The Hot and Dusty Instellar Medium through X-Ray Spectroscopy
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Summary

The interstellar medium is an enormous painting consisting of strong strokes of gas and dust which fill interstellar space and shades smoothly into the surrounding intergalactic canvas. Despite the extremely low particle density, on average lower than the vacuum in laboratories, from the interstellar medium, spectacular structures can arise which can be greatly different in temperature, density, composition and size. These define the patchy structure of the Milky Way, our home-galaxy.

The interstellar gas is primarily composed of hydrogen and helium. All the other elements (like carbon, oxygen, iron, magnesium), indicated as metals in astronomy, represent less than 2% of the total mass. Despite this small fraction, the metals have an important role in the chemical and physical processes of the Galaxy.

The interstellar medium is usually divided into three phases (cold, warm and hot phases) distinguished by the temperature and density of the gas. Cool and dense regions of the interstellar medium, contain most of the interstellar matter and they occupy less than 5% of the Galactic volume. The material is principally concentrated into giant clouds, known as molecular clouds, where molecular hydrogen coexists with neutral gas and interstellar dust. This cold medium is embedded in a hot buoyant medium (known as hot coronal gas) which occupies most of the volume of interstellar space and extends to the Galactic halo. In this floating and rarefied medium, matter is primarily ionised and heated by powerful shocks from stellar winds or supernova explosions. The space between the cold and hot phases is occupied by an extended intercloud medium, consisting of neutral and low ionised gas.

In this thesis we focus on the characterisation of the hot coronal gas and the interstellar dust, which represent only 1% of the interstellar matter. The novel methods and models developed for the investigation are presented in the sections below.

The hot medium

The existence of the hot interstellar medium was first postulated by Lyman Spitzer in 1956. He argued that the presence of clouds in pressure equilibrium observed at high latitude can only be explained by the existence of a Galactic corona made of tenuous gas at high temperature, above $10^{5.5}$ K. The final establishment of this hot gas corresponded with the detection of the diffuse O vi absorption line by the Copernicus satellite at ultraviolet wavelengths.

This very hot gas is in collisional ionisation equilibrium which means that the ionisation by collision with electrons is balanced by electron-ion recombination. The ionisation balance in collisionally-ionised plasmas depends only on the electron temperature, and it is therefore
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Figure A: The Horsehead Nebula located in the Orion constellation. It is visible as the dark indentation to the red emission nebula in the centre of the photograph. The emission nebula’s red colour is caused by electrons recombining with protons to form hydrogen atoms. Also visible at the bottom left is a greenish reflection nebula that reflects the blue light from nearby stars. Credits: John Chumack

tightly coupled to the local thermodynamic state of the gas.

The hot coronal gas is mainly studied through absorption lines (O\text{vi}, N\text{v}, and C\text{iv}) observed in the spectrum of hot stars. When the temperature of the plasma exceeds $10^6$ K, higher ionisation states, such O\text{vii}, O\text{viii}, Ne\text{ix}, and Ne\text{x}, are allowed. The absorption lines of these ions are located in the X-ray energy bandpass. Their detection has been possible with the launch the European X-ray satellite XMM-\textit{Newton} and the American Chandra X-ray Observatory both launched in 1999. Bright low-mass X-ray binaries in the Milky Way are ideal sources to study the intervening gas along the line of sight, simply using them as a background lantern. These sources consist of one compact object (a neutron star or a stellar mass black hole) which accretes material from a companion star. The infalling material releases gravitational potential energy in form of X-rays.

These X-ray high-ionisation absorption lines can also be produced by a plasma in photoionisation equilibrium. This kind of gas is photoionised by the radiation emitted by a strong X-ray source. It is usually a gas intrinsic to the source such as an accretion disc wind or atmosphere. Therefore, to identify the nature of these absorption lines is not trivial and an accurate analysis is necessary. In Chapter 2, a novel technique based on the Bayesian inference is developed to assess the nature of the high-ionisation plasma detected along the line of sight towards 4U 1820-30. This source is a tiny binary system whose dimension is 0.1 times the radius of the Sun. In the joint modelling of XMM-\textit{Newton} and Chandra we adopt state-of-art models of collisionally ionisation and photoionisation. The result of our fit indicates the existence of a single temperature $T \sim 10^6$ K plasma in collisional ionisation
equilibrium along the line of sight towards the source. To overcome the complexity of the X-ray spectroscopy modelling we used a statistical approach based on the Bayesian data analysis.

