eddington fraction of the source in outburst is a more complete understanding of this important source. The ASM was one of three instruments aboard the International Space Station X-ray Timing Explorer, with the exception of sporadic echoes visible in this image. A likely range of the distance to Circinus X-1 has been estimated to range from 4 kpc to 11 kpc. The lack of X-ray or radio pulses combined with spectral properties proposed by Jonker & Nelemans (2004) based on the XMM all sky monitor aboard the Rossi X-ray Timing Explorer past 10 years below the detection thresholds of the XMM national Space Station X-ray Timing Explorer. Despite these limitations, a more accurate determination of the distance is critical for a more complete understanding of this important source.
What can X-ray scattering do for you?

1. **Distance measurements to X-ray binaries**
   — variability
   — CO and IR measurements will help

   see Tiengo et al. (2010), Mao et al. (2014), Heinz et al. (2015),

2. **Trace the metals** *(neutral vs hot phase)*
   — measure depletion
   — determine metallicity in your plasma / gas of interest

   see Gatuzz et al. (2014)
Dust absorption features from obscured, moderately redshifted AGN?
need high resolution soft X-ray spectroscopy

Absorption or scattering features from CGM?
need quasar-galaxy pairs or lensed quasars,
larger effective area for dimmer objects, low NH

Scattering echoes from diffuse CGM or IGM dust?
need larger effective area, low background, high resolution
see Corrales & Paerels (2012), Corrales (2015)
Summary

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**Distance measurements to X-ray binaries**

**Trace the metals**