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An X-ray view of gas and dust in the diffuse interstellar medium

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Introduction

1.1 The Interstellar medium

The space between the stars is not empty, it is filled with matter and radiation which are the primary ingredients of the so-called "Interstellar medium" (ISM). The ISM is responsible for many astrophysical processes in our Galaxy and most importantly for the formation of new stars. Gas, in different phases, and dust grains are two important ingredients of the ISM. Most of the gas and dust are found in a relatively thin gaseous disk along the mid-plane of the Galaxy. Other constituents of the ISM include cosmic rays, electromagnetic radiation, gravitational and magnetic fields (Draine 2011).

1.1.1 ISM gas phases

The ISM evolves dynamically and it is found in different phases characterized by the temperature, density and ionization state. The different phases can be classified into categories which account for most of the mass of the ISM (Draine 2011, Tielens 2005).

Neutral gas: It contains predominantly warm atomic gas heated to temperatures $T \sim 10^{3.7}$ K with densities $n \sim 0.5 \text{ cm}^{-3}$. It is often named as the warm neutral medium (WNM) and it accounts for a significant fraction of the volume of the ISM, about 40%. Additionally, the so-called cold neutral medium (CNM) contains atomic gas at temperatures around $T \sim 10^2$ K and densities $n \sim 30 \text{ cm}^{-3}$. It is filling a smaller portion of the local interstellar medium compared to the WNM, around 1% of the total ISM volume.

Ionized gas: It consists of shock-heated gas with temperatures $T \geq 10^{5.5}$ K and a very low density of $n \sim 0.01 \text{ cm}^{-3}$. A fraction of it consists of the so-called coronal gas or hot ionized medium (HIM) and it is referred to gas that has been collisional ionized. The HIM occupies a large fraction of the ISM, about 50% of the total volume. In addition, the warm ionized medium (WIM) describes the gas that has been photoionised to temperatures around $T \sim 10^4$ K and its fractional volume is about 20%.

Molecular gas: It can be mainly found in gravitationally bound clouds. The typical temperature is $T \sim 10$ K and its density can vary from $\sim 1000 \text{ cm}^{-3}$ up to $\sim 10^6 \text{ cm}^{-3}$, the latter can be found in dense cores of molecular clouds. In these cool dense regions of the ISM, matter is predominantly in molecular form (e.g. H_2) and it is here that the formation of new stars takes place. The molecular gas occupies a small volume of the ISM, less than 5%.

1.1.2 Elemental enrichment of the ISM

The largest fraction of the visible matter in the Galaxy consists of hydrogen and helium, formed during the Big Bang. Heavier elements are formed during stellar evolution through thermonuclear reactions in stars. As stars evolve and die, material is injected into the ISM via stellar winds or supernova explosions (Whittet 2003). This process constantly enriches the ISM with heavier elements.

It is crucial to understand the elemental abundances and their distribution throughout the Galactic disk because it reveals the evolution history of our Galaxy. The observed abundances enable us to understand the chemical composition and physical state of both gas and dust in our Galaxy. The element abundances in the Sun of our Solar System provide a reference set, useful for astrophysical studies. In Fig. 1.1 we present the Lodders & Palme (2009) elemental abundances which are assumed in this thesis. The Lodders & Palme 2009 elemental abundances refer to solar system abundance data which have been derived from meteorites and the solar photosphere.

Oxygen, iron, magnesium, silicon and carbon are some of the most abundant elements in the ISM and are also the main ingredients of interstellar dust. These elements are observed to be under-abundant in the gas phase with respect to their Solar reference value (Savage & Sembach 1996) and therefore it is believed that they are locked-up in dust grains (see Jenkins 2009 for a review). The exact fraction of these elements included into dust form still remains an open question.

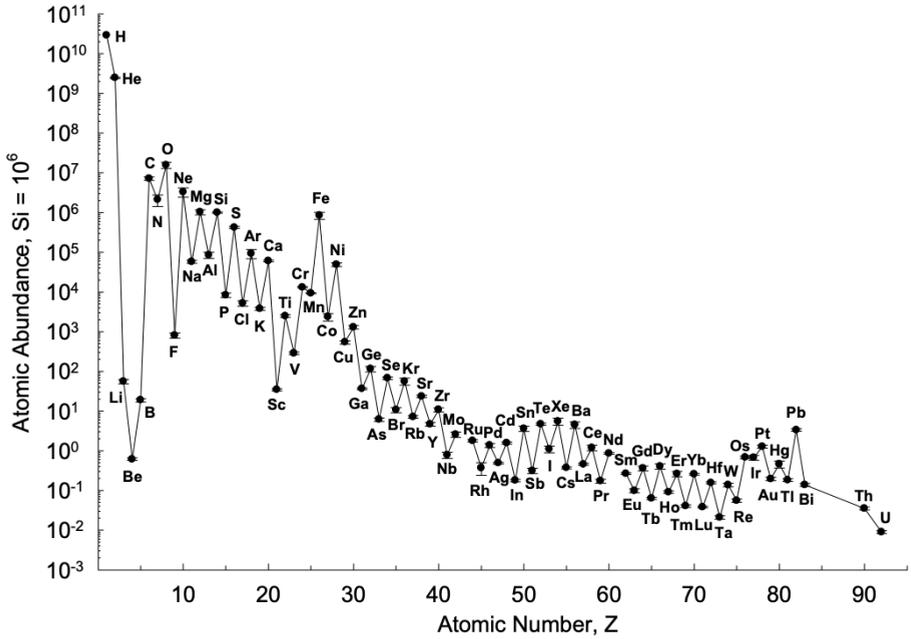


Figure 1.1: Elemental Solar system abundances as a function of atomic number (adapted from Lodders & Palme 2009).

1.2 Interstellar dust

Cosmic dust is ubiquitous and shows its presence in our Galaxy in many ways. Absorption and scattering through small dust grains creates the effect of reddening¹ and extinction² of the light from distant stars. Cold dust radiates in the infrared because of its continuum emission. Moreover, dust grains can scatter the light of a nearby star and create the so-called reflection nebulae. Finally, interstellar dust manifests its presence through the polarization of starlight which is caused by elongated dust grains aligned with the Galactic magnetic field.

