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## **X-ray spectroscopy of interstellar dust: from the laboratory to the Galaxy**

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# English summary

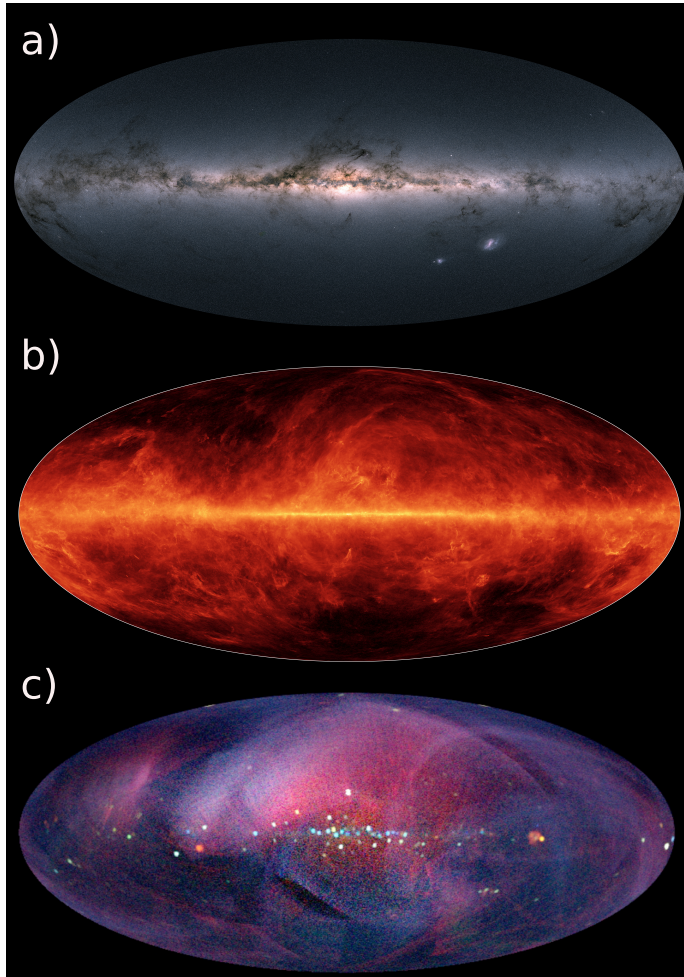
## **X-ray spectroscopy of interstellar dust** from the laboratory to the Galaxy

### Interstellar Dust from an Historical perspective

The space between stars, also called the interstellar medium (ISM), is not a perfect vacuum. Between the stars, we can observe clouds of dust and gas of varying shapes, densities and sizes. These clouds can be observed, for instance, as dark patches in our own Galaxy contrasting with the light from the stars, as can be seen in panel a of Figure A.11. The development in the quality of telescopes in the 18th century made it possible to observe these dark parts of the Galaxy in more detail, which led to an increase in interest in these objects. At first, some of the dark patches were thought to be holes in the sky (William Herschel: “Hier ist wahrhaftig ein Loch im Himmel”). However, in the early 20th century, these ‘holes’ were eventually discovered to be foreground clouds obscuring the stars behind them. In the 1890s Barnard started to photograph these clouds (eventually published in a catalogue, Barnard (1919)), which revealed many details, invisible to the naked eye. Agnes Clerke described them in her book ‘Problems in Astrophysics’ as obscuring bodies. Even in the case where no clouds are observed towards a star, it was found, already as early as 1847, that extinction of light still takes place. It took until 1930 to prove that the extinction, shown by the reddening of stars, is indeed caused by interstellar dust particles (independently described by Schalén (1929) and Trumpler (1930)).

### Motivation

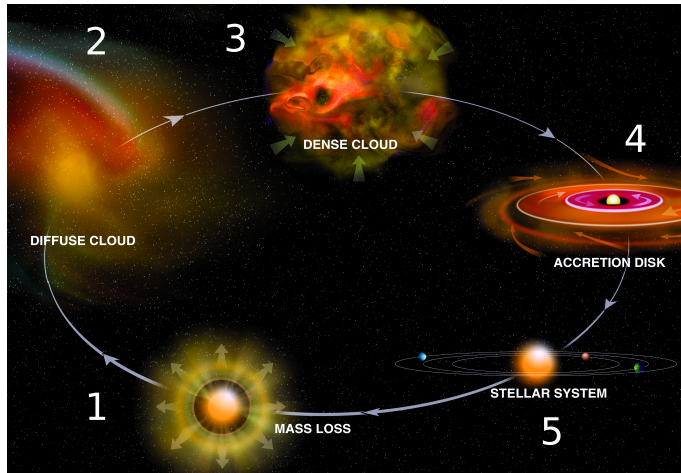
Since its discovery, the way dust has been perceived slowly changed. At first it was completely ignored, then it was considered to be a hindrance when trying to observe the stars and galaxies, but since the 1960s, dust has been more and more seen as an important component that drives many processes in the universe. The important role of dust in the universe is best shown by its role in every stage of the life cycle of stars, Figure A.12. Stars enrich the universe with elements, produced during the nucleosynthesis process and in this way, provide the building blocks for the interstellar dust particles, which are thrown into space by e.g., stellar winds or (super) novae. Dust is thought to form as condensates in the atmospheres of evolved stars, or in the aftermath of a violent supernova explosion, and perhaps as well in the ISM itself. When clouds of gas and dust clump together, a new star can be formed in the core of such a dense



