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Characterizing the chemistry of interstellar dust: the X-ray view

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Abstract. Extensive multi-wavelength (from radio to far-ultra-violet) spectroscopy studies on the nature of interstellar dust (ID) showed that this is a small, but fundamental, component of the Universe. Despite the wide knowledge acquired so far, fundamental issues, in particular about the dust formation and chemical composition, still remain open. The X-ray band offers an important energy window where the main constituents of ID can be directly studied. Before the advent of the large X-ray observatories *Chandra* and *XMM-Newton*, the use of the X-rays as a tool to study ID has been at a pioneering stage. Now the quality of the X-ray data finally allows for a deep understanding of the ID chemical properties.

Key words. ISM: dust, extinction – X-rays: ISM – X-rays: individuals: 4U 1820-30

1. Introduction

Dust constitutes a very small fraction of the material available in the interstellar space. The most abundant elements which may condense to form grains are C, O, Mg, Si and Fe. Such evidence is given by spectroscopy, e.g. in the ultraviolet. An apparent under-abundance, generally referred as depletion, with respect to the cosmic values in the gas phase of those elements shows that a large fraction of those (40–100%) must be in a solid phase (e.g. Savage & Sembach 1996). Carbon is mostly found in the form of graphite and polycyclic aromatic hydrocarbons molecules. The remaining refractory elements are believed to form silicates, where Mg, Fe, or both, combine with SiO_3 or SiO_4.

Since the launch of the first X-ray satellites it has been realized that both the gas and dust along a given line of sight could be studied. The method used is simply to study, via spectroscopy and imaging, the radiation which is scattered and absorbed by dust grains on our line of sight. The objects used as background light are bright X-ray binary systems, which in nature are distributed everywhere in the Galactic disk. Pioneering imaging studies on X-ray scattering halos brought important information on e.g. the dust size distribution (e.g. Mauche & Gorenstein 1986; Predehl & Schmitt 1995; Draine & Tan 2003) and distribution along the line of sight (e.g. Predehl & Schmitt 1995). Absorption by the intervening ISM has been difficult to study in the early days due to the limited spectral resolution. Only the profiles of the main absorption edges could be recognized (e.g. Schattenburg & Canizares 1986) and parametrized (e.g. Morrison & McCammon 1983; Wilms et al. 2000). The advent of high-energy-resolution

Send offprint requests to: E. Costantini instruments marked the beginning of a large-scale study of the ISM from the X-ray point of view.

The X-ray band is indeed an ideal laboratory to study the silicate content in the diffuse ISM. For instance, the absorption K edge of O (E = 0.538 keV), Mg (E = 1.30 keV) and Si (E = 1.84 keV) together with the Fe LII and LIII (0.71 and 0.72 keV, respectively) edges fall in the low-energy X-ray band. Also the Fe K edge, located at 7.1 keV, will be well detected by future X-ray instruments (e.g. Astro-H, to be launched in 2014). Carbon, whose edge is located at 0.28 keV is outside the reach of most instrumental energy bands. The effect of dust is to shift in energy and modify in shape the photoelectric absorption of a given species. The main features of a modified edge are in most cases well detectable, thanks to the energy resolution of the current spectrometers ($R = \lambda/\Delta\lambda = 400 - 1000$). Thus silicate abundance in the ISM can be now studied (Pinto et al. 2010; Costantini et al. 2012, hereafter C12).

In addition, iron absorption features are shallow at longer wavelength and their modeling is difficult, while the X-ray band provides as many as three sharp, non-blended, iron features: the Fe LII, Fe LIII and FeK edges. The nature of iron compounds in ID can be therefore directly studied (Lee et al. 2009, C12).

Not all the edges can be accessed at the same time. An increasing column density of the ISM along our line of sight will progressively cancel the softer-energy edges. For this reason, the more diffuse dust environment ($N_{\rm H} \approx 1 - 7 \times 10^{21}$ cm^{-2}) is studied through the oxygen and iron L edges. The denser environment, common in regions near the Galactic Center (GC), with $N_{\rm H} \approx 7 - 50 \times 10^{21}$ cm^{-2}, will be represented by the Mg and Si edges. Extremely dense environments ($N_{\rm H} > 80 \times 10^{21}$ cm^{-2}) will show a significantly deep Fe K edge. The handful of known X-ray sources behind such a high-column-density ISM will be valuable to study the contribution of iron very near to the GC. X-rays can therefore access a variety of dust environments, which may differ in composition, grain sizes and geometrical distribution. Moreover, both gas (neutral and ionized) and dust in the ISM can be simultaneously studied as both show distinctive features in this band (e.g. Pinto et al. 2010).

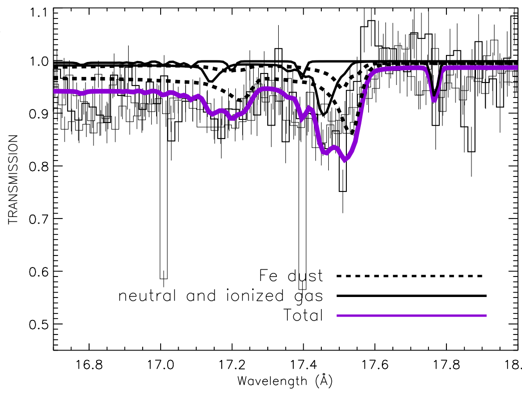

Fig. 1. Detail of the iron LII and LIII edges region in 4U 1820-30 spectrum. The model components contributing to the absorption (gas and dust)are also highlighted (adapted from C12).