In spiral galaxies, like the Milky Way, most of the interstellar dust (ID) is distributed along the Galactic plane. In Fig. 1.2, we see the Gaia’s all-sky survey of our Milky Way. The brighter regions indicate denser concentrations of bright stars, while darker regions across the Galactic plane correspond to foreground clouds of interstellar gas and dust. These clouds absorb the light of stars located behind them.

¹The effect of reddening occurs when dust absorbs and scatters the ‘blue’ light, making stars appear ‘redder’.

²Extinction is the absorption and scattering of electromagnetic radiation due to the intervening dust and gas between the observer and the astronomical object.

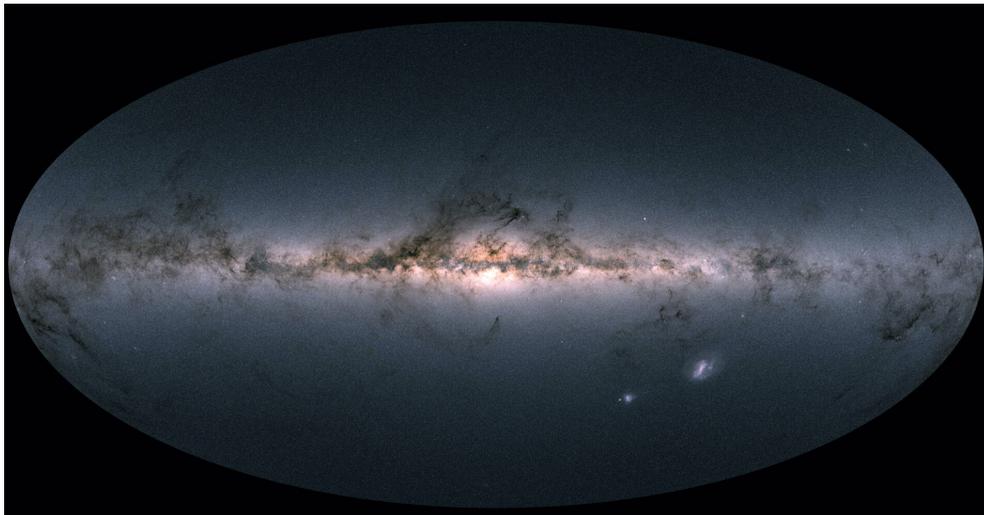


Figure 1.2: Our Galaxy in the optical band. The dust is mostly concentrated in the Galactic plane. The brighter regions indicate denser concentrations of very bright stars, while darker regions across the Galactic plane correspond to foreground clouds of interstellar gas and dust. Credit:ESA/Gaia/DPAC

1.2.1 The life-cycle of cosmic dust

The life-cycle of cosmic dust has been associated with that of stars. It appears at almost every stage of stellar evolution (Jones 1997) and plays a fundamental role in our Galaxy. Biologically important elements such as carbon, iron and oxygen are formed by nucleosynthesis in stars. These elements are also the building blocks of interstellar dust. Interstellar dust is believed to form as condensates in the atmosphere of evolved stars, during the Asymptotic Giant Branch (AGB) phase, and ejected into the ISM through their stellar winds. Other sources of interstellar dust are supernovae, both type Ia and core-collapse, young stellar objects, Wolf-Rayet stars, red supergiants and planetary nebulae (Jones 1997, Tielens 2001). However, the contribution of supernovae to the total production of dust grains is uncertain because reverse shocks may destroy most of the dust particles (e.g. Slavin et al. 2015). Once the new dust grains have been formed, they are ejected into the ISM and get mixed with other dust grains and interstellar gas.

The ISM is not homogeneous and can be found in clouds of different densities. The typical environments are the intercloud medium, the diffuse and dense clouds. The intercloud medium has a low density ($n_{\text{H}} \sim 0.004 - 30 \text{ cm}^{-3}$, where n_{H} is the hydrogen density) and fills most of the volume of the ISM, while the diffuse clouds have slightly

higher density ($n_{\text{H}} \sim 10^2 \text{cm}^{-3}$). Once the dust is ejected and mixed in the ISM with other gas and dust, it will cycle many times between the cloud and intercloud phase (Tielens 2005). During the interplay between the cycles, dust grains will be subject to both destruction and growth processes (Zhukovska et al. 2018). Dust can be destroyed by supernovae shocks through sputtering and shattering (e.g. Jones & Nuth 2011). Growth processes such as coagulation, nucleation and condensation can take place in the diffuse and dense regions of the ISM (Draine 2009).

The dense regions of the ISM have often densities of $n_{\text{H}} \sim 10^3 - 10^6 \text{cm}^{-3}$ and most of the gas is in the form of molecules. There, dust grains act as a catalyst for the formation of complex molecules (Whittet 2003) and provide the surface for chemical reactions (Henning 2010). In these regions, dust grains can also grow in size due to coagulation and form a mantle of ice around the dust particles (e.g. Pontoppidan et al. 2004).

Gravitationally bound dense molecular clouds can fragment when the internal gas pressure is not strong enough to prevent gravitational collapse (Shu et al. 1987). Filamentary structures along the molecular cloud have been observed by *Herschel*. Within the filaments, prestellar cores can form and further develop into protostars. Filaments are structures of gas and dust, where dust grains have a prestigious role. Polarization of starlight can reveal the structure of the magnetic field and give an estimate of its strength (Panopoulou et al. 2016).

When finally the cloud collapses, new stars and planetary systems are born. Dust plays a major role as building blocks in the formation of new planets inside the protoplanetary disk that surrounds the young stars. The high densities inside the protoplanetary disk will enable the dust grains to collide and build planetesimals. Then, a new star system is born and the whole process can start again.

1.2.2 Dust properties

ID is characterized by its morphology and size as well as its elemental constituents. Here, I will describe the main characteristics of dust grains.