**Figure A.11:** The Galaxy in three different wavelengths: a) The visible-near infrared: GAIA 330-1050 nm, image credit: ESA/Gaia/DPAC - b) infrared: Planck cold dust (20 K) map, image credits: ESA/NASA/JPL-Caltech - c) The X-rays: 0.5-16 keV MAXI all-sky survey, image credits: JAXA/RIKEN/MAXI team.

cloud. During the formation process of a star, dust plays a crucial role: from the collapse of the cloud to the formation of planets. Cosmic dust can be observed virtually everywhere: in our solar system, around young stars, in giant clouds, the Galaxy, but also in distant galaxies and it is already present in the earliest eras of the universe. Hence, studying dust can help us to understand how the universe evolved. Besides the already given arguments in favor of dust studies, there is of course another important reason to study dust; we and everything around us all consists of cosmic dust. Therefore, if we want to understand the origin of life, it is necessary to understand the origin, formation and composition of cosmic dust.





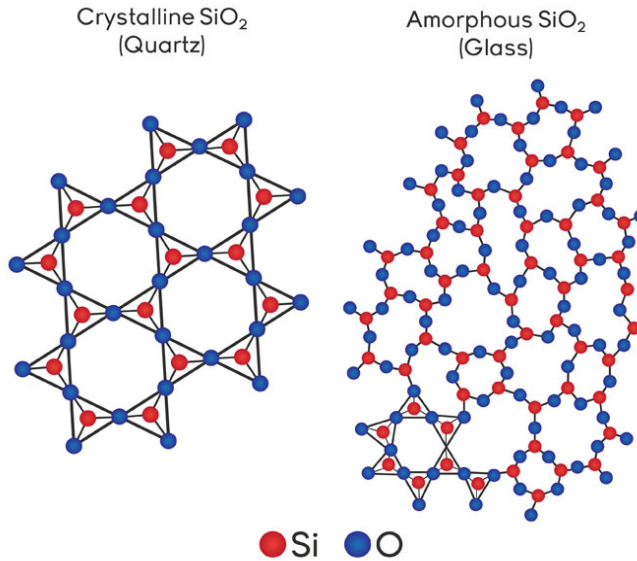
**Figure A.12:** The life cycle of stars and interstellar dust in five stages: 1) evolved star, 2) diffuse cloud, 3) dense cloud, 4) protostellar disk phase and 5) evolved planetary system. At each stage in this cycle dust plays a crucial role. Image credit: Bill Saxton, NRAO/AUI/NSF.

## The properties of interstellar dust

Since dust plays a role in many processes in the universe, it has become an essential component in many astronomical models. In order to develop accurate interstellar dust models, it is important to understand the properties of dust, what interstellar dust exactly consists of, how it interacts with radiation, what the grain size distribution is, what the shape and internal structure of the grains is, and whether these properties change in different environments. Since we know what elements stars produce and in which quantities, we can compare the abundance of an element (meaning the expected occurrence of an element with respect to hydrogen) in the gas phase with observations<sup>9</sup>. These observations show us that the abundance of some elements is lower than expected, which leads to the conclusion that these missing elements are locked up in dust particles. Dust thus exists mainly of carbon (C), silicon (Si), iron (Fe), magnesium (Mg) and oxygen (O). Combining this information with theory, astronomical observations (e.g., infrared spectroscopy) and studies of meteorites, dust in the ISM can be roughly divided into two main groups, namely silicates (e.g., pyroxene and olivine types, comparable to fine sand grains on earth) and carbonaceous dust (comparable to soot), with the addition of oxides (e.g., MgO, SiO, SiO<sub>2</sub>), carbides (mainly SiC) and metallic iron. However, there are still many uncertainties about interstellar dust. We do not exactly know how and where dust is produced, and how the properties of dust change in different environments. We would like to know what happens to dust in the violent environment of the ISM, where dust is bombarded by radiation and cosmic ray particles, and destroyed by shock waves. This may change the internal structure of the dust. If the dust grains had a crystalline structure

<sup>9</sup>Hydrogen and helium, produced in the Big Bang, are the most abundant elements in the universe. All the heavier and less abundant elements are produced in the life cycle of stars.

before their encounter with the ISM, they may lose this structure and become more and more amorphous, see Figure A.13. Furthermore, we do not exactly know the chemical composition of the dust particles.



