SESSION 12

Laboratory Astrophysics: from Observations to Interpretation
Proceedings IAU Symposium No. 350, 2019
F. Salama & H. Linnartz, eds.
doi:10.1017/S1743921320000332

Modelling the properties of interstellar dust using the Si K-edge

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Abstract. The properties of interstellar dust (ID) can be studied in great detail by making use of X-ray spectroscopy techniques. The radiation of X-rays sources is scattered and absorbed by dust grains in the interstellar medium. The X-ray band is especially suitable to study silicates - one of the main components of ID -since it contains the absorption edges of Si, Mg, O and Fe. In the Galaxy, we can use absorption features in the spectra of X-ray binaries to study the size distribution, composition and crystalline structure of grains. In order to derive these properties, it is necessary to acquire a database of detailed extinction cross sections models, that reflects the composition of the dust in the interstellar medium. We present the extinction profiles of a set of newly acquired measurements of 14 dust analogues at the Soleil Synchrotron facility in Paris, where we focus on silicates and the Si-K edge in particular, which is modelled with unprecedented accuracy. These models are used to analyse ID in the dense environments of the Galaxy.

Keywords. ISM: dust, extinction, X-rays: binaries

1. Introduction

Interstellar silicates are a major component of interstellar dust (Tielens 2001). Therefore, in order to make correct assumptions on the many processes in the universe where dust plays a role, it is important to put constrains on the properties of interstellar silicates. The composition of interstellar dust and, in particular, silicates can be roughly inferred from the abundance of elements and the amount of these elements that is missing from the gas phase and assumed to be locked up in dust (e.g. Jenkins *et al.* 2009). Infrared spectroscopy of ID and studies of meteorites and interplanetary dust give further insight in the composition of ID (e.g. Tielens et al. 2005). Observations in the infrared also indicate that dust is mostly amorphous (Kemper *et al.* 2004) and Galactic extinction studies have helped constrain the dust size distribution (e.g. Greenberg 1968). However, despite these studies, still many questions on the properties on ID remain to be answered. The X-rays are especially suitable to study the properties of silicate dust, since the edges of O, Fe, Si and Mg - the main components of interstellar silicates - fall in the soft X-ray band (e.g. Draine 2003; Lee *et al.* 2009; Costantini 2012). From these edges

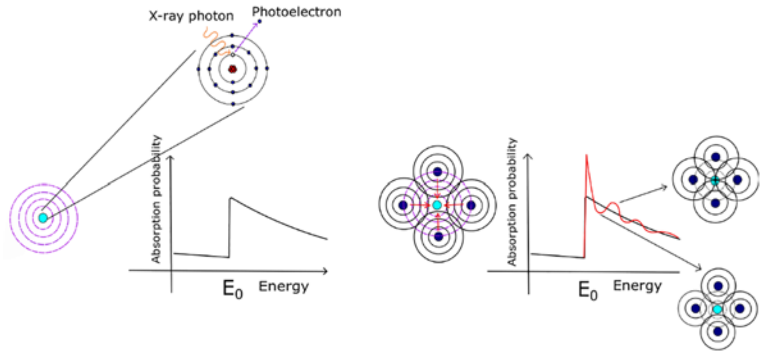

Figure 1. XAFS: the top left shows an X-ray photon which excites a core-electron. The wave function of the photo electron propagates outwards. When there are neighboring atoms present, the wave function of the photo electron interferes with waves that scatter from the neighboring atoms, producing an oscillatory fine structure, as shown on the right.

we can infer the composition, size distribution and structure (crystalline/amorphous) of the grains. We can use the spectra of X-ray binaries to study the intervening dust in the Galaxy. Here we show how we used the spectra of low mass X-ray binaries to study the properties of the dust toward the central Galactic environment using newly acquired laboratory data of the Si K-edge.

2. X-ray absorption fine structures (XAFS) and interstellar dust

X-ray absorption fine structures (XAFS) are modulations near the atomic edge (Meurant 1983). When an X-ray photon with the right energy excites a core electron, the ionized electron will behave like a photo electron, as described in Figure 1. When neighboring atoms are present, the wave function of the photo electron interferes with waves that scatter from the neighboring atoms, producing an oscillatory fine structure characteristic for the chemical composition of the mineral. Each composition has its own unique XAFS pattern and can thus be used to characterize the composition of the dust. In this analysis we focus on the K-edge of silicon.

3. From laboratory measurements to cosmic dust models of the Si K-edge

We measured the Si K-edge of 14 silicate dust analogues at the Soleil synchrotron facility in Paris, using the LUCIA beamline (Flank *et al.* 2006). The sample set contains pyroxene, olivine and quartz type dust and each of these types has both amorphous and crystalline counterparts. The sample were chosen in such a way that they represent possible components of silicate dust in the ISM. The sample set consists of both synthesized silicates and silicates of natural origin. The dust samples and their compositions are listed in Table 1. For more information on these samples and a detailed analysis of the laboratory data we refer to Zeegers *et al.* 2017 and Zeegers *et al.* 2019. The laboratory absorption spectra need to be converted to extinction spectra in order to include scattering features of the dust into the models. From the obtained absorption features shown in Figure 2 we derived the imaginary part of the optical constants and calculated the real part. Subsequently, we used a Mie scattering code (Wiscombe 1980) to derive the extinction, where we assumed an MRN size distribution for spherical grains.