Chemical composition

The chemical composition of dust grains and their properties in different Galactic environments still remain an open question. One way to approach this question is to consider the observed depletion of an element ³. We know that elements such as C, O, Mg, Si and Fe are the main building blocks of interstellar dust. Oxygen is one of the most abundant elements in the ISM and moderately depleted into dust (about 20%). Iron, silicon and magnesium present high depletion values from the gas phase

³Here, the depletion of an element is defined as the ratio of the dust abundance to the total abundance of a given element (both gas and dust).

(about 90% or more). Elements such as calcium and aluminum are less abundant in the ISM but highly depleted (Jenkins 2009).

The dust species are categorized into two main groups, namely silicates and carbonaceous grains. Additionally, oxides (e.g. SiO_2 , Fe_2O_3), carbides, sulfides and metallic Fe can also be found in dust (Draine 2011). Silicates are found also in the crust of the Earth, Moon and Mars (Henning 2010). Silicates and carbon-bearing materials have been also found in meteorites.

Although the depletion of elements provide insights into the composition and silicate content of ID, more direct methods have been developed, which provide accurate results. For example, the infra-red (Henning 2010) and X-ray (Section 1.3.2) spectral features due to dust provide good diagnostic tools for both the composition and size of interstellar grains. Regarding the stoichiometry of dust, it is still not clear what is the exact composition of ID. We do not know for example which types of silicates are the most abundant in the ISM. Pyroxenes ($\text{Mg}_{1-x}\text{Fe}_x\text{SiO}_3$) and olivines ($\text{Mg}_{2-x}\text{Fe}_x\text{SiO}_4$) are two interesting and well studied groups of minerals. However, the exact ratio of pyroxenes over olivines in ID along with the Mg:Fe ratio is still uncertain (Min et al. 2007, Chiar & Tielens 2006).

Crystallinity

Silicates can be classified into two broad categories according to their atomic structure, *crystalline* and *amorphous*. Crystalline silicates are characterized by a periodic long-range order of atoms (SiO_4 tetrahedra units⁴), while the amorphous materials do not show periodic structures and present a 3D disordered network of atoms. A sub-category of amorphous silicates is the *glassy* silicates. Glasses keep a certain amount of short-range order of atoms. A schematic representation of the crystalline and amorphous (glassy) atom configuration is presented in Fig. 1.3.

Silicates in amorphous configuration represent most of the dust in the ISM. Crystalline dust is unlikely to survive in large quantities due to the harsh environment of the ISM (e.g. Jones & Nuth 2011). The crystallinity can be studied both from the infra-red and the X-ray band. Infra-red studies of the $\sim 9 \mu\text{m}$ and $\sim 18 \mu\text{m}$ absorption features in the line-of-sight towards the Galactic center, suggest that up to 2.2% of dust in the interstellar medium is in crystalline form (Kemper et al. 2004). X-ray studies have shown a larger range of crystallinity which is between 0-30 % along different lines of sight (Zeegers et al. 2019, Rogantini et al. 2020).

⁴The silicon-oxygen tetrahedron is the basic compositional unit of silicates. It consists of one silicon cation, surrounded by 4 oxygen anions in a 3D pyramid geometry.

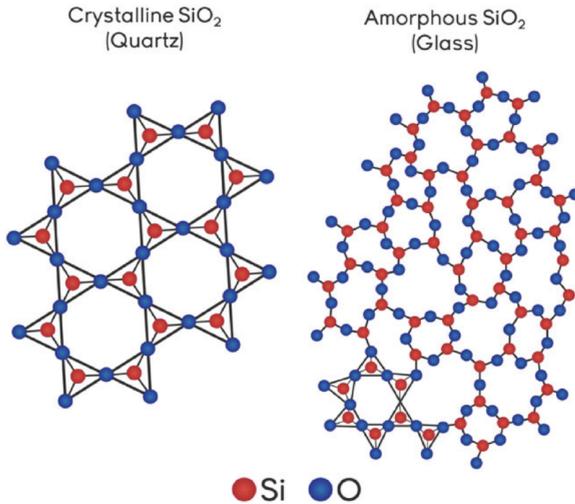


Figure 1.3: Crystalline (left) and amorphous/glass configuration for the same compound (quartz). Every silicon atom is connected with four other silicon atoms with the so-called oxygen bridge forming symmetrical tetrahedra. Credit: NDT Resource Center, Center for NDE, Iowa State University.

Size distribution

It is also important to study the size of interstellar grains because it reveals their origin and evolution. For instance, it can give us insights into the dust production and destruction mechanisms. The so-called *extinction curve*, is a wavelength-dependent extinction of starlight and its shape also depends on the grain size. Studying the dust in different wavelengths can constrain a dust size distribution model.

It is important, in dust studies, to adopt a dust size distribution in order to take into account a variety of particle sizes. In this thesis we use the Mathis-Rumpl-Nordsieck model (MRN) dust size distribution (Mathis et al. 1977). The MRN size distribution is defined as $n(a)da \approx a^{-3.5}da$, where $n(a)$ is the number of grains. The particle size range is $0.005 \mu m < a < 0.25 \mu m$.

1.3 X-ray spectroscopy of the ISM

The glory of the X-ray sky has been recently highlighted by *eRosita*, the primary instrument on-board the "Spectrum-Roentgen-Gamma" (SRG) mission (Fig. 1.4). The good angular resolution and high sensitivity of *eRosita* made it possible to map mil-

lions of compact sources and tens of thousands of X-ray extended regions ⁵. *eRosita* has observed Active Galactic Nuclei (AGN), clusters of galaxies, X-ray binaries, supernova remnants, Gamma-Ray bursts and star-forming regions. The white dots, distributed non-uniformly across the Sky, represent the hundreds of thousands galactic and extragalactic X-ray sources observed. Close to the Galactic center, the green and yellow regions represent the most energetic phenomena, such as supernova explosions. The red diffuse region, away from the Galactic plane shows the Local Bubble. The dust and gas located along the plane of the Galaxy absorb the soft X-ray photons. As a result, only the high-energy emitting sources can be seen, presented in blue color.