**Figure A.13:** On the left, the crystalline silicate quartz. On the right, glass with the same composition as quartz, but without the crystalline structure (amorphous). In quartz, every silicon atom is connected with four other silicon atoms via a so-called oxygen bridge and, in this way, forms a symmetrical tetrahedra. For clarity, the fourth silicon atom and the corresponding oxygen bridge are omitted. Image credit: NDT Resource Center, Center for NDE, Iowa State University.

## This thesis

High resolution X-ray spectroscopy is an important tool in interstellar dust studies. By studying dust features in X-ray spectra and scattering haloes around X-ray sources, we may be able to answer some of the fundamental questions about interstellar dust, as mentioned above. In this thesis, we focus on silicate dust types, one of the main constituents of ID. The X-rays are particularly suitable to study silicates due to the presence of absorption features of O, Mg, Si and Fe in the X-ray band. These elements form the most important components of silicates. We mainly use the silicon absorption feature, called the Si K-edge<sup>10</sup>, to study the properties of silicate dust. For each type of silicate dust, the features in the edge, called X-ray absorption fine structures (XAFS), are slightly different. This means that they are a unique fingerprint of the dust.

<sup>10</sup>This absorption feature occurs at the ionisation energy of a core atom in the K-shell of a silicon atom.

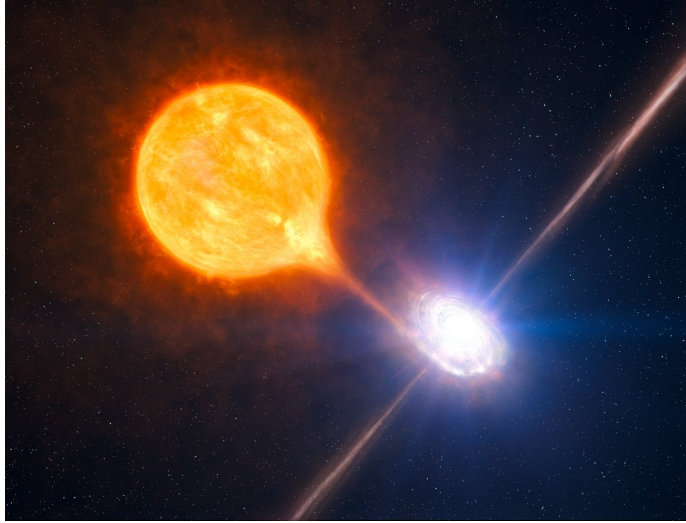
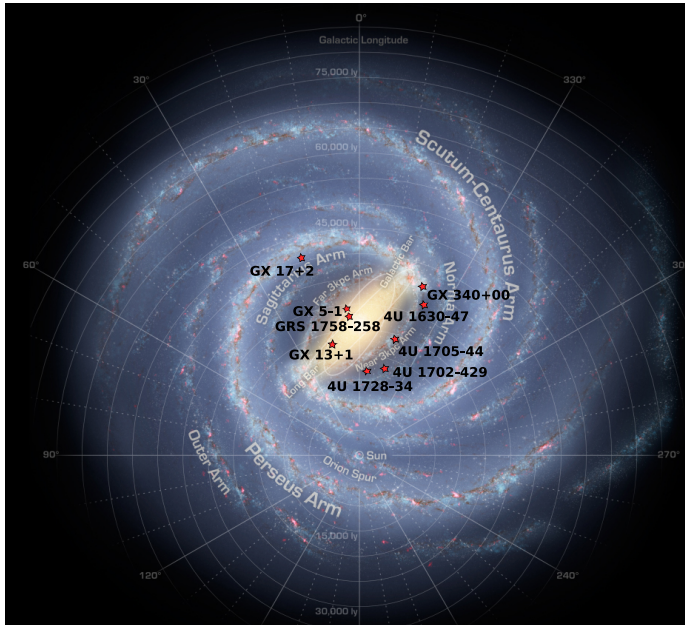


Figure A.14: Artist's impression of an X-ray binary, image credit: ESO/L. Calzada/M.Kornmesser.