**The dusty medium**

In the beginning of the last century, cosmic dust was regarded by astronomers as an annoying interstellar “fog” which impedes an accurate measurement of distances to stars. Only thirty years later the important role of interstellar dust as a catalyst in the evolution of galaxies, the formation of stars and planetary systems, and possibly, the origins of life was revealed. The advances of infrared astronomy, ultraviolet astronomy, and theoretical modelling had a tremendous impact on our understanding of the physical and chemical nature, origin and evolution of interstellar grains and their significance in the evolution of galaxies. Dust grains provide \( \geq 30\% \) of the total Galactic luminosity through infrared emission and they actively participate in the life cycle of stars starting with the formation of small refractory particles in stellar atmospheres to their modification in diffuse and molecular clouds and ultimately to their contribution to star forming regions.

Dust exists mainly of carbon, silicon, iron, magnesium and oxygen and it can be roughly divided into two main groups, namely carbonaceous dust (comparable to soot) and silicates.

**Figure B:** The twisty central shape is known as Snake Nebula (or Barnard 72) and it is a dark nebula in the Ophiuchus constellation in the centre of the Milky Way. Other dark clouds are present below the Snake Nebula, in particular Barnard 68 which is the first from the right. Astronomers used to consider these dark molecular clouds as holes in the sky or "heaven" as Herschel exclaimed in 1785. Now we know that the high concentration of dust and molecular gas contained in these dark clouds absorb practically all the visible light emitted from background stars. Credits: Mario Cogo, 2014 from Tivoli Southern Sky Guest Farm, Namibia
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(e.g., pyroxene and olivine type, comparable to tiny sand grains). In cold and dense environment embedded in molecular clouds the refractory core of silicates can accrete an ice mantle which is dominated by water and methanol. Laboratory astrophysics showed the importance of these ices for the synthesis of complex organic molecules which possibly leads to the origins of life.

There are still many uncertainties about interstellar dust such as the precise chemical composition of the grains, or their structure (crystalline or amorphous). Furthermore, the properties of the dust grains in dense environment are difficult to assess. In this direction, X-ray absorption spectroscopy is a powerful tool and it can give some answer to some of the open questions.

XMM-Newton and Chandra enabled the detection of particular dust features known as X-ray absorption fine structure (XAFS), in the spectra of bright X-ray binaries. Through the analysis of these fine structures it is possible to probe directly the chemical composition, cristallinity and size distribution of dust grains in different Galactic environments. X-rays are sensitive to a large range of densities and their energy band hosts the edges of the main elements included in dust. In particular, the current X-ray telescopes permit the study of oxygen, iron, magnesium and silicon which are the main components of silicate grains.

The goal of this thesis is to build astronomical models based on accurate laboratory measurements in order to fit the dust fine structures and exploit the diagnostic they offer. In Chapters 3 and 5 we present, respectively, the extinction\(^1\) models of the magnesium and iron K-edge for a large set of dust analogues. By joining all the extinction edge models, we will build the first X-ray interstellar dust extinction (XRIDE) model.

In Chapter 3 we use the spectrum of the low-mass X-ray binary GX 3+1 as a test case to study interstellar dust present along the line of sight toward the source. In particular, we investigate the magnesium and silicon K-edge using our extinction models. In Chapter 4 we expand the number of observed X-ray binaries to seven more sources located near the Galaxy centre. Amorphous olivine is the most representative dust compound along all the investigated lines of sight. We also find a significant contribution (3-15\%) of crystalline dust. This is in contrast with the observational results obtained from infrared spectroscopy, where only less than 2\% of crystalline dust is detected. This difference may be attributed to the sensitivity of X-rays to short range order, whereas, the infrared observations are focussed on long range order of the dust grains. To fully understand this discrepancy it is necessary to dedicate laboratory studies on the difference between the sensitivity of X-rays and infrared to the crystallinity of the solid.

The iron K-edge represents a unique feature to study the interstellar dust present in the densest region of the Galaxy. Unfortunately, both the sensitivity and the resolution of the current X-ray satellite are not high enough to enable the study of this edge. In Chapter 5 we present the potential of future X-ray missions, XRISM (to be launched in 2021) and Athena (to be launched in 2031), to observe the Fe K-edge and thanks to our extinction model, to reveal the content of iron in interstellar dust.

High-resolution X-ray spectroscopy represents a powerful method to reveal the characteristics of the interstellar dust and hot coronal gas. An accurate model and a solid statistical

\(^1\)X-ray extinction is the sum of X-ray absorption and scattering.
approach are important to interpret correctly the data and obtain robust results. In this perspective, this thesis contributes in the production of a new dust extinction model and the development of a simple Bayesian inference tool suitable for fitting high-resolution X-ray spectra. These tools provide both a way for interpreting present day data and a step forward in the necessary innovation path to interpret the complex X-ray observation from upcoming X-ray missions.