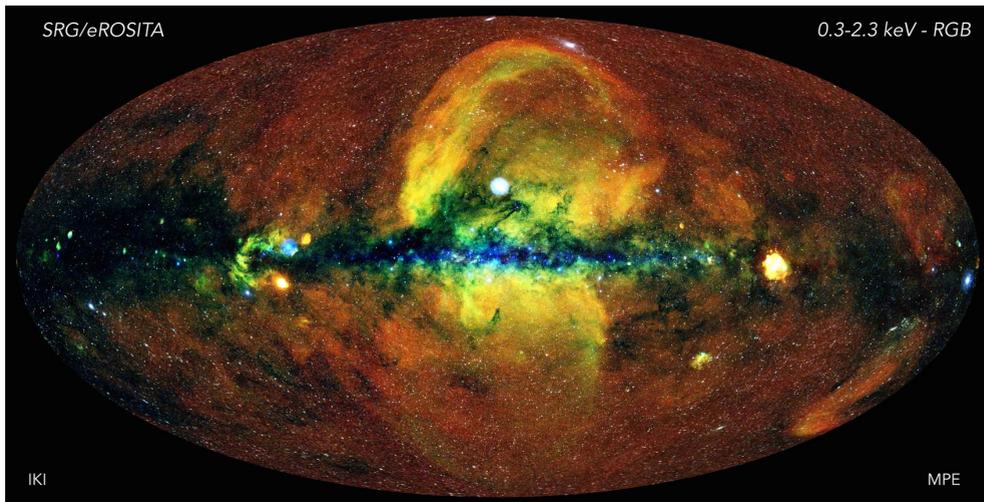


Figure 1.4: The X-ray sky as seen with eROSITA X-ray telescope. Credit: Jeremy Sanders, Hermann Brunner and the eSASS team (MPE); Eugene Churazov, Marat Gilfanov (on behalf of IKI)

X-ray radiation from astronomical X-ray sources can be absorbed by atoms and solids in the ISM. The absorption of X-rays by the interstellar medium has been predicted since the late '60s (Bell et al. 1967). Later on, the launch of *Einstein* and EXOSAT opened up a new window in the study of the ISM. These satellites were equipped with the earliest grating spectrometers with a resolving power reaching ($R = \frac{\lambda}{\Delta\lambda}$) 100 in the soft X-ray band (Dijkstra et al. 1978, Brinkman et al. 1980). Schattenburg & Canizares (1986) were the first to perform a detailed X-ray study of the ISM. They observed the Crab nebula with the *Einstein Observatory* and detected absorption features of oxygen. In 1999, the launch of XMM-*Newton* and

⁵detailed information about eRosita can be found here <https://www.mpe.mpg.de/7461950/erass1-presskit>

Chandra satellites revolutionized high-resolution X-ray spectroscopy. With a huge leap in spectral resolution of more than an order of magnitude compared to *Einstein*, these satellites enabled to study the signatures of the ISM in detail.

The photoabsorption edges of some of the most abundant elements in the Galactic ISM are present in the X-ray band (Fig. 1.5). At energies below 10 keV, the photoelectric effect represents the main interaction between X-ray radiation and matter. An X-ray edge appears at wavelengths where the energy of the incoming X-ray photon is just greater than the binding energy of a bound electron. In this case, we have a sudden jump in X-ray absorption which is causing a steep absorption-like feature. An edge is characterized by the element and the electron shell. The electrons of an atom belong to different shells, characterized by their energies. The closest to the nucleus, K-shell, has a higher binding energy and therefore the K-edges appear at higher energies in the spectrum, compared to the L-edges, which corresponds to the second closest to the nucleus.

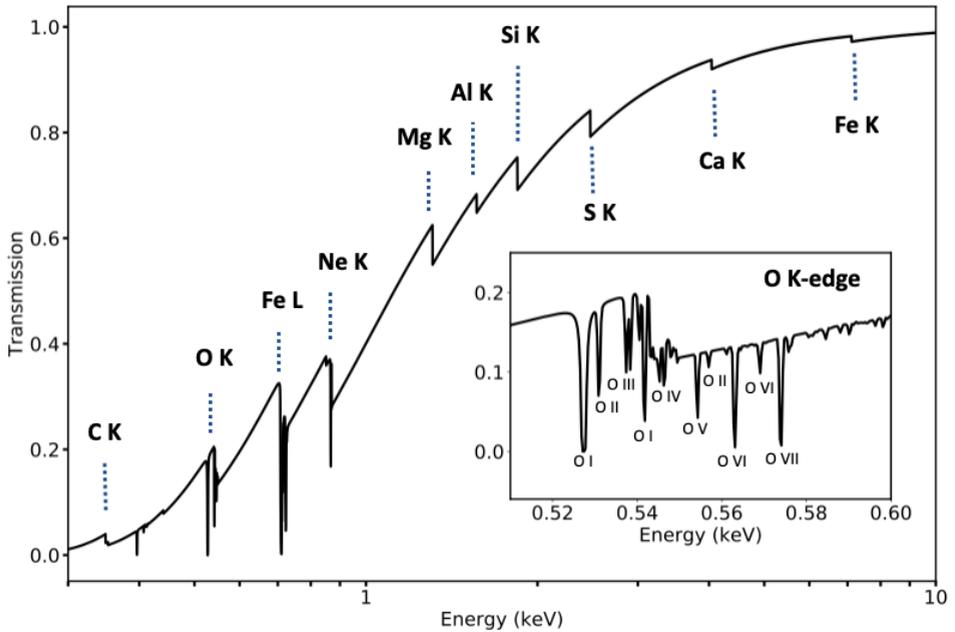


Figure 1.5: Illustration of the dominant X-ray photoabsorption edges for arbitrary hydrogen column densities. In the small panel we present the different oxygen atomic species around the oxygen K edge.

1.3.1 Advantages of the X-ray band

High-resolution X-ray spectroscopy is an excellent tool to study the abundance of chemical elements along with their depletions into solid species. One of the advantages of using the X-ray band is that it is sensitive to a wide range of column densities ($\sim 10^{20-23} \text{ cm}^{-2}$) which facilitates the study of different Galactic regions. Moreover, X-rays probe both neutral and ionised species, providing a window to study the different ISM phases. An example of this is shown in the inset of Fig. 1.5 where we can see the different oxygen species, from O I to O VIII. A thorough analysis of the oxygen K-edge is presented in Chapter 2.