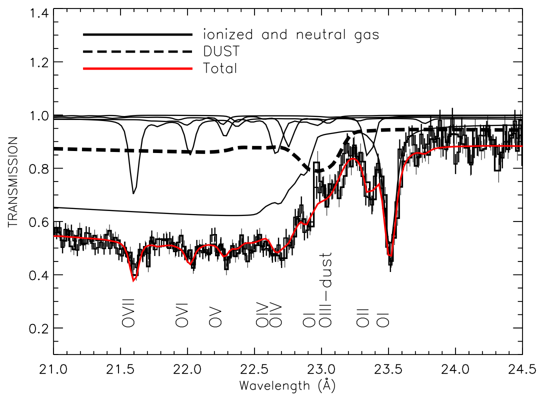

Fig. 2. Detail of the oxygen K edge region in 4U 1820-30 spectrum. The model components contributing to the absorption (gas and dust) are also highlighted (adapted from C12).

2. The case of 4U 1820-30

4U 1820-30 is a bright X-ray binary located in the globular cluster NGC 6624 at latitude $b = -7.9133°$ below the Galactic plane. The column density towards this source is $N_{\rm H} \sim 1.63 \times 10^{21}$ cm^{-2} (C12). In C12 a detailed study of the ISM absorption by gas and dust had been carried out using both *XMM-Newton*-RGS and *Chandra*-HETGS spectra. This allowed them to maximize the effective area and resolution both around the oxygen K and iron L edges. The existing dust model, implemented in SPEX (Kaastra et al. 1996), includes the absorption profiles of many basic compounds (silicates, oxides and simple species such as O_2, metallic iron, CO, etc., see C12 and references therein). In this way a first order modeling of the chemical composition of the dust along this line of sight is possible. Interestingly, Fe-rich silicates have been ruled out by the joint fit of the O and Fe edges. However, Fe has been found to be highly depleted in 4U 1820-30. The best fit points to absorption by metallic iron and traces of oxides (Fig. 1). The silicates absorption profiles which best describe the spectrum are Mg-rich (e.g. $MgSiO_3$, Fig. 2). This result adds up to other independent evidences of Mg-rich silicates dominating over the Fe-rich ones: X-ray scattering halos (Costantini et al. 2005), absorption in the iron L edge using *Chandra*-HETG (Lee et al. 2009) and infrared modeling (Min et al. 2007).

A possible aggregate which could simultaneously host Mg silicates and metallic iron could be in the form of a GEMS-like grain. The GEMS (Glass with Embedded Metal and Sulfides; Bradley 1994) which have been analyzed so far have interplanetary origin, but a fraction of them is consistent to be processed in the ISM (Keller & Messenger 2008). More observational evidences are needed to strengthen this possibility.

3. An improved ID data base

These exciting results show the potential of X-ray studies of dust. However this approach has still to be refined. A limited data base of dust absorption profiles may indeed lead to significant uncertainties in the interpretation. We are therefore collecting dust profiles measurements of a large number of dust compounds, with preference given also to the amorphous species. Existing laboratory measurements concern indeed mostly crystalline materials, while no more than 5% of dust is crystalline in the diffuse ISM (Kemper et al. 2001) and less than 2% towards the Galactic center (Li & Draine 2001). Using different facilities (Table 1), we are measuring, for each compound, all the relevant edges. The information which will be ultimately obtained from these measurements are the absolute cross section and the profile of the edge, modified by dust absorption. These will be implemented in the dust model in SPEX[1]. The energy resolution of the laboratory data is $0.8 - 3$ eV, therefore certainly suitable to fit the data of both the future and the current X-ray satellites. The global measurements of all edges for each compound will allow us to consistently fit at one time all the visible X-ray absorption edges in a given spectrum and reduce degeneracy in the results.

4. Conclusions and outlook

We have shown how, from the first works based on early mission data, we can now reach a high level of detail in the study of dust. This is especially true for the dust absorption features which can be modeled with unprecedented accuracy, provided to have high-quality X-ray-grating data. We have shown the potential of X-ray spectroscopy in directly studying the ID chemistry, with particular emphasis on the iron content in the ISM. We are performing additional laboratory measurements of dust compounds (both glassy and crystalline) to improve the dust model currently used with a set of consistently-studied edge profiles.

The X-ray satellites in operation are offering a rich archive of data, which allows us to especially focus on the softer energy edges. Future instrumentation will optimize the energy resolution in the Fe K region, but also the medium energy band will benefit from an improved resolution. In the near future the calorimeter on board Astro-H will allow us to easily study the dense environments near the Galactic center, via the Si and also the Mg edge. In exceptional cases, the Fe K edge will be also studied, providing fundamental infor-

[1] www.sron.nl/spex

Table 1. Facilities used for the measurements of relevant edges.

Facility		Edge	energy (keV)
DUBBLE-ESRF	synchrotron	Fe K	7.1
LUCIA-Soleil	synchrotron	Mg K, Si K	1.3 and 1.84
EMU	Electron microscope	O K, Fe L	0.543, 0.7

mation of the iron content in the densest dusty environment of our Galaxy.

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