Bright low mass X-ray binaries in the Milky Way are ideal sources to study the intervening gas and dust along their lines of sight, simply using them as a lantern shining through the ISM. These sources consist of two components, a neutron star or a black hole which accretes material from a companion star, usually a normal star (viz., not a giant star). These systems are very bright in X-rays, because the accreted material from the companion star forms a disk around the accretor, which emits in the X-rays due to the gravitational potential energy of the infalling matter. We cannot directly observe the X-ray radiation from Earth due to the Earth's atmosphere, therefore we need X-ray telescopes in space to observe the X-ray binaries. In this thesis, we make use of data from the Chandra X-ray observatory, an X-ray satellite launched in 1999. The spectra from this observatory are highly suitable for dust studies thanks to their high spectral resolution. Furthermore, we profit from the rich Chandra data archive which contains spectra of many X-ray binaries.

In Chapter 2 we used the spectrum of the X-ray binary GX 5-1 as a test case to study interstellar dust along the line of sight of this source. We used a set of six different silicates and measured their X-ray spectra at the Soleil synchrotron facility. These measurements were adapted to astronomical models and fitted to the spectrum of the X-ray binary. We find that the crystalline olivine silicate best fitted the spectrum. Furthermore, the scattering feature which occurs just below the K-shell absorption energy provides direct link to the grain particle size distribution. The impact of the presence of large particles along the line of sight is studied by modeling the edge with two different particle size distributions. Here we find indications for the presence of large particles along the line of sight towards GX 5-1.

In Chapter 3 we expanded our set of silicate samples to 14 and measured their Si K-edge features in a second measurement run at the Soleil synchrotron facility in 2017. We also expanded the number of observed X-ray binaries to nine different sources of which the location



**Figure A.15:** Artist's conception of a top-down view of the Milky Way, based on infrared images from NASA's Spitzer Space Telescope. The red stars indicate the position of the LMXBs studied in this thesis. Image credit: NASA/JPL-Caltech/R. Hurt

can be seen in Figure A.15. These sources are located in the densest regions of our Galaxy and this makes it possible to explore the dust in these regions of our Galaxy, which are otherwise hard to study. We find that amorphous olivine is dominant in most of the fits, but that there is still a significant contribution of crystalline silicates. This contrasts with results from the infrared, where less than 2% of amorphous dust is detected. The difference may be attributed to the sensitivity of XAFS to short range order, whereas, in the infrared, observations are focussed on long range disorder in the dust particles. Variations in the abundance of elements between different regions of the Galaxy are a key factor in understanding the formation and chemical evolution of the Galaxy. The chemical composition of the Galactic disk varies with time as stars continually enrich the ISM. Generally, an increase in abundance is measured toward the Galactic Center (GC). We find that the in the inner regions of the Galaxy abundances of silicon flattens and even decrease toward the GC. This may be caused by an increase in the typical silicate grains size or differences in the chemical evolution of the GC environment in comparison to the Galactic disk.

In Chapter 4 we present an outlook for edge studies with future telescopes: XARM (2021), Arcus (2023) and Athena (2028). We focus on the K-edges of carbon (C), sulfur (S), aluminium (Al), nickel (Ni), titanium (Ti) and calcium (Ca). In the relatively near future, the depletion and abundances of these elements will be determined with confidence. In the case of C and S, the characterization of the chemistry of the absorbing dust will be also determined. For Al and Ca, despite the large depletion in the interstellar medium and the prominent dust

absorption, in many cases the edge feature may not be changing significantly with the change of chemistry in the Al- or Ca- bearing compounds. The extinction signature of large grains may be detected and modeled, allowing a test on different grain size distributions for these elements. The low cosmic abundance of Ti and Ni will not allow us a detailed study of the edge features.

Lastly, in Chapter 5, we explore the possibility of detecting X-ray scattering by dust particles in a debris disk. We use as a best test case the debris disk around the star AU Microscopii. We find that models with a moderately strong stellar wind model and a composition of silicates and graphite are the ones that would enhance a theoretical halo. After comparing the models with observations of AU Microscopii, we find that the models do not produce a significant scattering halo, using the current spatial resolution. However, future X-ray missions may enable us to observe the X-ray halo of debris disks.

In conclusion, we showed that X-ray spectroscopy provides a powerful method to answer fundamental questions about interstellar dust. In the near future, when combining new broadband extinction models with the spectra of upcoming X-ray missions, this method will settle long standing uncertainties in the modeling of interstellar dust. Presently, as presented in this thesis, the silicon K-edge in the spectra of X-ray binaries already offers important insights into the chemistry of interstellar silicate dust.

*“Is there going to be anything left? - Only stardust”*

Doolin Dalton/Desperado (reprise) - Eagles