Along with the gaseous phase of the ISM, high-resolution X-ray spectroscopy allows us to study the cosmic dust. Dust grains can absorb and scatter X-ray light, enabling the study of dust chemical composition, crystallinity and size distribution (see Section 1.3.2). In the last few years, new tomographic techniques have been also developed based on X-ray observations which allow the mapping of the line-of-sight distribution of dust (Heinz & Corrales 2016, Corrales et al. 2019).

The X-ray spectra of X-ray binaries can be used to study the atomic and solid species of the ISM along different lines of sight. In particular low mass X-ray Binaries (LMXB) are good candidates due to their high flux and well-defined absorption features due to the ISM absorption. The transmission of X-rays is highly dependent on the relative column density of a particular line of sight. Approximately, values of $N_{\text{H}} \lesssim 5 \times 10^{21} \text{ cm}^{-2}$ are suitable to study spectral features below 1 keV, while values of $N_{\text{H}} \gtrsim 5 \times 10^{21} \text{ cm}^{-2}$ enable to study the absorption above 1 keV. Abundances and depletions of some of the most abundant elements such as oxygen, neon, iron, silicon and magnesium present in the neutral and ionised phase have been studied using *XMM-Newton* and *Chandra* observations (e.g. Wilms et al. 2000, Juett 2004, Pinto et al. 2010, 2013, Costantini et al. 2012). Additionally, absorption and scattering by interstellar dust have also been studied in detail using the capabilities of these instruments as well as new dust models based on laboratory measurements (Lee 2009; Lee & Ravel 2005, Zeegers et al. 2017, 2019, Rogantini et al. 2018, 2020, this thesis).

1.3.2 X-ray Absorption Fine Structures

The properties of interstellar grains can be studied through their fingerprints in the X-ray spectra, the X-ray Absorption Fine Structures (XAFS). XAFS are oscillatory modulations observed near the photoelectric absorption edges and appear when an X-ray photon interacts with a dust grain. The photon gets absorbed by an atom in the dust particle and the ejected photo-electron interacts with the neighboring atoms. This interaction modulates the wave-function of the photo-electron due to construc-

tive and destructive interferences (Newville 2004).

In Fig. 1.6, panel (a), we illustrate the absorption probability of an isolated atom. The resulting cross-section is a smooth function, contrary to the one presented in panel (b). In panel (b) we can see the XAFS with the oscillatory modulations clearly present, in particular in the post-edge region. The atomic structure of the dust grain modifies the shape of these modulations, revealing several properties of the grains, e.g. their chemical composition. Therefore, XAFS are suitable to study the dust chemistry and crystallinity. To this end, accurate XAFS models are needed for a proper modelling of these interstellar dust features. In the literature there are models of XAFS available for some of the photoelectric edges (Lee & Ravel 2005, Lee et al. 2009, Westphal et al. 2019). For a complete dust modelling of X-ray spectra we need an accurate broadband model which includes all the observed edges. In the next section we describe our group work to build a broadband X-ray model of interstellar dust based on laboratory measurements and emphasize the contribution of this thesis to this model.

1.3.3 Dust laboratory measurements and application

In order to study the properties of ID with X-ray spectra we need to obtain a detailed broadband model of interstellar dust. For this reason, we are building the X-ray Interstellar Dust Extinction (XRIDE, Costantini et al. in prep.) model to investigate the scattering and absorption of electromagnetic waves by interstellar grains. It consists of a large sample of different interstellar dust analogues, mainly silicates, oxides and iron sulfides for which the extinction cross sections have been computed starting from laboratory measurements. Zeegers et al. (2017, 2019), Rogantini et al. (2018, 2019, 2020), Costantini et al. (2019) studied the dust through the Si, Mg, S, Al, C and Fe K-edges using different synchrotron beamlines in Europe. In this thesis, we continue the campaign with the investigation of the O K- (Chapter 2) and Fe L-edges (Chapter 3). To obtain the laboratory measurements, we used the Scanning Transmission Electron Microscope (STEM) located at the University of Cadiz. In Chapter 2 we describe in detail the acquisition process of the measurements and their analysis.

In order to compute the scattering and absorption of radiation by ID we first calculate the optical constants of the complex refractive index of the particles using our laboratory measurements and the Kramers-Kronig relations (Kronig 1926, Watts 2014). The optical constants are then used to derive the extinction cross section. There are different approximations to calculate the extinction cross section and the choice depends on the parameter space of interest, i.e. particle size and energy (Hoffman & Draine 2016). In this thesis we use the Mie Theory (Mie 1908, Wiscombe 1980) which provides a good approximation for the soft X-ray spectral region. To obtain the total extinction cross section as a function of energy, we integrate over a dust size