In Figure 3, we show, as an example, models of olivine (sample 1). In red we show the classic MRN (Mathis *et al.*) size distribution and in blue we show a model with large particle sizes. The feature at ~ 6.75 before the edge is more prominent when large

Table 1. Samples

No.	Name	Chemical formula	Structure	Comments
1	Olivine	$Mg_{1.56}Fe_{0.4}Si_{0.91}O_4$	crystal	Natural olivine, origin: Sri Lanka
2	Pyroxene	$Mg_{0.9}Fe_{0.1}SiO_3$	amorphous	Synthesized
3	Pyroxene	$Mg_{0.9}Fe_{0.1}SiO_3$	crystal	Synthesized
4	Enstatite	$MgSiO_3$	crystal	Natural enstatite, origin Kiloza, Tanzania
5	Pyroxene	$Mg_{0.6}Fe_{0.4}SiO_3$	amorphous	Synthesized
6	Pyroxene	$Mg_{0.6}Fe_{0.4}SiO_3$	crystal	Synthesized
7	Olivine	$(Mg_{0.5}Fe_{0.5})_2SiO_4$	amorphous	Synthesized
8	Pyroxene	$Mg_{0.75}Fe_{0.25}SiO_3$	amorphous	Synthesized
9	Fayalite	Fe_2SiO_4	crystal	Synthesized at the University of Frankfurt, Physical Institute
10	Enstatite	$MgSiO_3$	amorphous	Synthesized
11	Forsterite	Mg_2SiO_4	crystal	Commercial product of Alfa Aesar.
12	Quartz	SiO_2	crystal	natural rock crystal from Brazil
13	Quartz	SiO_2	amorphous	Commercial product of Qsil Ilmenau, Germany, named "ilmasil".
14	Quartz	SiO_2	amorphous	Commercial amorphous silica powder supplied b Fisher Scientific.

Notes: Samples 2, 3, 5, 7, 8 and 10 were synthesized for this analysis in laboratories at AIU Jena and Osaka University.

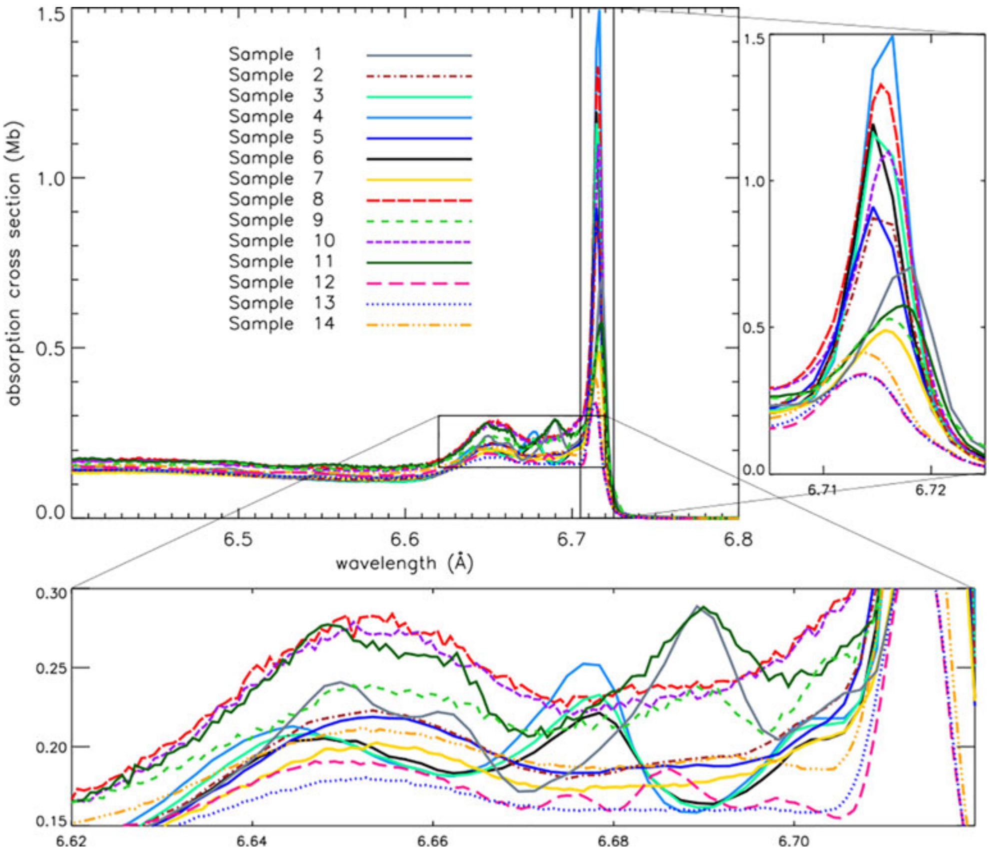

Figure 2. Laboratory measurements of the Si K-edge. The x-axis shows the energy in angstroms and the y-axis shows the amount of absorption in Mb per Si atom. Note the difference between crystalline and amorphous samples.