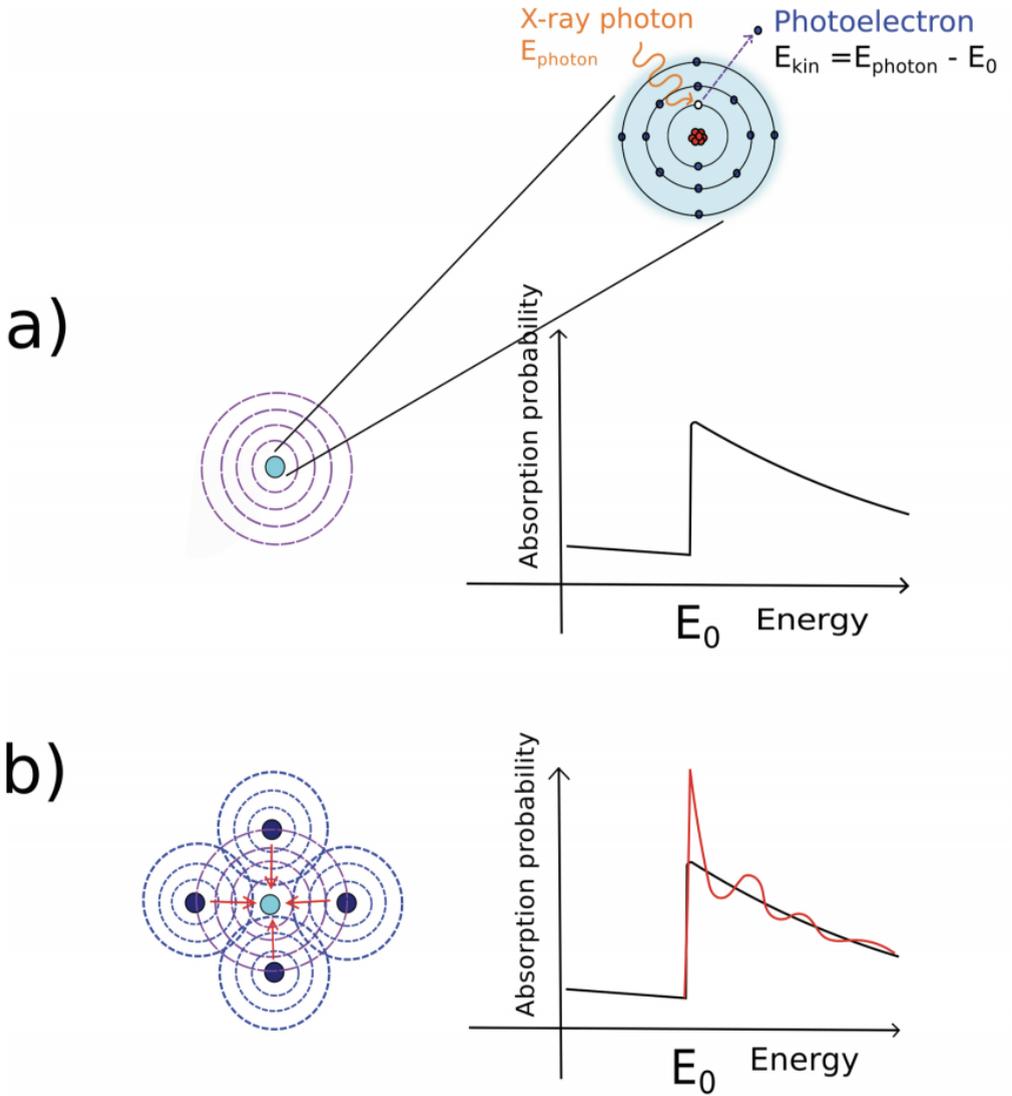


Figure 1.6: Illustration of a) photoabsorption edge. The the case of a single atom, the absorption probability is a smooth function. b) XAFS. In case of multiple atoms, the absorption probability is modified due to constructive and destructive interference. Credit: S. Zeegers

distribution, in our case MRN (see Section 1.2.2). Finally, we implement the new models into the SPEX X-ray fitting code (Kaastra et al. 2018).

Once the dust models are available, we apply them to high-resolution X-ray spectra of bright background sources. The typical column densities we examine in this thesis for the oxygen K- and iron L-edges are in the range of $\sim (1 - 8) \times 10^{21} \text{ cm}^{-2}$. To study the oxygen K-edge and the iron L-edges we use both XMM-*Newton* and *Chandra* observations. As we describe in Chapter 4, for the study of the oxygen K-edge we use the Reflection Grating Spectrometers (RGS, den Herder et al. 2001) on board of XMM-*Newton*. For the iron L-edges we use the High Energy Transmission Grating (HETGS, Canizares et al. 2005) on board of *Chandra*.

1.4 Photoionised gas in the vicinity of X-ray binaries

The discovery of photoionised plasma in the vicinity of X-ray binaries is a key ingredient to understand the physics of accretion and their feedback to the surrounding medium. After the launch of XMM-*Newton* and *Chandra* satellites it is possible to study in detail the nature of the photoionised gas through narrow absorption features. Ionised plasmas may be ubiquitous in X-ray binaries but they are easier to detect in high-inclination X-ray binary systems because of the equatorial geometry of the gas above the disk (Boirin et al. 2005, Díaz Trigo & Boirin 2013).

From observables we know that the accretion disks of compact objects are characterised by a complex structure and different components including a blackbody-like component from the disk, Compton up-scattering by a hot corona, as well as reprocessed X-ray emission from the disk (e.g. Done et al. 2007). The latter is responsible for the fluorescence lines and the Compton hump, known as reflection. Our knowledge about the vertical structure of the disk is limited. It is believed however that when the source luminosity reaches or exceeds the Eddington limit⁶ the disk is puffed up by radiation pressure (e.g. Poutanen et al. 2007). The same phenomenon happens when a disk exhibits winds due to radiation or magnetic pressure. The vertical structure of the accretion disk for compact objects at lower rates of accretion, such as 10% Eddington is not yet well understood.

In some low mass X-ray binaries an extended disk atmosphere has been observed (Díaz Trigo & Boirin 2016). The presence of this atmosphere has been associated with photoionisation of the outer parts of the accretion disk by the central X-ray source. The gas tends to move towards a situation of hydrostatic equilibrium and the disk scale height is increasing (Jimenez-Garate et al. 2005). In Figure 1.7 the theoretical view of the expansion of the outer parts of the disk is presented. The

⁶Eddington limit, is the maximum luminosity that an accreting object of a given mass can have in order to balance the radiation and gravitational forces.

exact nature and geometry of this gas is still unclear. For this reason it is important to study the photoionisation process around these sources using astronomical X-ray observations.

The light curve of high-inclination X-ray binaries ($\sim 70^\circ - 90^\circ$) can reveal events such as dips and eclipses. These two phenomena appear in the light curve as an abrupt drop in the count-rate (as in EXO 0748-676, Chapter 5). Eclipses appear when the companion star is passing in front of the compact object and hides the primary emission by the disk. Dips may be caused due to dense clouds (clumps) crossing our line of sight. It is believed that dips are over-densities in the impact region between the accretion stream and the disk. Time-resolved spectroscopy combined with photoionisation modelling is, therefore, a powerful and direct probe to study the vertical scale structure of the accretion disk, i.e the disk atmosphere.

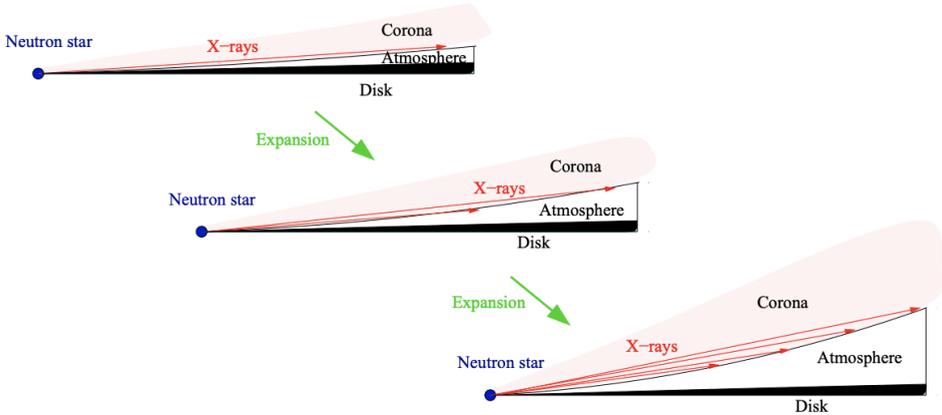


Figure 1.7: Illustration of an accretion disk atmosphere and the theoretical view of the expansion of the outer parts of the disk. The outer parts of the disk are heated due to X-ray irradiation from the central source (Jimenez-Garate et al. 2002 modified).

In Chapter 5, we investigate the photoionisation state of the accretion disk atmosphere in the low-mass X-ray binary EXO 0748-676. We performed time-resolved X-ray spectroscopic analysis which enabled us to resolve an extended disk atmosphere and probe its nature. We found strong emission lines during the eclipses indicating the presence of hot ionised gas above the surface of the accretion disk. We performed photoionisation modelling using SPEX and we discovered two different gas components, out of pressure equilibrium with each other. In Fig 1.8 we present an illustration of the extended disk atmosphere of EXO 0748-676. A hotter diffuse plasma is located above the disk, while a cooler, dense components (possibly clumpy) is instead believed

to be part of the region where the accretion stream from the companion star impacts the disk.

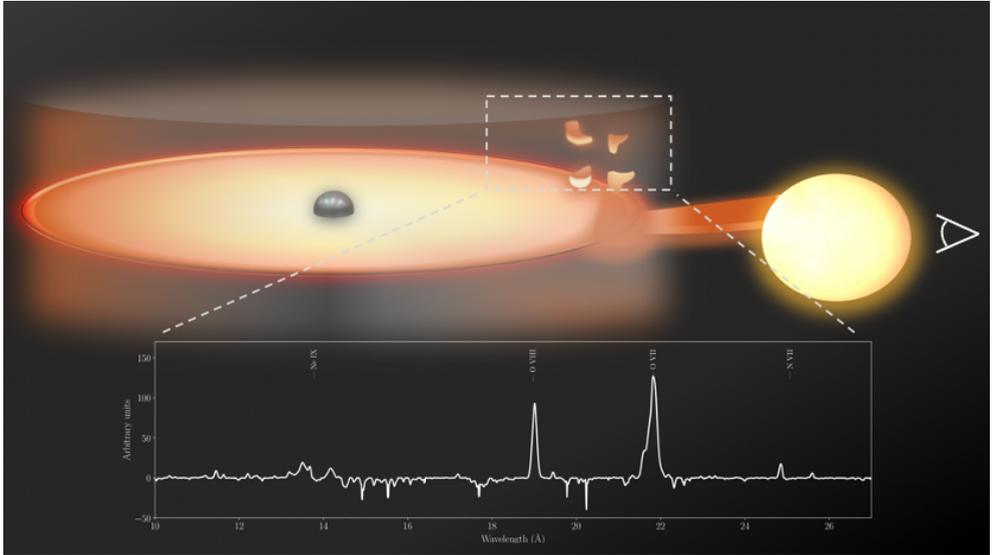


Figure 1.8: Artistic illustration of the low mass X-ray binary EXO 0748-676. Above the disk mid-plane we show the extended atmosphere of photoionised plasma, as well as the over-densities, possibly clumpy, that are believed to be produced by the impact of the accretion stream onto the disk. Below the binary we present the lines detected from the extended disk atmosphere and the clumps. A detailed explanation is presented in Chapter 5.

1.5 Future prospects

The capabilities of the *XMM-Newton* and *Chandra* satellites have played a major role in the new discoveries of the last 20 years. However, improved sensitivity and spectral resolution of the upcoming spectrometers will bring a breakthrough in X-ray astronomy and in particular for the study of interstellar gas and dust as well as the physics of compact objects in general. Below I briefly describe some of the newly planned missions or concept missions that are relevant for this research field. In Figure 1.9 we present the line detection figure-of-merit for selected currently operational and future observatories. The figure-of-merit provides information on the instrumental sensitivity and the capability of the mission to detect weak lines.

XRISM (the X-ray Imaging and Spectroscopy Mission, Tashiro et al. 2018) is a JAXA/NASA collaborative mission, with ESA participation (as well as SRON and

University of Geneva), expected to launch in 2021-2022. XRISM will carry a calorimeter spectrometer, *Resolve*, with an energy resolution of 5 eV in the 0.3-12 keV bandpass and an X-ray imager, *Xtend*. As presented in Costantini et al. (2019) *XRISM* will facilitate detailed studies of absorption edges of sulfur and iron.

Athena (the Advanced Telescope for High Energy Astrophysics) is a future X-ray telescope of the European Space Agency, currently under development and expected to be launched around 2031. *Athena* will revolutionize our understanding of the X-ray Universe (Nandra et al. 2013). It will have a large effective area and a spectral resolution of 2.5 eV in the 0.3-10 keV band. With *Athena* we will be able to study in detail the interstellar dust properties in the hard X-ray band. In particular we will be able to study the Fe K-edge, which is challenging with the current instruments (Rogantini et al. 2018).