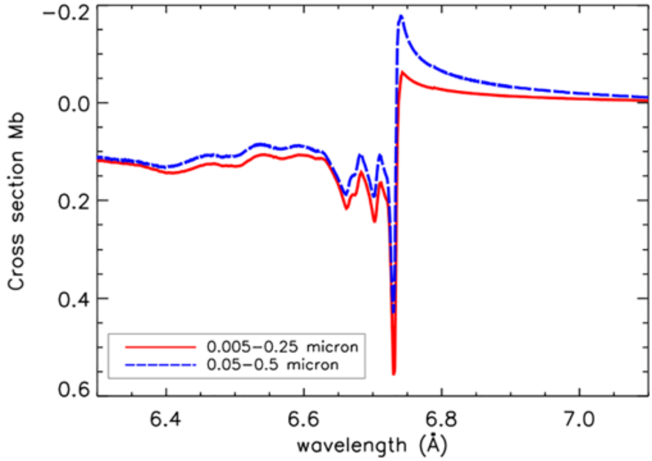

Figure 3. Two grain size distributions: the red line shows the MRN size distribution with grain sizes $0.005 - 0.25\ \mu$m while the blue line shows a particle size range between $0.05 - 0.5\ \mu$m.

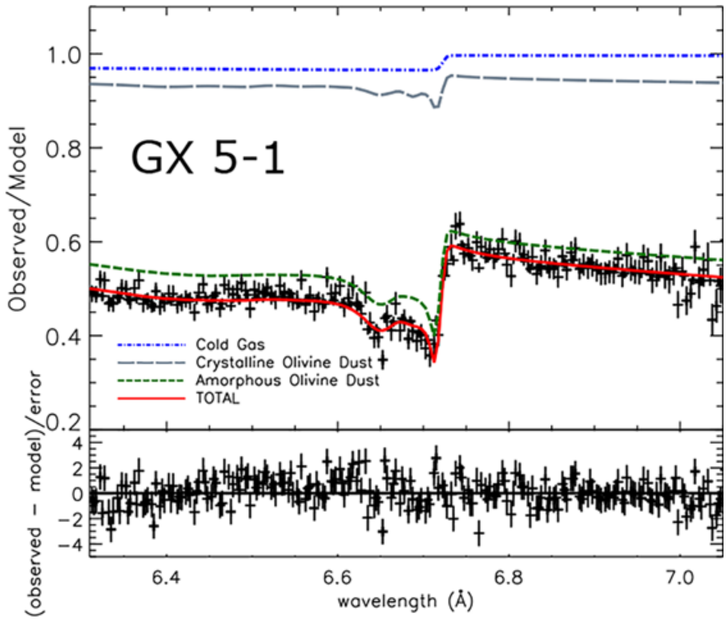

Figure 4. Fit of the Si K-edge of X-ray binary GX 5-1. The best fitting dust mixture is shown by the dashed green line (amorphous olivine, sample 8) and the grey long dashed line (crystalline olivine, sample 1). The contribution of cold gas is shown by the blue line and the total fit by the red line.

particles dominate the size distribution. We can use this scattering feature to study grain size distribution of the ID. The models of all samples were added to the SPEX fitting code (Kaastra *et al.* 1996).

4. Observing dust features in the Si K-edge of X-ray binaries

We observed the dust along the line of sight of a sample of nine Low Mass X-ray binaries (LMXBs) in the Central Galactic environment: GX 5-1, GX 13+1, GX 17+2, GX 340+00, 4U 1705-44, 4U 1630-47, 4U 1728-34, 4U 1702-429 and GRS 1758-258. Here we probe the dust in the densest environments of the Galaxy. We make use of archival observations by the *Chandra X-ray Observatory*. As an example we show in Figure 4 the best fitting dust mixture to the spectrum of LMXB GX 5-1.

5. Results

We find that the dust along most lines of sight toward the X-ray binaries can be well fitted with olivine-type dust. The contribution of crystalline dust is larger than in the infrared. We find values of the crystallinity varying between $\zeta_1 = 0.04 - 0.12$, where we define the crystallinity as $\zeta_1 =$ crystalline dust/(crystalline dust +amorphous dust). This may be explained by the characteristics of X-rays in these objects, which probe the order of atoms in the short-range, instead of probing the long-range disorder of the atoms in the infrared. Iron-poor pyroxenes are not favored in the fits. However, the Fe K-edge is more suitable to study the iron content in silicates, since the Si K-edge itself is not very sensitive to changes in the iron content of the silicates. Possible observations of the Fe K-edge in X-ray binaries with the future *Athena* telescope may provide more insight into the iron content of silicates (Rogantini *et al.* 2018).

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