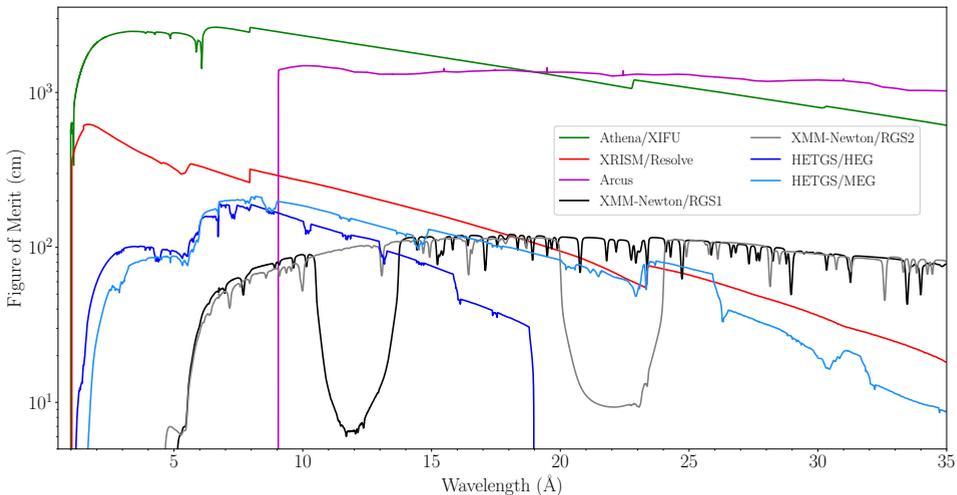


Figure 1.9: Line detection figure-of-merit for selected operational and future observatories. The figure of merit is in this case the square root of the effective area multiplied by the resolving power.

Arcus is a proposed X-ray observatory (Smith 2016) which would provide unprecedented high energy resolution data in the soft X-ray band (<1 keV). With a resolving power of $R \sim 3000$, *Arcus* will be the ideal satellite to study the oxygen K-edge (Chapter 2) as well as the neon K- and Fe L-edges. Also, with *Arcus* it will be possible to study for the first time the carbon K-edge in detail (Costantini et al. 2019). This will provide revolutionary results on the composition of the carbonaceous matter of the interstellar grains. This new mission with improved capabilities in the

soft X-ray band is necessary and, if combined with *XRISM* and *Athena*, it will give us further insights into the ID chemistry.

Finally, it is important to underline that the success of studies based on high-resolution X-ray spectroscopy is highly dependent on our knowledge of the atomic data. As explained in Chapter 3, accurate atomic databases are necessary and, once combined with very high-resolution spectra, will revolutionize our understanding of the hot, cold and dusty Universe.

1.6 Thesis outline

This thesis focuses on astrophysical processes from small scales like in compact objects, to larger scales as in the diffuse ISM. Particular emphasis is given to the study of the interstellar gas and dust along the Galactic plane. We use high-resolution X-ray spectroscopy as a tool to study the dust composition and crystallinity using the oxygen K- and iron L-edges. The new extinction models developed here aim to unveil the dust properties. We also use the oxygen K-edge as a laboratory to study the different ISM phases. Moreover, a smaller fraction of this thesis is focused on the nature and structure of the photoionised gas detected in the vicinity of X-ray binaries. Below, I describe the content of each chapter.

- *Chapter 2*: Here, we study the interstellar gas and dust in the oxygen K-edge. In order to model the dust features we obtain new laboratory measurements of interstellar dust analogues using the facilities located at the University of Cadiz, Spain. In this Chapter, we present the experiment and the treatment of the laboratory data in detail as well as the computation of the dust extinction cross sections. We further implemented these models into the SPEX spectral fitting program and apply them to the XMM-*Newton* spectrum of the low-mass X-ray binary Cygnus X-2. In this way we were able to study the depletion of oxygen into dust as well as the column densities of the different oxygen atomic species. We also investigate systematic uncertainties in the atomic data of the oxygen K-edge by comparing the databases of SPEX and XSTAR. Finally, we focus on future missions and we present the improvement of this study using a space observatory such as the mission concept of *Arcus*.

- *Chapter 3*: In this Chapter we continue the study of interstellar dust focusing on the iron L-edges. Iron in the ISM is believed to be highly depleted in solid phase providing an ideal case to study the XAFS and unveil the chemical composition of dust. Thanks to our experimental campaign, we obtained the models of twelve extinction profiles of the iron-L edge at $E=0.7$ keV. This complemented the measurements of oxygen taken during the same campaign. We study the absorption in the Fe L-edges

from the high-resolution *Chandra* spectrum towards the bright X-ray binary Cygnus X-1. We find that the dust particles are mainly of the family of silicates, with a majority of Mg-rich composition. Along the line of sight of Cyg X-1 there is also a multi-temperature gas, from cold gas up to temperatures of about 10^6 K.

- *Chapter 4*: Here, we expand the study of the previous Chapters to several lines of sight of bright X-ray sources along the Galactic plane. We fit simultaneously the oxygen K- and iron L-edges combining the capabilities of the high-resolution spectrometers on board *XMM-Newton* and *Chandra* satellites. In this way we are able to constrain the dust composition. We find that Mg-rich amorphous pyroxene is the compound that fits best to our spectra, while amorphous olivine is the second most dominant compound. We also find that about 10-25 % of oxygen is in dust, depending on the line of sight, and more than 90 % of iron is locked up in dust grains.

- *Chapter 5*: The focus of this Chapter is the physics of compact objects. We investigate the vertical structure of the accretion disk for the case study of the low-mass X-ray binary EXO 0748-676. We study the *XMM-Newton* spectrum during the eclipses which enabled us to resolve an extended disk atmosphere. We investigate the photoionised gas in the outer accretion disk corona and we probe its geometry. The photoionisation calculation was performed using the available models in SPEX.